CARDIORESPIRATORY, KINEMATIC, NEUROMUSCULAR AND METABOLIC CHARACTERISTICS DURING THE RECOVERY PERIOD AFTER AN ULTRAMARATHON RACE

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Theresa Lee Burgess

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STUDY ONE

The aim of this study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon on submaximal oxygen consumption and stride length. The experimental group consisted of 11 male runners (39.7 ± 9.3 years) competing in a 90 km ultramarathon. Ten male runners (41.0 ± 10.8 years) who did not run the 90 km ultramarathon formed the control group. Maximum oxygen consumption and peak treadmill running speed were measured two weeks before the ultramarathon. Daily measurements of muscle pain and plasma creatine kinase (CK) activity were recorded for seven days after the ultramarathon. Muscle pain, plasma CK activity, and blood lactate concentrations were recorded before, and oxygen consumption, respiratory exchange ratio (RER), heart rate, rate of perceived exertion (RPE), and stride length were all measured during a 15-minute submaximal treadmill test seven days before the ultramarathon, and on days 4, 7, 14, 21, and 28 after the ultramarathon. Peak blood lactate concentrations were determined 3 minutes after the completion of each treadmill test. Plasma CK activity and muscle pain remained significantly elevated in the experimental group for two days ($p < 0.00002$) and four days ($p < 0.02$) respectively after the ultramarathon. There was a significant increase in the post-submaximal treadmill test blood lactate concentrations, compared to pre-test values for each day ($p < 0.00001$). Submaximal oxygen consumption was significantly reduced in the experimental group for up to 28 days ($p < 0.0004$), and stride length was significantly reduced for 14 days ($p < 0.05$) after the ultramarathon. Furthermore, in the experimental group RER was significantly increased for up to seven days ($p < 0.05$), and RPE was significantly increased for up to four days ($p < 0.04$) after the ultramarathon. In conclusion, the decreased submaximal oxygen consumption following the ultramarathon may be interpreted as a positive training adaptation. However, other responses to the ultramarathon were not compatible with improved running performance. Furthermore, symptoms other than pain should be used to define the recovery period after an ultramarathon race.

STUDY TWO

The aim of this study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon on submaximal oxygen consumption and running kinematics in experienced ultramarathon runners. Eleven male runners (41.0 ± 8.4 years) participating in a 90 km ultramarathon formed the experimental group. The control group consisted of 13 male runners (40.2 ± 11.1 years) who did not compete in the 90 km ultramarathon race. Maximum oxygen consumption and peak treadmill running speed were measured two weeks before the ultramarathon. Daily measurements of muscle pain and plasma creatine kinase (CK) activity were recorded for seven days after the ultramarathon. Muscle pain and plasma CK activity were recorded before, and oxygen consumption, respiratory exchange ratio (RER), heart rate, rate of perceived exertion (RPE), and lower limb running kinematics, stride length, and vertical displacement of the centre of mass were all measured during a 15-minute submaximal treadmill test seven days before the ultramarathon, and on days 4, 7, 14, 21, and 28 after the ultramarathon. Plasma CK activity and muscle pain remained significantly elevated in the experimental group for two days ($p < 0.002$) and seven days ($p < 0.00004$) respectively after the ultramarathon. Submaximal oxygen consumption was significantly reduced in the experimental group for up to 28 days ($p < 0.02$), and RER was significantly increased for up to four days ($p < 0.05$) after the ultramarathon. In addition, RPE was significantly increased for up to 28 days ($p < 0.04$) after the ultramarathon. Although there was a moderate association between submaximal oxygen consumption and the vertical displacement of the centre of mass, only discrete changes in kinematic variables were observed during the recovery period after the ultramarathon race. These kinematic adaptations may reflect compensatory alterations in motor unit activation or shock attenuation. Further studies should determine whether the long-term reduction in submaximal oxygen consumption is associated with improvements in running performance.

STUDY THREE

The aim of this study was to investigate the effects of exercise-induced muscle damage and fatigue, induced by an ultramarathon, on muscle preactivation and running performance in experienced ultramarathon runners. The experimental group consisted of 11 male runners (42.2 ± 6.1 years) competing in a 90 km ultramarathon. Twelve male runners (37.5 ± 5.9 years) who did not run the 90 km ultramarathon formed the control group. Maximum oxygen consumption and peak treadmill running speed were measured two weeks before the ultramarathon. Daily measurements of muscle pain and plasma creatine kinase (CK) activity were recorded for seven days after the ultramarathon. A track test, consisting of a 1.4 km submaximal run, 20 m sprint tests, a 5 km time trial run, and the measurement of muscle pain and plasma CK activity was performed seven days before, and 10 days after the ultramarathon. The rate of perceived exertion (RPE) and heart rate were measured during the submaximal and time trial runs. Surface electromyographic (EMG) activity was recorded in the vastus lateralis, vastus medialis, biceps femoris and medial gastrocnemius muscles during the submaximal, sprint, and time trial runs to determine muscle preactivation. Plasma CK activity and muscle pain remained significantly elevated in the experimental group for four days ($p < 0.006$) and three days ($p < 0.05$) respectively after the ultramarathon. 5 Km time trial performance remained relatively unchanged in both the experimental (pre-race 21.5 ± 1.5 minutes vs. post-race 21.5 ± 1.6 minutes) and control (pre-race 20.8 ± 2.3 minutes vs. 20.7 ± 2.3 minutes) groups after the ultramarathon race. However, in the experimental group RPE was significantly increased during the submaximal ($p < 0.03$) and time trial ($p < 0.009$) runs, and heart rate was significantly increased during the time trial run ($p < 0.03$) after the ultramarathon race. Muscle preactivation was also significantly reduced in the experimental group biceps femoris ($p < 0.05$) and medial gastrocnemius ($p < 0.04$) muscles after the ultramarathon race. The change in 5 km time trial time was correlated to the total years of running ($r = -0.61$; CI: -0.89 to -0.02; $p < 0.05$), the number of marathons ($r = -0.76$; CI: -0.93 to -0.30; $p < 0.007$), and the number of ultramarathon races ($r = -0.77$; CI: -0.94 to -0.31; $p < 0.006$) for the experimental group. Therefore, endurance running performance remained relatively unchanged during the recovery period after an ultramarathon race. In addition, neuromuscular adaptations may act as a protective mechanism following exercise-induced muscle damage and fatigue.

STUDY FOUR

The aim of this study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon race on submaximal oxygen consumption and glucose metabolism in experienced ultramarathon runners. Eleven male runners (42.2 ± 6.1 years) participating in a 90 km ultramarathon formed the experimental group. The control group consisted of 12 male runners (37.5 ± 5.9 years) who did not compete in the 90 km ultramarathon race. Maximum oxygen consumption and peak treadmill running speed (PTRS) were measured two weeks before the ultramarathon. Daily measurements of muscle pain and plasma creatine kinase (CK) activity were recorded for seven days after the ultramarathon. A 20-minute submaximal treadmill test (75% of PTRS) was performed seven days before, and 10 days after the ultramarathon. An initial resting blood sample was taken for the determination of resting plasma glucose and lactate concentrations, and plasma CK activity. A 1.5 µCi of [U-^{14}C] bicarbonate bolus and a priming dose of 6 µCi [U-^{14}C] glucose were infused, followed by a constant infusion of [U-^{14}C] glucose at a rate of 0.17 µCi.min^{-1} for the duration of the submaximal test. Muscle pain was measured before, and oxygen consumption (VO_2), respiratory exchange ratio (RER), heart rate (HR), and the rate of perceived exertion (RPE) were measured during the submaximal treadmill test. Expired carbon dioxide (CO_2) samples, and blood samples for plasma glucose and lactate concentrations were taken every 5 minutes during the submaximal treadmill test. The glucose oxidation rate was calculated on completion of the testing procedure. Plasma CK activity and muscle pain remained significantly elevated in the experimental group for four days ($p < 0.006$) and three days ($p < 0.05$) respectively after the ultramarathon. In the experimental group, there was a significant reduction in submaximal oxygen consumption ($p < 0.04$), and significant increases in RER ($p < 0.02$), average heart rate ($p < 0.02$), and RPE ($p < 0.05$) after the ultramarathon. There was also a strong tendency for the glucose oxidation rate to be decreased in the experimental group after the ultramarathon race, compared to pre-race values. The paradoxical increase in RER and reduction in glucose oxidation rate, together with the reduction in submaximal oxygen consumption, may indicate the preferential use of type II muscle fibres following exercise-induced muscle damage. It should therefore be established whether these adaptations are favourable or detrimental to long-term endurance running performance.

CHAPTER ONE
INTRODUCTION AND SCOPE OF THE THESIS

Exercise-induced muscle damage is a common occurrence following unaccustomed exercise, and is characterised by a complex interaction of central and peripheral adaptations involving cellular, mechanical, and neural mechanisms[98;133;196]. Exercise-induced muscle damage is also associated with alterations in functional capacity, including force loss, changes in the length-tension relationship, and neuromuscular adaptations[137;175;198;225;394;422;468;658].

Collectively, studies investigating the effects of endurance running have demonstrated ultrastructural muscle damage[15;94;284;591;592], and numerous metabolic[23;342;587;642], neuromuscular[32;120;475;476;586], and biomechanical[29;32;268;369;474] adaptations. These changes may occur as a result of both endurance running training and competition, and may be associated with a decrement in endurance running performance. It is also acknowledged that there appears to be large inter-individual variation in the ultrastructural muscle damage associated with endurance running[284;592;656].

Regular endurance training is also associated with numerous morphological, metabolic, and neuromuscular adaptations. These adaptations function primarily to reduce the extent of cellular disturbances during subsequent training bouts[480]. Furthermore, the cumulative effects of regular exercise training are linked to chronic adaptations of skeletal muscle, including increased mitochondrial enzyme activity and protein concentration, increased capillary density, and an increased reliance on fat as a fuel, with a reduction in glycolytic flux. These adaptations are associated with an improvement in endurance performance[271].

Notwithstanding the positive effects of regular endurance exercise, relatively few studies have investigated the response of direct measurements of endurance performance, such as time to exhaustion at a fixed workload or time trial performance, to exercise-induced muscle damage[412]. Recently, Marcora and Bosio[412] observed a significant reduction in self-paced time trial performance in moderately trained runners following exercise-induced muscle damage. Nevertheless, further studies are required to understand the relationship between exercise-induced muscle damage and endurance running performance.

Running economy is an important determinant of endurance running performance[50;76;146;166;359;453;480;571]. Numerous physiological, psychological, training, biomechanical, and environmental factors have been identified as influencing running economy[170;457;571]. However, little is known regarding the cumulative effect of prolonged periods of vigorous training and competition, exercise-induced muscle damage, and fatigue on running economy[455;456]. In addition, the recovery pattern following prolonged endurance running has not been studied extensively[524].

Noakes[479] proposed five different models to explain the possible physiological and other training-induced changes that may be associated with delaying or preventing the onset of fatigue, and therefore improving endurance performance. However, due to the complex nature of exercise performance, it is unlikely that the factors contributing to performance will be restricted to one physiological system[479]. Similarly, it may be hypothesised that the recovery from ultra-endurance exercise may involve a complex integration of physiological, biomechanical, and neuromuscular factors that may include a concurrent effect on endurance performance. However, there is currently a lack of evidence to support this novel hypothesis.

Therefore, the principle aim of this thesis was to determine the effects of exercise-induced muscle damage on cardiorespiratory, kinematic, neuromuscular, and metabolic characteristics during the recovery period following an ultramarathon race.

The specific questions arising from this aim include:

1. Are alterations in running economy evident during the recovery period following exercise-induced muscle damage induced by an ultramarathon race?

2. Is running economy influenced by changes in stride parameters and running kinematics during the recovery period after an ultramarathon race?

3. What are the effects of an ultramarathon race, and subsequent muscle damage and fatigue, on muscle preactivation in experienced ultramarathon runners?

4. What are the effects of exercise-induced muscle damage and fatigue on glucose metabolism during the recovery period after an ultramarathon race?

5. Is running performance affected during the recovery period following an ultramarathon race?

In preparation for the experimental section of the thesis, a comprehensive review of the literature on exercise-induced muscle damage and running economy will be presented. This will be followed by a description of the studies which are designed to answer the questions outlined above. The experimental section will be followed by a summary and conclusion section, which includes a model that has been proposed to explain and integrate the cardiorespiratory, kinematic, neuromuscular, and metabolic changes following an ultramarathon race.

CHAPTER TWO
LITERATURE REVIEW: EXERCISE-INDUCED MUSCLE DAMAGE AND RUNNING ECONOMY

2.1 EXERCISE-INDUCED MUSCLE DAMAGE

Endurance training is associated with both central and peripheral adaptations, including altered neural recruitment patterns, skeletal muscle morphology, and substrate metabolism[140;271]. However, exposure to unaccustomed exercise, or exercise with an increased intensity or duration may lead to exercise-induced muscle damage. Evidence of exercise-induced muscle damage includes morphological changes, delayed onset muscle soreness, and impaired muscle function[135;136;138;196;468;547;596]. Lengthening muscle actions are also associated with greater evidence of exercise-induced muscle damage than isometric or shortening muscle actions[244;325;356;467;468]. Exercise-induced muscle damage is a common occurrence during distance running, as it involves prolonged or intense stretch shortening cycle exercise[22;23;120;284;586;656]. Further, muscles adapt to the stress of repeated exercise, such that subsequent bouts of exercise result in a reduction in the symptoms of exercise-induced muscle damage[137;196;428;429]. This review will outline the effects of endurance running, the adaptations of skeletal muscle to endurance training, and the proposed mechanisms underlying exercise-induced muscle damage, delayed onset muscle soreness, and the repeated bout effect.

2.1.1 MUSCLE DAMAGE AND ENDURANCE RUNNING

Numerous studies have investigated the physiological effects of marathon and ultramarathon races. Previous studies on runners of the 90 km Comrades marathon have provided information regarding changes in electrocardiographic (ECG) activity[165;433;500], serum enzyme activities[164], C-reactive protein levels[616], fluid balance[164], renal function[310], including the factors explaining the development of hyponatraemic encephalopathy[309], and the decrement of muscle power associated with muscle damage[120]. In addition, several studies have observed ultrastructural skeletal muscle damage in relation to marathon and ultramarathon races[284;587;591;592;656].

2.1.1.1 Ultrastructural effects of endurance running

Hikida et al[284] investigated the effects of a 42 km marathon on the muscle morphology of 10 male distance runners. Muscle biopsy samples were obtained before the marathon, at 15 minutes after the marathon, and on days 1, 3, 5, and 7 after the marathon. Interestingly, both the pre-race and post-race muscle biopsies demonstrated signs of repetitive trauma and muscle damage, including evidence of muscle fibre necrosis and inflammation, leukocytic and phagocytic activity, and the presence of erythrocytes and mitochondria in the interstitial space.

In addition, muscle fibre changes included disruptions of the sarcolemma, degeneration and streaming of the Z-lines, "contractile knots", empty basal lamina tubes in which the contents of the muscle fibre and the sarcolemma had broken down, and the accumulation of phagocytes, erythrocytes, and mitochondria within the muscle extracellular spaces. There were also crystalline inclusions within the mitochondria, and in the muscle samples collected after the marathon, mitochondria were observed being actively engulfed by phagocytes in the basal lamina. These structural abnormalities were most prevalent at days one and three after the marathon, and persisted for the seven-day testing period after the marathon[284].

Furthermore, degenerative peripheral myofibrils were observed, with an associated loss of Z-lines, abnormally aligned sarcomeres, and the presence of bodies containing only microfilaments in the muscle biopsy. Atrophic fibres and satellite cells were also detected, mainly in the later biopsy samples taken after the marathon[284].

The authors theorised that, as the structural abnormalities were observed in the pre-race muscle biopsy samples and remained evident for the seven-day period after the marathon, the intensive training for the marathon and the marathon itself were sufficient to induce inflammation and fibre necrosis. It was also proposed that the inflammatory response following the marathon may contribute to the sensation of delayed onset muscle soreness[284].

A potential weakness of this study was the lack of a non-exercising control group. It may therefore be possible that the signs of muscle damage were due to a technical artefact, particularly as signs of muscle damage were present in both pre-race and post-race biopsy samples. However, previous work using the same techniques on groups of sedentary and athletic subjects did not illustrate similar patterns of muscle damage[14].

In a similar study, Warhol et al[656] examined skeletal muscle injury and repair in 40 male distance runners following a marathon. Gastrocnemius muscle biopsy samples were obtained immediately after the marathon, and on days 1, 2, 3, 5, 7, 10, 14, 21, 28, 42, 56, 70, and 84 after the race. Evidence of cell injury, including interstitial collagen deposition and thickened capillary basal lamina, was noted in the samples prior to the marathon. It was proposed that these changes may be associated with the training involved in the preparation for the race.

After the marathon up to 25% of the muscle fibres of runners exhibited areas of myofibrillar loss. The myofibrillar loss was extremely patchy, and was not greater than 10% of the fibre length. Other ultrastructural changes in the muscle biopsy samples included intra- and extracellular oedema with endothelial injury, myofibrillar lysis, dilation and disruption of the t-tubule system, and mitochondrial damage which was manifested by dissolution of cristae and loss of mitochondrial matrix[656].

All subjects showed depletion of glycogen and lipid stores within two days after the race. At seven days after the race, satellite cells and interstitial cells that resembled fibroblasts were present in the muscle tissue. At four weeks after the marathon there was evidence of myofibrillar damage resolution, with abundant mitochondria and central cell nuclei, indicative of regeneration[656].

Muscle biopsy samples at eight and 10 weeks after the marathon showed further evidence of continued regeneration and repair, and the mitochondria had abnormal size and shape. Prominent satellite cells were also present at this stage. It was hypothesised that the satellite cells may be the precursor to new skeletal muscle cells[656]. It is now well accepted that this is indeed the case[256].

At 10 to 12 weeks after the race, the muscle biopsy samples had central nuclei, and an increased content of endoplasmic reticulum. These characteristics are associated with the regenerative process. In addition, the changes observed in the muscle samples in this study were focal, and confined to individual sarcomere units. It may be proposed that these changes are indicative of repetitive cell injury, but not of muscle fibre necrosis[656].

Kuipers et al[372] monitored the histological and ultrastructural features of the vastus lateralis muscle in untrained male and female subjects during an 18 to 20 month training period. During this period, training distance was gradually increased, and subjects also participated in 15 km, 25 km, and 42 km races at 6, 11, and 18 months during the training period respectively. Muscle biopsy samples from the vastus lateralis were obtained five days before each race, and at 0.5 to six hours, and eight to nine days after each race.

The first pathological changes were observed in the muscle biopsy sample immediately after the 15 km race. Ultrastructural changes included central nuclei, irregular Z-lines and hypercontractions of sarcomeres, particularly in the peripheral areas of the muscle fibres. However, no sarcolemmal damage or mitochondrial abnormalities were observed. The pathological features were present in both type I and type II muscle fibres. The frequency of the abnormalities also appeared to increase with the length of the training runs. These findings indicated that training for distance running may be associated with pathological changes in the muscles, reflected by the continuous degeneration and regeneration of skeletal muscle. It was therefore proposed that the extent of changes in the morphological characteristics of skeletal muscle may be related to the total training distance, rather than to the exercise intensity. In addition, the study highlighted the combined effects of training and racing, and the possible cumulative effects of repetitive bouts of muscle damage[372].

Sjöström et al[592] obtained muscle biopsy samples from the gastrocnemius muscle of a well-trained veteran distance runner before and after an extremely long run. The runner covered a distance of 3529 km in a seven-week period, with an average distance of 70 km per day.

The pre-run sample did not show significant evidence of any pathological changes. This finding was contrary to the finding of Warhol et al[656] and Hikida et al[284]. Immediately after the run, the muscle biopsy sample was characterised by muscle fibres of varied size and shape that were tightly packed in well-defined fascicles. There was an increase in perifascicular connective tissue, which was also infiltrated by inflammatory cells. Other pathological changes included an increase in the amount of central nuclei, and evidence of necrosis, phagocytosis, and regeneration[592].

Many fibres from the post-run sample also appeared to be uneven and had a "moth-eaten" appearance, suggesting possible architectural disturbances. The presence of angular fibres and fibre-type grouping may have been a result of repetitive denervation and re-innervation of parts of the fibre population. It was theorised that these findings were indicative of a reactive healing process, and that fibre damage and disintegration had been in progress for a long period. In addition, there was an increase in the relative amount of type I muscle fibres and a decrease in the size of the remaining type II muscle fibres in the post-run sample, compared to the pre-run sample. This may represent selective vulnerability of muscle fibre types to extreme endurance exercise[592]. Similar findings were reported by Matin et al[417].

Sjöström et al[593] compared muscle biopsy samples from the vastus lateralis muscle of sprinters and marathon runners. The muscle biopsy samples of the sprinters had polygonal-shaped fibres, well-organised fascicles, and similar morphological features between subjects. However, the muscle biopsy samples of the marathon runners showed considerable inter-individual variability in the overall muscle morphology. The structural deviations that were observed included poor organisation of the fascicles, abundant and diffuse connective tissue, central nuclei, and irregularly shaped fibres. There was also evidence of fibre-type grouping. It was proposed that type II muscle fibres may be more vulnerable to damage, as the subjects with the lowest number of type II muscle fibres had the least muscle pathology.

Furthermore, Goodman et al[249] obtained muscle biopsy samples from the lateral gastrocnemius muscle of runners 24 hours before, and 24 hours after a 21 km run. Ultrastructural examination revealed pleomorphic mitochondria with increased density, subsarcolemmal accumulation of mitochondria, lipofuscin granules, and paracrystalline inclusions within mitochondria, in both the pre- and post-exercise samples. However, there were no disturbances in the myofibrillar architecture, and the plasma membrane remained intact in the pre- and post-exercise samples. Therefore, there was little evidence of any ultrastructural damage following the 21 km run, but all subjects exhibited signs of chronic muscle damage associated with endurance running training and racing.

Overgaard et al[502] investigated a group of runners who had completed a 100 km ultramarathon race, and found that total muscle calcium (Ca^{2+}) content was increased by 22% immediately after the race. The increased calcium content coincided with large increases in plasma creatine kinase activity and lactate dehydrogenase concentrations.

More recently, Overgaard et al[501] determined that significant increases in muscle calcium content occurred for up to 48 hours following a 20 km run. A significantly lower muscle calcium content was observed following a 10 km run, suggesting that calcium accumulation is positively related to running distance or the time spent running.

St Clair Gibson et al[609] obtained muscle biopsy samples from a 28 year old male international level runner who complained of a progressive decline in running performance, that was associated with an increasing inability to tolerate high-distance training, particularly above 100 km.wk^{-1}. An initial muscle biopsy sample was obtained from the vastus lateralis muscle. Four months later, a second muscle biopsy sample was obtained from the same vastus lateralis muscle, and also from the triceps muscle. The triceps muscle sample was obtained to represent a non-weightbearing muscle not involved in locomotion, and therefore not actively recruited during running.

The initial muscle biopsy sample showed no evidence of inflammation, necrosis, or regeneration of muscle fibres. The muscle interstitium, capillary vessels, lipid and glycogen content all appeared normal. However, histochemical analysis revealed uneven mitochondrial distribution with subsarcolemmal mitochondrial aggregation. In addition, several muscle fibres had a ragged, red appearance[609].

Similar findings were observed in the second vastus lateralis muscle biopsy sample. Interestingly, no such abnormalities were present in the triceps muscle biopsy sample. Further analysis of the vastus lateralis muscle biopsy samples using electron microscopy showed that the mitochondria were varied in size, and contained a dense matrix with an increased number of coarse and broad cristae. The abnormal mitochondria were found in large subsarcolemmal aggregates, as well as along the sarcomere[609].

It was theorised that the mitochondrial abnormalities may have been due to mitochondrial myopathy, unknown infective or toxic agents, or the excessive exercise routine that occurred for much of the subject's life up until early adulthood. It was further proposed that exercise-induced muscle damage associated with long-term endurance running training was the most likely explanation, as the mitochondrial abnormalities were limited to the vastus lateralis muscle biopsy samples[609].

In addition, the mitochondrial abnormalities in the subsarcolemmal space may be an exaggerated example of the normal response to endurance training. The authors also speculated that the mitochondrial abnormalities might have been the underlying mechanism responsible for the reported decrements in the subject's running performance[609].

2.1.1.2 Aging and endurance running

Anecdotal evidence from elite marathon runners suggests that there is a period of approximately 10 to 15 years, during which time the runners are able to be competitive within their age-group[480]. Lambert and Keytel[380] also reported that the age-group winners in a 56 km ultramarathon race had all been running for approximately 15 years.

In addition, a case report of an endurance runner, who had accumulated a training distance of 153 944 km and a racing distance of 16 604 km in 37 years of running, showed that running performance started to decrease at a faster rate than was expected for his increasing age after he had been competing for approximately 15 years[379].

Conversely, Rae et al[549] examined the interaction between aging and 10 years of racing in endurance runners. Using the race data of runners between 20 and 60 years of age who had completed between nine and eleven 56 km ultramarathon races, it was established that the combined effects of 10 years of aging and 10 years of racing did not improve or worsen running performance. Interestingly, running performance improved and declined at greater rates in the younger runners, compared to the older runners.

Furthermore, anecdotal evidence suggests that endurance runners who begin training and racing later on in their lives are able to perform at a higher standard compared to endurance runners of the same age who have been competitive for many years[480].

Trappe et al[637] examined the alterations in the skeletal muscle characteristics among distance runners in a 20-year follow-up study. The runners were divided into three groups based on their current participation in competitive running events, and included a competitive group, a group who trained for physical fitness, and a group who no longer participated in physical activity.

The combined data from all three groups demonstrated that there was a significant increase in the proportion of type I muscle fibres with age. This response was however attenuated in the competitive group, where mean muscle fibre composition remained unchanged. The competitive runners experienced an approximately 25% reduction in muscle succinate dehydrogenase activity, suggesting a lower oxidative capacity of the skeletal muscle. This alteration in fibre composition may therefore be independent of prolonged endurance running, but may be influenced by the individual's genetic fibre composition[637].

Trappe et al[637] and Widrick et al[672] also showed a reduction in type I and type II muscle fibre area, when compared to previous values from 20 years earlier, or sedentary controls respectively. Although Widrick et al[672] determined that the smaller fibre area might be related to a reduction in force in the gastrocnemius muscle of runners compared to a sedentary control, the reduction in muscle fibre area may not be a disadvantage for endurance running.

A smaller muscle fibre diameter would reduce the diffusion distance between the mitochondria and the capillary, leading to a more efficient delivery of oxygen and fuel to the working muscle[672]. Furthermore, although endurance runners had an increased shortening velocity and contractile speed, sedentary individuals were consistently more powerful in both type I and II muscle fibres[637;638;672;673].

2.1.1.3 Metabolic effects of endurance running

Sherman et al[587] determined that muscle glycogen stores were depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after a marathon. Five days later, muscle glycogen concentrations were still below the pre-race values, although glycogen synthase activity had returned to normal. The time taken to normalise muscle glycogen concentrations after exercise that causes muscle damage is not well known, but is thought to be 10 days or longer[498].

The muscle glucose transporter GLUT-4 has been examined as a potential source of impaired glycogen resynthesis following exercise-induced muscle damage. However, Asp et al[23] showed that GLUT-4 content remained unchanged after a marathon, despite increased plasma creatine kinase activity, and decreased muscle glycogen concentration 48 hours after a marathon. In addition, after the marathon muscle glycogen depletion occurred predominantly in type I muscle fibres, compared to type II muscle fibres.

Further, Tuominen et al[642] demonstrated a reduction in the basal glucose oxidation rate following a marathon. The reduction in glucose oxidation rate was compensated for by an increase in free fatty acid concentration.

Kirwan et al[342] demonstrated an ongoing insulin resistance, with a 37% decrease in insulin-mediated whole body glucose disposal, 48 hours after performing exercise that caused muscle damage. The low muscle glycogen concentrations during the recovery period were attributed to either a decreased uptake of glucose through the disrupted sarcolemma in the damaged cells, or to an increased insulin resistance.

An alternative explanation is that exercise-induced muscle damage results in an infiltration of inflammatory cells to the damaged muscle. The inflammatory cells have a large affinity for glucose oxidation, and release a factor that stimulates glucose oxidation and lactate production by the surrounding muscle cells. These processes appear to result in a competition between the inflammatory cells and the glycogen-depleted muscle fibres for blood glucose[156]. However, this theory is speculative, and requires further investigation.

2.1.1.4 Neuromuscular effects of endurance running

There is much evidence to suggest that endurance running performance after a marathon may be reduced as a result of the impairments in muscle strength and work capacity. Sherman et al[586] measured isokinetic strength in the leg extensors after a marathon, determined by maximal peak torque, and maximal work capacity, determined during a leg extensor fatigue test. These tests were conducted before, and at 15 to 20 minutes, and one, three, five, and seven days after a marathon. A 47% reduction in work capacity was observed immediately after the marathon, and isokinetic strength was reduced for up to seven days after the marathon.

Ker and Schultz[335] found that the endurance capacity of the inspiratory muscles decreased by 27% three days after an 87 km race. It was concluded that this reduction in endurance capacity of the inspiratory muscles would negatively affect running performance.

Exercise-induced muscle damage has also been associated with changes in the joint angle-torque relationship. Avela et al[32] reported a 30% reduction in strength and the rate of force development in ankle extensor muscles following a marathon. Ankle extensor strength had returned to pre-race values by day two after the marathon, whereas the rate of force development had recovered by day four after the marathon. The acute fatigue effects of endurance running on isometric strength have also been observed immediately following a marathon[475] and a 65 km ultramarathon race[445], with 26% and 30% reductions in knee extensor isometric strength respectively[445;475].

Lepers et al[384] determined the effects of a two-hour run on the concentric, eccentric, and isometric strength characteristics of the quadriceps muscle, and counter-movement jump performance. Significant reductions in peak torque and counter-movement jump performances were observed after the two-hour run. There was also a greater loss of eccentric torque production, compared to concentric torque production. It was suggested that this specificity in torque loss was related to an impairment of the muscular contractile mechanism rather than a modification to the neural input.

Nicol et al[475;476] demonstrated changes in neuromuscular function after a marathon race. Sprint velocity decreased during the marathon. Reductions in maximal isometric knee extension torque and drop jump performance were observed after the marathon. Changes in drop jump performance were accompanied by alterations in the ground reaction forces, suggesting a reduction in the tolerance to stretch load, as well as a reduction in the recoil characteristics of the muscles. In addition, maximal integrated electromyographic activity (iEMG) of the vastus lateralis and vastus medialis decreased after the marathon race. This could be interpreted as a modification in the neural activation of muscle to compensate for the exercise-induced contractile fatigue, which occurs towards the end of a marathon. Based on the extent of these neuromuscular adaptations, it was also hypothesised that neuromuscular changes may persist for a prolonged period after a marathon, and may account for the associated decrement in running performance.

Chambers et al[120] investigated the effects of a 90 km ultramarathon on the vertical jump performance. The vertical jump (drop jump and counter-movement jump) performance provides an indirect assessment of the ability to utilise stored elastic energy in the quadriceps muscle, whereas the squat jump measures muscle power without the activation of the stretch shortening cycle. The runners performed the vertical jump tests before the race, immediately after the race, daily for five days after the race and thereafter, weekly for a further four weeks after the race.

Vertical jump performance was significantly reduced immediately after the ultramarathon race, both with and without the use of the stretch shortening cycle. Drop jump, counter-movement jump, and squat jump heights were significantly reduced for 3, 11, and 18 days after the ultramarathon respectively, when compared to pre-race values[120]. These results suggest that the stretch shortening cycle may possibly attenuate the decrement in performance associated with exercise-induced muscle damage[98].

In addition, the pre-race counter-movement jump height was only one centimetre (cm) higher than the squat jump height, indicating a low stretch shortening cycle activity, as well as a low ability to utilise stored elastic energy in the quadriceps muscle. It may be proposed that the elastic component of the quadriceps muscle may have been reduced before the ultramarathon race, potentially as a result of the high training volume performed by the distance runners in preparation for the ultramarathon race[120].

2.1.1.5 Biomechanical effects of endurance running

Current literature provides equivocal evidence regarding the effects of endurance running on stride length, and running kinematics and kinetics. Reductions in stride length have been observed following a marathon[268;369]. In contrast, increases in stride length have been noted as a consequence of fatigue[103;195;590]. In addition, Millet et al[442] reported an increase in contact times during hopping immediately following a 65 km ultramarathon, compared to pre-race values.

Hausswirth et al[268] investigated the effects of simulated triathlon and marathon runs, compared to an isolated 45-minute run, on running mechanics in seven well-trained triathletes. Running kinematic data were recorded at 1, 23, and 45 minutes during a 45-minute treadmill test using a video motion analysis system. There was a significant decrease in stride length immediately after the marathon run, compared to the isolated run.

The knee extension angle at heelstrike was significant reduced, and there were significant increases in the maximum knee flexion angle during swing phase, and the vertical oscillation of the ankle following the marathon and triathlon runs, compared to the isolated run. It was hypothesised that these biomechanical factors may be associated with the decrease in running economy that was observed at the end of the triathlon and marathon runs[268].

Nicol et al[474] determined the fatigue effects of a marathon on running kinematics and kinetics. Seven males and one female, all experienced endurance runners between 20 and 35 years of age, performed an individual and paced marathon run. The individual marathon speed was based on the subject's current training state and their last performance in a competition. The biomechanical variables were measured during a 6-minute treadmill run just before and immediately after the marathon. Subjects were required to run for three minutes at a slow speed, for two minutes at a medium speed, and for one minute at a fast speed. The slow, medium, and fast speeds corresponded to 75%, 100%, and 125% of the individual marathon speed respectively. Biomechanical data of a complete stride were recorded by a two-dimensional video measurement during the last 30 seconds at each running speed. The biomechanical variables included angular displacement and velocity of the hip, knee and ankle joints; joint angles of the thigh, lower leg and foot; vertical oscillation of the centre of gravity; and step length, support time, and non-support time.

The kinematic analysis of the pre- and post-marathon treadmill tests established a large degree of inter-individual variation in biomechanical variables in both the fatigued and non-fatigued states. Although there were no significant differences in stride length before or after the marathon, the duration of the push-off phase relative to the total ground contact time was significantly increased at slow and medium speeds after the marathon, compared to pre-marathon values. There were also significant increases in the knee flexion angle at heelstrike, the hip extension range of movement during swing phase, and the maximum hip extension velocity at the medium speed after the marathon, compared to pre-marathon values[474].

The authors theorised that the kinematic changes may reflect deterioration of the muscular tolerance to impact, with an associated loss in the recoil characteristics of the muscle[474].

Further, Kryöläinen et al[369] examined the effects of a marathon on kinematic measurements in seven experienced triathletes. Each subject ran an individual marathon, paced by a cyclist. The pace of the marathon was based on each subject's current training state. Kinematic measurements were recorded at two intervals of 20 seconds during a five-minute submaximal run, one week before the marathon, at 0 km, 13 km, 26 km and 42 km during the marathon, two hours after the marathon, and at two, four, and six days after the marathon. Minor changes in kinematic measurements were observed during the experimental period, with a significant increase in mean stride frequency, and a significant reduction in mean stride length. It is unclear to what extent these changes occurred during the marathon, or in the recovery period after the marathon, as the time points of changes in stride frequency and stride length were not reported.

Mean ground contact time, vertical displacement of the centre of gravity, external mechanical work, and power remained relatively constant pre- and post-marathon. There were also no significant changes in angular displacement or velocity of the hip, knee and ankle joints before, during, or in the recovery period after the marathon. In addition, although the mean values remain relatively constant, a large degree of inter-individual variation was observed. It was proposed that the differences in stride frequency and length may be an attempt to compensate for the impaired neuromuscular function during, and in the recovery period after the marathon[369].

Avela et al[29;32] determined the effects of a marathon on kinematic measurements and neuromuscular function in nine experienced male endurance runners. The marathon was run in two separate competition races. Testing was conducted one hour before the marathon, and immediately after the race. Angular displacement, ground contact time, and neuromuscular function were assessed during maximal stretch shortening cycle exercises using a sledge ergometer. Interestingly, there were no significant differences in the knee and ankle joint displacements before or after the marathon, despite significant reductions in average force, take-off velocity, electromyographic (EMG) activity of the vastus medialis and soleus muscles, and the short-latency reflex component after the marathon, compared to pre-race values.

There was also a tendency for contact time to increase after the marathon, compared to pre-race values. Marathon running resulted in a subsequent reduced ability to perform maximal stretch shortening cycle exercise. It was proposed that these changes may primarily be due to reduced neural input into the muscles, with associated impairment of peripheral mechanisms[29;32]. However, Kryöläinen et al[369] suggested that alterations in running mechanics during fatiguing submaximal exercise should be different to those changes measured in maximal effort. Further studies are therefore required to determine changes in running kinematics and kinetics associated with endurance running.

2.1.1.6 Summary of the literature: muscle damage and endurance running

Collectively, these studies demonstrate that endurance running results in ultrastructural muscle damage[15;94;284;591;592], and metabolic[23;342;587;642], neuromuscular[32;120;475;476;586], and biomechanical[29;32;268;369;474] adaptations. These changes may occur as a result of both endurance running training and competition, and may be associated with a decrement in endurance running performance. It is also acknowledged that there appears to be large inter-individual variation in the ultrastructural muscle damage associated with endurance running[284;592;656].

However, it is well documented that endurance training alters the enzymatic, biochemical, and morphological characteristics of skeletal muscle[155;248;372;418;672]. These training adaptations may be associated with improvements in muscle efficiency, and may therefore enhance endurance running performance. The following section will review the adaptations of skeletal muscle to endurance training.

2.1.2 ADAPTATIONS OF SKELETAL MUSCLE TO ENDURANCE TRAINING

Endurance training is associated with both central and peripheral adaptations, including altered neural recruitment patterns, skeletal muscle morphology, and substrate metabolism[140;271].

2.1.2.1 Morphological adaptations of skeletal muscle

2.1.2.1.1 Skeletal muscle fibre type and cross-sectional area

The majority of endurance-trained athletes have a higher proportion of type I muscle fibres in the lower limb muscles than untrained, middle-distance, or sprint-trained athletes[134;542;558]. Further, cross-sectional data have determined that the proportion of type I muscle fibres in trained subjects is related to the number of years of previous endurance training. It may therefore be proposed that either individuals with a high proportion of type I muscle fibres naturally progress into endurance sport, or that there may be a training-induced interconversion between muscle fibre types[271].

Jansson and Kaijser[312] established a similar distribution of type I muscle fibres in the deltoid, vastus lateralis, and gastrocnemius muscles of elite orienteers. In addition, the ratio of type I muscle fibres was significantly higher in the elite orienteers, compared to a sedentary control group. These findings emphasise the potential role of genetic factors in skeletal muscle fibre type distribution.

Coggan et al[144] were unable to identify changes in the percentage of type I muscle fibres from the lateral gastrocnemius muscle following a 10-month endurance training programme in 60 to 70 year old men and women. However, the percentage of type IIa fibres increased by approximately 9%, whereas the percentage of type IIb muscle fibres decreased by approximately 8%. It was theorised that the endurance training was associated with a conversion of type IIb muscle fibres to type IIa muscle fibres.

In addition, Kuipers et al[372] and Gollnick et al[248] were not able to identify any alterations in the muscle fibre type ratio in subjects training for a marathon, or following a five-month endurance training programme, respectively.

Conversely, Howald et al[303] demonstrated that six weeks of endurance cycling training was associated with a 12% increase in type I muscle fibres, and a 24% decrease in type II muscle fibres, in the absence of any evidence of muscle fibre type conversion.

Therefore, although there is some evidence to support an alteration in the ratio of type IIa to type IIb muscle fibres with endurance training, there is currently little evidence to support a training-induced interconversion of type II to type I muscle fibres, particularly in well-trained endurance athletes[271].

Furthermore, Harber et al[265] investigated the contractile properties of muscle fibres in endurance-trained runners. Interestingly, it was determined that the contractile properties of the muscle fibres may be sensitive to alterations in training intensity. Interval training was the most effective training method that stimulated changes in cellular function of the muscle fibres.

Trappe et al[639] examined muscle fibre adaptations associated with marathon training in recreational runners. Subjects completed a 13-week training programme, during which time there was a reduction in type I and type IIa muscle fibre diameter, no alteration in the force-generating capacity, and increased peak power and the contractile speed of type I muscle fibres. Moreover, after a taper there were no significant changes in the contractile properties if type I muscle fibres, however there were increases in the strength and power of type IIa muscle fibres. It is therefore hypothesised that the contractile properties of type I and type II muscle fibres respond differently to an endurance training stimulus. In addition, there may be a high degree of plasticity within the different muscle fibre types[636].

There is equivocal evidence regarding changes in muscle fibre size in relation to endurance training. Coggan et al[144] demonstrated increases in the lateral gastrocnemius cross-sectional area in 60 to 70 year old men and women following a 10-month endurance training programme. The cross-sectional area of type I, IIa, and IIb muscle fibres increased by 12%, 6%, and 12% respectively following the 10-month training period. In addition, Costill et al[155] showed that type I muscle fibres were 29% larger than type II fibres in elite distance runners, but were unable to determine any differences in muscle fibre size in untrained subjects or middle-distance runners. Furthermore, other studies have also been unable to demonstrate any changes in the cross-sectional area of muscle fibres in relation to endurance training[248;372].

2.1.2.1.2 Capillary density

Type I muscle fibres have a higher capillary density and oxidative capacity than type II muscle fibres[271]. A higher proportion of type I muscle fibres may therefore be associated with a lower submaximal oxygen cost during exercise[160], due to a potentially lower adenosine triphosphate (ATP) turnover during muscle contraction. Jensen et al[315] examined the effects of intense intermittent endurance training on capillary growth in previously untrained human skeletal muscle. The endurance training was associated with an increase in capillary density and the proliferation of endothelial cells. The capillary growth was equally distributed around type I and type II muscle fibres. In addition, the increase in capillary density was evident within four weeks of endurance training, and appeared to be a transient adaptation to endurance training. There was no further capillarisation, and a reduction in the proliferation of endothelial cells following seven weeks of endurance training.

2.1.2.1.3 Sarcoplasmic reticulum

Holloway et al[290] investigated the repetition-dependent effects of heavy, intermittent cycle exercise on the sarcoplasmic reticulum calcium transport properties in the muscle of untrained subjects. There was a rapid adaptation of the sarcoplasmic reticulum calcium handling properties to the repetitive exercise stimulus. In addition, the adaptations were associated with a reduced perturbation in calcium uptake, which may be mediated by an improved maintenance of calcium-activated adenosine triphosphatase (Ca^{2+}-ATPase) enzyme activity. A more efficient release and re-uptake of calcium may therefore be associated with an improved fatigue resistance.

2.1.2.1.4 Oxidative and glycolytic enzymes

Many of the adaptations associated with endurance training may be related to alterations in skeletal muscle oxidative capacity[303;527]. There are significant increases in the size and number of skeletal muscle mitochondria following endurance training[338]. There is also a simultaneous increase in mitochondrial enzyme content, particularly in those enzymes associated with fatty acid metabolism, and the shuttle systems that transport hydrogen ions into the mitochondria for utilisation in the respiratory chain[316;643].

These changes occur in the presence of increased ATP demand and supply during exercise. Other training-related adaptations include an increased maximum rate of ATP production, and improved ATP-adenosine diphosphate (ADP) homeostasis. It is theorised that the activation of different components of the oxidative phosphorylation system may be related to the behaviour of calcium ions[358].

Activation of the mitogen-activated protein kinase (MAPK) signalling cascade may be associated with the regulation of many of the exercise-induced adaptations in skeletal muscle[689]. Adenosine monophosphate (AMP)-activated protein kinase (AMPK) may also down-regulate genes involved in the glucose-signalling system in hepatocytes[685], and up-regulate genes associated with glucose uptake and substrate metabolism in skeletal muscle[682]. AMPK may also be related to the acute increase in GLUT-4 translocation following exercise, and the chronic increase in mitochondrial enzyme activity following exercise[681;682].

Furthermore, peroxisome proliferator receptor-γ co-activator-1α (PGC-1α) has been linked to the coactivation of multiple mitochondrial transcription factors[291], and therefore may be an important regulator of mitochondrial content in skeletal muscle. PGC-1α may also be associated with the regulation of aerobic metabolism, mitochondrial architecture, and type II muscle fibre to type I muscle fibre transformation[141;531;532;627]. The exercise-induced up-regulation of PGC-1α appears to occur in response to endurance training, but not to resistance training in skeletal muscle[140;531].

Endurance training also results in increased gene expression of metabolic proteins, including genes encoding enzymes and transporters involved in carbohydrate and fat metabolism, such as hexokinase and lipoprotein lipase[688]. Moreover, the post-exercise recovery period is associated with increased mRNA abundance and transcription of various metabolic genes[531]. The up-regulation of metabolic genes peaks in the initial hours following endurance exercise, and generally returns to resting levels within 24 hours after exercise[531;688].

2.1.2.2 Substrate metabolism

Endurance-trained athletes have a slower rate of depletion of muscle glycogen stores during submaximal exercise, compared to untrained subjects[271]. Endurance training is also associated with a reduction in the production, uptake, and oxidation of plasma glucose during moderate and intense exercise[142;143]. The reduction in carbohydrate utilisation is linked to a proportional increase in fat oxidation[271].

The early training-induced shift in substrate selection may be related to an improved muscle respiratory capacity that results from increased mitochondrial density[159]. Mitochondria from endurance-trained muscle also have an increased ability to produce energy at higher free fatty acid concentrations. Therefore, at specific exercise intensities, trained muscles are less dependent on carbohydrate metabolism, compared to untrained muscles. Subsequently, fat is more readily available as a source of fuel at higher exercise intensities. There is also a corresponding reduction in hydrogen ions, a by-product of carbohydrate metabolism[316;334], and muscle contractility is preserved[313;316;418]. In addition, muscle glycogen stores are conserved[109;418].

However, other factors such as a greater supply of fat due to an increase in intramuscular triglyceride concentration[271], or morphological adaptations such as an increased recruitment of active muscle mass[157], may be associated with subsequent adaptations in substrate utilisation following intensified training in well-trained athletes[271].

2.1.2.3 Acid-base status

The ability to transport lactate across the sarcolemma is significantly higher in endurance-trained subjects, compared to untrained subjects[529]. There also appears to be a positive relationship between the intensity of training, and lactate transporter values[530]. In addition, the relative increase in the proportion of type I muscle fibres that is observed in endurance-trained athletes, is also associated with a relative increase in lactate transport capacity[533].

2.1.2.4 Neuromuscular adaptations

Endurance training may be associated with neuromuscular adaptations that include an increased recruitment of muscle fibres and therefore a large, active muscle mass[272]. Noakes[480] proposed that improved performance following endurance training may be related to an increased ability of the brain to recruit a larger muscle mass for extended periods of time[260;262]. These training-induced neural adaptations may account for increased force and power production within the first eight weeks of training[260;674].

In addition, Paavolainen et al[505] demonstrated that the capacity of individual cross-bridges to generate force is closely related to running performance. Noakes[480] theorised that regular endurance training may facilitate changes in muscle cross-bridge activity. Alterations in muscle cross-bridge activity may also positively influence running economy[582], and may therefore improve running performance.

Häkkinen et al[259] examined the effects of a combined strength and endurance training, compared to a strength training programme alone on functional and structural neuromuscular adaptations. Both groups demonstrated similar improvements in the one-repetition maximum load, maximum isometric force, maximum integrated electromyography of the vastus lateralis muscle, cross-sectional area of the quadriceps femoris muscle group, and mean fibre areas of type I, IIa and IIb muscle fibres. However, an improvement in the rate of force development only occurred in the strength-training group. It was theorised that improved power development may be partially mediated by more rapid voluntary neural activation of the trained muscles.

Saunders et al[569] observed the effects of endurance training in cyclists. Endurance training was associated with a reduction in quadriceps muscle activity, potentially due to the decreased oxygen demand of a bout of high-intensity submaximal exercise. However, the underlying mechanism for the attenuation of end-exercise muscle activity is unclear. It was proposed that the training-induced increase in muscle mitochondrial content and oxidative capacity may be associated with a decreased reliance on anaerobic energy supply, which therefore extends the time to fatigue the muscle fibres. Subsequently, less additional muscle fibres will be recruited to replace the fatigued fibres, therefore decreasing the end-exercise active muscle and oxygen consumption.

Moreover, Widrick et al[673] compared the force-velocity and power-velocity properties of single muscle fibres between endurance-trained and sedentary subjects. The endurance-trained group showed significant reductions in type I and type IIa muscle fibre diameter, single fibre peak power output, and absolute force production, compared to the control group. The endurance-trained group also had significantly higher maximum shortening velocities, compared to the control group.

It was proposed that, although the ability to produce force was reduced in the endurance-trained group, the increased shortening velocity enabled the muscle fibres to maintain a higher level of force production. Thus, there was an increased relative contribution of type I muscle fibres to the total power output, and a decreased reliance on the fatigable type IIa muscle fibres[673].

Additionally, Blazevich et al[57] demonstrated a training-induced increase in fascicle length, which was linked to changes in the force and velocity characteristics of the muscle. It was also established that alterations in the muscle architecture, including fibre hypertrophy, increased fascicle or fibre angle, and increased fascicle length are related to increases in muscle mass and the force-generating ability of the muscle. Further studies are required to determine the effect of these training-induced adaptations on the length-tension relationship of muscle.

2.1.2.5 Summary of the literature: adaptations of skeletal muscle to endurance training

Regular endurance training is therefore associated with numerous morphological, metabolic, and neuromuscular adaptations. These adaptations function primarily to reduce the extent of cellular disturbances during subsequent training bouts. Furthermore, the cumulative effects of regular exercise training are linked to chronic adaptations of skeletal muscle, including increased mitochondrial enzyme activity and protein concentration, increased capillary density, and an increased reliance on fat as a fuel, with a reduction in glycolytic flux. These adaptations are associated with an improvement in endurance performance[271].

However, unaccustomed exercise, or increased exercise intensity or duration is commonly associated with exercise-induced muscle damage. Furthermore, lengthening muscle action has been identified as the principle factor responsible for the development of exercise-induced muscle damage[98]. This will be discussed further in the next section.

2.1.3 LENGTHENING MUSCLE ACTIONS (ECCENTRIC EXERCISE)

Numerous studies have established that lengthening, or "eccentric" muscle actions are related to a greater degree of muscle damage, compared to shortening (concentric) or isometric muscle actions[244;325;468]. Human movement is rarely associated with isolated lengthening muscle action. Alternatively, the stretch shortening cycle occurs during functional activities, and describes the sequence of an active lengthening muscle action followed by an active shortening muscle action. These integrated muscle actions are linked to performance enhancement, compared to an isolated shortening muscle action[348;351]. Lengthening muscle actions actively contribute to the stretch shortening cycle. Exercise-induced muscle damage is therefore a common occurrence following prolonged or intense stretch shortening cycle exercise, such as distance running[22;23;120;284;586;656].

During an "eccentric" muscle action, there is active lengthening of the skeletal muscle with simultaneous force resistance[332;490]. Therefore, as described by Faulkner[215], the most appropriate description of an "eccentric" muscle action is a lengthening muscle action. Similarly, "concentric" muscle actions should be referred to as shortening muscle actions. An isometric muscle action describes the process of muscle activation and force generation, without simultaneous contraction and joint movement. Wherever possible, the terminology as proposed by Faulkner[215] will be used. There may be occasions however where studies are discussed which have used the older terminology (concentric, eccentric and isometric). To avoid confusion, the older terminology may be used in this context.

It is theorised that, when muscle fibres are lengthened during an lengthening muscle action, the actomyosin bonds undergo a mechanical detachment, rather than an ATP-dependent process[220]. Lengthening muscle actions are also highly efficient[354;427], thus higher muscle strain is distributed over fewer muscle fibres[202;391;427].

In addition, lengthening muscle actions are associated with an improved force-generating ability, compared to concentric, or shortening muscle actions[215]. Lengthening muscle actions also require reduced levels of voluntary activation by the nervous system to achieve a required level of force generation[13-15;58;185;202;205;208;211;225;427;468;511;598]. The differences in neural recruitment patterns between lengthening and shortening muscle actions may be related to a modulation of the relative excitability within the motorneurones innervating a muscle[202;392].

It has been hypothesised that the increased tension of lengthening muscle actions may disrupt the intermediate filaments of the cytoskeletal Z-bridges, and stretch out the space between the pairs of intermediate filaments that surround the Z-lines of single sarcomeres, resulting in destruction and streaming of the Z-lines[661]. This may be heightened by damage to the sarcolemma or sarcoplasmic reticulum, which would result in an increase in the intracellular calcium concentration. The increased calcium concentration would activate proteolytic enzymes and lead to further structural protein degradation[15;94;661].

Additional ultrastructural changes that occur in response to repeated lengthening muscle actions include sarcolemmal disruption, fragmentation of the sarcoplasmic reticulum, dilation of the transverse tubule system, disruption of myofibrillar contractile components and the cytoskeleton, alterations in the extracellular myofibre matrix, and swollen mitochondria[226;227;231;284;372;592;609;656].

The symptoms of exercise-induced muscle damage include soreness, swelling, and stiffness, and are collectively referred to as delayed onset muscle soreness[138;151;209;304;371;402].

2.1.4 DELAYED ONSET MUSCLE SORENESS

Delayed onset muscle soreness (DOMS) describes the combined sensation of muscle pain, stiffness, and tenderness that develops after unaccustomed exercise[13;138;371;402;598], or after increased exercise intensity or duration, and is particularly evident following lengthening muscle actions or repetitive stretch shortening cycle activity[15;138;371;598]. Delayed onset muscle soreness is usually first evident within eight to 24 hours after the exercise bout, peaks within 24 to 72 hours after the exercise bout, and typically dissipates within seven to 10 days after the exercise bout[13;14;196;205;402;438;468].

The underlying mechanisms for the pain associated with delayed onset muscle soreness are not well understood. It is generally accepted that delayed onset muscle soreness is associated with muscle or connective tissue damage, and may be related to the inflammatory response that may be induced by lengthening muscle actions[13;135;304;402;547;596].

It is suggested that soreness may result from swelling and pressure in the muscle[596]. Although biopsy studies have demonstrated increases in muscle fibre area and intramuscular pressure[230], discrepancies between the timing of peak muscle soreness and oedema have been identified[483].

It is also proposed that chemicals such as histamines, prostaglandins, and bradykinins may be associated with the development of muscle soreness following exercise-induced muscle damage. It is theorised that these substances are released when the muscle is damaged, resulting in activation of type III and IV nerve afferents, leading to the sensation of pain[497]. However, there is no direct evidence to support this theory[133;409;464;488].

Furthermore, other symptoms associated with delayed onset muscle soreness include reductions in range of movement and force production, increases in limb volume, swelling and stiffness, and leakage of myofibrillar proteins into the blood[99;129;135;136;151;205;222;371;402;468;485;489;491;596]. However, although the symptoms of delayed onset muscle soreness are induced by lengthening muscle actions or repetitive stretch shortening cycle exercise, and are considered to be indirect markers of muscle damage, it may be possible that the symptoms do not accurately reflect the extent or time course of exercise-induced muscle damage[133;488].

Lieber et al[390] identified structural changes in rabbit muscle within five to 15 minutes following lengthening muscle action-induced injury. However, delayed onset muscle soreness is usually only first evident several hours after an exercise bout[13;196;402;438]. In addition, Nosaka et al[488] established a relatively poor correlation between delayed onset muscle soreness induced by upper limb eccentric exercise protocols, and other indirect indicators of muscle damage that included limb circumference, muscle stiffness, maximal isometric force, and plasma creatine kinase activity. Furthermore, it is known that neuromuscular function is disturbed for at least 11 days after a 90 km ultramarathon[120], and signs of regeneration are still present in the muscle of runners 12 weeks after a standard marathon, despite the absence of pain[656].

2.1.5 MECHANISMS UNDERLYING EXERCISE-INDUCED MUSCLE DAMAGE AND DELAYED ONSET MUSCLE SORENESS

Armstrong[15] proposed a model that defines four phases of exercise-induced muscle damage. These phases include the initial events following a damaging bout of exercise, and the autogenic, phagocytic, and regenerative processes associated with exercise-induced muscle damage.

Following a damaging bout of exercise, there is an initial response from intrinsic proteolytic and degradative pathways within the muscle fibres. The degradation of lipid and protein structures in the damaged cells occurs through autogenic processes associated with the inflammatory response. The phagocytic phase is characterised by the rapid breakdown of damaged muscle fibres through the action of phagocytic cells and macrophages. The final phase involves the regeneration of the damaged muscle fibres[15].

2.1.5.1 Initial events following exercise-induced muscle damage

It is theorised that the initial events following exercise-induced muscle damage may be related to mechanical or metabolic mechanisms. The mechanical theory includes adaptations at the levels of the whole muscle and the muscle fibre, as well as at the myofibrillar level, specifically in the cytoskeleton. The metabolic theory includes alterations in calcium concentrations, muscle temperature and pH, insufficient mitochondrial respiration, and oxygen free radical production[332;428].

2.1.5.1.1 Mechanical theory

a) Responses to lengthening muscle actions

Previous studies have demonstrated increases in passive and dynamic muscle stiffness following lengthening muscle actions. These increases are generally attributed either to increased cross-bridge stiffness, or to increased tendon stiffness[428;553]. Faulkner et al[216] demonstrated that, although there was a significant increase in force development during lengthening muscle actions compared to isometric muscle actions, there was only a 10% increase in strongly bound cross-bridges during the lengthening muscle actions.

It was proposed that the increase in force per active muscle unit resulted in mechanical disruption of ultrastructural elements within the muscle fibres, such as the Z-line and contractile filaments[216;231].

In addition, as previously discussed, lengthening muscle actions are coupled with a preferential recruitment of type II muscle fibres[202], and a reduction in muscle fibre recruitment, resulting in a subsequent increase in loading of individual muscle fibres[15;99].

It has also been theorised that lengthening muscle actions are associated with an overstretching of sarcomeres beyond an optimum length[450]. This process is facilitated by the lack of homogeneity in sarcomere length. It is proposed that, during active muscle lengthening, the majority of the change in length will be accommodated by the weakest sarcomeres until a critical point is reached. Thereafter, the sarcomeres undergo rapid and uncontrolled alterations in length, which results in no overlap between actin and myosin myofilaments. On relaxation, some sarcomeres may return to the normal resting length. However, other sarcomeres do not return to the normal resting length, which results in a loss of inter-digitation of the myofilaments, and subsequent disruption[545]. This process has been described as the "popping" sarcomere theory[449].

Furthermore, after repeated lengthening muscle actions, and "popping" sarcomeres, there may be disruption of the sarcolemma and the sarcoplasmic reticulum of adjacent muscle fibres[449]. This initiates a series of events, including a loss of calcium homeostasis[15] and an inflammatory response[402;596], resulting in the characteristic pathology associated with exercise-induced muscle damage. During prolonged endurance exercise, repetitive lengthening muscle actions will facilitate the alteration in sarcomere uniformity, therefore further contributing to the sarcomere "popping"[97;449].

b) Cytoskeletal responses

The cytoskeleton of skeletal muscle is comprised of structural proteins, such as titin, desmin and nebulin, which maintain the structural integrity of the myofibrillar lattice[517]. Although muscle tissue is extremely plastic, destructive changes of muscle structure may occur in response to unusual demands.

Changes that may occur as a result of exercise-induced muscle damage include primary or secondary sarcolemmal disruption[15], swelling or disruption of the sarcotubular system[15;94], disruption of the contractile components of the myofibril, abnormalities of the extracellular matrix, and cytoskeletal damage[226;227].

The alterations that occur in the contractile proteins, actin and myosin, following exercise-induced muscle damage have been well documented. Changes include Z-line streaming, focal disruptions of the A-band and mitochondrial disruptions[94;661]. However, Fridén et al[226] presented evidence that implicates cytoskeletal disturbances as a major contributing factor to the observed ultrastructural changes.

The myofibrillar cytoskeleton of skeletal muscle is made up of two sets of filaments, mainly the exosarcomeric cytoskeleton and the endosarcomeric cytoskeleton[655]. The exosarcomeric cytoskeleton consists of intermediate filaments composed of the proteins desmin, vimentin, and synemin. The intermediate filaments are arranged both transversely and longitudinally around the fibre[661].

The transverse filaments link adjacent myofibrils at the Z-line, and are thought to be responsible for the myofibril's axial register, and therefore, the striated appearance of skeletal muscle. The longitudinal filaments run from Z-line to Z-line and envelop the myofibril, in order to serve as attachment sites for mitochondria, nuclei, and the sarcolemma, as well as limiting the extensibility of the sarcolemma[661].

The endosarcomeric cytoskeleton acts as a third filament system that co-exists with actin and myosin within the sarcomere. This system is believed to be extensible and is made up of the giant proteins, titin and nebulin. Nebulin is thought to be rigidly attached to the Z-line, and to extend the length of the I-band in relaxed muscle. Nebulin is linked to the maintenance of actin's lattice array[661].

The function of titin is related to resting muscle elasticity, as well as to the central position of myosin in the sarcomere[227;661]. Titin connects the thick filaments and the Z-lines, and prevents the thick filaments from moving from the centre of the sarcomere. The structure of titin allows it to accommodate physiological stretch, by first straightening without unfolding, and then unfolding a portion of the molecule known as the PEVK domain. The PEVK domain is a non-globular region of titin and contains a proline-rich sequence with an unknown secondary or tertiary structure. The PEVK domain elongates at moderate to long sarcomere lengths where passive tension increases steeply[204].

The unfolding of the PEVK domain increases the capacity of the muscle to stretch further. The length of the PEVK sequence varies depending on the type of muscle fibre, and determines the stiffness of the muscle tissue. The more elastic type II muscle fibres have a greater titin: actin ratio, compared to the less elastic type I muscle fibres[18].

Fridén et al[226] examined the intermediate filaments in muscle biopsy samples from subjects with delayed onset muscle soreness three days after a bout of exercise designed to induce muscle damage. Using immunofluorescent localisation of desmin, longitudinally oriented bands of fluorescence were observed between successive Z-lines. Furthermore, in transverse muscle sections, there were frequent intensely fluorescent spots interspersed with the myofibrillar network. As a result, two theoretical mechanisms of cytoskeletal disruption were proposed.

Firstly, it was theorised that the cytoskeletal disruption may reflect mechanical disturbances of the desmin filaments as a result of the high tension associated with lengthening muscle actions or distension of the cytoskeleton caused by oedema. A subsequent increase in the intracellular pressure due to the release of osmotic components from disruptions in the Z-discs will therefore result in an uneven distribution of forces on the cytoskeletal attachments[226;611].

Secondly, it was proposed that the changes in the myofibrils were a response to the extensive myofibrillar lesions, and may be indicative of sarcomereogenesis. This explanation would be in keeping with the fact that the intermediate filaments surrounding the Z-line may contribute to the addition of sarcomeres to myofibrils. Furthermore, an increased synthesis of desmin and the reorganisation of the cytoskeletal system may be essential for the reorganisation of the myofibril. In addition, the peak in ultrastructural damage that was evident two to three days after the eccentric exercise bout may indicate that the initial damage activates proteolytic enzymes within the muscle fibre, which results in further degradation of the cytoskeleton[226].

However, it has also been hypothesised that the high tension of contraction may break the intermediate filaments of the cytoskeletal Z-bridges, and stretch out the space between the pairs of intermediate filaments that surround the Z-lines of single sarcomeres, resulting in destruction and streaming of the Z-lines[661].

This may be heightened by damage to the sarcolemma or sarcoplasmic reticulum, which would result in an increase in the intracellular calcium concentration. The increased calcium concentration would activate proteolytic enzymes and lead to further structural protein degradation[15;94;661].

In addition, Lieber et al[390] demonstrated a significant loss of desmin in 2.5% of rabbit muscle fibres recruited five minutes after a 30-minute bout of exercise designed to induce muscle damage. One day after the exercise, desmin loss rose to approximately 23% in rabbit extensor digitorum longus muscle. Increased staining intensity of the intrasarcomeric cytoskeletal protein titin was observed in most, but not all, muscle fibres that had a loss of desmin staining. Similar findings have been reported in other studies[226]. Therefore, cytoskeletal disturbances of desmin appear to represent an early manifestation of muscle damage.

It may further be theorised that the disruption of both the endosarcomeric and exosarcomeric cytoskeleton may be associated with altered skeletal muscle mechanical properties and force production. However, the influence of cytoskeletal adaptations on muscle function is not well understood, and further research is required to determine the significance of these adaptations[661].

2.1.5.1.2 Metabolic theory

a) Calcium concentrations

A disturbance in calcium homeostasis occurs during the initial phase of exercise-induced muscle damage, through the disruption of the sarcoplasmic reticulum release and reuptake of calcium[47;603]. It is further hypothesised that an elevated calcium concentration may occur as a result of damage to the surface membrane following the separation of actin and myosin during lengthening muscle actions, facilitating the entry of extracellular calcium[13;467].

In addition, exercise-induced muscle damage may result in the opening of stretch-responsive channels, with or without alterations in t-tubule orientation. It is proposed that these adaptations may also lead to an increase in intracellular calcium through voltage-sensitive channels[45;136].

The subsequent increases in intracellular calcium concentrations are thought to contribute to the progression of exercise-induced muscle damage. An increased intracellular calcium concentration stimulates calcium-sensitive phospholipase A_2, which leads to an alteration in the permeability of the sarcolemma, through the production of leukotrienes and prostaglandins. This results in the leakage of intramuscular enzymes, such as creatine kinase[15;239].

Further, increased calcium concentrations activate the non-lysosomal cysteine protease calpain[47]. It is theorised that calpain may initiate skeletal muscle protein breakdown, inflammation, and regeneration following exercise-induced muscle damage[603].

Specifically, calpain is thought to be involved in proteolysis, and cleaves a variety of protein substrates, including cytoskeletal and myofibrillar proteins[47], such as desmin[47;94;284]. Calpain may also be involved in the disturbance of mitochondrial function[609].

In addition, increased calcium concentrations and the subsequent inflammatory cascade may also be linked to increased production of reactive oxygen species and the release of lysphospholipids, leading to lipid peroxidation[15]. Elevated calcium concentrations may also be associated with a disruption of the excitation-contraction coupling process, potentially reducing the maximal isometric force. Increased calcium also results in a transient shortening of the muscle fibres, with a subsequent increase in the resting tension of the muscle[254].

b) Muscle temperature, pH, and adenosine triphosphate (ATP) concentrations

Lengthening muscle actions are associated with higher local muscle temperatures, compared to shortening muscle actions[173;178]. Increased temperature, particularly above 38 ºC, is associated with uncoupling of the calcium-activated ATPase activity from calcium transport by the sarcoplasmic reticulum, and may also be related to alterations in the fluidity of the lipid membrane surrounding the ATPase pump. These factors may limit the reuptake of calcium by the sarcoplasmic reticulum[94].

The increase in hydrogen ions (H^+) or the reduction in pH that occurs during fatiguing exercise also influences the reuptake of calcium by the sarcoplasmic reticulum. It is theorised that the hydrogen ions may compete with the calcium ions for the calcium binding site on the ATPase pump[94;386]. This may reduce the capacity for calcium release from the cell through ATPase pumps[14;633].

Furthermore, a reduction in the rate of calcium pumping by the sarcoplasmic reticulum may occur as a result of reductions in local ATP concentrations, or the free energy from ATP hydrolysis due to increased ADP concentrations[94].

Therefore, the initial response to exercise-induced muscle damage is associated with both mechanical and metabolic adaptations. It is proposed that the relative contribution of these adaptations to exercise-induced muscle damage may be dependant on the nature of the exercise stimulus[548].

2.1.5.2 Autogenic phase

An inflammatory response occurs secondary to the initial events of exercise-induced muscle damage. It is thought that the inflammatory response may be initiated by the early mechanical disruption associated with exercise-induced muscle damage[133;402;521;535;536;596]. Inflammation is characterised by the movement of fluid, plasma proteins, and leucocytes into the damaged tissue[133;402;521;596]. The inflammatory response may also exacerbate the initial muscle damage, through the abundance of inflammatory cells, the release of reactive oxygen species, and the activation of phospholipases and proteases[133;402].

Signalling occurs between the damaged muscle cells and the mononucleated cells that subsequently appear at the site of injury. Inflammatory cells, involved in the removal of cellular debris, and myogenic cells, involved in the replacement of damaged cells, both respond to muscle damage[633]. Cytokines, which are small polypeptides, control the movement of these cells into the damaged muscle tissue[548], and appear to provide an important link between the immune and neuroendocrine systems[402;548;597]. Specifically, it is theorised that a small group of cytokines, including interleukin (IL)-1, IL-2, IL-6, interferon, and tumour necrosis factor-α (TNF-α) are the principle mediators of the inflammatory response[307].

2.1.5.3 Phagocytic phase

There is an initial accumulation of neutrophils at the site of tissue damage. Neutrophils destroy necrotic tissue through phagocytosis. This is performed in conjunction with resident macrophages within the muscle tissue[537].

Neutrophils release chemotactic agents to amplify the inflammatory response by recruiting additional neutrophils and mononuclear cells[548]. The neutrophils also release proteolytic enzymes and oxygen radicals that further degrade tissue, and increase membrane permeability. The increased mobilisation and activation of neutrophils may therefore contribute to the creatine kinase efflux following exercise-induced muscle damage[537].

An increase in monocyte and macrophage levels within the muscle follows the initial accumulation of neutrophils. Cytokine production by monocytes and lymphocytes is linked to subsequent intramuscular degradation, additional neutrophil and monocyte chemotaxis and ultimately, healing[519]. Macrophages invade the damaged muscle tissue and remove cellular debris by phagocytosis. Macrophages are also primarily responsible for the reabsorption of neutrophils in necrotic tissue, and the sequestration of persistent foreign material or antigens[402]. After the removal of the damaged muscle fibres, there is an increase in a second sub-population of macrophages, which are associated with muscle regeneration. Therefore, monocytes and macrophages are involved with the breakdown and removal of cellular debris, and the regeneration of cells[633].

Several studies have reported increased levels of cytokines, monocytes and macrophages following downhill running[218], eccentric cycling[409], and high-force eccentric upper limb protocols[324;560]. The majority of studies have shown that macrophages appear to be the predominant inflammatory cell type during all stages of the inflammatory process following the first 12 hours post-injury[136;402;596;633]. Increased concentrations of lymphocytes, myogenic cells, and mast cells have also been reported following a marathon run[284;592], or forced muscle lengthening[613].

In addition, increased xanthine oxidase[280] and acid phosphatase[324] activity have been observed following exercise designed to induce muscle damage. Xanthine oxidase may contribute to the development of reactive oxygen species following exercise-induced muscle damage, and may therefore exacerbate the existing damage[280]. Increased acid phosphatase activity has been observed up to 12 days after eccentric exercise, and may reflect the presence of macrophages[324].

The increased levels of monocytes and macrophages associated with the phagocytic phase usually return to baseline levels within a three to four week period following the exercise stimulus[402].

2.1.5.4 Regeneration phase

The process of repair and regeneration is initiated by the inflammatory response to muscle damage[616]. The process of revascularisation is essential for effective muscle regeneration. Improved revascularisation is associated with a reduction in the extent of fibrosis in the damaged muscle[121;256], and an increased delivery of immune cells to the damaged muscle, resulting in enhanced phagocytosis and the release of growth factors and cytokines necessary for satellite cell activation and proliferation[256].

Regeneration begins within the basal lamina of the original muscle fibre[104]. Satellite cells located underneath the basal lamina undergo an initial activation reaction, which results in the enlargement of the nucleus and an increase in DNA synthesis. Studies have also demonstrated that, in the complete absence of the basal lamina, no regeneration can occur[105].

The satellite cell activation occurs within 24 to 48 hours after exercise-induced muscle damage[121;256]. The satellite cells then proliferate and migrate to the damaged area. Myogenic factors are associated with the proliferation of satellite cells[256]. It is theorised that the infiltration of macrophages may be an essential prerequisite for regeneration, potentially through the stimulation of satellite cell division[133]. It has also been shown that muscle regeneration does not occur in the absence of macrophage infiltration[256].

Numerous growth factors and cytokines perform the role of progression factors in the regeneration process[121;221;256;270], and are responsible for the progression of activated satellite cells (muscle precursor cells) through the cell cycle up to the stage at which DNA is synthesised[256]. Satellite cells will proliferate at least once before fusing to form myotubes[121;256;555].

The proliferated satellite cells may then perform different functions. The satellite cells may remain undifferentiated, and may therefore restore the population of dormant satellite cells within the muscle. The satellite cells may also fuse with damaged fibres, adding a nucleus and contributing to the maintenance of the cytoplasm to nuclei ratio. Several satellite cells may also fuse to form myotubes that will eventually mature into myofibres, and replace the necrotic muscle fibres[256;257;270].

The fusion of myoblasts and myotubes is a complex process that involves the extracellular matrix, cell surface molecules, growth factors, and increased calcium and hydrogen ions in the extracellular space. Myoblasts fuse into multinucleated myotubes, which then fuse to form myofibrils. The fusion of myoblasts and myotubes usually occurs between three to seven days after exercise-induced muscle damage. The fusion of myotubes to form myofibrils occurs between seven to 10 days after exercise-induced muscle damage. The maturation process of the myotubes includes the collection of contractile filaments, the formation of synapses and motor endplates, and connection to the appropriate motorneurone. The myofibrils then mature to form myofibres, with peripherally located nuclei[256].

The development of neuromuscular junctions during the regeneration process consists of two main phases[104;105]. The first phase involves the growth of nerves into the regenerating muscle, either through regeneration from the cut ends of nerves leading to the muscle, or through sprouting of nerves in the tissue adjacent to the regenerating muscle[56;104;105]. The second phase involves the formation of a functional neuromuscular junction[105].

However, Warhol et al[656] demonstrated signs of repair and regeneration in the muscle biopsy samples of marathon runners. The mitochondrial and myofibrillar damage showed progressive repair by three to four weeks after the race. Muscle biopsy samples obtained at between eight to 12 weeks after the race showed central nuclei, satellite cells, an increased content of endoplasmic reticulum and prominent Golgi areas.

All of these findings are characteristic of the regenerative process. It may therefore be proposed that the exercise-induced muscle damage associated with prolonged endurance training and distance running may be incompletely or ineffectively repaired[656]. Further studies are needed to determine the effects of repeated bouts of muscle damage and repair on skeletal muscle regeneration and function.

2.1.6 BIOCHEMICAL INDICES OF EXERCISE-INDUCED MUSCLE DAMAGE

Numerous studies have examined the appearance of muscle proteins in the blood following eccentric exercise to provide indirect evidence of exercise-induced muscle damage[196;603]. Elevated levels of plasma creatine kinase (CK) activity, lactate dehydrogenase and myoglobin concentrations have been identified following various forms of exercise designed to induce muscle damage. However, plasma CK activity is most commonly used as an indirect indicator of muscle damage[99;123;137;196;264;299;357;408;580;594;600;603], perhaps because the magnitude of increase is so great compared to the other proteins. Practically, the determination of plasma CK activity is relatively simple and cost-effective[133].

Creatine kinase is a dimeric enzyme which catalyses the reversible phosphorylation of ADP, by creatine phosphate, to form ATP and free creatine[299]. Creatine kinase is a large molecule, and is therefore unlikely to enter into the bloodstream directly from the cells. Increased circulating plasma CK activity is usually only observed following muscle fibre damage accompanied by membrane leakage, or necrosis of the muscle fibre[478;601].

Creatine kinase activity may also be influenced by a variety of factors, including the type of exercise, the intensity and duration of exercise, training status, environmental conditions, and genetic factors[133;299;478;601]. Indeed, the two types of exercise predominantly used to induce muscle damage, downhill running and high-force lengthening muscle actions, show very different patterns of plasma CK activity. For example, after downhill running, plasma CK activity usually peaks between 12 to 24 hours after exercise[99;133].

Conversely, after high-force eccentric exercise protocols, such as maximal lengthening muscle action of the elbow flexors, the increase in CK activity does not begin until approximately 48 hours after the damaging bout of exercise, with peak CK activity occurring only between four to six days following the exercise protocol[133;135]. The differences in plasma CK activity following downhill running and high-force eccentric exercise protocols is well-documented[133], however the underlying mechanism for the different responses is unclear.

Furthermore, there is considerable inter-subject variability in plasma CK activity following exercise-induced muscle damage. The large variability in plasma CK activity is not well understood, but does not appear to be related to physical activity, gender, or muscle mass[133]. Studies have also demonstrated dissociation between plasma CK activity and the extent of exercise-induced muscle damage[483;583]. It is postulated that the individual variation in plasma CK activity may be associated with differences in the rate of CK clearance by muscle and the reticuloendothelial system[135]. However, this theory is speculative and requires further investigation.

Other muscle enzymes that have been used as indicators of muscle damage include aspartate aminotransferase and carbonic anhydrase isoenzyme II[603]. In an attempt to identify more accurate markers of muscle damage, recent emphasis has been placed on the predominantly bound proteins of the contractile apparatus of skeletal muscle. These include myosin heavy chain[406], the contractile proteins of thick filaments, and skeletal troponin I, the regulatory proteins of thin filaments[601;602]. These proteins are all unique to skeletal muscle[601]. An increase in the circulation of either myosin heavy chain or skeletal troponin I after exercise would indicate cell membrane leakage and degradation of the contractile apparatus[601;602].

In addition, Milias et al[440] investigated the effects of eccentric exercise on the blood levels of platelet activating factor (PAF). Platelet activating factor is a potent inflammatory mediator implicated in a number of pathophysiological processes. Platelet activating factor, plasma CK activity, lactate dehydrogenase (LDH), C-reactive protein, complement C3, plasma level of fibrinogen and whole blood level of leukocytes were determined following a high-force upper limb exercise protocol designed to induce muscle damage.

The levels of platelet activating factor, leukocytes, plasma CK activity and lactate dehydrogenase were significantly elevated after eccentric exercise. Other biochemical parameters such as C-reactive protein, complement C3, and fibrinogen were unchanged after the exercise protocol. There was also an inverse relationship between the level of platelet activating factor and peak torque production and range of movement following muscle damage. These findings suggest that platelet activating factor may potentially be used as an indirect indicator of exercise-induced muscle damage[440].

More recently, Tofas et al[634] investigated changes in the markers of collagen breakdown in association with exercise-induced muscle damage. The biochemical indices of muscle damage and collagen damage included plasma CK activity and lactate dehydrogenase concentration, and serum hydroxyproline and hydoxylysine respectively. Subjects performed a series of plyometric jumping exercises to induce muscle damage. Significant increases in plasma CK activity and lactate dehydrogenase concentration were observed after the plyometric exercise protocol. Serum hydroxyproline increased 24 hours after exercise, peaked at 48 hours after exercise, and remained elevated for up to 72 hours after exercise. Serum hydroxylysine was only measured at 48 hours after exercise, and was significantly elevated compared to baseline measurements. Intense plyometric exercise was therefore associated with exercise-induced muscle damage and increased levels of serum hydroxyproline and hydoxylysine. It may be suggested that future studies investigating muscle damage should include the measurement of biochemical indices of exercise-induced collagen degradation.

2.1.6.1 Summary of the literature: biochemical indices of exercise-induced muscle damage

It is therefore evident that although plasma CK activity is one of the most commonly used indicators of exercise-induced muscle damage, it provides only an indirect marker of muscle damage[133]. The measurement of other muscle proteins, such as myosin heavy chain or skeletal troponin I, may also provide an indirect indication of exercise-induced muscle damage[406;601;602]. More recently, studies have demonstrated that the biochemical indices of inflammatory mediators, such as platelet activating factor[440], and collagen degradation, such as serum hydroxyproline and hydoxylysine[634], may also potentially be utilised as markers of exercise-induced muscle damage.

It may be proposed that plasma CK activity should be considered as only one of the indirect indicators of exercise-induced muscle damage. Changes in skeletal muscle function following muscle damage, and symptoms of delayed onset muscle soreness, such as swelling and muscle soreness, should be evaluated together with plasma CK activity to provide an indirect description of exercise-induced muscle damage[133].

2.1.7 FUNCTIONAL CHANGES ASSOCIATED WITH EXERCISE-INDUCED MUSCLE DAMAGE

It is well documented that skeletal muscle function, including force production, is significantly impaired following muscle damaging exercise[137;175;198;225;394;422;468;658]. It is proposed that alterations in muscle function may provide the most effective measure of the magnitude and time course of exercise-induced muscle damage. Changes in skeletal muscle function following lengthening muscle actions include force loss, shifts in optimum muscle length and the length-tension relationship, an increase in passive tension, and alterations in neuromuscular control[98;450].

2.1.7.1 Force loss

The prolonged strength loss that occurs following eccentric exercise is considered to be a valid and reliable indirect measure of exercise-induced muscle damage[133;659]. Isometric strength is reduced immediately after eccentric exercise, and the recovery period is prolonged and variable. Downhill running protocols typically result in force losses of between 10% and 30%[133;205;207], whereas high force eccentric exercise, such as maximal lengthening muscle actions of the elbow flexors, may result in force losses of between 50% and 65%[133;465;484;577].

Although Clarkson et al[135] reported that a typical recovery period following maximal eccentric exercise of the elbow flexors was approximately two weeks, other studies have reported that strength loss may persist for longer, with recovery taking up to 12 weeks[304;578].

Immediate and prolonged reductions in isometric force have also been observed in the knee and ankle extensors following exercise-induced muscle damage. Komi and Viitasalo[356] demonstrated a 35% reduction in maximum knee extensor strength, a decrease in the rate of force development, and an increase in neural activity at any given muscle tension both immediately and two days after maximal eccentric exercise. Byrne and Eston[95] reported 30% to 40% reductions in knee extensor strength, with incomplete recovery in muscle strength up to seven days after an eccentric quadriceps exercise protocol.

Furthermore, Avela et al[32] reported a 30% reduction in ankle extensor strength and the rate of force development following a marathon. Ankle extensor strength had returned to pre-race values by day two after the marathon, whereas the rate of force development had recovered by day four after the marathon. The effects of endurance running on isometric strength have also been observed immediately following a marathon[475] and a 65 km ultramarathon race[445], with 26% and 30% reductions in knee extensor isometric strength respectively[445;475]. It is therefore evident that repetitive stretch shortening cycle exercise of the lower limb muscles results in prolonged reductions in muscle strength, and a decreased rate of force development[98].

It is theorised that the differences in the magnitude and time course of strength loss between the elbow flexors and the lower limb muscles may be due to the severity of the initial muscle damage, as well as less natural activation of the elbow flexors during normal daily activities[98].

The exact mechanism by which force is lost after lengthening muscle actions has not been clearly established. Studies investigating the time course of recovery following exercise-induced muscle damage have shown a poor relationship between muscle soreness and force loss[120;324;468;488;556]. It may therefore be postulated that the inherent ability of the muscle to produce force may be lowered[4;46;95;196;450;468].

In addition, previous studies have demonstrated a disproportionate loss of strength at short muscle lengths, when compared to optimal or long muscle lengths[95;97;128;576;577]. A shift to the right of the optimal angle for torque generation occurs following exercise-induced muscle damage[322]. It is uncertain whether the shift in optimum length persists for as long as the reduction in muscle strength after lengthening muscle actions, and further investigation is required[98;576;577].

2.1.7.2 Changes in the length-tension relationship: shift in optimum length

Several studies have reported a shift in optimum length following eccentric exercise[74;80;81;92;97;322;451;525;526;540;576;577;669;671;684]. The optimum angle for torque generation shifts to the right following lengthening muscle actions, indicating a shift in the length-tension relationship towards longer muscle lengths for maximal force generation[322;669]. The shift in optimum length has been observed in both animal[80;92;451;684] and human[74;81;97;322;525;526;540;576;577;669;671] studies.

The shift in the length-tension relationship appears to be a reliable and useful measure of exercise-induced muscle damage, and is thought to be independent of levels of fatigue[452]. The magnitude of the shift in optimum length appears to correlate with the extent of exercise-induced muscle damage[322].

It is theorised that, following a bout of eccentric exercise that causes muscle damage, there is an increase in series compliance due to the presence of overextended and non-contracting sarcomeres[545]. It is therefore proposed that a longer muscle length is required to achieve the same degree of myofilament overlap and force production following exercise-induced muscle damage[322;450;545].

Brockett el al[81] and Bowers et al[74] observed sustained shifts in optimum length following lengthening muscle actions for 18[81] and 24[74] days respectively. However, the exact time course for the shift in optimum length following exercise-induced muscle damage remains unclear[87].

Other factors that may influence the magnitude of the shift in optimum length include the intensity[525;526;671] and volume[74;81;540] of eccentric exercise, as well as the length of the muscle during eccentric exercise[74;526;540]. Increased exercise intensity[525;526;671] and volume[74;81;540] are both associated with greater shifts in optimum length.

Whitehead et al[670] determined the effects of lengthening muscle actions performed over different muscle lengths on the active and passive length-tension relationship in mammalian muscle. A larger shift in optimum length for active tension, as well as a larger decrease in peak isometric contraction occurred at longer muscle lengths, compared to shorter muscle lengths.

In contrast, Paschalis et al[509] examined the effects of eccentric exercise performed over different muscle lengths in the rectus femoris muscle in healthy males, and demonstrated that eccentric exercise resulted in a greater extent of muscle damage and loss of peak torque at shorter muscle lengths, compared to longer muscle lengths. Further studies are required to investigate alterations in optimum length and the length-tension relationship in endurance-trained subjects[87].

Furthermore, Herbert and Gandevia[281] determined the relationship between joint angle, torque and pennation in the human brachialis muscle. Changes in joint angle and joint torque were associated with changes in pennation angle, which determines the extent of change in muscle fibre length, thereby influencing force production at a specific muscle length or velocity.

In addition, Mademli and Arampatzis[403] observed a reduction in fascicle length, together with an increase in the pennation angle of the gastrocnemius muscle following sustained and fatiguing submaximal isometric exercise. It is proposed that these changes in muscle architecture may influence the length-tension relationship of the muscle, and may therefore be related to alterations in the contractile capacity of muscle.

2.1.7.3 Passive tension

An increase in passive tension is evident following a bout of eccentric exercise that causes muscle damage[304;543;545;671]. The rise in passive tension is present immediately after the eccentric exercise bout, and is accompanied by a shift in optimum length and an increase in active tension[671]. When measured across the full physiological range, the rise in passive tension peaks at a length close to the optimum for active tension[671].

It is postulated that the rise in passive tension occurs as a consequence of sarcomere disruption and membrane damage at the level of the sarcoplasmic reticulum or the t-tubules following lengthening muscle actions. The subsequent uncontrolled release of calcium into the sarcoplasm results in activation of the contractile filaments, leading to the development of an injury contracture[543].

It is theorised that the contracture will be maintained while ATP levels remain elevated following muscle damage. Further, sarcomeres within the region of muscle damage will also shorten, resulting in stress being applied to adjacent areas, subsequently extending the contracture. These processes result in a gradual increase in passive tension[543].

In addition, there is an increase in work absorption following a bout of eccentric exercise that causes muscle damage. Whitehead et al[671] suggested that the increase in work absorption may be due to actively cycling cross-bridges within damaged sections of muscle fibres. Structural evidence supporting this theory includes Z-line dissolution, A-band disruption, and fibre clotting in rat muscle[499], and cytoskeletal disruption, and the presence of fibres in hypercontracted regions of rabbit muscle following lengthening muscle actions[228].

2.1.7.4 Neuromuscular control

Exercise-induced muscle damage following intense plyometric or repetitive stretch shortening exercise is associated with prolonged reductions in maximal force and electromyographic activity, ground reaction forces, stretch reflex sensitivity, muscle and joint stiffness regulation, and vertical jump performance[32;294;475;476].

Nicol et al[475;476] demonstrated changes in neuromuscular function after a marathon race that included reductions in maximal isometric knee extension torque, maximal integrated electromyographic activity (iEMG) of the vastus lateralis and vastus medialis, and drop jump performance.

Chambers et al[120] demonstrated that vertical jump performance was significantly reduced immediately after an ultramarathon race, both with and without activation of the stretch shortening cycle. Drop jump, counter-movement jump, and squat jump heights were significantly reduced for 3, 11, and 18 days after the ultramarathon respectively, when compared to pre-race values[120]. Byrne and Eston[95] also observed reductions in vertical jump performance for up to four days after exercise-induced muscle damage.

Avela et al[29;32] determined the effects of a marathon on neuromuscular function in endurance runners. Neuromuscular function was assessed before and after the marathon during maximal stretch shortening cycle exercises using a sledge ergometer. Marathon running resulted in a significant reduction in the ability to perform maximal stretch shortening cycle exercise. There were significant reductions in average eccentric and concentric forces, take-off velocity, and electromyographic (EMG) activity of the vastus medialis and soleus muscles. The reduction in EMG activity was more pronounced in the preactivation and lengthening phases of the stretch shortening cycle, compared to the shortening phase of the stretch shortening cycle. Stretch reflex sensitivity was also significantly decreased after the marathon.

Several mechanisms were proposed to explain the reduction in muscle function following the marathon. The reduction in neural input may be due to the occurrence of central fatigue, supraspinal fatigue, peripheral inhibition, disfacilitation of the alpha-motorneurone pool, or impairment of peripheral mechanisms. In addition, the reduced stretch reflex sensitivity was associated with decreased muscle stiffness. It was theorised that the reduced muscle stiffness may be related to the reduction in muscle function, leading to an impaired utilisation of elastic energy[29;32].

Furthermore, a reduction in neuromuscular efficiency of the knee extensors, exhibited as a decrease in the force: integrated electromyographic (iEMG) activity, has also been observed following eccentric exercise[98;183;356]. Impairments in proprioception have also recently been observed after exercise-induced muscle damage[439;576]. These studies collectively demonstrate that the force-generating capacity of muscle and motor control may be affected by a bout of eccentric exercise which causes muscle damage[98].

2.1.7.5 Proposed mechanisms for altered muscle function after lengthening muscle actions

It is theorised that the reduction in force and tension producing capabilities following lengthening muscle actions may be associated with alterations in peripheral mechanisms, such as disorganisation of the contractile machinery and calcium regulation, excitation-contraction coupling failure, redistribution of sarcomere lengths, and selective muscle fibre damage[46;384;450;545;658]. However, the role of central fatigue and alterations in neuromuscular control should also be considered in the loss of muscle function following exercise-induced muscle damage[98;450].

2.1.7.5.1 Central changes

It is proposed that the structural changes associated with lengthening muscle actions may be accompanied by alterations in neuromuscular performance[356]. A reduction in neuromuscular efficiency of the knee extensors has been observed following eccentric exercise[98;183;356]. The reduction in neuromuscular efficiency is exhibited as a decrease in the force: integrated electromyographic (iEMG) activity, both during and after lengthening muscle actions. A decrease in the force: iEMG ratio indicates that increased central activation is required for the generation of maximal or submaximal forces. In addition, alterations in the firing patterns of damaged muscles, including the recruitment of additional motor units and increased firing frequencies, may occur as compensatory mechanisms for the changes in contractile function[55;85;196].

However, the literature provides equivocal evidence for changes in neuromuscular efficiency following exercise-induced muscle damage, with some studies demonstrating increased neural activation after a damaging bout of exercise[356;426;468], while other studies reported that neural activation remained unchanged[46] or was impaired[85] after exercise which caused muscle damage.

Furthermore, a reduction in voluntary activation during maximal exercise may be expected following exercise-induced muscle damage, due to inhibition related to increased muscle soreness, swelling, and stiffness[98]. However, studies have demonstrated no relationship between alterations in the level of voluntary activation and force loss following lengthening muscle actions[238;577].

Although these findings suggest that the immediate and prolonged loss of isometric strength following lengthening muscle actions may be due to peripheral mechanisms, either at or distal to the neuromuscular junction, current methodologies cannot completely discount the potential involvement of central mechanisms in the loss of muscle function after exercise-induced muscle damage[6;98;235]. Further studies are therefore required to determine the role of central fatigue following eccentric exercise that causes muscle damage.

2.1.7.5.2 Excitation-contraction coupling impairment

Excitation-contraction coupling describes the sequence of events that starts following the release of an action potential at the neuromuscular junction and ends when calcium is released from the sarcoplasmic reticulum, thereby causing a muscle contraction[658]. A reduced efficiency of the excitation-contraction coupling process has been observed in animal studies. These studies have established a reduction in the rate of calcium released from the sarcoplasmic reticulum in maximally activated tetanic force, suggesting that a failure to fully activate the contractile machinery is the primary mechanism responsible for the loss of force after lengthening muscle actions. In addition, it was estimated that approximately 75% of the reduction in maximal force production might be related to excitation-contraction coupling failure immediately after the exercise bout which caused muscle damage. These alterations also contributed to the reductions in maximal force production for up to five days after the damaging exercise bout[308;660].

Furthermore, a manifestation of excitation-contraction coupling failure may include the development of low frequency fatigue following exercise-induced muscle damage. Following a damaging bout of exercise, there is a reduction in the ability to generate force at lower stimulation frequencies, compared to higher stimulation frequencies. The low frequency fatigue may persist for weeks after the damaging exercise bout[175;285;323;325;465;468;568]. It is theorised that damage to components of the excitation-contraction coupling system may result in a reduction in the amount of calcium released with each action potential, thereby leading to low frequency fatigue[98].

Excitation-contraction coupling impairment may therefore be associated with reductions in both maximal and submaximal force generation. In addition, the disproportionate loss of strength at short muscle lengths, compared to optimal or long muscle lengths, following lengthening muscle actions may also be related to decreased efficiency of excitation-contraction coupling, as the activation curve for calcium shifts to higher calcium levels at short sarcomere lengths[38;95;97;128;564;577].

2.1.7.5.3 Selective muscle fibre damage

Several studies have reported selective damage to type II muscle fibres after lengthening muscle actions[80;95;211;227;229;231;324;384;388;427;651;652]. For example, Byrne and Eston[95] demonstrated reductions in isometric strength for up to seven days after a damaging bout of exercise. It was observed that the muscle damaged through lengthening muscle actions was characterised by an inability to generate high force and power. However, there was a simultaneous improvement in the ability to maintain specific force and power levels indicating an improvement in strength endurance. Based on these functional outcomes, it was concluded that type II muscle fibres were selectively recruited and subsequently damaged during exercise involving predominantly lengthening muscle actions. In addition, during repeated electrically stimulated[39;175] or sustained maximal voluntary isometric muscle actions[95], eccentrically exercised muscle appeared weaker but less fatigable.

Fridén and Lieber[227;229;389] proposed a mechanism to explain selective type II muscle fibre damage, suggesting that during the initial stages of lengthening, type II glycolytic fibres are instantaneously fatigued. These fibres are subsequently unable to regenerate ATP, enter a state of rigor, and undergo systematic mechanical disruption. In addition, structural differences between type I and type II muscle fibres may also predispose type II muscle fibres to selective damage. Type II muscle fibres are characterised by narrower Z-lines, reflecting a lower actin-myosin attachment, and thus a weaker sarcomere connection[227;229].

Furthermore, Brockett et al[80] suggested that in muscle of mixed fibre composition, there are differences in the susceptibility of motor units to active lengthening due to inherent differences in optimal length-tension characteristics. Lengthening muscle actions resulted in a greater shift in optimal muscle length for fast-twitch motor units, compared to slow-twitch motor units. It was further theorised that, as the ability of fast-twitch units to exert a given force occurs at a shorter optimal length, a subsequent stretch may be associated with greater disruption of type II muscle fibres.

2.1.7.5.4 Redistribution of sarcomere length

Lengthening muscle actions may be associated with a redistribution of sarcomere lengths. According to the "popping sarcomere" hypothesis, active lengthening is characterised by a non-uniform distribution of alterations in sarcomere length. On relaxation, some sarcomeres return to normal length. However, during active lengthening some sarcomeres become overextended beyond myofilament overlap, and fail to reinterdigitate on relaxation[95;97;128;577].

During a subsequent contraction, the disrupted sarcomeres are not able to generate active tension, and may place additional load on neighbouring sarcomeres through transverse connections between myofibrils. This is postulated to result in a growing region of disrupted sarcomeres. The remaining functional sarcomeres may therefore be required to adopt shorter lengths in order to compensate for the overextended sarcomeres. In addition, there is a random distribution of disrupted sarcomeres along the muscle fibres, leading to an increase in series compliance[95;97;128;577].

These factors result in an acute shift in optimum length, with a subsequent shift in the length-tension relationship towards longer muscle lengths. There may also be an associated disproportionate loss of strength at short muscle lengths, when compared to optimal or long muscle lengths following eccentric exercise[95;97;128;577].

Furthermore, it is theorised that a second shift in optimum length may occur following a bout of eccentric exercise that causes muscle damage. One of the proposed mechanisms for the second shift in optimum length is sarcomereogenesis, that is the addition of sarcomeres in series within a muscle fibre. Numerous animal studies have provided direct evidence of sarcomereogenesis[93;345;397;398]. Once sarcomereogenesis has occurred, sarcomere length will be shorter for a given muscle length[449]. It is hypothesised that this adaptation may improve muscle compliance, thereby preventing the myofilaments from working on the descending limb of the length-tension curve, and facilitating improved muscle stability at longer muscle lengths[87].

2.1.7.6 Summary of the literature: functional changes associated with exercise-induced muscle damage

Therefore, much evidence suggests that exercise-induced muscle damage is associated with significant reductions in maximal and dynamic force production. The inability to generate high force and power following exercise-induced muscle damage may be related to both peripheral mechanisms, such as disorganisation of the contractile machinery and calcium regulation, excitation-contraction coupling failure, redistribution of sarcomere lengths, and selective muscle fibre damage[46;98;384;450;545;658], as well as central mechanisms[98]. It may be theorised that continual interaction between central and peripheral factors may regulate the changes in muscle function associated with exercise-induced muscle damage.

2.1.8 BIOMECHANICAL CHANGES ASSOCIATED WITH EXERCISE-INDUCED MUSCLE DAMAGE AND ENDURANCE RUNNING

The literature provides conflicting evidence regarding the biomechanical adaptations associated with delayed onset muscle soreness and exercise-induced muscle damage. As previously described in Section 2.1.1.5, stride length has been observed to decrease[268;369], increase[103;195;590], or remain relatively unchanged[474] following prolonged running. Hausswirth et al[268] also demonstrated a reduction in the knee extension angle at heelstrike, and increases in the maximum knee flexion angle during swing phase, and the vertical oscillation of the ankle following a marathon run. Nicol et al[474] established increases in the duration of the push-off phase relative to the total ground contact time after a marathon. Marathon running also resulted in increases in the knee flexion angle at heelstrike, the hip extension range of movement during swing phase, and the maximum hip extension velocity.

In contrast, although Kryöläinen et al[369] showed a significant reduction in mean stride length after a marathon, no other significant changes in mean ground contact time, vertical displacement of the centre of gravity, external mechanical work, power, or angular displacement and velocity of the hip, knee and ankle joints were observed during or after a marathon run.

Furthermore, Avela et al[29;32] found no significant differences in the knee and ankle joint displacements before or after a marathon run, despite significant reductions in average force, take-off velocity, electromyographic (EMG) activity of the vastus medialis and soleus muscles, and the short-latency reflex component after the marathon. However, Nicol et al[474] and Kryöläinen et al[369] both demonstrated a large degree of inter-individual variation in biomechanical variables before and after marathon running.

Biomechanical adaptations have also been observed during treadmill running to exhaustion[195;306;448]. Hunter and Smith[306] reported a decrease in stride frequency during a one-hour high intensity run. However, both vertical stiffness and leg stiffness remained relatively unchanged over the duration of the run.

In addition, both stiffness and stride frequency showed considerable inter-individual responses to fatigue. It was proposed that the variability in stride frequency may reflect the selection of a self-optimal stride frequency during exercise and fatigue, and that the optimisation of stride frequency may indicate a balance between the elastic storage of energy and the energy cost of accelerating limbs[306].

In contrast, Dutto and Smith[195] determined the effects of a 45-minute treadmill run at 80% of peak oxygen consumption (VO_{2peak}) on the spring-mass characteristics of male runners. There were significant reductions in vertical stiffness and leg stiffness over the duration of the run. There was also a significant correlation between changes in stride rate and vertical stiffness. The changes in the stiffness properties of the leg were related to changes in the vertical displacement of the centre of mass and leg length during stance phase. However, it is unclear whether the observed adaptations are advantageous in relation to the development of fatigue.

Mizrahi et al[448] showed reductions in stride rate, the knee flexion angle at heelstrike, and the vertical excursion of the hip following 30 minutes of treadmill running. There was also a significant increase in the average impact acceleration of the shank. It was concluded that the kinematic changes associated with fatigue were consistent with the substantially higher impact accelerations, thereby increasing the risk of overload injuries to the shank.

It is theorised that the observed alterations in running kinematic and kinetics following prolonged running may be associated with deterioration of the muscular tolerance to impact, with an associated loss in the recoil characteristics of the muscle[474].

Alternatively, the biomechanical changes may reflect compensatory adaptations related to impaired neuromuscular function during the recovery period after a marathon run[369]. There may also be a reduction in neural input to the muscles, with associated impairment of peripheral mechanisms[29;32].

Interestingly, with the exception of Kryöläinen et al[369], the aforementioned studies did not assess changes in biochemical markers of muscle damage. It is therefore uncertain whether the observed changes in running kinematics and kinetics occurred in the presence of fatigue, exercise-induced muscle damage, or a combination of both conditions.

Kryöläinen et al[369] demonstrated increases in circulating skeletal troponin I concentration and serum creatine kinase activity following the marathon run, with peak values occurring two hours and two days after the marathon respectively. It was therefore evident that Kryöläinen et al[369] induced muscle damage in subjects using the marathon run, suggesting that the experimental biomechanical adaptations occurred in the presence of exercise-induced muscle damage.

Braun and Dutto[78] examined the effects of a 30-minute downhill run (-10% gradient) at 70% of peak oxygen consumption on nine experienced distance runners and triathletes. Stride length was measured using two-dimensional (2D) motion analysis software at 65%, 75%, and 85% of peak oxygen consumption before, and 48 hours after the downhill run. Leg muscle soreness was assessed using a rating of pain scale, and was used to indicate the presence of delayed onset muscle soreness. Stride length was significantly reduced by an average of 3.2% after the downhill run, compared to baseline measurements. It was hypothesised that factors contributing to the reduction in stride length following exercise-induced muscle damage may include altered motor unit activation patterns, the general discomfort associated with delayed onset muscle soreness that may have resulted in subjective modification of gait, and a potential reduction in range of movement of the ankle, knee, or hip joints.

Similarly, Chen et al[125] used a 30-minute downhill run (-15% gradient) at 70% of peak oxygen consumption to determine the effects of exercise-induced muscle damage on stride length, stride frequency, and range of movement of the ankle, knee, and hip joints in male soccer players. Markers of muscle damage included a maximal voluntary isometric contraction (MVC) of the knee extensors, perceived muscle soreness, plasma creatine kinase activity, and myoglobin concentration.

Kinematic parameters were assessed during level running at 65%, 75%, and 85% of peak oxygen consumption before, immediately after, and daily for five days after the downhill run. A 2D motion analysis system was used to record and analyse kinematic measurements. Muscle soreness, plasma creatine kinase activity and myoglobin concentration were significantly increased, whereas the MVC was significantly decreased after the downhill run. Changes persisted for up to five days after the downhill protocol, indicating that downhill running successfully induced muscle damage. Stride length was reduced by 3% to 6% for up to three days after downhill running. The ankle and knee joint range of movement were also reduced by 1% to 7% for up to three days after downhill running. It was postulated that the reductions in kinematic parameters following downhill running may be associated with a decreased ability to utilise the stretch shortening cycle[125].

Hamill et al[263] also examined the effects of a 30-minute downhill run (-26% gradient) at 74% of maximum heart rate (HR_{max}) on kinematic parameters in recreational female runners. Running kinematics were measured before, and at 48 and 120 hours after the downhill run. An increase in the maximum ankle dorsiflexion angle during stance phase was determined after downhill running. In addition, reductions in the maximum knee flexion angles during stance and swing phase, and a decrease in the maximum hip flexion angle at heelstrike were observed following the downhill run.

Furthermore, Dutto and Braun[194] investigated the changes in ankle and knee joint dynamics following a 30-minute downhill run (-10% gradient) at 70% of peak oxygen consumption on nine well-trained male runners. Running biomechanics were recorded using 2D motion analysis software at 75% of peak oxygen consumption before, and 48 hours after the downhill run. Muscle soreness was assessed using a rating of pain scale. There were significant reductions in the knee flexion angle at heelstrike, knee range of movement during swing phase, peak angular velocity of knee flexion and extension during stance phase, and peak angular velocity of dorsiflexion during stance phase after downhill running, compared to baseline measurements. There were strong tendencies for reductions in ankle and knee range of movement during stance phase, and peak angular velocity of dorsiflexion during swing phase following the downhill run, compared to baseline values.

In addition, there were no significant differences in leg stiffness, despite the significant reduction in torsion stiffness of the knee, from the point of maximum knee flexion velocity to the point of maximum knee flexion during stance phase after downhill running. There was a related tendency for leg stiffness to increase from heel strike to the point of maximum knee flexion during stance phase. There was also a tendency for ankle stiffness to be slightly lower later in stance phase following the downhill run. It was theorised that impaired function of the knee musculature associated with delayed onset muscle soreness alters knee joint stiffness, and that this may affect vertical leg stiffness. It was further suggested that the tendency for increased vertical leg stiffness during stance phase may be related to the reduction in knee range of movement and angular velocity during stance phase, potentially providing a protective mechanism against the pain associated with exercise-induced muscle damage[194].

In contrast, Westerlind et al[666] examined the effects of two 45-minute downhill runs (-10% gradient) at 50% of maximum oxygen consumption (VO_{2max}) on the stride length of recreational runners. Subjects performed a 45-minute level treadmill run four days before the first 45-minute downhill run. The second 45-minute downhill run was performed two weeks after the first downhill run. A 2D video analysis system was used to record stride measurements during the treadmill runs. Markers of muscle damage included muscle soreness and plasma creatine kinase activity. There were no significant changes in stride length during the level or downhill runs, despite increases in plasma creatine kinase activity and perceived muscle soreness. However, it is recognised that the relatively small sample size used in this study may not have been sufficiently sensitive to detect discrete changes in kinematic parameters.

Paschalis et al[508] determined the effects of an eccentric exercise protocol on stride length, pelvic orientation, and ankle, knee, and hip joint angles in recreationally active males. Muscle damage was induced in the knee extensors of both legs using a maximal eccentric exercise protocol. Gait biomechanics were recorded during walking and running on a treadmill for two minutes at 1.2 $m.s^{-1}$ and 2.8 $m.s^{-1}$ respectively before, and 48 hours after the eccentric exercise protocol. Kinematic data were collected using a three-dimensional (3D) optoelectronic system. Plasma creatine kinase activity, lactate dehydrogenase concentration, muscle soreness, and peak eccentric and isometric force were all used as indices of exercise-induced muscle damage.

There were significant increases in muscle soreness, plasma creatine kinase activity, and lactate dehydrogenase concentration, and significant reductions in eccentric and isometric peak torque production after the eccentric exercise protocol. There were no significant differences in stride frequency or stride time following the eccentric exercise protocol. However, there were significant reductions in the knee flexion angle during both walking and running after the eccentric protocol, compared to pre-exercise values. During running, the knee flexion angle was significantly decreased during the post-exercise impact, support, and swing phases of the gait cycle, compared to pre-exercise values. There was also a significant increase in pelvic rotation during walking, and a significant decrease in pelvic tilt during running post-exercise, compared to pre-exercise values[508].

It also appeared that the bout of eccentric exercise of the knee extensors that caused muscle soreness did not influence hip and ankle angles during either walking or running. It was proposed that these alterations in walking and running kinematics may be attributed to a self-protection mechanism designed to prevent further muscle damage. However, this theory is speculative, and requires further investigation[508].

2.1.8.1 Summary of the literature: biomechanical changes associated with exercise-induced muscle damage

Current literature provides equivocal and relatively limited evidence regarding the alterations in running kinematics and kinetics associated with exercise-induced muscle damage. The complex interaction between training adaptations, fatigue, and exercise-induced muscle damage may further confound the relationship between biomechanical changes and muscle damage. It is also recognised that differences in muscle damage protocols, for example, marathon running, 30-minute downhill running protocols, or maximal stretch shortening cycle exercise may influence the kinematic and kinetic response to exercise-induced muscle damage. In addition, numerous studies have used 2D analyses to determine changes in biomechanical variables following muscle damage. It is acknowledged that the use of 2D analysis might conceal kinematic or kinetic characteristics that directly affect muscle function, compared to the use of three-dimensional (3D) analysis. Further studies are required to determine biomechanical adaptations during the recovery period following exercise-induced muscle damage.

2.1.9 EFFECT OF EXERCISE-INDUCED MUSCLE DAMAGE ON ENDURANCE RUNNING PERFORMANCE

It is well established that exercise-induced muscle damage is associated with prolonged reductions in muscle strength[133;196;229;543;576]. More recently, studies have determined that measurements of athletic performance requiring muscle power are negatively influenced by exercise-induced muscle damage[96;97;646]. Twist and Eston[646] established that intermittent sprint performance and peak power output were reduced for 48 hours and 72 hours respectively following a plyometric exercise protocol that caused muscle damage. Byrne and Eston[95] also reported immediate and prolonged decrements in peak power output for up to 48 hours following eccentric exercise. In addition, Miles et al[439] observed impairments in the ability of damaged muscle to generate rapid force, with reductions in peak velocity, and increases in movement time and time to reach peak velocity following exercise-induced muscle damage.

However, the effect of exercise-induced muscle damage on endurance running performance is unclear[412]. The literature provides equivocal evidence regarding alterations in cardiorespiratory and metabolic function, and running economy following damaging bouts of exercise. Braun and Dutto[78] determined that submaximal oxygen consumption was increased by 3.2% at 48 hours after a 30-minute downhill run, compared to baseline measurements. Similarly, Chen et al[125] showed that submaximal oxygen consumption was increased by between 4% to 7% up to three days after a 30-minute downhill run, compared to baseline measurements. Increased submaximal oxygen consumption has also been reported in the presence of delayed onset muscle soreness following a duathlon[102] and a marathon[369]. In addition, Gleeson et al[242] observed increases in minute ventilation, breathing frequency, respiratory exchange ratio, heart rate, and rating of perceived exertion 48 hours after eccentric exercise, compared to values following concentric exercise. Gleeson et al[241] also showed increased blood lactate and plasma cortisol concentrations during submaximal exercise 48 hours after eccentric exercise, compared to values during submaximal exercise following concentric exercise.

Conversely, other studies have reported no alterations in steady-state oxygen consumption, cardiorespiratory responses, and energy metabolism following a 30-minute downhill run[263], a 120-repetition maximum voluntary contraction protocol[510], a series of lower extremity resistance exercises[581], or a 100-drop jump protocol[412]. Although these physiological findings suggest that endurance performance will either

decrease or remain unchanged following exercise-induced muscle damage, relatively few studies have investigated the response of direct measurements of endurance performance, such as time to exhaustion at a fixed workload or time trial performance, to exercise-induced muscle damage[412].

Carmichael et al[106] showed that mice demonstrated a significant reduction in running time to exhaustion 24 to 48 hours following exercise-induced muscle damage. Furthermore, Marcora and Bosio[412] observed a significant reduction in self-paced time trial performance in moderately trained runners following a 100-drop jump protocol that induced muscle damage. Following exercise-induced muscle damage, there was a reduction in running speed while maintaining the same average rate of perceived exertion. In addition, the rate of perceived exertion also increased in subjects with exercise-induced muscle damage running at similar exercise intensities. It was theorised that the perception of effort may have a role in mediating the decrement in endurance performance associated with exercise-induced muscle damage[412]. Further studies are required to understand the peripheral and central mechanisms relating to perceived exertion, exercise-induced muscle damage, and endurance running performance.

2.1.10 THE REPEATED BOUT EFFECT

It is well documented that a single bout of unaccustomed, predominantly eccentric exercise results in skeletal muscle damage[124;135;197;482]. It is also well established that a repeated bout of the same, or similar eccentric exercise results in significantly reduced symptoms of muscle damage, such as muscle soreness, swelling, range of movement, strength, and circulating levels of muscle proteins, compared to the symptoms following the initial bout of exercise[124;135;137;465;482;487]. This protective adaptation to a single bout of eccentric exercise is referred to as the repeated bout effect[135;428;429;482].

It is evident that the initial bout of eccentric exercise does not have to be of a considerable magnitude to develop the protective adaptation of the repeated bout effect[84;137;492]. A minimum range of between two and 10 maximal lengthening muscle actions of the elbow flexors has been associated with a protective adaptation during subsequent bouts of maximal contractions[84;492].

Furthermore, near maximal contraction intensities during the initial bout of eccentric exercise are important to develop the protective adaptation of the repeated bout effect[428]. Nosaka and Newton[487] established that eight weeks of eccentric training at 50% of one-repetition maximum did not result in significant reductions in the symptoms of muscle damage during an ensuing bout of maximal eccentric exercise. This may have implications relating to the submaximal exercise intensities associated with endurance running training.

The repeated bout effect has been shown to last for between several weeks[99] and six months[491]. Byrnes et al[99] reported reductions in muscle soreness and smaller increases in plasma creatine kinase activity and myoglobin concentration when a second bout of downhill running was repeated up to six weeks, but not nine weeks, after an initial 30-minute downhill run. However, Nosaka et al[491] examined the protective adaptations following two bouts of eccentric exercise of the non-dominant elbow flexors separated by either 6, 9, or 12 months. A faster recovery in maximal isometric force was evident after a repeated bout of exercise at six or nine months. A reduction in muscle soreness and smaller increases in swelling, plasma creatine kinase activity, and T2 relaxation time of magnetic resonance images were observed after a repeated bout of exercise at six months, compared to responses following the initial bout of exercise. There were also no significant differences in range of movement between the repeated bouts of exercise, and the 12-month group showed no protective adaptations associated with the repeated bout effect. Therefore, it was theorised that the repeated bout effect for the majority of the symptoms of muscle damage lasts at least six months, but appears to be lost between nine and 12 months following the initial bout of exercise.

It was proposed that the differences between the two studies may be attributed either to the different exercise protocols designed to induce muscle damage, that is, downhill running compared to high-force muscle lengthening exercise of the elbow flexors, or to the differences in the extent of muscle damage induced by the different exercise protocols[99;491]. Byrnes et al[99] reported significantly lower plasma creatine kinase values, compared to the values reported by Nosaka et al[491]. In addition, both studies noted a large degree of inter-subject variability in the extent of the symptoms of muscle damage following the exercise protocols[491].

The repeated bout effect also appears to be specific to the exercised muscle groups. There is currently no evidence of protective adaptations in contralateral muscle groups that have not been subjected to an initial bout of damaging exercise[132;152].

In addition, Eston et al[206] demonstrated protective adaptations of the repeated bout effect during a downhill run that followed maximal eccentric isokinetic contractions, suggesting that the protective effect is not altered by variations in the mechanism of eccentric exercise.

Although the conditions required for inducing the protective adaptations of the repeated bout effect are relatively well understood, the underlying mechanisms of this phenomenon remain unclear. Several theories have been proposed to explain the repeated bout effect[428;429]. These can be summarised as the neural, mechanical, and cellular theories.

2.1.10.1 Neural theory

Lengthening muscle actions are associated with less motor unit activation for a given muscle force, and preferential recruitment of type II muscle fibres, compared to shortening muscle actions[202;305;432]. The "neural theory"[75;97;244;428;429;431;482;657] proposes that an initial bout of muscle damaging exercise is followed by a more efficient recruitment of motor units, increased recruitment of type I muscle fibres, activation of a larger motor unit pool, a more even distribution of workload over the active fibres, increased motor unit synchronisation, and improved use of synergist muscles[244;428;429;431;657].

An increase in the amplitude of the electromyography (EMG) signal relative to torque production has been observed following eccentric training[296;298]. This finding supports the potential redistribution of contractile stress among a greater number of muscle fibres[296;298;428]. Conversely, McHugh et al[430] and Warren et al[657] showed no change in EMG amplitude between repeated exercise bouts in the hamstring or tibialis anterior muscles respectively. However, Warren et al[657] observed a reduction in median frequency for the tibialis anterior muscle, indicating either an increased recruitment of type I muscle fibres, or increased motor unit synchronisation associated with the repeated bout effect.

Although Warren et al[657] provide evidence of a neural adaptation to an initial bout of eccentric exercise, the repeated bout effect has also been demonstrated with the electrical stimulation of rat tibialis anterior muscle[563] and human elbow flexor muscles[490], thereby indicating that there may be a peripheral component to the repeated bout effect[490].

Alternatively, Nosaka and Newton[486] theorised that the smaller magnitude of neuromuscular changes observed following the second bout of exercise may possibly be related to an intrinsic mechanism that inhibits the recovering muscles from generating the same amount of force that occurred during the initial bout of exercise-induced muscle damage. It was proposed that if similar levels of force were produced during the second bout of exercise, additional muscle damage would occur, resulting in delayed recovery and regeneration. However, this theory is speculative, and requires further investigation.

2.1.10.2 Mechanical theory

The "mechanical theory"[137;196;398;402;612] is based on the principle that exercise-induced muscle damage is associated with a mechanical disruption of myofibrils. It is therefore proposed that alterations in the mechanical properties of the musculoskeletal system may be related to the protective adaptations of the repeated bout effect[428;429]. Mechanical adaptations may occur at the level of the cytoskeleton and myofibril, the muscle fibre, and the whole muscle[398;402;428;429;612].

Pousson et al[539] and Reich et al[553] have demonstrated increases in passive and dynamic stiffness following eccentric training of human elbow flexors and rat triceps brachii muscles respectively. The alterations in stiffness have been attributed to increased tendon or cross-bridge stiffness[539], or cytoskeletal adaptations in order to maintain sarcomere alignment and structure[553].

In addition, Barash et al[40] observed increased desmin content between three to seven days after lengthening muscle action-induced muscle damage in rat muscle. It was theorised that the increase in desmin may have been associated with remodelling of the intermediate filament system, in order to provide a form of mechanical support to prevent excessive loading of sarcomeres. Conversely, Sam et al[567] demonstrated a reduction in myofibrillar disruption in mouse muscle lacking desmin, compared to normal mouse muscle.

There are also contradictory findings relating to changes in passive stiffness following eccentric exercise. Lapier et al[382] hypothesised that increased passive stiffness secondary to increased intramuscular connective tissue, with an associated reduction in myofibrillar stress, may be a protective adaptation following eccentric exercise.

In contrast, increased passive muscle stiffness may increase the susceptibility to muscle damage[431], and may be associated with increased symptoms of muscle damage[429]. Furthermore, acute increases in passive stiffness have been observed following exercise-induced muscle damage[304;671]. However, changes in passive stiffness associated with the repeated bout effect are unknown, and further investigation is needed.

2.1.10.3 Cellular theory

The "cellular theory" includes potential adaptations of the contractile mechanism of the muscle, as well as potential adaptations in the inflammatory response to exercise-induced muscle damage[428;429]. It is theorised that cellular adaptations associated with the repeated bout effect may include strengthening of the cell membrane[137], removal of select populations of weak fibres or sarcomeres following the initial muscle damage[16;99;407], and the longitudinal addition of sarcomeres[397].

Morgan[449] theorised that the longitudinal addition of sarcomeres following an initial bout of eccentric exercise would be associated with a reduction in individual sarcomere strain. A decrease in sarcomere strain would facilitate the overlapping of myofilaments, thereby reducing the extent of sarcomere "popping", and limiting the subsequent cellular disruption.

Further, Lynn and Morgan[397] observed an 8% increase in serial sarcomeres in rat vastus intermedius muscle following one week of downhill running, compared to a 4% decrease in serial sarcomeres following one week of uphill training. These results support the theory of longitudinal addition of sarcomeres, and may therefore provide a cellular mechanism for the repeated bout effect.

This theory may also be supported by indirect measures through studies investigating alterations in the length-tension curve following muscle damage. Theoretically, the longitudinal addition of sarcomeres would be associated with a shift in the length-tension curve to the right, as an increase in serial sarcomeres would require a greater muscle length to achieve optimal sarcomere length. However, there is conflicting evidence regarding alterations in the length-tension relationship following exercise-induced muscle damage.

Brockett et al[81] observed a shift in the length-tension curve to the right following recovery from an initial bout of lengthening hamstring muscle actions. In contrast, length-tension curves have been shown to return to normal within two days after eccentric exercise which caused muscle damage[322;671], suggesting that other mechanisms might be responsible for the protective adaptations of the repeated bout effect.

Another early theory attempted to provide an explanation for the repeated bout effect, and suggested that an initial bout of damaging exercise may facilitate the identification and removal of a select population of weak sarcomeres. The variability in sarcomere length might facilitate the process of selective sarcomere damage. During the repair process, according to this theory, the weak sarcomeres are replaced by stronger, strain resistant sarcomeres, and theoretically, there should be an improved uniformity in sarcomere length in a repeated bout of exercise[449].

There is equivocal evidence to support this theory. It is evident that high contraction intensity is required to provide protection during subsequent bouts of high intensity exercise[487]. The high intensity stimulus may be adequate to strain the weak sarcomeres without excessive myofibrillar disruption, thereby facilitating the replacement of the weak sarcomeres. However, it has also been demonstrated that the initial bout of eccentric exercise does not have to be of a considerable magnitude to develop the protective adaptation of the repeated bout effect[84;137;492].

Moreover, Clarkson and Tremblay[137] proposed that strengthening of the sarcolemma or the sarcoplasmic reticulum may decrease the extent of sarcolemmal disruption following eccentric exercise, preventing the calcium influx, and thus minimising the subsequent loss of calcium homeostasis and cellular disturbance.

Furthermore, it has been estimated from animal models that impairments of excitation-contraction coupling may account for 50% to 75% of the strength loss that occurs in the first five days following exercise-induced muscle damage[658]. Although this estimate is based on electrically stimulated maximal contractions in an animal model, and should therefore be interpreted with caution in relation to voluntary contractions in human skeletal muscle, adaptations in excitation-contraction coupling may provide a mechanism for the reduced strength loss following a repeated bout of exercise. The strengthening of the sarcoplasmic reticulum may therefore minimise the impairment of excitation-contraction coupling, and may provide a potential mechanism for the protective adaptations of the repeated bout effect[137;428].

However, other studies provide equivocal evidence for adaptations in excitation-contraction coupling, as a similar loss of force has been measured after initial and repeated bouts of exercise[84;137;197;465]. Conversely, adaptations in excitation-contraction coupling would be associated with immediate and subsequent reductions in strength loss following eccentric exercise[428].

A reduction in the symptoms of muscle damage in a repeated bout may also be attributed to an adaptation mediated by the inflammatory response. Pizza et al[535] observed decreased neutrophil and monocyte activation following a repeated bout of eccentric exercise. It is postulated that a dulled inflammatory response to a repeated bout may be a potential adaptation to avoid excessive mechanical disruption of myofibrils[428;429;536].

It may also be proposed that a reduction in the inflammatory response to a repeated bout of exercise may be secondary to a reduction in the mechanical disruption, and thus a reduction in the stimulus for an inflammatory response. The cellular theory may therefore reflect a combination of a reduction in myofibrillar disruption, as well a reduction in the inflammatory response to exercise-induced muscle damage[428].

2.1.10.4 Summary of the literature: the repeated bout effect

There is currently little consensus in the literature regarding the mechanisms of the repeated bout effect. It is evident that one theory cannot explain the various observations of the repeated bout effect that are discussed in the literature. In addition, some of the equivocal findings and discrepancies between the theoretical mechanisms of the repeated bout effect, and the experimental data may perhaps be explained by distinctions between primary and secondary muscle damage. It is therefore possible that the repeated bout effect may occur through the interaction of neural, mechanical, and cellular mechanisms that are dependent on the changes associated with the initial bout of exercise that causes muscle damage, and the specific muscle groups involved[428;429]. The repeated bout effect is an important factor when considering adaptations to endurance exercise and running performance.

2.1.11 SUMMARY OF THE LITERATURE: EXERCISE-INDUCED MUSCLE DAMAGE

It is therefore evident that exercise-induced muscle damage is a common occurrence following unaccustomed exercise, or exercise of increased intensity or duration, and is characterised by a complex interaction of central and peripheral adaptations involving cellular, mechanical, and neural mechanisms[98;133;196]. Exercise-induced muscle damage is also associated with alterations in functional capacity, including force loss, changes in the length-tension relationship, and neuromuscular adaptations[137;175;198;225;394;422;468;658].

Although the functional and physiological adaptations associated with exercise-induced muscle damage suggest that endurance performance will either decrease[412] or remain unchanged, relatively few studies have actually measured endurance performance, such as time to exhaustion at a fixed workload or time trial performance. Therefore, further studies are required to understand the relationship between exercise-induced muscle damage and endurance running performance.

Regular endurance training is also associated with numerous morphological, metabolic, and neuromuscular adaptations. These adaptations function primarily to reduce the extent of cellular disturbances during subsequent training bouts. Furthermore, the cumulative effects of regular exercise training are linked to chronic adaptations of skeletal muscle, including increased mitochondrial enzyme activity and protein concentration, increased capillary density, and an increased reliance on fat as a fuel, with a reduction in glycolytic flux. These adaptations are associated with an improvement in endurance performance[271].

Running economy is an important determinant of endurance running performance[50;76;146;166;359;453;480;571]. Numerous physiological, psychological, training, biomechanical, and environmental factors have been identified as influencing running economy[170;457;571]. However, little is known regarding the cumulative effect of prolonged periods of vigorous training and competition, exercise-induced muscle damage, and fatigue on running economy[455;456]. These factors will be discussed in the next section.

2.2 RUNNING ECONOMY

Running economy is defined as the relationship between oxygen consumption and the velocity of running, or alternatively as the aerobic demand of running[101;115;116;166;170;318;457;480;571]. Running economy is expressed as the submaximal oxygen consumption (VO_2) at a specific running velocity[8;146;455;571]. Runners with good running economy have reduced submaximal oxygen consumption at a fixed submaximal workload, compared to runners with a poor running economy[480;571;628]. Running economy may vary among runners with a similar maximum oxygen consumption (VO_{2max}) by as much as 30%[170;571]. In a homogeneous group of runners, running economy is strongly related to distance running performance, with better runners having lower oxygen consumption at submaximal running speeds[50;76;146;166;359;453;480;571]. It may therefore be suggested that improvements in running economy may be associated with improved distance running performance[166;480;571].

2.2.1 RUNNING ECONOMY AND PERFORMANCE

Previously, maximum oxygen consumption was considered to be an important factor in predicting running performance. Indeed, among a heterogeneous group of runners, there is a high correlation between maximum oxygen consumption and running performance. However, in a homogeneous group of runners, maximum oxygen consumption becomes poorly correlated with running performance, whereas running economy, or submaximal oxygen consumption, becomes strongly correlated with running performance[166;480].

The relationship between running economy and performance is well documented. Early research suggested that the variability in performance between two middle-aged ultramarathon runners with similar maximum oxygen consumption values could be attributed to the individual differences in economy[154]. Conley and Krahenbuhl[146] studied a group of twelve elite distance runners, with maximum oxygen consumption values of between 67 to 78 $ml.kg^{-1}.min^{-1}$, and 10 km times of between 30.5 and 33.5 minutes. Submaximal oxygen consumption was assessed at 14, 16, and 18 $km.h^{-1}$ three to six days after the runners had completed a 10 km race.

There was a poor relationship between the 10 km running performance and maximum oxygen consumption. However, there was a strong relationship between submaximal oxygen consumption at the three different running speeds and running performance during the 10 km race, with the more economical runners performing the best during the 10 km race. It was suggested that a high maximum oxygen consumption (above 67 $ml.kg^{-1}.min^{-1}$) assisted the runners in achieving an elite level of performance, but within the homogeneous group of elite athletes, running economy, and not maximum oxygen consumption, was associated with improved performance. In addition, DiPrampero et al[188] stated that a 5% increase in running economy may be related to an approximately 3.8% improvement in distance running performance.

Svedenhag and Sjödin[621] observed elite male distance runners over a 22-month period to determine variations in running economy and performance. The runners underwent alternating periods of slow, distance, uphill, and interval training during the 22-month period. There were significant reductions in submaximal oxygen consumption at 15 and 20 $km.h^{-1}$, and associated improvements in performance over 5000 m.

Furthermore, Weston et al[668] examined the differences in running economy and performance between Kenyan and Caucasian distance runners. Although the Kenyan group had average maximum oxygen consumption values approximately 13% lower than the Caucasian group, the 10 km performance time was similar between groups. Importantly, the Kenyan group had average running economy values approximately 5% better than the Caucasian group.

Conversely, Williams and Cavanagh[676] failed to identify a significant relationship between running economy at 13 $km.h^{-1}$, and 10 km performance in a group of 16 runners. The maximum oxygen consumption values, as well as the percentage of slow-twitch muscle fibres correlated best with the 10 km performance. However, the fixed submaximal exercise intensity used in this study did not account for individual variations in submaximal oxygen consumption at different relative exercise intensities, and may have contributed towards the poor relationship between exercise performance and running economy in this study.

A better running economy enables a runner to maintain a higher velocity during a race[170;457]. In a cross-sectional study, Morgan et al[453] examined the relationships between running performance, maximum oxygen consumption, and running economy. The predicted running velocity at maximum oxygen consumption was derived by combining the relative contributions of maximum oxygen consumption and running economy[170;457]. Results indicated that the strength of the relationship between the 10 km running time and the running velocity at maximum oxygen consumption exceeded that associated with either running economy or maximum oxygen consumption [453].

More economical runners are also able to run at a lower percentage of their maximum oxygen consumption, resulting in a lower blood lactate concentration at a given speed. Therefore, running economy at slower speeds may be a predictor for running performance at faster speeds[214]. In addition, although a relatively linear relationship appears to exist between submaximal oxygen consumption and running velocity during steady-state submaximal exercise, this relationship changes during high intensity exercise, where running performance is also dependent on anaerobic energy sources[170].

Furthermore, DiPrampero et al[187] stated that the maximal velocity that a runner can maintain during a race is dependent on the maximal metabolic power of the runner, and the energy cost of the run. This provides an explanation for the relative energy cost for a given velocity. It follows that runners with a lower energy cost at a given running velocity may have a metabolic advantage.

In summary, an improvement in running economy is related to an improvement in distance running performance[571]. Therefore, any intervention that results in a reduction in submaximal oxygen consumption during steady-state exercise may facilitate an improvement in exercise performance[571]. The numerous factors that may influence running economy will be discussed in the next section.

2.2.2 FACTORS AFFECTING RUNNING ECONOMY

Several factors have been identified as influencing running economy[170;457;571]. The following section will review the factors affecting running economy, including the intra-individual variability in running economy, and the physiological, psychological, training, biomechanical, and environmental factors affecting running economy.

2.2.2.1 Intra-individual variability

Consideration of the intra-individual variation in running economy is essential, particularly when evaluating the effectiveness of interventions aimed at modifying running economy[455;457]. Daniels et al[169] measured running economy in 10 well-trained male athletes. The subjects performed a total of 15 treadmill tests, consisting of four equally spaced testing sessions of either three or six runs at a set running velocity, over a seven-month period. Running speed, footwear and test equipment were controlled. An 11% variation in running economy was observed. Although the mean intra-individual differences were minimal, the ranges of individual differences were large. The comparatively high individual variation in running economy observed in this study may reflect a lack of rigorous experimental design, the relatively small number of subjects participating in the study, and poor control of confounding variables that may influence running economy, for example, circadian variation, training and performance activity, and sufficient familiarisation of the subjects with laboratory conditions and treadmill running[170;456;458].

Morgan et al[458] investigated the variability in running economy and mechanics among 17 trained male runners. Subjects performed between 30 to 60 minutes of treadmill familiarisation. Running economy was recorded during two level treadmill runs performed at the same time of day, in the same footwear, and in a non-fatigued state. Running economy demonstrated high day-to-day reliability (r = 0.95), with a mean coefficient of variation of 1.32%.

Further, Williams et al[678] examined the intra-individual variations in running economy in moderately trained male runners. Subjects were tested over a four-week period and performed a treadmill running test five days a week. Running economy was recorded at three different running speeds, being 2.68, 3.13, and 3.58 $m.s^{-1}$. The coefficient of variation between running economy at the three running speeds was not significant, that is, one speed did not result in any more or less variation in running economy than another. It was concluded that running economy, in conditions where treadmill accommodation, equipment, footwear, and the time of day of testing are controlled, is a relatively stable physiological measurement in moderately trained male runners.

Pereira and Freedson[522] studied the intra-individual variation in running economy between runners with different training levels. Seven highly trained male runners, with an average maximum oxygen consumption of 69.1 $ml.kg^{-1}.min^{-1}$, and eight moderately trained male runners, with an average maximum oxygen consumption of 58.3 $ml.kg^{-1}.min^{-1}$, were tested over a three-week period. Running economy was measured during three 15-minute level treadmill running sessions at approximately 88% of the running speed associated with the individual lactate threshold. The coefficient of variation for steady-state oxygen consumption was 1.8% for the highly trained group, and 2.0% for the moderately trained group. It was theorised that biological variation accounted for approximately 94% of the intra-individual variation in running economy.

Furthermore, Morgan et al[454] determined the intra-individual variation in running economy among trained and untrained subjects. Submaximal oxygen consumption was assessed during two to four level treadmill running tests among groups of elite, sub-elite, and moderately trained runners, as well as a group of untrained subjects. Due to the wide variation in exercise performance among the trained and untrained subjects, submaximal oxygen consumption was normalised to body mass and the distance travelled during the treadmill running test. The average within-group variability in submaximal oxygen consumption was similar among the elite, sub-elite, moderately trained and untrained groups. It may therefore be proposed that intra-individual variation in running economy does not differ according to individual training status or performance capability.

In addition, Brisswalter and Legros[79] demonstrated that running economy, respiratory measures, and stride rate were stable indicators of the energy cost associated with running in elite middle distance runners. A coefficient of variation of 4.7% for running economy was observed in 10 elite 800 m runners.

Saunders et al[572] examined the typical error associated with equipment, testing, and biological variation on running economy in 11 elite male runners. Runners were assessed on two separate occasions within a seven-day period. On each occasion, runners were required to perform three four-minute bouts of submaximal treadmill running at 14, 16, and 18 $km.h^{-1}$. The typical error for the pooled data of the three running speeds was 2.4% for submaximal oxygen consumption.

In summary, the intra-individual variation in running economy ranges from 1.3% to 11%. However, the degree of intra-individual variation may be substantially reduced with rigorous experimental design, and controlling for potential confounding variables such as circadian variation, footwear, and sufficient familiarisation of the subjects with laboratory conditions and treadmill running[170;456;458;572].

2.2.2.2 Physiological factors affecting running economy

2.2.2.2.1 Age

The majority of studies investigating changes in running economy associated with age have concentrated on changes in children and adolescents[11;359;361;644]. Daniels et al[168] studied children engaged in running training from later childhood to late adolescence (10 to 18 years of age). It was established that, when correcting for the increases in body mass, the maximum oxygen consumption values remained relatively unchanged, while there was a steady improvement in running performance. It was suggested that growth and training contributed to the improvements in running economy and performance in childhood and adolescence, although the relative contributions of these two factors were not well understood.

Improvements in running economy occur steadily with increasing age in normal active children and adolescents, even in the absence of formal training. In later childhood, running economy fails to respond to short-term running instruction or training, however long-term participation in training may augment the natural improvements in running economy that occur with increasing age[361].

Krahenbuhl and Williams[361] reviewed over 70 studies relating to the changes in aerobic capacity during childhood. It was concluded that children are less economical than adults, as they exhibit higher resting metabolic rates, greater ventilatory equivalents for oxygen, and disadvantageous stride rates and stride lengths.

Additional factors that may account for the observed variability in running economy between younger and older children, as well as between children and adults include differences in leg length, body surface area to body mass ratio, reduced glycolytic capacity, and training and growth factors[167;168;359;361;644].

Furthermore, Thorstensson[630] suggested that children may be less able to store and utilise elastic energy during running.

Morgan et al[454] performed a retrospective analysis and has provided some evidence to suggest that, within a limited age span of approximately 20 years, running economy remained relatively constant in adult distance runners. Astrand et al[24] reported similar findings in a longitudinal study, where the submaximal oxygen consumption of physically active subjects remained relatively unchanged at fixed submaximal workloads after 20 years.

However, relatively little is known regarding the extent and magnitude of the variation in running economy in older adults. Pate et al[514] assessed running economy of distance runners between 20 and 60 years of age, while running on a level treadmill. Age was significantly and positively correlated to submaximal oxygen consumption, suggesting that running economy declines with increasing age. Additional studies have identified a similar relationship between age and running economy during walking and running[11;210;662]. It is proposed that the age-related changes in running economy may be explained by reductions in muscle elasticity, together with antagonistic relaxation and associated reductions in muscle recruitment during running that occurs with increasing age[383].

Moreover, the age-related decline in running economy may also be associated with decreased hip flexibility, reduced stride length, increased body fat mass, and increased cardiorespiratory demands[383;589;644], and may be attenuated through regular exercise training[361]. Davies and Dalsky[176] also showed that the reduction in running economy with increasing age is not gender-specific, and that running economy at a fixed relative workload is similar for both male and female subjects. Moreover, Evans et al[210] investigated the physiological determinants of 10 km performance in highly trained female runners of different ages. Although running economy decreased with increasing age, the age-related decline in running performance was not strongly related to the decrease in running economy.

2.2.2.2.2 Gender

There is much evidence to suggest that the aerobic demand of submaximal running is not significantly different between trained males and females when expressed relative to body mass[170;419;457]. Westerlind et al[667] evaluated changes in running economy during 30 minutes of level and downhill running in males and females, and reported no gender differences in submaximal oxygen consumption during level or downhill running.

However, some studies have reported gender differences in running economy. Bransford and Howley[76] observed significantly lower aerobic demands relative to body mass in trained and untrained male runners, compared to trained and untrained female runners respectively. It was hypothesised that differences in the vertical displacement of the centre of mass, and training experience and intensity may account for the gender difference in submaximal oxygen consumption. Conversely, Glace et al[240] investigated the effects of a two-hour submaximal run, at an intensity which elicited ventilatory threshold, on running economy in male and female distance runners. Submaximal oxygen consumption was recorded before, and at 60 and 120 minutes during the run. At 120 minutes, there was a significant increase in submaximal oxygen consumption in the male group, indicating a decrease in running economy, compared to the female group.

These contrary findings regarding the gender differences in running economy indicate the importance of investigating performance-based criteria to assess gender variations in running economy. Daniels and Daniels[166] examined the running economy of male and female middle and long-distance runners through a series of submaximal treadmill tests. At common absolute running velocities, submaximal oxygen consumption was lower in the male runners compared to the female runners. However, at similar relative intensities of running, there were no apparent gender differences in running economy.

Further, Pate et al[513] used recorded times for a 24.2 km road race to match male and female distance runners, and found no significant differences in running economy between the male and female runners when matched for running performance.

In addition, Speechly et al[604] investigated the differences in ultra-endurance exercise performance in male and female distance runners. The male and female runners were matched according to their 42.2 km race speeds. Although the female runners performed significantly better during a 90 km ultramarathon race compared to the male runners, there were no gender differences in running economy between the groups. It was theorised that the superior performance of the female runners may be due to a higher fractional utilisation of maximum oxygen consumption compared to the male runners during the ultramarathon race.

2.2.2.2.3 Heart rate and ventilation

Inter-individual variations in running economy have been associated with differences in heart rate and ventilation. It has been suggested that myocardial and ventilatory work may account for between 1% to 2%, and 7% to 8% of the overall energy cost of exercise respectively[343;446;515]. Heart rate and ventilation reflect the efficient delivery of oxygen to the active muscles. Both have been shown to positively correlate with submaximal oxygen consumption, indicating that an improvement in running economy may be associated with reductions in heart rate and ventilation[514;515;687].

Bailey and Pate[34] noted that training-induced reductions in heart rate and ventilation may result in a decrease in submaximal oxygen consumption, with subsequent lower aerobic demands during exercise. Other authors have reported similar observations[190;565].

A reduction in heart rate is associated with an increase in stroke volume[73;579], and decreases in intrinsic heart rate, sympathetic tone, and circulating catecholamines[369]. A reduction in ventilation is associated with an increase in tidal volume, and a decrease in breathing frequency[34].

Furthermore, myocardial oxygen consumption also constitutes a proportion of whole body oxygen consumption during exercise. A reduction in myocardial oxygen consumption would result in a more effective combination of reduced heart rate and increased stroke volume, and would therefore result in an improvement in running economy[34].

In addition, Thomas et al[628] investigated the changes in heart rate, ventilation, and running economy during a simulated 5 km race. Heart rate and ventilation increased significantly, and running economy decreased significantly over the duration of the 5 km run. There was also a significant positive correlation between ventilation and submaximal oxygen consumption, indicating that the increase in ventilation was associated with a greater oxygen cost during the 5 km race. It was proposed that training interventions aimed at improving running economy should therefore focus on improving physiological characteristics such as heart rate and ventilation.

2.2.2.2.4 Core temperature

Numerous studies have determined that a higher core temperature is associated with an increase in oxygen consumption during submaximal exercise[269;457;480;605]. Saltin and Stenberg[566] reported a 5% increase in submaximal oxygen consumption during three hours of constant-load exercise under normal conditions. MacDougall et al[399] established that submaximal oxygen consumption was significantly higher in subjects exercising at 70% of maximum oxygen consumption under hyperthermic conditions, compared to normal or hypothermic conditions. Thomas et al[628] observed a significant increase in core temperature, and a significant decrease in running economy over the duration of a simulated 5 km race.

Armon et al[12] also determined that increased body temperature may have a major role in the oxygen drift which occurs as the duration of exercise increases. The positive association between body temperature and submaximal oxygen consumption may be due to increases in peripheral circulation and ventilatory rate, and a decrease in the efficiency of oxidative phosphorylation that occur during exercise in the heat[399;605].

In contrast, Rowell et al[561] demonstrated no significant alteration in submaximal or maximal oxygen consumption during exercise in the heat. Furthermore, additional studies have reported a reduction in oxygen consumption during the latter portion of a prolonged run[90;233;413]. It was proposed that the mechanical efficiency of the active muscle increases when the core temperature is mildly elevated. This adaptation results in a reduction in oxygen consumption by an amount equal to, or greater than, the increase caused by changes in the cost of circulation, ventilation, and sweating[571].

In addition, training-induced alterations such as a lower core temperature and an increased plasma volume associated with exercise in the heat, may attenuate the magnitude of the thermoregulatory response, and therefore reduce the increased energy requirements associated with heat stress[34;575].

2.2.2.2.5 Muscle fibre type

Inter-individual variations in running economy may be linked to differences in muscle fibre type, as oxygen is ultimately processed in the muscle to produce energy[455]. During activity, type II muscle fibres require more energy than type I muscle fibres to perform the same work, due to a higher rate of cross-bridge cycling and ATP consumption[130;362;455;550]. It has also been proposed that that different muscle fibre types have specific viscoelastic properties, such that type I muscle fibres are able to retain stored elastic energy for longer without cross-bridge detachment[68;72]. This reduces the reliance on energy generated by oxidative phosphorylation, and may therefore result in a reduction in submaximal oxygen consumption. Studies have shown that muscle fibre type distribution significantly affects oxygen uptake kinetics and oxygen consumption during exercise[42;160;365].

Kryöläinen et al[365] observed an inverse relationship between energy expenditure and the percentage of type II muscle fibres. In addition, Bosco et al[68] reported a significant association between the aerobic demand of running, and the ratio of efficiency of muscular work performed during pre-stretch jumps compared with no pre-stretch jumps, implying that the elastic behaviour of muscles during jumping may be associated with running performance. Conversely however, Williams and Cavanagh[676] were unable to determine differences in muscle fibre type in 31 trained male runners who exhibited good, medium or poor running economy. In addition, Franch et al[224] showed no association between muscle fibre type distribution and running economy in recreational distance runners.

2.2.2.2.6 Fatigue

The majority of studies investigating the relationship between running economy and fatigue propose that running economy declines during prolonged exercise, and that there is a positive association between the magnitude of the decline in running economy, and the exercise intensity and duration[114;267;268;605;683;687].

Xu and Montgomery[687] demonstrated significant increases in submaximal oxygen consumption in trained male distance runners during 90-minute runs at 65% and 80% of maximum oxygen consumption. Similarly, Sproule[605] reported increases in submaximal oxygen consumption immediately after 60-minute runs at 70% and 80% of maximum oxygen consumption. Both studies also showed greater increases in submaximal oxygen consumption at higher exercise intensities[605;687]. Significant reductions in running economy have also been observed over the duration of a simulated 5 km race[628], and for up to two days after a competitive duathlon event[102].

Further, Nicol et al[474] determined the fatigue effects of a paced marathon run on submaximal oxygen consumption in experienced endurance runners. Oxygen consumption was assessed four days before the marathon, at 20 km during the marathon, and immediately after the marathon. Oxygen consumption was determined during six-minute runs at 75%, 100%, and 125% of the individual marathon speed. Oxygen consumption was significantly increased immediately after the marathon at 75% and 100% of the individual marathon speed, compared to pre-marathon values.

Kryöläinen et al[369] also examined the effects of a paced marathon run on submaximal oxygen consumption in seven experienced triathletes. Submaximal oxygen consumption was assessed, in a five-minute submaximal run, one week before the marathon, at 0 km, 13 km, 26 km and 42 km during the marathon, two hours after the marathon, and at two, four, and six days after the marathon. The study showed that submaximal oxygen consumption was significantly increased at the end of the marathon (42 km), and two hours after the marathon. Interestingly, no other significant differences in submaximal oxygen consumption were observed during the marathon run[369].

Brueckner et al[86] reported a similar finding, where significant increases in the energy cost of running were only observed after 32 km and 42 km of running at a constant speed on an indoor track. In addition, Hausswirth et al[268] showed that submaximal oxygen consumption was increased during and at the end of simulated triathlon and marathon runs, when compared to values obtained during an isolated 45-minute run. However, Davies and Thompson[174] showed gradual increases in submaximal oxygen consumption during a high-intensity, four-hour run on a treadmill. In this study, the increase in submaximal oxygen consumption became more significant after 110 minutes of running.

It is hypothesised that both central and peripheral factors may contribute to the deterioration in running economy associated with prolonged exercise[174]. The increase in submaximal oxygen consumption during fatiguing exercise may be associated with increases in pulmonary ventilation[34] and heart rate[605;667;687], increases in energy expenditure associated with the dissipation of heat generated during exercise[258;605], increases in blood catecholamine and growth hormone concentrations[78;327], and increases in fat metabolism[687].

In addition, the increase in submaximal oxygen consumption may also be related to skeletal muscle damage and weakness that may occur during prolonged exercise, and may therefore also reflect an increase in muscle fibre recruitment[102;174;185;370;523;687]. More fibres are recruited to produce the required force, or to maintain a constant running velocity[102;174;369;474].

It may also be proposed that the alterations in neuromuscular function associated with fatigue may also affect running economy. There is evidence to suggest that at the end of a marathon, greater muscle recruitment is required to produce the same resultant force during the push-off phase[369;474;476]. Furthermore, alterations in stride length and running kinematics have also been linked to the development of fatigue during prolonged running, and may also be associated with reductions in running economy[200;268;369;474].

In contrast, Morgan et al[456] investigated the effects of a 30-minute maximal run at 89% of maximum oxygen consumption on running economy and running mechanics in male runners. No alterations in running economy were recorded on days one, two, and four after the maximal run, suggesting that there were no lasting effects of fatigue from the high intensity protocol on submaximal oxygen consumption. It was proposed that although 30 minutes of high intensity running does produce some evidence of fatigue, it does not sufficiently alter running mechanics to result in an increase in running economy.

Results from other studies also suggest that fatigue may not affect running economy[83;191]. Dressendorfer[191] examined steady-state oxygen consumption in trained male runners during a controlled bout of submaximal exercise, and following a paced outdoor 21.1 km run. There were no differences in submaximal oxygen consumption following the 21.1 km run, compared to the control values.

In addition, Glace et al[240] observed gender differences in the submaximal oxygen consumption response to a two-hour submaximal. At 120 minutes, there was a significant increase in submaximal oxygen consumption in the male runners, indicating a decrease in running economy, compared to the female runners. However, little is known regarding the cumulative effect of prolonged periods of vigorous training and frequent competitive distance racing on running economy[455;456].

2.2.2.2.7 Exercise-induced muscle damage

The literature suggests that exercise-induced muscle damage, and the resultant symptoms of delayed onset muscle soreness, may be associated with increases in submaximal oxygen consumption. Early work by Klausen and Knuttgen[344] demonstrated a gradual rise in oxygen consumption during exercise involving active lengthening of the muscle. A 25% increase in average oxygen consumption was reported during 25 to 50 minutes of eccentric cycling exercise. In addition, Dick and Cavanagh[185] reported significant increases in oxygen consumption and EMG activity from the vastus lateralis and vastus medialis muscles after 20 minutes of downhill running.

More recently, Braun and Dutto[78] examined the effects of a 30-minute downhill run, with a gradient of -10% at 70% of peak oxygen consumption, in experienced distance runners and triathletes. Submaximal oxygen consumption was measured at 65%, 75%, and 85% of peak oxygen consumption before, and 48 hours after the downhill run. Submaximal oxygen consumption was increased by 3.2% at 48 hours after the downhill run, compared to baseline measurements.

Similarly, Chen et al[125] used a 30-minute downhill run, with a gradient of -15% at 70% of peak oxygen consumption, to determine the effects of exercise-induced muscle damage on submaximal oxygen consumption in male soccer players. Submaximal oxygen consumption was measured at 65%, 75%, and 85% of peak oxygen consumption before, immediately after, and daily for five days after the downhill run. Submaximal oxygen consumption was increased by between 4% and 7% for up to three days after the downhill run, compared to baseline measurements. In addition, increased submaximal oxygen consumption has been reported in the presence of delayed onset muscle soreness following a duathlon[102] and a marathon[369].

The increase in submaximal oxygen associated with lengthening muscle actions and exercise-induced muscle damage may be explained in part by changes in motor unit recruitment related to muscle damage, and/or local muscle fatigue[78;102;185;370;523], whereby the active skeletal muscle fibres are unable to generate sufficient force, and additional motor units must be recruited to maintain a given level of work. The damaged fibres would continue to use oxygen, and the newly recruited muscle fibres would also contribute to an increase in submaximal oxygen consumption[185].

Alterations in stride length and running kinematics have also been associated with exercise-induced muscle damage[78;125;369;474]. It has been proposed that changes in kinematic parameters after downhill running may be related to an impaired ability to utilise the stretch shortening cycle, and therefore, elastic energy[29;96;125]. These biomechanical changes may also contribute to an increase in submaximal oxygen consumption in association with exercise-induced muscle damage[125].

Westerlind et al[666;667] proposed that, based on the repeated bout effect, muscle damage during subsequent bouts of eccentric exercise would be reduced and that fewer alterations in submaximal oxygen consumption would be observed, when compared to an initial bout of eccentric exercise. However, similar increases in submaximal oxygen consumption were observed during two successive bouts of downhill running performed two weeks apart. It was suggested that other factors, such as increases in heart rate, ventilation, and core temperature, in addition to muscle damage, may be contributing to the changes in oxygen consumption during downhill running. In support of this theory, increases in heart rate, minute volume, respiratory rate, and the rate of perceived exertion were observed during submaximal cycling exercise performed two days after an exercise bout which caused muscle damage[242].

Conversely, Marcora and Bosio[412] reported no changes in submaximal oxygen consumption during a 10-minute submaximal run at 70% of maximum oxygen consumption, following a 100-drop jump protocol designed to induced muscle damage in recreational runners. In addition, other studies have reported no changes in steady-state oxygen consumption at 55% and 75% of maximum oxygen consumption for five days after a 120-repetition maximum voluntary contraction protocol to induce muscle damage[510], or at approximately 70% of maximum oxygen consumption 24 to 30 hours after a protocol designed to cause muscle damage using a series of lower extremity resistance exercises[581].

Moreover, Petersen et al[524] used a marathon race to determine the effects of exercise-induced muscle damage energy expenditure at marathon pace in eight elite marathon runners. Energy expenditure was measured one week before the marathon, immediately after the marathon, and at two and five days after the race. Energy expenditure was significantly elevated by approximately 4% immediately after the marathon. However, energy expenditure was significantly reduced at two and five days after the race, compared to pre-race values. Energy expenditure was decreased by 6% and 9.5% at two and five days after the marathon respectively.

In addition, Hamill et al[263] examined the effects of a 30-minute downhill run, at a gradient of -26% at 74% of maximum heart rate, on recreational female runners. Submaximal oxygen consumption was measured before, and at 48 and 120 hours after the downhill run. There were no changes in the energy cost of running following the downhill run. These studies suggest that exercise-induced muscle damage does not alter steady-state oxygen consumption[263;412;510;581]. Further studies are needed to confirm these paradoxical findings, and to further understand the peripheral and central mechanisms that may mediate the physiological response to exercise-induced muscle damage.

2.2.2.3 Psychological factors affecting running economy

Theoretically, functional efficiency should be maximised through effective interaction between physiological and psychological processes. It may be further hypothesised that psychological state, that is a particular cognitive or emotional condition of the mind, may facilitate the maintenance of optimum performance levels[101;162]. Morgan[459] suggested that perception and cognition could possibly influence exercise metabolism.

Williams et al[679] examined the effect of mood state on running economy. Moderately trained runners were assessed over a four-week period. Submaximal oxygen consumption was measured at three treadmill speeds that approximated 50, 60, and 70% of maximum oxygen consumption. Mood state was determined using the Profile of Mood States (POMS) scale. The POMS scale assessed tension, depression, confusion, vigour, anger, and fatigue, and provided an indication of total mood disturbance.

Although no significant group relationship was observed between running economy and mood state, for individual subjects over the four weeks, strong relationships were determined between running economy and mood state. Specifically, strong linear relationships were demonstrated between submaximal oxygen consumption and tension, depression, anger, vigour, and confusion. This suggests that less negative emotion is associated with an improvement in running economy[679].

The monitoring of psychological variables has been shown to increase the use of associative techniques among sub-elite runners, with a resultant improvement in running economy[101;455]. Accordingly, Caird et al[101] examined the effects of biofeedback and relaxation techniques on running economy in sub-elite male runners. The runners completed a six-week training programme that included the use of relaxation techniques. Submaximal oxygen consumption was assessed every week during a 10-minute treadmill test at 70% of individual peak treadmill running speed. Biofeedback of heart rate, ventilation, and submaximal oxygen consumption was presented to the runners during the treadmill test.

It was established that the use of a combined biofeedback and relaxation intervention resulted in an improvement in running economy. The improved running economy may have been related to reductions in submaximal heart rate and ventilation. In addition, the changes in running economy were unaccompanied by changes in fitness as a result of training[101].

Furthermore, in humans, sleep has been shown to decrease activation of the sympathetic nervous system, resulting in significant reductions in heart rate, blood pressure, cardiac output, and oxygen consumption[599]. Pierce et al[528] examined the effects of an acute bout of sleep on running economy. Subjects performed a treadmill running test immediately following a one-hour bout of sleep. Initially, an acute bout of sleep resulted in improvements in running economy. However, as the study progressed, the control group (who did not sleep) showed gradual and progressive improvements in running economy. The implications of these finding are uncertain, and may indicate either differences in psychological arousal or anxiety, due to participation in the study, or the possibility of a delayed sympathetic arousal in the early stages of exercise following sleep.

It is recommended that future studies could measure catecholamine levels in the blood, to determine whether a relationship exists between the sympathetic nervous system and running economy[101]. In addition, the complex interactions between physiological, psychological, and neurophysiological factors and running economy require further investigation[162].

2.2.2.4 Training factors affecting running economy

Although numerous studies indicate that trained runners are more economical than untrained runners[76;170;189;360;420;538], there is currently little consensus regarding the effects of training and running economy. This is mainly due to a lack of rigorous experimental design, small sample sizes, and poor control of potential confounding variables, such as levels of fatigue, state of training, sufficient familiarisation of subjects with treadmill running, and footwear[457;571]. A number of studies have reported improvements in running economy after training interventions[76;147;148;168;170;182;224;454;503;516;518;538;621;623], while other studies have shown no change[189;376;443], or even a reduction in running economy following training interventions[171;376]. The initial level of fitness of the subjects is an important factor when considering the effects of training on running economy[168].

2.2.2.4.1 Endurance training

Endurance training enhances the function of the cardiorespiratory system, and the oxidative capacity of skeletal muscle[289;503]. The improved oxidative capacity of skeletal muscle is associated with increases in the morphology and functionality of skeletal muscle mitochondria[571]. An increase in the oxidative capacity of skeletal muscle allows for a reduction in the amount of oxygen utilised per mitochondrial respiratory chain at a defined submaximal workload. It is proposed that these responses result in subsequent improvements in running economy, a slower utilisation of muscle glycogen in the active musculature, and a smaller disturbance in homeostasis[289].

Moreover, studies examining the differences in running economy between trained and untrained subjects have suggested that a repetitive training stimulus may result in improvements in running style and biomechanics, the optimisation of motor unit recruitment patterns, and the development of an efficient oxidative energy supply[76;454;518]. It has also been theorised that differences in running economy may be related to training load, as better running economy has been associated with high levels of running experience and training volume[319;454;515]. It is further theorised that routine, long-term exposure to distance running may be the stimulus for improvements in running economy[319;454]. Indeed, Mayhew[421] observed a significant inverse relationship between running efficiency and years of training.

Differences in running economy have also been observed between middle-distance and long-distance runners, with better running economy being associated with long-distance runners[170;538]. The improved running economy in the long-distance runners has largely been attributed to a lower vertical displacement of the centre of mass, that may possibly be related to neuromuscular adaptations induced by long, slow distance training[620].

Equivocal results have been reported in the literature regarding the effects of various training programmes on running economy. Conley and Krahenbuhl[146] and Scrimgeour et al[582] reported improvements in running economy following training interventions. In addition, Sjödin and Svedenhag[591] observed improvements in running economy in elite distance runners of between 1% and 4% over one year.

In contrast, Bailey and Messeir[35] found no significant differences between pre-training and post-training measurements of running economy. Lake and Cavanagh[377] investigated the effects of a six-week training programme on the running economy and running mechanics of previously untrained male runners. Submaximal oxygen consumption was assessed during a 10-minute submaximal treadmill run at 3.36 $m.s^{-1}$ before and after the six-week training period. A control group, that did not perform any endurance training, was included in the study. There were significant improvements in maximum oxygen consumption, the fractional utilisation of maximum oxygen consumption, and running performance following the six-week training programme. However, submaximal oxygen consumption was significantly higher following the training intervention. In addition, there were no differences in running mechanics after the training programme.

It was postulated that, during the early stages of endurance training, running style is resistant to change, and improvements in running performance are predominantly due to physiological and metabolic adaptations. It was further suggested that factors leading to improvements in running economy might only occur after a longer period of exposure to an endurance training stimulus[377].

Furthermore, Bailey and Pate[34] proposed that alterations in training status may lead to physiological and biomechanical adaptations that may both positively or negatively affect running economy. Positive adaptations may include improved running biomechanics and skeletal muscle oxidative capacity[34]. Negative adaptations may include training-induced increases in body mass distribution in the limbs[115;416].

It is also important to identify whether exercise intensity influences running economy. Franch et al[224] investigated the effects of three different types of intensive running training on running economy in male recreational runners. Subjects performed continuous distance training, long-interval training, or short-interval training three times a week over a six-week period. The long-interval training consisted of four to six repetitions of interval training with four minutes of running at a high intensity followed by three minutes of recovery. The short-interval training consisted of 30 to 40 repetitions of interval training, with 15 seconds of running at a high intensity followed by 15 seconds of recovery. The continuous distance training and long-interval training resulted in an approximate 3% improvement in running economy, while the short-interval training had a minimal effect on running economy. However, a potential confounding variable for this study was that, although the duration of the training sessions were 20-30 minutes, training distance was not controlled. The short-interval training group (3.1 km; 20.4 $km.h^{-1}$) covered less distance than both the long-interval training (5.7 km; 16.6 $km.h^{-1}$) and continuous distance (6.4 km; 15.0 $km.h^{-1}$) groups respectively.

Further, Thomas et al[629] determined that interval training at 90% of maximum heart rate was more beneficial to the development of aerobic capacity than continuous running. Helgerud et al[278] also demonstrated a 6.7% improvement in running economy following an eight-week interval programme, compared with a control group that only participated in regular soccer training.

In addition, Paavolainen et al[503] reported a 2.8% improvement in 5 km running performance, and a 7.8% improvement in running economy following a nine-week training programme that included sprint, jump, and strength training.

Conversely, Helgerud et al[279] compared the effects of aerobic endurance training at different intensities, and with different methods that were matched for total work and frequency. Subjects performed long slow distance training at 70% of maximum heart rate, lactate threshold training at 85% of maximum heart rate, short-interval training, or long-interval training three times a week over an eight-week period. The short-interval training consisted of 15 seconds of running at 90-95% of maximum heart rate followed by 15 seconds of active recovery at 70% of maximum heart rate. The long-interval training consisted of four minutes of running at 90-95% of maximum heart rate followed by three minutes of active recovery at 70% of maximum heart rate.

All groups showed a significant improvement in running economy from pre- to post-training of approximately 5%. However, there were no significant differences in running economy between groups, suggesting that improvements in running economy do not appear to be related to the intensity of training, within running intensities corresponding to between 70% and 95% of maximum heart rate[279].

Recently, Chen et al[126] investigated the effects of 30 minutes of running performed daily after downhill running on the recovery of running economy and muscle function. Fifty male subjects participated in the study, and were evenly distributed into a control group, and groups that were required to perform 30 minutes of level running at 40%, 50%, 60%, and 70% of maximum oxygen consumption respectively, daily for six days after a 30-minute downhill run. Submaximal oxygen consumption was measured before, and at two, five, and seven days after downhill running during a five-minute level treadmill run performed at 85% of maximum oxygen consumption. Submaximal oxygen consumption was significantly increased for seven days after downhill running. However, no significant differences in the recovery of running economy were observed between the control and exercise groups, or between different exercise intensities.

These findings therefore indicate that daily running after exercise-induced muscle damage does not appear to influence the recovery of running economy, regardless of the exercise intensity. It is recommended that further studies should investigate the effects of high intensity endurance running on the recovery of running economy, as the maximum intensity utilised in this study was only 70% of maximum oxygen consumption[126].

Therefore, these paradoxical findings regarding the effects of endurance training programmes may possibly be explained in part by the varied duration, usually between six and 12 weeks, of the training studies. The duration of these studies may be too short to determine improvements in running economy. Moreover, there may be a certain threshold of training, or a particular type of training that is necessary for precipitating improvements in running economy[318]. The initial level of fitness is also an important factor when considering whether training alters running economy[168]. It is also possible that training exerts only a minor influence on running economy, and that economical runners are endowed with an anatomical or genetic make-up that produces an economical running style, and that favours success in endurance events[170].

2.2.2.4.2 Muscle power and strength training

Although endurance performance is largely dependent on aerobic metabolism[49], the ability to sustain a high running velocity also requires effective neuromuscular function in voluntary and reflex neural activation, muscle force and elasticity, running mechanics, and anaerobic capacity[503]. Strength training may be associated with improvements in running economy[571]. Improvements in maximal leg strength through regular resistance training may improve running economy and performance by reducing the percentage of maximal force required for each contraction, and therefore the recruitment of type II muscle fibres[283]. Strength training may also facilitate improvements in anaerobic characteristics, for example, the ability to increase lactate flux, the production of short contact times, and improvements in the rate of force development[88;286;302].

Heavy resistance training has been associated with improvements in endurance performance in untrained subjects[283;411;424], and improvements in running economy in moderately trained female distance runners[317]. Conversely, isolated strength training has been associated with impaired endurance development[606]. Indeed, muscle fibre hypertrophy that occurs in response to strength training may negatively affect running economy through the redistribution of body mass to the extremities[461].

Several studies have reported improvements in running economy following a combination of endurance and strength training. Millet et al[443] examined the effects of a 14-week combined resistance and endurance training programme, compared to an endurance-only training programme, in well-trained triathletes. The resistance programme consisted of six different strength exercises for the lower limbs. Subjects were required to perform three sets of three to five repetitions to failure twice a week. A 6.9% improvement in running economy was observed following the combination of resistance and endurance training, compared to endurance-only training. In addition, Johnston et al[317] examined the effects of a 10-week strength training programme, with concurrent endurance training, and demonstrated a 3.8% improvement in running economy.

Maximal strength training has been used to describe strength training using high loads and few repetitions, with the emphasis being placed on the neural adaptations to strength enhancement as opposed to muscle hypertrophy[287]. Støren et al[615] recently investigated the effects of maximal strength training on running economy and time to exhaustion in well-trained male and female runners. Subjects were randomly assigned to a maximal strength training (MST) group or a control group. The MST group performed four sets of four-repetition maximum half-squats three times per week for a period of eight weeks as a supplement to their normal endurance training. The control group continued with their normal endurance training during the eight-week period. Running economy was assessed at 70% of maximum oxygen consumption, and time to exhaustion was assessed at maximal aerobic speed, before and after the eight-week training period.

A 5% improvement in running economy was observed in the MST group following the eight-week training period, compared to pre-intervention. Time to exhaustion at maximal aerobic speed improved by 21% in the MST group following the eight-week training period, compared to pre-intervention values. Running economy and time to exhaustion at maximal aerobic speed were also both significantly improved in the MST group following the eight-week training period, compared to control group values. In addition, runners in the MST group exhibited no changes in body weight following the training period compared to pre-intervention values, suggesting that neural adaptations and changes in recruitment patterns were the main training responses following the maximal strength training intervention[615].

Furthermore, it was proposed that the improvement in running economy may be related to the significant increase in one-repetition maximum following the maximal strength training intervention, which may be associated with increased musculotendinous stiffness. Increased musculotendinous stiffness may enhance the storage and release of elastic energy, thereby improving running economy. However, as musculotendinous stiffness was not assessed in this study, this theory remains speculative, and requires further investigation[615].

Noakes[480] hypothesised that runners with poor economy may have muscles with a reduced ability to utilise the impact energy produced as they eccentrically absorb the force of landing. The relative stiffness of the musculotendinous system may be associated with the ability to store and utilise elastic energy[680]. Heise and Martin[275] suggested that less economical runners might have a more compliant running style during ground contact. Explosive-strength or plyometric training induces neuromuscular adaptations that may facilitate improvements in running economy. Plyometric training enhances the muscles' ability to generate power by stimulating the stretch shortening cycle with activities such as jumping, hopping, and bounding[645]. The proposed adaptations to plyometric training include increased activation of motor units with less muscle hypertrophy than resistance training[261], increased stiffness of the musculotendinous system[606], and modifications of the contractile component, the series elastic component, and the parallel elastic component[153].

Paavolainen et al[503] investigated the effects of a nine-week plyometric and endurance training programme in male cross-country runners. The total training volume was controlled, but the experimental group replaced 32% of the training volume with plyometric training, whereas the control group replaced 3% of the training volume with plyometric training. Neuromuscular characteristics were evaluated using a 20 m sprint test, and a five-jump test. The experimental group demonstrated a 2.8% improvement in 5 km running performance, a 7.8% improvement in running economy, and improved neuromuscular characteristics. No significant changes were measured in the control group. It was theorised that plyometric training may induce alterations in motor control that would enable a muscle to resist an imposed stretch more efficiently, and therefore result in an increased accumulation of elastic energy by the musculotendinous complex.

Spurrs et al[606] examined changes in performance following a six-week plyometric training programme performed in conjunction with normal running training in moderately trained male runners. The total training volume was controlled. The experimental group underwent plyometric training two to three times a week for the six-week period, in addition to the normal running training. The control group did not perform any plyometric training.

Submaximal oxygen consumption was measured during an incremental test to exhaustion. The subjects ran at each speed for three minutes. Submaximal oxygen consumption was determined by averaging values for the last minute at 12, 14, and 16 $km.h^{-1}$. The experimental group showed significant improvements in running economy of 6.7% at 12 $km.h^{-1}$, 6.4% at 14 $km.h^{-1}$, and 4.1% at 16 $km.h^{-1}$ following the plyometric training programme. It is however questionable as to whether steady-state submaximal oxygen consumption had been achieved during the incremental test to exhaustion, particularly as subjects rested for one minute for blood sampling, after each three-minute increment. The experimental group also showed a 2.7% improvement in 3 km running performance, and improved muscle-tendon stiffness and rate of force development following the training programme, in the absence of significant changes in maximum oxygen consumption. No significant changes were measured in the control group[606].

In a similar study, Turner et al[645] demonstrated a 6% improvement in running economy across three running speeds, as well as a 3% increase in 3 km running performance following a six-week plyometric training programme[606].

Further, Saunders et al[574] investigated the effects of a nine-week plyometric training programme in highly trained distance runners. The plyometric training was performed in conjunction with normal running training. The experimental group performed plyometric training for 30 minutes, three times a week for the nine-week period, in addition to normal running training. The control group did not perform any plyometric training. Submaximal oxygen consumption was measured during four-minute treadmill runs 14, 16, and 18 $km.h^{-1}$. The experimental group showed a significant improvement in running economy of 4.1% at 18 $km.h^{-1}$, but no significant changes were observed at the slower speeds. This was accompanied by significant improvements in the average power during plyometric activities, and the rate of force development.

These findings suggest that explosive-strength training and maximal strength training may improve running economy and performance, and that the improvements may be related to enhanced neuromuscular performance. Furthermore, plyometric training may be advantageous to resistance training as it is associated with the development of less muscle hypertrophy than resistance training[261]. Practically, it may be proposed that a combination of endurance and strength training, specifically including interval training and explosive-strength training, will facilitate optimal cardiorespiratory and neuromuscular adaptations, thereby maximising improvements in running economy.

2.2.2.4.3 Detraining and overtraining

Relatively few studies have investigated the effects of detraining and overtraining on running economy. The effects of short-term reductions of training load on economy are equivocal. One study showed that running economy remained unchanged following a 10-day period of reduced training[301]. However, a further study demonstrated improvements in running economy following a three-week period of reduced training. The improvement in running economy was attributed to elevated carbohydrate utilisation following the reduction in training load[300].

The literature also provides conflicting evidence regarding the effects of overtraining on running economy. Tanaka et al[624] reported that running economy was relatively unchanged following a 40% increase in training volume. In contrast, Kuipers and Keizer[373] suggested that insufficient recovery from short-term overtraining would increase the aerobic demand of running, due to added recruitment or stimulation of motor units. In addition, overtraining is thought to be associated with an alteration in the plasma tryptophan: branched chain amino acid ratio[469]. An increase in this ratio is thought to alter the levels of serotonin in the brain. Serotonin (5-HT) is implicated in the regulation of tiredness, mood and sleepiness, and may be related to the development of central fatigue. It may therefore be proposed that an alteration in the tryptophan: branched chain amino acid ratio may be associated with an increased energy cost of running in an overtrained state[469;624]. This however is merely a theory and needs to be tested for a decision to be made on its validity.

2.2.2.5 Environmental factors affecting running economy

Environmental factors, such as the air and wind resistance, up- and downhill running, temperature and altitude have large effects on running economy. Other factors that may influence running economy include running surface, shoes, and clothing[480].

2.2.2.5.1 Air and wind resistance

Early work by Pugh[546] showed that the extra oxygen cost of running associated with treadmill running increased as a function of the square of the opposing wind velocity. It was further estimated that the cost of overcoming air resistance during outdoor running was 8% of the total energy cost of running. Davies[172] supported these findings, although lower energy costs of between 2% and 4% for overcoming air resistance were reported. In addition, the energy cost of running increases as the velocity of a headwind increases[172;480]. A practical issue related to distance running is the potential reduction in energy cost associated with drafting. It has been suggested that drafting may reduce the energy cost of running by up to 5%[43]. However, limited data are available to support these findings.

2.2.2.5.2 Uphill and downhill running

Davies[172] calculated the additional energy cost of running uphill, and conversely, the energy saving of running downhill. It was estimated that the energy saving that occurs when running downhill is approximately half of the energy loss when running uphill at an equivalent gradient. Uphill running was associated with an increase in the energy cost of running by approximately 2.6 $ml.kg^{-1}.min^{-1}$ for every 1% increase in gradient. Downhill running was associated with a reduction in the energy cost of running by approximately 1.5 $ml.kg^{-1}.min^{-1}$ for every 1% decrease in gradient.

2.2.2.5.3 Temperature

MacDougall et al[399] observed significant increases in submaximal oxygen consumption in subjects exercising at 70% of maximum oxygen consumption under hyperthermic conditions, compared to exercising under normal or hypothermic conditions.

It was proposed that thermoregulatory mechanisms, including an increased energy requirement for the peripheral circulation, increased sweating, hyperventilation, and a decreased efficiency of energy metabolism, may have been associated with the reduction in running economy under hyperthermic conditions[399].

However, the mild elevation in core temperature that results from training in warm to hot conditions may be associated with improvements in running economy by increasing the efficiency of the active musculature. Bailey and Pate[34] suggested that the acute and chronic training-induced adaptations to exercise in the heat, for example, an increased plasma volume and a lower core temperature, may attenuate the magnitude of the thermoregulatory response, and reduce the increased energy requirements related to heat stress.

Heat acclimatisation, together with training, results in an increased plasma volume, the maintenance of stroke volume, decreased myocardial work, and decreased whole blood viscosity[34]. In addition, the combined effects of training and acclimatisation allow runners to have a lower heart rate and core temperature at a fixed submaximal workload, which may further improve running economy[628].

In support of this theory, Nielsen et al[477] showed that repeated exposure to exercise in hot, humid conditions resulted in a reduction in submaximal oxygen consumption, and an average 6% improvement in running economy. It may be hypothesised that training in moderate heat may improve running economy and performance at normal temperatures, although there is currently insufficient evidence to support this theory.

In addition, Folland et al[223] investigated the effects of leg heating and cooling on stride parameters and running economy. Water immersion was used to passively manipulate leg temperature. Submaximal oxygen consumption was measured during three 10-minute treadmill runs at 70% of peak oxygen consumption following 40 minutes of randomised leg immersion in cold (21.0 ºC), thermoneutral (34.6 ºC), or hot (41.8 ºC) water. There were no differences in running economy following immersion in the cold, thermoneutral, or hot water, despite significant reductions in stride length following the cold water immersion. These findings suggest that larger alterations in stride mechanics are required to influence running economy.

2.2.2.5.4 Altitude

The effect of altitude training on endurance performance has been widely investigated[91;184;251;253;385;571;573]. The underlying mechanisms of the improvement in performance as a result of altitude training are unclear[184;385], but may be linked to haematological changes[91;385], and local muscle adaptations[251]. Altitude acclimatisation is associated with both peripheral and central adaptations that improve oxygen delivery and utilisation, and which may be related to improvements in running economy. However, current literature has reported either no change in submaximal oxygen consumption[385;640], or reductions in submaximal oxygen consumption following altitude exposure[329;470;573]. A discussion of these studies follows.

Saunders et al[573] examined the effects of 20 days of sleeping at a simulated high altitude and training at a low altitude in elite distance runners. Subjects were randomly assigned into live high-train low (LHTL), live moderate-train moderate (LMTM), or live low-train low (LLTL) groups. The LHTL group lived at a simulated high altitude of 2000 to 3100 m, and trained at a low altitude of 600 m above sea level. The LMTM group lived and trained at a natural altitude of 1500 to 2000 m, while the LLTL group lived and trained at a natural altitude of 600 m. Submaximal oxygen consumption was measured while subjects ran on the treadmill at 14, 16, and 18 $km.h^{-1}$.

There was a significant reduction in submaximal oxygen consumption averaged across the three running speeds in the LHTL group. Running economy improved by 3.3% in the LHTL group, compared to the LMTM and LLTL groups. The increase in running economy occurred in the absence of any changes in cardiorespiratory measures or haemoglobin mass[573].

Furthermore, Katayama et al[329] demonstrated that intermittent exposure to normobaric hypoxia (12.3% oxygen) for three hours per day over a two-week period resulted in improvements in running economy of between 2.6% and 2.9%. The increase in running economy was accompanied by a reduction in heart rate, and a tendency towards an improved 3 km running performance.

In addition, Neya et al[470] recently determined the effects of nightly normobaric hypoxia and high intensity training under intermittent normobaric hypoxia on running economy in moderately trained middle-distance and long-distance runners. Subjects were randomly assigned to one of three groups; (i) hypoxic residential, (ii) hypoxic training, or (iii) control. The hypoxic residential group lived at a simulated altitude of 3000 m for 29 nights. The hypoxic training group performed twelve 30-minute sessions of high-intensity treadmill running at a simulated altitude of 3000 m, in addition to the normal training load. The control group continued with normal training at 60 m above sea level. There was a significant reduction of approximately 5% in submaximal oxygen consumption for the hypoxic residential group, compared to the hypoxic training and control groups. The increase in running economy also occurred in the absence of any changes in haemoglobin mass.

Conversely, Truijens et al[640] investigated the effect of intermittent hypobaric hypoxia combined with sea level training on exercise economy in well-trained swimmers and runners. Subjects were randomly assigned to either hypobaric hypoxia, a simulated altitude of 4000 m to 5500 m, or normobaric normoxia, a simulated altitude of 0 m to 500 m. The runners and swimmers both rested in a hypobaric chamber for three hours per day, five days a week for a period of four weeks. Exercise economy was determined by the relationship between oxygen uptake and speed using running and swimming sport-specific protocols before and after the altitude exposure period.

There were no significant differences between runners and swimmers in the hypoxic or normoxic groups in submaximal oxygen consumption, exercise economy, heart rate, or inspiratory ventilation following the altitude exposure. These findings suggest that intermittent exposure to hypobaric hypoxia does not improve exercise economy in well-trained swimmers and runners[640].

The proposed mechanisms that may improve running economy following altitude exposure may only be speculated, due to the equivocal evidence related to improvements in running economy following altitude exposure. Potential mechanisms may include a decreased cost of ventilation, improved mitochondrial efficiency, increased carbohydrate utilisation for oxidative phosphorylation, and a shift towards increased glycolytic involvement of adenosine triphosphate (ATP) regeneration. In addition, a decrease in by-product accumulation, such as inorganic phosphate, hydrogen, and adenosine diphosphate, increases the amount of energy released from ATP hydrolysis, and decreases the need to maintain hydrolysis rates at pre-acclimatisation levels[253;470].

However, further studies are necessary to explain the inconsistent changes in running economy following altitude exposure, and to determine the optimal altitude exposure required to facilitate improvements in running economy.

2.2.2.5.5 Running surface, shoes, and clothing

The influence of running surface on the oxygen cost of running was first observed by Passmore and Durnin[512], who showed that the oxygen cost of walking across a ploughed field was approximately 35% greater than the cost of walking at the same speed on a smooth, firm surface. Running on sand is also associated with an increased aerobic demand[534;686]. In addition, Jensen et al[314] demonstrated an average reduction in running economy of between 41% and 52% when runners changed from a horizontal path to heavy forest terrain. However, the impairment in running economy was less in orienteers, who were familiar with heavy terrain running, compared to the track runners. This indicates the importance of training specificity in relation to running surface.

Running economy also appears to be influenced by extra weight added to the legs or feet[480]. In-shoe orthotics increase shoe weight, and may therefore adversely affect running economy. Burkett et al[89] demonstrated an approximately 1.4% decrease in running economy following the addition of an 80 g orthotic to each running shoe. Berg and Sady[48] also noted increases in the energy cost of running following the addition of orthotics, although smaller increases of 0.4% to 1.1% were observed. Noakes[480] suggested that the added weight of the orthotic results in a decline in running economy in direct proportion to its weight.

Recently, Roy and Stefanyshyn[562] investigated the effects of increased midsole longitudinal bending stiffness on running economy by inserting carbon fibre plates into running shoe midsoles, and measuring running economy, local joint energetics, and muscle activity, compared to a control group with a normal running shoe midsole. An increased midsole stiffness was associated with an approximately 1% improvement in running economy, compared to the control group. However, no changes in joint energetics or muscle activity were observed, and as a result the underlying mechanisms of the improved running economy are not well understood.

Kyle and Caiozzo[375] examined the effects of athletic clothing on aerodynamic drag, and therefore on running economy. Aerodynamic drag increased by 0.5% due to shoes with exposed laces, by 0.9% due to long socks, by 4.2% due to loosely-fitting clothing, and by 6.3% due to long hair.

2.2.2.6 Biomechanical factors affecting running economy

Biomechanical factors may be associated with a substantial proportion of the inter-individual variability in running economy[415;416;457;675]. Alterations in running mechanics that result in a runner using less energy at a given speed may be related to improvements in running performance[8;119]. However, recent studies showed reductions in running economy associated with alterations in running technique[163;641]. The literature also provides equivocal evidence for the effect of biomechanical factors on running economy, particularly in relation to discrete kinematic variables. Accordingly, this review will focus on the anthropometric, stride length, kinematic, kinetic, motor unit recruitment, muscle elasticity, flexibility, and optimum length components that may affect running economy.

2.2.2.6.1 Anthropometry

Body mass, height, limb dimensions, and body fat are anthropometric characteristics that have been discussed as potentially affecting running economy. There is also evidence that leg mass and the distribution of mass may influence running economy. Williams and Cavanagh[676] observed an inverse relationship between body mass and submaximal oxygen consumption, and between maximal thigh circumference and submaximal oxygen consumption, indicating that heavier runners are more economical than runners who weigh less. This inverse relationship may be related to differences in segmental mass distribution[115]. Lighter runners tend to possess a greater percentage of body mass in the extremities compared to heavier runners, and may therefore have to perform a relatively greater amount of work in the movement of the limbs, leading to a decline in running economy[461].

Similarly, a training-induced redistribution of body mass to the extremities, associated with alterations in muscle size, results in a significant increase in submaximal oxygen consumption[461]. Studies have also indicated that the aerobic demand of carrying a given load at the distal segments of the body is greater than carrying the same load on the trunk[414].

2.2.2.6.2 Stride length

Stride length and frequency are perhaps the most fundamental kinematic variables that may affect running economy[457]. The process of shortening or lengthening a stride has an important effect on all of the active musculature. Each muscle is forced to work on a slightly different region of its force-velocity curve[119;554]. This change would alter the efficiency of the active musculature during running, and would therefore lead to an increase or decrease in the energy demand during running[119;170;457;554].

The aerobic demand of running at a given speed is lowest at a self-selected stride length[81;119;328;457;480]. A curvilinear relationship exists between stride length and submaximal oxygen consumption, such that submaximal oxygen consumption increases in a curvilinear way as stride length is either lengthened or shortened from that self-selected by the runner. The process by which a runner selects a particular running style and gait pattern appears to be subconscious[119]. Cavanagh and Williams[119] proposed that runners acquire an optimal stride length over time based on perceived exertion. In addition, the self-selection of an optimal stride length at a given running speed may be related to physiological adaptations as a result of repeated training.

Further, Bailey and Messier[35] trained novice runners for seven weeks, and compared changes in running economy associated with either freely selected or regulated stride lengths. This study demonstrated that the variability in stride length inherent in novice runners has no relationship with running economy during the initial phases of training. Therefore, any significant changes in stride length that affect running economy may be as a result of accumulated training over an extended period of time.

With training, there is a tendency for stride length to increase, and stride frequency to decrease[480]. It is also hypothesised that at lower stride frequencies, muscles need to develop relatively high external power to achieve longer stride lengths, whereas at high stride frequencies, the mechanical power associated with moving the limbs increases. At these extreme high or low stride frequency-length conditions, the reliance on the less economical type II muscle fibres increases, thereby increasing submaximal oxygen consumption, with a resultant decline in running economy[457].

These results suggest that running economy is not particularly sensitive to small deviations in stride length and stride frequency, from the optimal stride frequency-length combination. The specific mechanisms underlying the curvilinear relationship between stride length, stride frequency, and running economy are unclear, but may be associated with fundamental muscle force and power generating capabilities[416].

The interactions between stride length alterations, exercise-induced muscle damage, fatigue, and running economy are not well understood. Reductions in stride length have been observed following a marathon[268;369], and after 30 minutes of downhill running[78;125]. In contrast, increases in stride length have been noted with fatigue[103;195;590]. Further studies are required to investigate these contradictory findings.

2.2.2.6.3 Kinematics and kinetics

Current literature provides equivocal evidence regarding the relationship between the vertical displacement of the centre of mass and running economy. Although it may be logical to assume that there is an inverse relationship between the vertical displacement of the centre of mass and running economy, there is little evidence to support this theory. Cavanagh et al[118] demonstrated a lower vertical displacement of the centre of mass in elite distance runners, compared to good distance runners. However, this difference was not significant, and submaximal oxygen consumption was not measured, thereby limiting the interpretation of these findings.

Williams and Cavanagh[676] investigated the relationship between distance running mechanics and running economy in 31 male runners. Biomechanical measurements were obtained for subjects grouped according to low, medium, and high submaximal oxygen consumption values during running at 3.6 $m.s^{-1}$. There was a consistent trend for an effect of lower vertical displacement of the centre of mass on lower submaximal oxygen consumption, but this association was not significant.

More recently, Dutto and Smith[195] determined changes in the spring-mass characteristics of runners while running on a treadmill to exhaustion. Both vertical stiffness and leg stiffness declined as the duration increased. In addition, changes in vertical stiffness were strongly associated with changes in the vertical displacement of the centre of mass. Decreased vertical stiffness was related to increased vertical displacement of the centre of mass during stance phase. However, the energy cost of running was not assessed in this study. It therefore remains to be determined whether the observed alterations in vertical and leg stiffness and the vertical displacement of the centre of mass are advantageous or disadvantageous in relation to running economy and fatigue.

Studies have also provided limited information on the relationship between joint angles during the running gait cycle and running economy. Cavanagh et al[118] showed that elite runners displayed more acute knee angles during swing phase, and less ankle plantarflexion range of movement during toe-off, compared to good distance runners. However, no measurements of running economy were performed, therefore limiting the interpretation of these findings.

Williams and Cavanagh[676] obtained biomechanical measurements from runners grouped according to low, medium, and high submaximal oxygen consumption values while running at speed of 3.6 $m.s^{-1}$. Improved running economy in elite male distance runners was associated with a more extended lower leg at heelstrike, a reduction in ankle plantarflexion range of movement at toe-off, and a more acute knee angle during mid-support of the stance phase. In addition, improved running economy was also related to reduced arm movement during the running cycle, as measured by wrist excursion during the running gait cycle.

Furthermore, other discrete kinematic variables that may be associated with improvements in running economy include low vertical displacement of the centre of mass, increased forward lean of the trunk, more acute knee angles during swing phase, and decreased ankle plantarflexion, knee flexion, and hip extension range of movement during toe-off[677].

Williams and Cavanagh[676] demonstrated that improved running economy in elite male distance runners was associated with increased maximal plantarflexion and horizontal heel velocities at foot contact, and lower minimum resultant linear velocity of the knee during foot contact.

Williams et al[677] also observed that slower thigh extension velocity and lower knee extension velocity were related to improved running economy in elite female distance runners. Further, Anderson and Tseh[9] determined the relationship between running economy and kinematic variables in 27 male and female distance runners. Positive correlations were established between running economy and the angular velocity of shoulder rotation, and angular displacement of the hip and shoulder joints about the vertical axis of the trunk. In addition, a negative correlation was found between running economy and angular displacement of the arm at the shoulder in the saggital plane.

However, current literature provides equivocal evidence regarding the relationship between running kinematics, running economy, and exercise-induced muscle damage. Changes in angular kinematics have been reported for up to 48 hours after eccentric exercise[508], following 30 minutes of downhill running[125;194;263], and a marathon[474]. Conversely, little change in angular kinematics has been observed after a marathon[369], and after a prolonged maximal run[456].

Dutto and Braun[194] measured changes in ankle and knee joint kinematics following a 30-minute downhill run at 75% of peak oxygen consumption in male runners. Sagittal plane kinematics were recorded before, and 48 hours after the 30-minute downhill run. Reductions in both ankle and knee range of movement during stance phase were observed after downhill running. There were also changes in knee stiffness following the downhill run, and the changes in knee stiffness were associated with increased vertical leg stiffness for the initial portion of stance phase after downhill running.

In addition, Hamill et al[263] reported increased maximum ankle dorsiflexion during stance phase, a reduction in maximum knee flexion during stance and swing phase, and decreased maximum hip flexion at heelstrike following a 30-minute downhill run.

Furthermore, Paschalis et al[508] examined the effects of muscle damage to the knee extensor muscles, induced through a high-force eccentric exercise protocol, on walking and running biomechanics in healthy male subjects. Kinematic data were obtained before, and 48 hours after the eccentric exercise protocol. There were significant reductions in the knee joint range of movement during the stance and swing phases of both walking and running following muscle damage. There was also an increase in pelvic rotation and a decrease in pelvic tilt after the eccentric exercise protocol.

However, although these studies demonstrated changes in running kinematics following exercise-induced muscle damage, the effect of these alterations in running kinematics on running economy has yet to be determined.

Chen et al[125] used a 30-minute downhill run, with a gradient of -15% at 70% of peak oxygen consumption, to determine the effects of exercise-induced muscle damage on running economy. Submaximal oxygen consumption was measured at 65%, 75%, and 85% of peak oxygen consumption before, immediately after, and daily for five days after the downhill run. Submaximal oxygen consumption was increased by between 4% and 7% for up to three days after the downhill run, compared to baseline measurements. The reduction in running economy was accompanied by decreased range of movement of the ankle and knee joints of between 1% and 7%, and decreased stride length of between 3% and 6%, for two to three days following the downhill run.

Further, Nicol et al[474] determined the fatigue effects of a marathon on running kinematics and kinetics. Biomechanical variables were measured during a six-minute treadmill run just before and immediately after the marathon. Subjects were required to run for three minutes at a slow speed, for two minutes at a medium speed, and for one minute at a fast speed. The slow, medium, and fast speeds corresponded to 75%, 100%, and 125% of the individual marathon speed respectively. A large degree of inter-individual variation in biomechanical variables was observed in both the fatigued and non-fatigued states.

Although there were no significant differences in stride length before or after the marathon, the duration of the push-off phase relative to the total ground contact time was significantly increased at the slow and medium speeds after the marathon, compared to pre-marathon values. There were also significant increases in the knee flexion angle at heelstrike, the hip extension range of movement during swing phase, and the maximum hip extension velocity at the medium speed after the marathon, compared to pre-marathon values. It was theorised that the kinematic changes may reflect deterioration of the muscular tolerance to impact, with an associated loss in the recoil characteristics of the muscle[474].

Conversely, Kryöläinen et al[369] examined the effects of a marathon on kinematic measurements in seven experienced triathletes. Only minor changes in kinematic measurements were observed during the experimental period, despite a significant increase in mean stride frequency, and a significant reduction in mean stride length. It is unclear to what extent these changes occurred during the marathon, or in the recovery period after the marathon. Mean ground contact time, vertical displacement of the centre of gravity, external mechanical work, and power remained relatively constant pre- and post-marathon. There were also no significant changes in the angular displacement or velocity of the hip, knee and ankle joints before, during, or in the recovery period after the marathon. It was proposed that the differences in stride frequency and length may be an attempt to compensate for the impaired neuromuscular function during, and in the recovery period after the marathon.

In addition, Avela et al[29;32] determined the effects of a marathon on kinematic measurements in nine experienced male endurance runners. The marathon was run in two separate competition races. Testing was conducted one hour before the marathon, and immediately after the race. Angular displacement, ground contact time, and neuromuscular function were assessed during maximal stretch shortening cycle exercises using a sledge ergometer. Interestingly, there were no significant differences in the knee and ankle joint displacements before or after the marathon, despite changes in neuromuscular function that included significant reductions in average force, take-off velocity, electromyographic (EMG) activity of the vastus medialis and soleus muscles, and the short-latency reflex component after the marathon.

Although certain kinematic variables have been associated with improvements in running economy, further studies are required to determine the relationship between exercise-induced muscle damage, running kinematics, and running economy.

2.2.2.6.4 Ground reaction forces

Ground reaction forces represent the functional and mechanical requirements during stance phase. During ground contact, muscle activation occurs in order to provide stability and the maintenance of forward momentum. Excessive changes in momentum in the vertical, antero-posterior, and medial-lateral directions are wasteful in terms of metabolic energy requirements[276].

Heise and Martin[276] demonstrated that less economical runners displayed greater total and net vertical impulses during foot contact, indicating wasteful vertical motion. Although a positive relationship was observed between vertical ground reaction force and submaximal oxygen consumption, other ground reaction force characteristics, such as twisting, antero-posterior and medial-lateral moments were not significantly correlated with submaximal oxygen consumption.

Kryöläinen et al[364] established that ground reaction forces and the rate of force production increased with increasing running speed. It was proposed that increasing the pre-landing and braking activity of the leg extensor muscles may improve the ability of the runner to tolerate higher impact loads. Muscle preactivation is essential for the timing of muscle activity with respect to ground contact. Muscle preactivation increases the sensitivity of the muscle spindle through improved alpha-gamma coactivation potentiating stretch reflexes, thereby enhancing musculotendinous stiffness, and leading to a subsequent improvement in running economy.

Vertical ground reaction force is a major determinant of the metabolic cost during running[213;276;362]. However, horizontal forces may also substantially influence the metabolic cost of running. Pugh[546] demonstrated that the metabolic cost of running increased with the square of the head-wind velocity.

Chang and Kram[122] used a harness to alter horizontal force to assist and impede runners. The metabolic cost of running was increased by 30% with a 6% impeding force. In contrast, the metabolic cost of running was decreased by 33% with a 15% assisting force. It was concluded that generating horizontal force is metabolically more expensive per unit of force than instituting a horizontal braking force during steady-state running.

Nummela et al[495] investigated the relationship between neuromuscular characteristics and running economy and running performance in distance runners. Subjects performed various running tests that included a 20 m maximal sprint test, a submaximal test at 4.28 $m.s^{-1}$ to measure running economy, a 5 km time trial, a maximal anaerobic running test (MART), and a VO_{2max} test. Average EMG activity of the five lower limb muscles was calculated during the 5 km time trial. The ability to produce power above VO_{2max} (MART VO_{2gain}) was calculated by subtracting the maximum oxygen consumption from the oxygen demand of the maximal velocity during the maximal anaerobic running test.

The results showed significant relationships between running economy and MART VO_{2gain}, and between the running speed and the average EMG ratio during the ground contact phase at 3 km during the 5 km time trial. These findings suggest running economy and distance running performance may be related to the neuromuscular capacity to generate force[495].

Nummela et al[493] also determined the relationship between running economy, running mechanics and running speed in young endurance runners. Subjects performed two separate tests on an indoor track. The first test consisted of eight repetitions of a 30 m sprint with increasing speed, and ground reaction forces were measured during each running speed. The second test was an incremental test of five to six 1000 m laps. Running economy was measured at a running speed of 3.89 $m.s^{-1}$. Ground contact time was significantly correlated with both running economy and maximal running speed. In addition, there was a significant correlation between the mass-specific horizontal force and maximal running speed. However, there was no relationship between maximal running speed and vertical effective force. It was concluded that the short ground contact time associated with both improved running economy and high speed running emphasises the importance of fast force production for endurance running performance.

Furthermore, Williams and Cavanagh[676] demonstrated that improved running economy was related to lower first peaks in the vertical component of the ground reaction force, smaller antero-posterior and vertical peak forces, and a rear-foot striking pattern. It was suggested these characteristics may affect muscular demands before and during stance phase, thereby influencing running economy. In addition, runners with a forefoot striking pattern may have to rely more on the musculature to assist with cushioning the impact with the ground during running, while runners with a rear-foot striking pattern may be able to rely more on the cushioning effects of the skeletal system and footwear[117;676].

It is therefore evident that the net resultant force generated on the ground may affect the muscle moments and forces at each joint. As a result, the vertical and horizontal ground reaction forces should not be considered as independent determinants of the metabolic cost of running[122].

2.2.2.6.5 Motor unit recruitment patterns

There is a paucity of literature regarding the relationship between motor unit recruitment patterns and running economy. It is theorised that alterations to muscle activation patterns may influence running economy, and that differences in activation patterns in bi-articular muscles may exist between economical and uneconomical runners[277;364]. Heise et al[277] determined that improved running economy was associated with an earlier onset of rectus femoris activation, which remained active for a longer duration during each phase of the running cycle. It was proposed that more economical runners may have an increased reliance on rectus femoris, which is an efficient bi-articular muscle, for the dual action of hip flexion and knee extension, and a decreased reliance on the less efficient mono-articular hip flexors. In addition, the more economical runners also had a shorter hamstring-gastrocnemius coactivation period during swing phase, compared to the less economical runners.

Abe et al[1] investigated the relationship between integrated electromyographic (iEMG) activity of the vastus lateralis muscle and the metabolic energy cost of running during a prolonged 90-minute run. The iEMG activity of the vastus lateralis muscle was divided into lengthening and shortening phases using a force platform and a knee joint goniometer. The ratio of lengthening to shortening iEMG activity of the vastus lateralis muscle significantly decreased over the duration of the 90-minute run, due to an increase in iEMG activity of the vastus lateralis muscle during the shortening phase of running. In addition, the metabolic energy cost of running significantly increased over the duration of the 90-minute run. A significant inverse relationship was established between the metabolic energy cost of running, and the lengthening to shortening ratio of iEMG activity of the vastus lateralis muscle.

Furthermore, Heise et al[274] recently observed the relationship between an index of running economy and the temporal electromyographic characteristics of leg muscles in female runners. Subjects performed a 30-minute treadmill run at a speed coinciding with a hard rating of perceived exertion. Oxygen uptake and electromyographic data were collected towards the end of the treadmill run. Running economy was calculated as a function of oxygen consumption and distance. Muscle coactivation durations were calculated for the rectus femoris, vastus lateralis, biceps femoris, and gastrocnemius muscles.

Reductions in submaximal oxygen consumption were significantly associated with greater on-time duration of rectus femoris during stance phase, and greater on-time coactivation duration of rectus femoris-gastrocnemius during stance phase. This study established a clear relationship between running economy and the coactivation of biaticular leg muscles during stance phase. It is hypothesised that this control strategy may be related to the enhanced return of elastic energy, thereby facilitating improvements in running economy[274].

Muscle coactivation has also been directly related to joint stiffness. Through coordinated activity, simultaneous lower limb muscle coactivation may be associated with increased joint stiffness, and an increased return of elastic energy, thereby reducing the metabolic cost of exercise[277;364].

Further, increased joint stiffness during stance phase may facilitate effective propulsion during the running cycle. It has also been suggested that the effective coordination of bi-articular muscle activity may be associated with more efficient ground reaction forces[277;364]. In addition, the optimisation of motor unit recruitment patterns may contribute to training-related improvements in running economy[455].

2.2.2.6.6 Muscle elasticity

The ability to effectively store and release elastic energy may be associated with improvements in running economy[8]. During running, elastic energy is stored during the eccentric or lengthening components of the running cycle, particularly as the muscles absorb the shock of landing. The release of elastic energy in subsequent contractions contributes to propulsion during the running cycle. The improvement in muscular performance following an initial lengthening prestretch has been attributed to the storage and release of elastic energy, and may be related to an increase in running economy[68;115;364].

Muscle elasticity may be influenced by the rate and magnitude of stretch, the level of activation and stiffness of the musculotendinous unit, muscle length at completion of the stretch, and the time delay between the completion of the stretch and the initiation of the subsequent shortening muscle action[68;115;571]. A short and rapid stretch with a short coupling time, and a high force at the end of prestretch are all factors that are associated with an increase in musculotendinous elasticity[364].

Heise and Martin[275] investigated the relationship between "leg spring" characteristics and the aerobic demand of running. No relationship was observed between the normalised leg spring stiffness and running economy, however there was an inverse relationship between the normalised effective vertical stiffness and running economy.

The inverse relationship between the normalised effective vertical stiffness and running economy suggests that less economical runners possess a more compliant running gait during ground contact, which may place greater force demands on the extensor musculature[275].

Kryöläinen et al[364] showed that stiffer muscles around the ankle and knee joints in the braking phase of running increased force potentiation during the push-off phase of the running cycle. It has been speculated that the Achilles tendon and tendons in the arch of the foot may store 35% and 17% of the energy stored and released during a step respectively, when running at moderate speeds[336]. In addition, Cavagna et al[113] estimated that, without the contribution of the storage and release of elastic energy, submaximal oxygen consumption during running may be increased by approximately 30% to 40%.

Voigt et al[653] investigated the influence of Young's elastic modulus of tendon tissue, tendon dimensions, and instantaneous moment arms on the efficiency of human movement in repetitive jumping tests and in a submaximal running test. The correlation between running economy and high mechanical efficiency became successively better with increasing contributions of tendon work in relation to the total work during repetitive jumping. This observation indirectly suggests that these tendon variables have a strong influence on running economy.

Furthermore, Arampatzis et al[10] investigated the influence of the mechanical and morphological properties of the musculotendinous unit on running economy in endurance runners. Submaximal oxygen consumption and running kinematics were recorded during three 15-minute treadmill runs performed at 3, 3.5, and 4 $m.s^{-1}$ respectively. Maximal isometric ankle and knee joint moments, and electromyographic activity of the vastus lateralis, vastus medialis, rectus femoris, and triceps surae were recorded during maximal voluntary contractions. Tendon properties the triceps surae were determined using ultrasound during a maximal voluntary contraction of the ankle plantarflexors.

The maximal tendon force, maximal plantarflexion moment, normalised stiffness, and energy storage capacity during a maximal voluntary contraction of the triceps surae were significantly increased in the group with high running economy, compared to the moderate running economy and low running economy groups. There were no significant differences between groups in the morphological tendon characteristics, including fascicle length, ratio (fascicle length to tibial length), angle of pennation, and thickness[10].

More economical runners demonstrated increases in contractile strength and normalised tendon stiffness in the triceps surae musculotendinous unit, a more compliant quadriceps tendon and aponeurosis at low-level tendon forces, an improved capacity for the storage of elastic energy during a maximal voluntary contraction, and no differences in muscle architecture, compared to less economical runners[10].

It is proposed that these factors may be associated with an increased ability to generate force during running, thereby decreasing the volume of active muscle at a given workload, leading to a subsequent improvement in running economy. Therefore, one of the major functions of muscles during running may be to modulate musculotendinous stiffness, to effectively utilise elastic energy and improve running economy[10].

2.2.2.6.7 Flexibility

Flexibility, particularly of the trunk and lower limbs, may influence running economy. It has been proposed that a less flexible musculotendinous system may improve running economy, as increased stiffness may be associated with improvements in elastic energy storage and return[19;243;571].

Gleim et al[243] used a "tightness" score to examine the relationship between flexibility and walking and running economy in untrained subjects. The "tightness" score was based on the sum of eleven different trunk and lower limb flexibility measurements. Subjects with the lowest flexibility scores were the most economical when running at speeds of 3 to 11 $km.h^{-1}$, indicating that "non-pathological musculoskeletal tightness" was related to an increase in running economy. It was theorised that inflexibility in the transverse and frontal planes of the trunk and hip improved the stability of the pelvis during ground contact, resulting in a reduction in excessive range of movement, muscle stabilising activity, and therefore the energy cost of running.

Similarly, Craib et al[161] determined the relationship between nine measurements of trunk and lower limb flexibility and running economy in well-trained male distance runners. Improved running economy was associated with inflexibility in the hip and calf regions, particularly dorsiflexion and standing hip rotation.

Jones et al[320] also observed a negative relationship between running economy and the sit-and-reach test performance in elite distance runners. In addition, Kryöläinen et al[364] showed that stiffer muscles around the ankle and knee joints in the braking phase of running increased force potentiation in the push-off phase. It may be hypothesised that the inverse relationship between flexibility and running economy may be linked to a reduction in muscle stabilising activity around the pelvis and foot, and an increase in the storage and return of elastic energy.

However, Magnusson[404] identified that there is a lack of evidence connecting long-term alterations in flexibility to alterations in the passive properties of the musculotendinous system. Furthermore, Magnusson et al[405] showed that increases in joint range of movement following a three-week stretching programme were due to an increase in stretch tolerance rather than changes in the viscoelastic properties of muscle.

Subsequently, Nelson et al[462] investigated the effects of a 10-week stretching programme on flexibility, using the sit-and-reach test, and running economy in physically active subjects. The stretching programme was associated with significant improvements in flexibility, while submaximal oxygen consumption remained relatively unchanged. Therefore, an increase in flexibility does not necessarily result in a reduction in running economy. Further studies are required to investigate the association between flexibility exercises, musculotendinous stiffness properties, and running economy.

In addition, Hayes and Walker[273] determined the effects of three different types of pre-exercise stretching on running economy in competitive middle-distance and long-distance runners. Subjects were divided into groups that performed a control condition, static stretching, progressive static stretching, or dynamic stretching. The stretches were performed for 30 seconds, and were repeated twice before a 10-minute run at a pace below the pace coinciding with the lactate threshold.

The three stretching interventions resulted in significant improvements in flexibility, however there were no significant changes in submaximal oxygen consumption. These findings therefore indicate that pre-exercise stretching does not appear to influence running economy. It is recognised that the stretching interventions utilised in this study were only performed immediately prior to execise testing. Additional studies are needed to determine the effect of regular pre-exercise stretching on running economy[273].

2.2.2.6.8 Changes in the length-tension relationship: shift in optimum length

There is a lack of evidence regarding the relationship between the shift in optimum length following eccentric exercise and running economy. The optimum angle for torque generation shifts to the right following lengthening muscle actions, indicating a shift in the length-tension relationship towards longer muscle lengths for maximal force generation[322;669].

The shift in optimum length may be related to a reduction in active stiffness at shorter muscle lengths, potentially due to sarcomereogenesis[449;450;543]. In addition, the shift in optimum length may also be associated with an increase in passive stiffness at longer muscle lengths[553]. In terms of neuromuscular function, a more compliant musculotendinous unit has an increased ability to store elastic energy, whereas a stiffer musculotendinous unit is capable of producing a faster rate of power output. During stretch shortening cycle exercise, increased compliance at the beginning of the stretch may be associated with improved storage of elastic energy. In addition, increased stiffness towards the end of the stretch shortening cycle may be related to improvements in the amount and rate of energy released. These adaptations may therefore enhance the action of the stretch shortening cycle[87]. It may be further postulated that improved efficiency of the stretch shortening cycle associated with the shift in optimum length may be associated with improvements in running economy. However, this theory is speculative, and requires further investigation.

2.2.3 SUMMARY OF THE LITERATURE

It is therefore evident that numerous physiological, psychological, training, biomechanical, and environmental factors may influence running economy[8;170;457;571]. However, the complex relationship between endurance training, exercise-induced muscle damage and fatigue associated with distance running, and running economy is not well understood. In addition, although distance running is associated with structural muscle fibre damage[15;94;284;591;592], little is known regarding the cumulative effect of prolonged periods of vigorous training and frequent competitive distance racing on running economy[455;456].

The training-induced adaptations associated with endurance training, including the enhanced function of the cardiorespiratory function, improved skeletal muscle oxidative capacity[289;503], improvements in running style and biomechanics, and the optimisation of motor unit recruitment patterns[76;454;518] may all be related to improvements in running economy.

However, there is equivocal evidence regarding the effects of exercise-induced muscle damage and fatigue on running economy. A reduction in running economy has been reported following 30-minute downhill runs[78;125], 60-minute[605] and 90-minute runs[687], a 5 km run[628], a duathlon[102], and marathon runs[369;474]. In contrast, running economy has remained unchanged following a 30-minute maximal run[456], a 30-minute downhill run[263], a 21 km run[191], and various eccentric exercise protocols[412;510;581]. Alterations in stride length have also been associated with exercise-induced muscle damage[78;125;369;474].

In addition, although it has been established that neuromuscular function is disturbed for 11 days after an ultramarathon[120], little is known about the time course of recovery of running economy and stride length following an ultramarathon.

Therefore, the aim of the first study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon on running economy and stride length in experienced ultramarathon runners.

CHAPTER THREE
STUDY ONE: CHANGES IN SUBMAXIMAL OXYGEN CONSUMPTION AND STRIDE LENGTH AFTER A 90 KM ULTRAMARATHON

3.1 INTRODUCTION

Marathon and ultramarathon races impose severe physiological stresses on runners[120;284]. Previous studies on runners of the 90 km Comrades marathon have provided information regarding changes in electrocardiographic (ECG) activity[165], serum enzyme activities, fluid balance[164], renal function[310], factors explaining the development of hyponatraemic encephalopathy[309], and the decrement in muscle power associated with muscle damage[120].

It is well documented that muscle damage is a common occurrence associated with distance running[120;284]. Exercise-induced muscle damage is characterised by a disruption of the sarcolemma[15], sarcotubular system[15;94], contractile components of the myofibril, the extracellular matrix and the cytoskeleton[227]. Distance running is also associated with impaired muscle function[120;450;455] and delayed onset muscle soreness[369]. Previous studies have shown that muscle pain associated with delayed onset muscle soreness usually dissipates within 96 hours after exercise[78;98], but may persist for up to 10 days after exercise[135].

The relationship between muscle damage associated with distance running and running economy has not been well established. Running economy is defined as the relationship between oxygen consumption and the velocity of running, or as the aerobic demand of running[166;457;571].

In a homogeneous group of runners, running economy is strongly related to distance running performance, with better runners having lower oxygen consumption at submaximal running speeds[166;480]. Oxygen consumption is reduced at submaximal running speeds after training for distance running[571;582], suggesting that training may be associated with improvements in running economy.

There are numerous factors that influence running economy[571]. Physiological factors include age[361], gender[166], body mass[49], heart rate and ventilation[515], muscle fibre type[68] and training[455]. Environmental factors which influence running economy include running surface[512], up- and downhill running[172], wind speed and direction[546], altitude[573], and environmental temperature[477].

However, current literature provides conflicting evidence regarding the effects of exercise-induced muscle damage and fatigue on running economy. A reduction in running economy, or an increase in submaximal oxygen consumption, has been reported following 30-minute downhill runs[78;125], 60-minute[605] and 90-minute runs[687], a 5 km run[628], a duathlon[102], and marathon runs[369;474]. In contrast, submaximal oxygen consumption has remained unchanged following a 30-minute maximal run[456], a 30-minute downhill run[263], a 21 km run[191], and various eccentric exercise protocols[412;510;581]. Alterations in stride length have also been associated with exercise-induced muscle damage[78;125;369;474]. Kryöläinen et al[369] observed reductions in stride length and running economy after a marathon. In addition, previous studies have identified a relationship between changes in stride length and running economy[119;457].

While it is known that neuromuscular function is disturbed for at least 11 days after an ultramarathon[120], little is known about the time course of recovery of running economy and stride length following an ultramarathon. Accordingly, the aim of this study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon on running economy and stride length in experienced ultramarathon runners.

3.2 METHODS

3.2.1 SUBJECTS AND STUDY DESIGN

Twenty-one healthy male runners were selected for the study, which had a quasi-experimental design. A schematic diagram of the research design is shown in Figure 3.1. The study was granted ethical clearance by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town (Appendix III). Subjects gave written consent after being informed about the demands of the study. The subjects completed a questionnaire to determine their age, training history, medical and surgical history, and any past or present injuries to the lower limbs.

The subjects were also familiarised with the laboratory equipment and testing protocols that would be used during the trial. This familiarisation process was conducted to reduce error associated with subjects performing unaccustomed exercise.

Eleven runners, who participated in the Comrades marathon (a 90 km ultramarathon race between Durban and Pietermaritzburg, South Africa)[145] were assigned to the experimental group. Ten runners, who did not participate in the ultramarathon race formed the control group. The groups were matched according to age, training history and running performances. The subjects were requested to avoid any medication, and strenuous training and racing, other than the ultramarathon race, for the duration of the study (± 42 days). Subjects were instructed to maintain the same diet and training regimen for 24 hours prior to the standard test (Figure 3.1). To facilitate adherence with instructions, subjects completed a training logbook for the duration of the study. In addition, subjects were questioned about their compliance with instructions prior to each laboratory test. Testing occurred at a similar time (to within one hour) for each subject for the duration of the study.

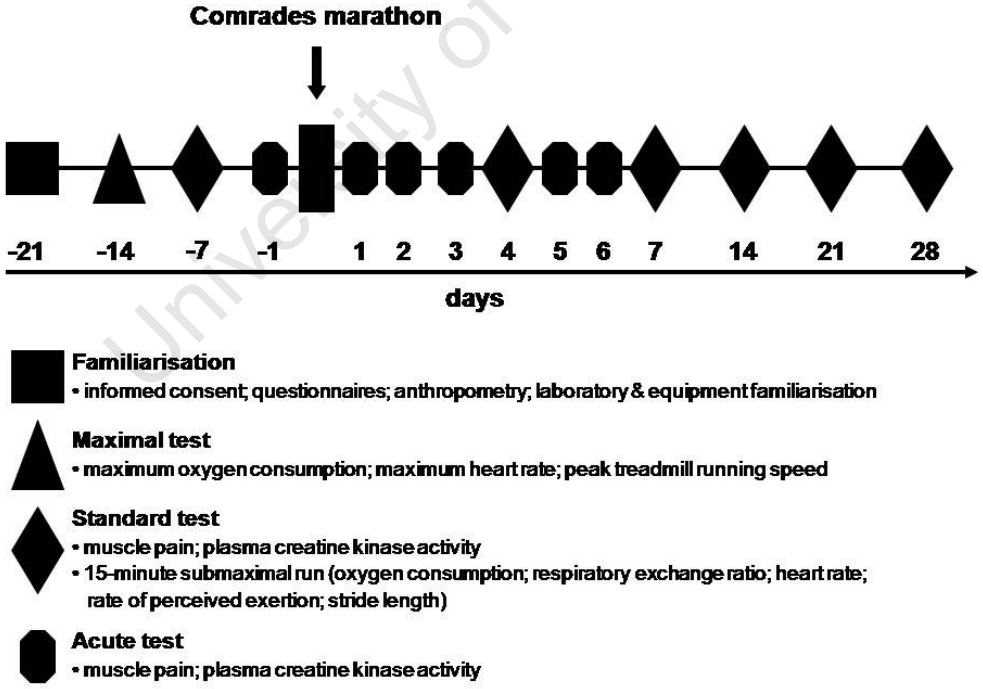

Figure 3.1: *Study design.*

3.2.2 MAXIMAL TEST

Preliminary testing was conducted on all subjects three weeks before the Comrades marathon (Figure 3.1). All subjects had their body composition assessed. Body fat was represented as the sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, calf, thigh and abdomen), as described by Ross and Marfell-Jones[559], and also as a percentage of body mass[193]. Harpenden skinfold callipers (Baty International, West Sussex, United Kingdom) were used to measure skinfold thickness.

A maximal treadmill test was performed two weeks before the ultramarathon race to determine maximum oxygen consumption (VO_{2max}), peak treadmill running speed (PTRS), and maximal heart rate (HR_{max}). The maximal test was performed on a treadmill (Quinton Instruments, Seattle, WA, USA), with the elevation set at 1%, in order to reproduce the energetic cost of running outdoors on a flat surface[321].

The subjects warmed up before the maximal test. The timing and intensity of the warm-up was specific for each subject, and was maintained for the duration of the study. The test was started with the speed set to 10 $km.h^{-1}$. This speed was maintained for two minutes, after which it was increased by 0.5 $km.h^{-1}$ every 30 seconds until the subjects were unable to maintain the speed of the treadmill. During the maximal test, subjects wore a mouthpiece and a nose clip. The duration of the incremental phase of the maximal test was approximately 10 minutes.

The expired air passed through a computer attached to an Oxycon Alpha automated gas analyser (Jaeger/Mijnhardt, Groningen, The Netherlands) for the determination of oxygen consumption (VO_2) and respiratory exchange ratio (RER) every 15 seconds. Before each test, the gas analyser was calibrated with a Hans Rudolph 5530 L syringe using room air, as well as with an on-line CO_2:N_2 gas mixture of known composition. Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at five-second intervals. Maximum oxygen consumption was defined as the oxygen consumption value that coincided with volitional fatigue. Peak treadmill running speed was defined as the highest speed that the runner could maintain for a complete 30-second increment prior to fatigue. Maximum heart rate was recorded as the highest heart rate during the last 30 seconds of the treadmill test. The treadmill speed for the 15-minute standard submaximal test was 75% of the peak treadmill running speed.

3.2.3 STANDARD TESTS

Each subject completed six standard tests (Figure 3.1). The first test was conducted seven days before the Comrades marathon. The standard test was repeated at 4, 7, 14, 21, and 28 days after the race. Laboratory conditions were standardised at a temperature of approximately 20 °C, and a relative humidity of approximately 60%.

Muscle pain was measured subjectively, where subjects rated lower limb pain in the quadriceps muscle group of both legs according to a "rating of perceived pain" on a scale of 0 to 10, where 0 represents "*no pain*", and 10 represents "*maximal pain*". Subjects were required to rate "*pain at rest*" in the quadriceps muscle group. This method of measurement of muscle pain has previously been shown to be highly correlated with objective pain measures[583].

Two 5 ml blood samples were taken from the subject's antecubital vein before the submaximal treadmill test, for the analysis of blood lactate concentration and plasma creatine kinase (CK) activity. A further 5 ml sample was taken exactly three minutes after completing the test, in order to determine peak blood lactate concentrations. The blood samples were collected into pre-chilled tubes containing potassium oxalate and sodium fluoride, and lithium heparin, for the analysis of blood lactate concentrations and plasma creatine kinase activity, respectively. The samples were kept on ice until centrifugation.

Blood samples were centrifuged at 2000 x *g* for 10 minutes at 4 °C upon completion of the standard test. Samples were stored at -20 °C until the analysis of blood lactate concentrations and plasma creatine kinase activity. Blood lactate concentrations, from both before and after the submaximal treadmill test, were measured by spectrophotometric (Beckman DU-62, Beckman Instruments, Fullerton, California, USA) enzymatic assays (Lactate PAP, bioMērieux, Lyon, France). Plasma CK activity was measured by spectrophotometric (Beckman DU-62, Beckman Instruments, Fullerton, CA) enzymatic assays (CK-NAC activated, Boehringer Mannheim Automated Analysis for BM/Hitachi Systems 704, Meylan, France).

Subjects warmed up in a similar way for each standard submaximal treadmill test. The test started with the treadmill speed set at 10 $km.h^{-1}$ and a 1% elevation. This speed was maintained for two minutes, and was then increased to the speed that coincided with 75% of the peak treadmill running speed for each subject. Each subject maintained this speed for 15 minutes.

During the submaximal test, oxygen consumption (VO_2), respiratory exchange ratio (RER), and heart rate (HR) were recorded, as previously described for the maximal test, at 3, 6, 9, 12, and 14.5 minutes. Subjects were also required to indicate their rate of perceived exertion (RPE), using a modified Borg scale[423], at 3, 6, 9, 12, and 14.5 minutes. Stride frequency was manually counted for 30 seconds at 4, 9, and 14 minutes. Two independent investigators performed manual counting to ensure accuracy of this method. Running velocity was expressed as $m.min^{-1}$, and the distance covered in 30 seconds was calculated. Stride length was derived according to the following calculation:

$$Stride\ length = \frac{distance}{step\ frequency} \times 2$$

3.2.4 ULTRAMARATHON RACE

Subjects in the experimental group completed a 90 km ultramarathon race. The Comrades marathon is run annually between Durban and Pietermaritzberg, South Africa. However, the start and finish of the race alternate each year, and the race is therefore run in different directions. In this study, the race started at sea level, in Durban, and finished at an altitude of 650 m, in Pietermaritzberg. The highest point of the race is 870 m above sea level. Anecdotally, this race is described as the "*up*" run[145]. A race profile of the "*up*" run is included in Appendix I.

Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at one-minute intervals for the duration of the ultramarathon race. Race heart rate data were averaged, and expressed as a percentage of maximum heart rate to provide an indication of exercise intensity during the ultramarathon race.

3.2.5 ACUTE TESTS

Daily muscle pain measurements, as described for the standard tests, and blood samples, for the analysis of plasma CK activity, were collected one day before, and for seven days after the Comrades marathon, to quantify muscle damage (Figure 3.1).

Blood samples (5 ml) were collected into tubes containing lithium heparin, and were kept on ice until centrifugation at 2000 x *g* for 10 minutes at 4 °C. Samples were stored at -20 °C until the analysis of plasma CK activity. Plasma CK activity was measured by spectrophotometric (Beckman DU-62, Beckman Instruments, Fullerton, CA) enzymatic assays (CK-NAC activated, Boehringer Mannheim Automated Analysis for BM/Hitachi Systems 704, Meylan, France).

3.2.6 STATISTICAL ANALYSES

Although data for submaximal oxygen consumption, respiratory exchange ratio, the rate of perceived exertion, and heart rate were analysed at 3, 6, 9, 12, and 14.5 minutes during the submaximal test, only the data (except stride length) at 3 and 12 minutes are shown in the results. These time points were selected to represent the warm-up and steady-state phases of the submaximal test respectively. Stride length at 4, 9, and 14 minutes were selected for analysis. Average values were calculated for the time points presented by averaging the data immediately preceding, at, and immediately following the respective time point.

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in descriptive variables between the experimental and control groups were assessed using an independent t-test.

Statistical significance for the two main effects of group and time, and the interaction (group x time) of all other variables were assessed using a two-way analysis of variance (ANOVA) with repeated measures. Tukey's *post hoc* comparisons were performed where necessary. A Mann-Whitney U test was used to assess differences in the pain scores between groups. A Friedman's ANOVA and Kendall's concordance was used to assess differences in the pain scores within groups over time. All data are presented as the mean ± standard deviation (SD). Statistical significance was accepted as $p < 0.05$.

3.3 RESULTS

3.3.1 SUBJECTS

The descriptive characteristics of subjects are shown in Table 3.1, and the training and racing history of subjects are shown in Table 3.2. There were no significant differences between groups for any of these variables.

Table 3.1: *Descriptive characteristics of subjects in the experimental (n = 11) and control (n = 10) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Age (years)	39.7 ± 9.3	41.0 ± 10.8
Body mass (kg)	74.9 ± 14.6	75.6 ± 9.6
Height (cm)	177.5 ± 7.6	178.1 ± 8.7
Sum of skinfolds (mm)	95.9 ± 36.0	93.1 ± 38.3
Body fat (%)	21.6 ± 5.1	21.6 ± 4.1
Maximum heart rate ($b.min^{-1}$)	177 ± 11	176 ± 18
VO_2max ($ml.kg^{-1}.min^{-1}$)	54.7 ± 7.2	54.3 ± 5.2
Peak treadmill running speed (PTRS) ($km.h^{-1}$)	16.7 ± 1.5	16.4 ± 1.5

Table 3.2: *Training and racing history of subjects in the experimental (n = 11) and control (n = 10) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Total years running	7.6 ± 7.6	6.3 ± 4.4
Pre-competition training distance ($km.wk^{-1}$)[$]	70.5 ± 10.6	74.0 ± 13.5
Average training distance ($km.wk^{-1}$)	56.6 ± 6.5	58.5 ± 10.8
Number of standard marathons (42 km)	30 ± 30	22 ± 25
Personal best 10 km time (min)	43.1 ± 3.0	41.0 ± 4.4
Personal best 42 km time (min)	209.2 ± 15.8	210.7 ± 22.8

[$] *Average training distance in the 3 months preceding the race*

The subjects in the experimental group completed the 90 km race in 606.6 ± 39.2 minutes. The average intensity (% HR_{max}) during the race was 84 ± 4%.

3.3.2 MUSCLE PAIN

The subjects in the experimental group had painful muscles for four days after the race (Figure 3.2). Specifically, the subjective pain scores (arbitrary units) were significantly higher in the experimental group on days 1 (4.2 ± 0.8 vs. 0; $p < 0.0002$), 2 (2.8 ± 1.1 vs. 0; $p < 0.0002$), 3 (2.1 ± 1.4 vs. 0; $p < 0.0005$), and 4 (1.3 ± 1.4 vs. 0.3 ± 0.7; $p < 0.02$) after the ultramarathon. For the duration of the study thereafter, there were no differences between groups (Figure 3.2).

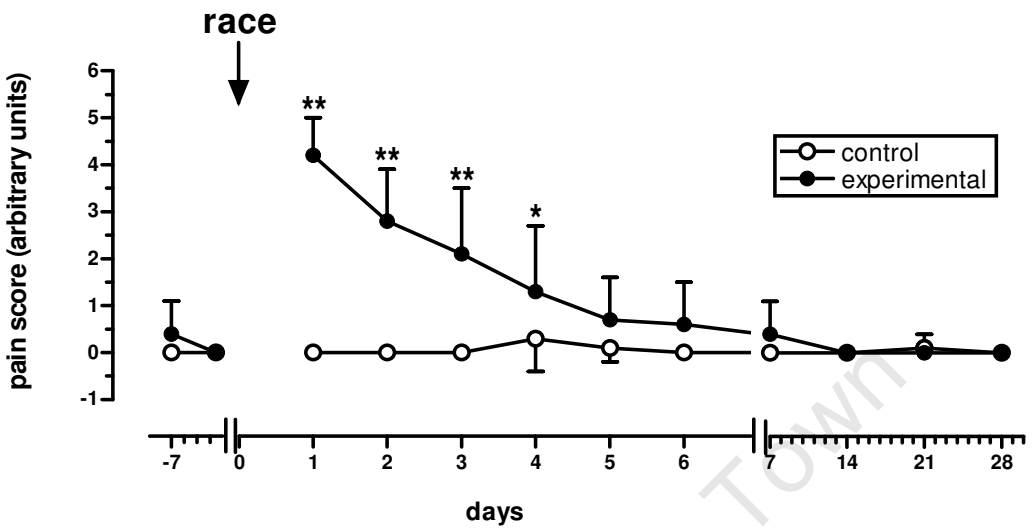

Figure 3.2: *Subjective pain (arbitrary units) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1,2, and 3 vs. control days 1, 2, and 3 respectively ($p < 0.0005$)

* experimental day 4 vs. control day 4 ($p < 0.02$)

3.3.3 PLASMA CREATINE KINASE ACTIVITY

There was a significant interaction between groups over time for plasma CK activity ($F_{(12, 228)} = 23.65$; $p < 0.0001$) (Figure 3.3). The plasma CK activity was significantly higher in the experimental group on days 1 and 2 ($p < 0.00002$) after the ultramarathon. From day 3 onwards, for the duration of the experiment, there were no differences between groups.

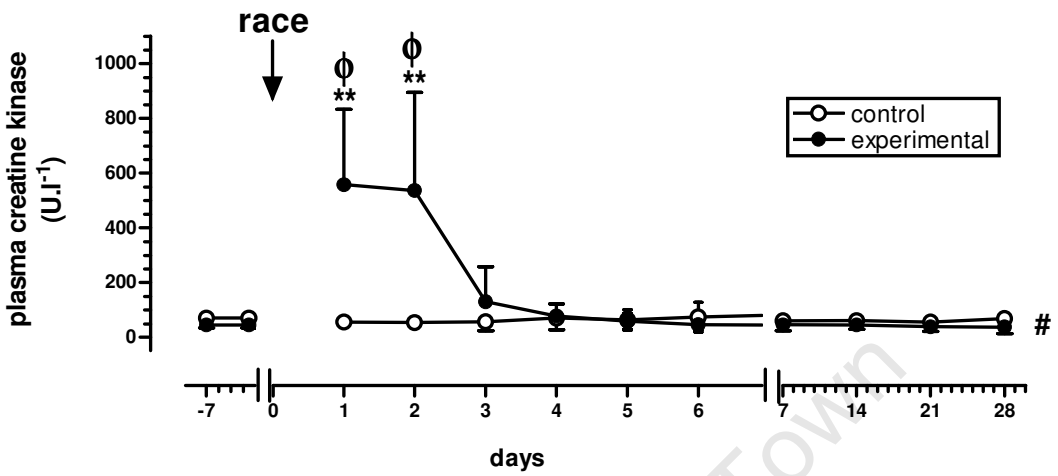

Figure 3.3: *Plasma creatine kinase activity (U.l^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1 and 2 vs. experimental days -7, -1, 3, 4, 5, 6, 7, 14, 21, and 28 ($p < 0.00002$)

ϕ experimental days 1 and 2 vs. control days -7, -1, 1, 2, 3, 4, 5, 6, 7, 14, 21, and 28 ($p < 0.00002$)

interaction of group x time ($p < 0.0001$)

3.3.4 OXYGEN CONSUMPTION

The differences in oxygen consumption (VO_2) ($ml.kg^{-1}.min^{-1}$) at 3 minutes (representing the warm-up) and 12 minutes (representing steady-state) in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 3.4. There was a significant interaction between groups over time for oxygen consumption at 3 minutes ($F_{(5, 95)} = 5.18$; $p < 0.0004$).

At 3 minutes, oxygen consumption was significantly lower in the experimental group at days 4 ($p < 0.0002$), 7 ($p < 0.0002$), 14 ($p < 0.0002$), 21 ($p < 0.0002$), and 28 ($p < 0.0004$), compared to pre-race values.

There was no difference between groups at 12 minutes, whereas there was a significant difference in the measurement over time ($F_{(5, 90)} = 5.98$; $p < 0.00009$). At 12 minutes, oxygen consumption was significantly lower in the experimental group at day 4 ($p < 0.03$), compared to pre-race values.

3.3.5 RESPIRATORY EXCHANGE RATIO

The differences in respiratory exchange ratio (RER) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 3.5. There was a significant interaction between groups over time for respiratory exchange ratio at 3 minutes ($F_{(5, 95)} = 2.85$; $p < 0.02$) and 12 minutes ($F_{(5, 90)} = 2.54$; $p < 0.04$). At 3 minutes, respiratory exchange ratio was significantly higher in the experimental group at days 4 ($p < 0.05$) and 7 ($p < 0.002$), compared to pre-race values. At 12 minutes, respiratory exchange ratio was significantly higher in the experimental group at day 7 ($p < 0.006$), compared to pre-race values.

Oxygen consumption

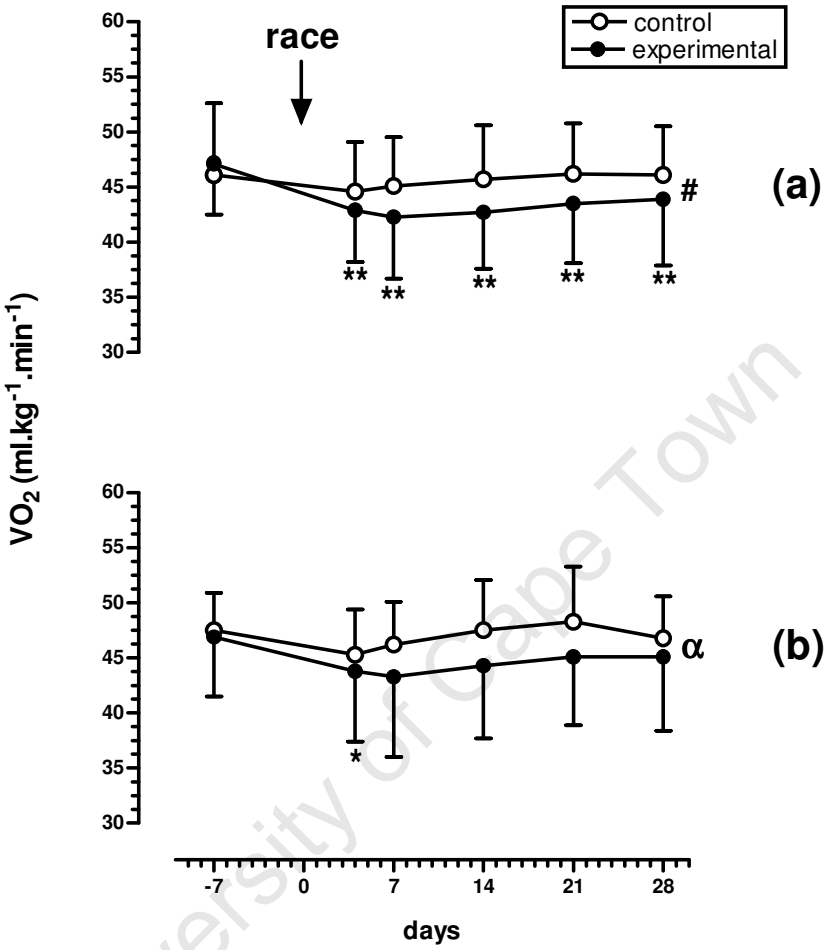

Figure 3.4: *Oxygen consumption (ml.kg^{-1}.min^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: ** experimental day -7 vs. days 4, 7, 14, 21, and 28 ($p < 0.0004$)
interaction of group x time at 3 minutes ($p < 0.0004$)

(b) 12 minutes: ** experimental day -7 vs. day 4 ($p < 0.03$)
α main effect of time at 12 minutes ($p < 0.00009$)

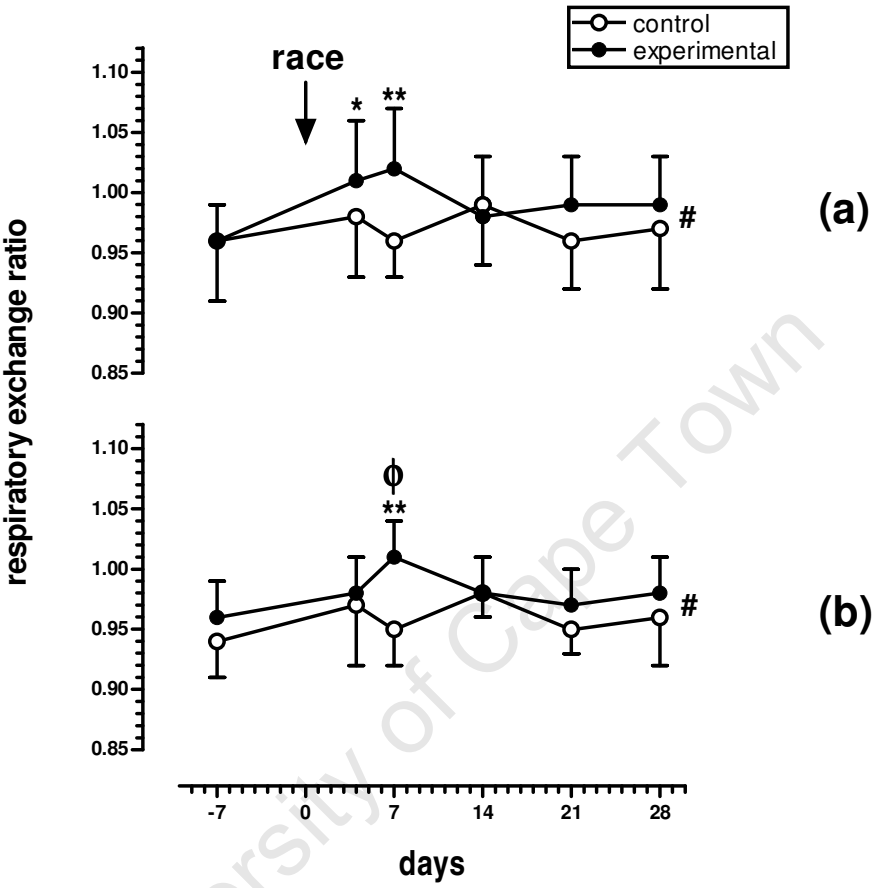

Figure 3.5: *Respiratory exchange ratio (RER) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: * experimental day -7 vs. experimental day 4 ($p < 0.05$)
** experimental day -7 vs. experimental day 7 ($p < 0.002$)
# interaction of group x time at 3 minutes ($p < 0.02$)

(b) 12 minutes: ** experimental day -7 vs. experimental day 7 ($p < 0.006$)
ϕ experimental day 7 vs. control days -7, 7, 21, and 28 ($p < 0.04$)
interaction of group x time at 12 minutes ($p < 0.04$)

3.3.6 HEART RATE

The differences in heart rate ($b.min^{-1}$) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 3.6. There was a significant interaction between groups over time for heart rate at 3 minutes ($F_{(5, 95)} = 2.83$; $p < 0.02$). At 3 minutes, heart rate tended to be higher in the experimental group. There were no significant differences in heart rate between groups or over time at 12 minutes.

3.3.7 RATE OF PERCEIVED EXERTION

The differences in the rate of perceived exertion (RPE) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 3.7. There was a significant interaction between groups over time for the rate of perceived exertion at 3 minutes ($F_{(5, 95)} = 2.75$; $p < 0.03$), with the rate of perceived exertion being significantly higher in the experimental group. At 3 minutes, there was a significant difference in the experimental group between day 4 and days 7 ($p < 0.007$), 14 ($p < 0.04$) and 28 ($p < 0.02$). There was no difference between groups at 12 minutes, whereas there was a significant difference in the measurement over time ($F_{(5, 90)} = 4.22$; $p < 0.002$), with the rate of perceived exertion being significantly higher in the experimental group. At 12 minutes, there was a significant difference in the experimental group between day 4 and days 21 ($p < 0.02$) and 28 ($p < 0.003$).

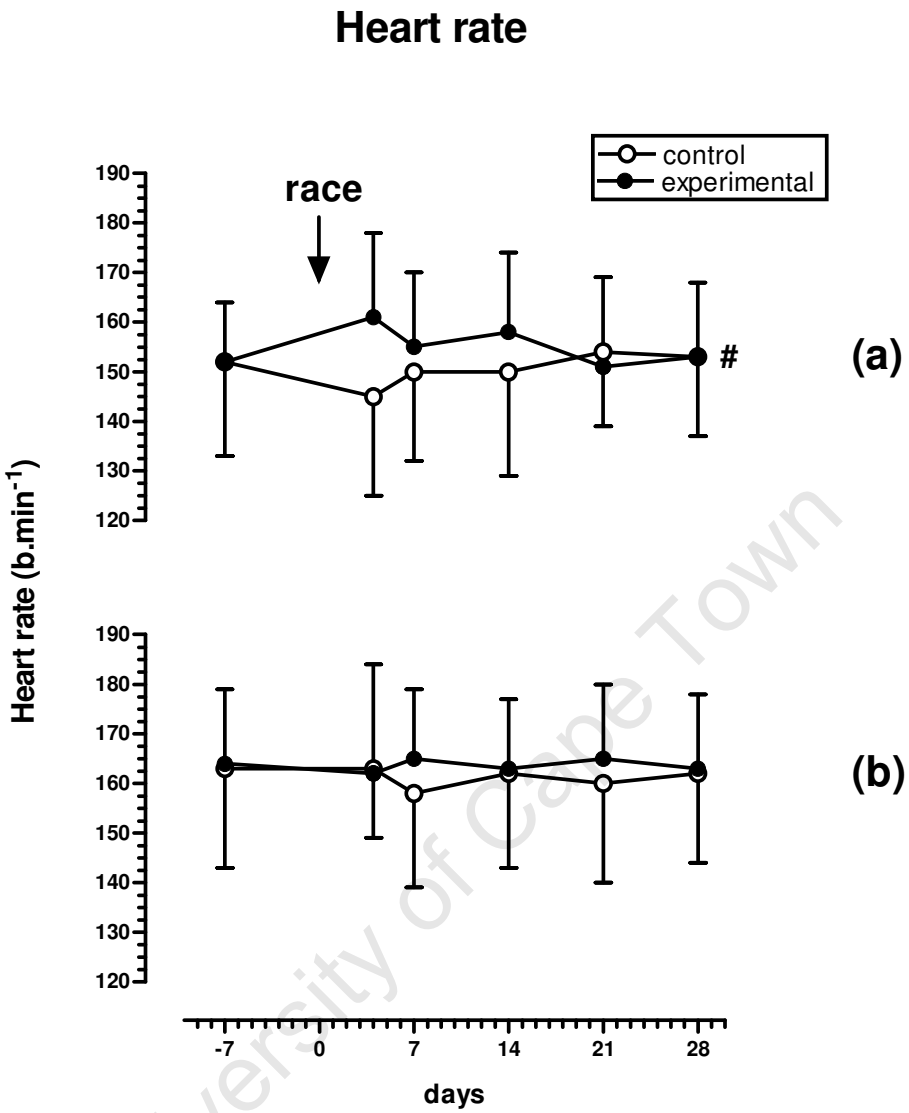

Figure 3.6: *Heart rate (b.min^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: # interaction of group x time at 3 minutes ($p < 0.02$)

Rate of perceived exertion

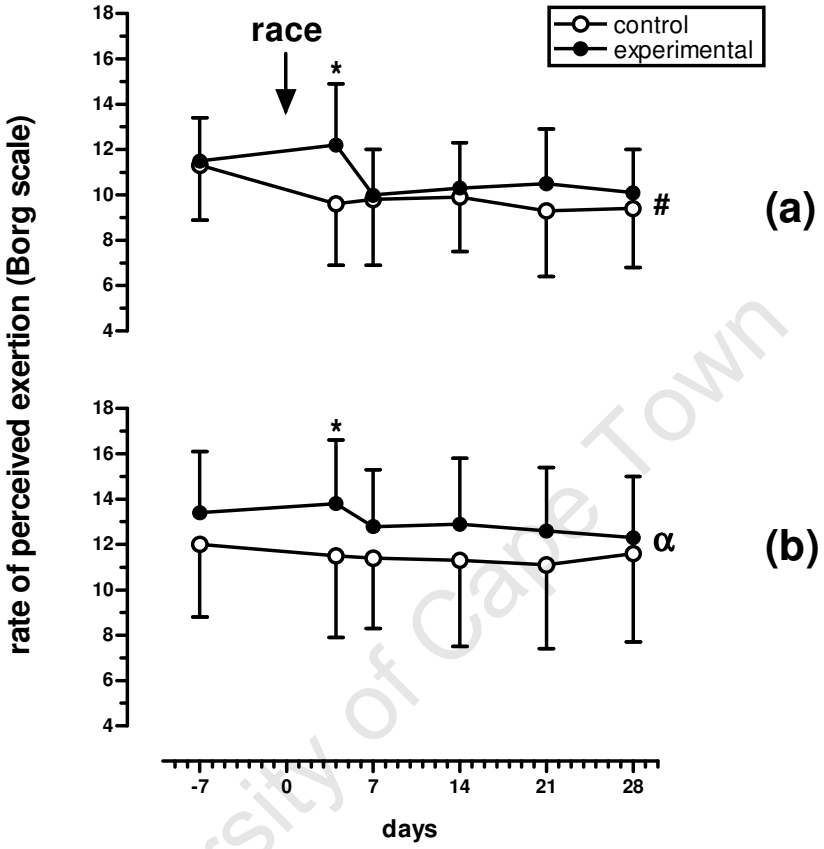

Figure 3.7: *Rate of perceived exertion (Borg scale) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: * experimental day 4 vs. experimental days 7, 14, and 28 ($p < 0.04$)
interaction of group x time at 3 minutes ($p < 0.03$)

(b) 12 minutes: * experimental day 4 vs. experimental days 21 and 28 ($p < 0.02$)
α main effect of time at 12 minutes ($p < 0.002$)

3.3.8 STRIDE LENGTH

Differences in stride length (m) at 4 minutes, 9 minutes, and 14 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 3.8. There was no difference between groups at 4 minutes, whereas there was a significant difference in the measurement over time ($F_{(5, 95)}$ = 3.03; $p < 0.02$), with stride length tending to be reduced in the experimental group. There was a significant interaction between groups over time for stride length at 9 minutes ($F_{(5, 95)}$ = 3.37; $p < 0.008$), and 14 minutes ($F_{(5, 90)}$ = 4.46; $p < 0.002$). Stride length was also significantly reduced in the experimental group at both 9 minutes [day -7 vs. days 4 ($p < 0.02$), 7 ($p < 0.0003$), and 14 ($p < 0.002$)] and 14 minutes [day -7 vs. days 7 ($p < 0.02$) and 14 ($p < 0.05$)], compared to pre-race values.

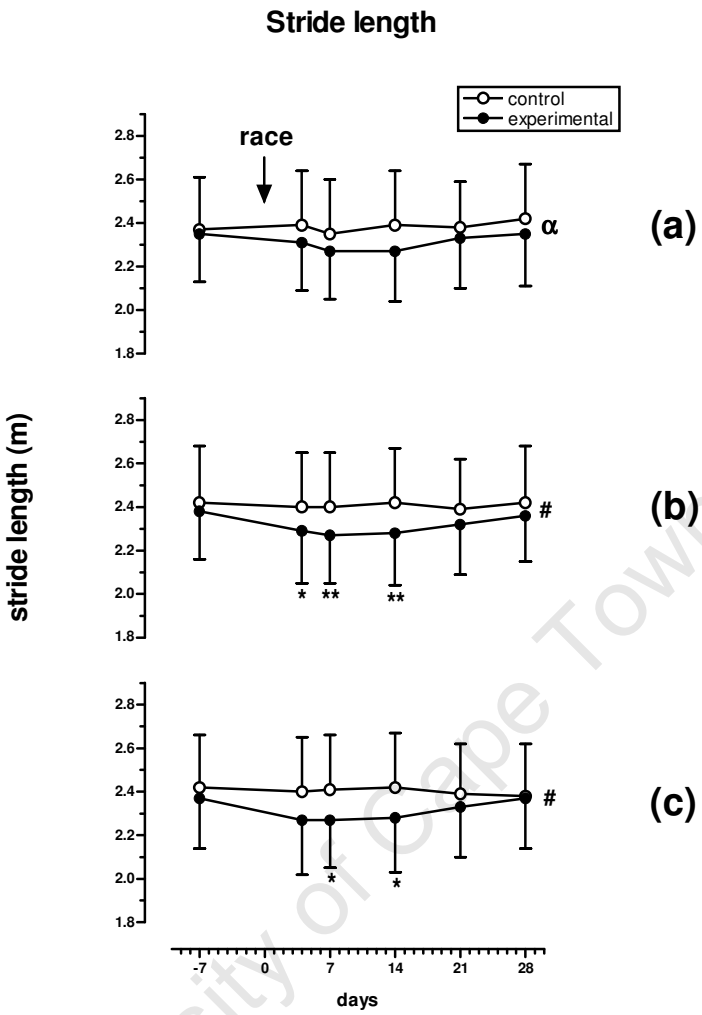

Figure 3.8: *Stride length (m) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at (a) 4 minutes, (b) 9 minutes, and (c) 14 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 4 minutes: α main effect of time ($p < 0.02$)

(b) 9 minutes: ** experimental day -7 vs. experimental days 7 and 14 ($p < 0.002$)
* experimental day -7 vs. experimental day 4 ($p < 0.02$)
# interaction of group x time at 9 minutes ($p < 0.008$)

(c) 14 minutes: * experimental day -7 vs. experimental days 7 and 14 ($p < 0.05$)
interaction of group x time at 14 minutes ($p < 0.002$)

3.3.9 BLOOD LACTATE CONCENTRATION

The differences in pre- and post-submaximal treadmill test blood lactate concentrations are shown in Table 3.3. There was a significant increase in the post-submaximal treadmill test blood lactate concentrations, compared to pre-submaximal treadmill test blood lactate concentrations for each day ($p < 0.00001$). However, there were no significant differences either between groups or over time in pre- and post-submaximal treadmill test blood lactate concentrations.

Table 3.3*: Blood lactate concentrations (mmol.l^{-1}) of subjects in the experimental (n = 11) and control (n = 10) groups (a) before and (b) 3 minutes after the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL		CONTROL	
	(a) Pre	(b) Post**	(a) Pre	(b) Post**
-7	1.59 ± 0.79	3.96 ± 1.50	1.56 ± 0.86	3.76 ± 2.35
4	1.87 ± 0.64	3.73 ± 1.35	1.59 ± 0.36	4.10 ± 2.45
7	1.61 ± 0.79	4.42 ± 1.85	1.50 ± 0.56	3.94 ± 1.94
14	1.69 ± 0.92	3.97 ± 1.44	1.52 ± 0.83	3.95 ± 2.17
21	1.48 ± 0.84	3.97 ± 1.29	1.38 ± 0.53	3.35 ± 1.83
28	1.55 ± 1.20	3.50 ± 1.10	1.38 ± 0.63	3.20 ± 1.54

Significant differences:

** pre- vs. post- submaximal treadmill test blood lactate concentrations ($p < 0.00001$)

3.4 DISCUSSION

The 90 km ultramarathon induced muscle pain in the experimental group consistent with delayed onset muscle soreness. The onset of muscle pain in the experimental group occurred within the first 24 hours following the ultramarathon (Figure 3.2). These findings are consistent with other studies investigating the onset of delayed onset muscle soreness resulting from exercise-induced muscle damage[135;482]. In the experimental group, subjective pain had returned to pre-race values by day five after the 90 km race. Studies have shown that muscle pain associated with delayed onset muscle soreness usually dissipates within 96 hours after exercise[78;98;138], but may persist for up to 10 days after exercise[135]. Although subjective pain in the experimental group remained significantly elevated for up to four days after the ultramarathon, this does not necessarily reflect the magnitude of muscle damage[98] or the long-term changes in neuromuscular function which have been shown to occur. For example, it is known that neuromuscular function is disturbed for at least 11 days after an ultramarathon[120]. However, it is recognised that subjective pain scores were based on self-reported information before and after the ultramarathon race, and the inability to control self-reported data is a potential limitation of this study design.

Plasma CK activity is a commonly used indicator of muscle damage[369]. Creatine kinase is released into the blood when the cell membrane is damaged, or when there is an alteration in cell membrane permeability[14]. Plasma CK activity was significantly higher in the experimental group at days one and two after the ultramarathon (Figure 3.3). These findings are consistent with other studies that also reflect a rapid increase in CK activity from 24 hours after a marathon[369;496]. There was also a large degree of intra-subject variability in plasma CK activity levels, particularly in the experimental group at days one and two after the ultramarathon.

The individual variation in plasma CK activity due to exercise-induced muscle damage may be associated with differences in the rate of CK clearance by muscle and the reticuloendothelial system[135]. Other studies have shown dissociation between plasma CK activity and the impairment of muscle function after exercise-induced muscle damage[137;583]. In addition, plasma CK activity in the experimental group had returned to pre-race values at day four after the ultramarathon. Although plasma CK activity is a good indirect and qualitative indicator of muscle damage[133], it does not reflect the extent of muscle damage[135].

The most interesting finding of this study was that submaximal oxygen consumption in the experimental group was significantly reduced for up to 28 days after the ultramarathon, particularly in the early phase of the submaximal test (Figure 3.4). The reduction in submaximal oxygen consumption after the 90 km race is contrary to findings of other studies investigating changes associated with exercise-induced muscle damage. These studies show increases in oxygen consumption during and after a marathon[369], after a duathlon[102], after 30 minutes of downhill running[78;125], after 90 minute runs at 65% and 85% of maximum oxygen consumption[687], and during a 5 km run[628]. Further studies have reported no changes in steady-state oxygen consumption at 70% of maximum oxygen consumption following a 100-drop jump protocol to induce exercise-induced muscle damage[412], at 55% and 75% of maximum oxygen consumption following a 120-repetition maximum voluntary contraction protocol to induce exercise-induced muscle damage[510], or at approximately 70% of maximum oxygen consumption following a muscle damage protocol using a series of lower extremity resistance exercises[581].

The conventional interpretation is that a reduction in oxygen consumption at a fixed submaximal workload corresponds with an improvement in running economy[166;480]. However in this study, the reduction in submaximal oxygen consumption occurred at some stages in the presence of increased muscle pain and an increase in the rate of perceived exertion in the experimental group. The sensation of muscle pain, communicated to the central nervous system via unmyelinated C fibre afferents, may contribute to the perception of muscle fatigue and exertion[242].

The causes of the reduction in submaximal oxygen consumption in this study may only be speculated. The first possible explanation may be related to changes in muscle recruitment patterns. There is a proportional relationship between oxygen consumption and the amount of muscle recruited to perform work[99]. As discussed by Gleeson et al, exercise-induced muscle damage may be associated with an increase in type II fibre recruitment[241]. As type II motor units are larger than type I motor units, there may be a resultant decrease in the number of motor units activated, together with a reduction in oxygen consumption.

In addition, the extensive muscle damage to the anti-gravity muscles of the lower limbs that occurs after endurance events may result in the compensatory recruitment of agonistic and synergistic muscles. This may improve the mechanical efficiency of running, and result in a reduction in oxygen consumption. This theory is speculative and requires further investigation.

An alternative explanation for the reduced submaximal oxygen consumption after the race is that the muscle damage associated with the race caused an increase in passive stiffness. Previous studies have shown that increased passive stiffness due to exercise-induced muscle damage takes longer than 10 days to recover to pre-exercise values[135;304]. It has been suggested that inflexibility in certain areas of the musculoskeletal system may enhance running economy in sub-elite male runners, by increasing the storage and re-use of elastic energy[161].

In support of this interpretation, an inverse relationship has been shown between normalised effective vertical stiffness and running economy[275], which suggests that less economical runners are more compliant during the ground contact phase of running. Therefore, runners with a non-compliant gait and increased muscle stiffness due to exercise-induced muscle damage may possibly be more economical at a fixed submaximal workload.

The next finding was that stride length in the experimental group was significantly reduced for up to 14 days after the ultramarathon (Figure 3.8). This finding is consistent with other studies investigating stride length changes associated with exercise-induced muscle damage after a marathon[369], and after 30 minutes of downhill running[78]. A reduction in stride length is associated with a subsequent reduction in ground contact time which may result in a reduced coupling time between stretch and shortening on the recoil of elastic energy[69;348]. This may enhance the potentiation effect of the stretch shortening cycle, resulting in an increased utilisation of stored elastic energy, with a subsequent reduction in submaximal oxygen consumption.

In addition, a reduction in ground contact time may result in a reduction in the rate of conversion of stored elastic energy to mechanical energy required to perform useful work, and a decrease in the amount of energy lost as heat. This may also contribute to the reduction in submaximal oxygen consumption. Previous studies on running performance have highlighted the importance of force production during the ground contact phase, and effective muscle coactivation around the knee and ankle joints[364].

The respiratory exchange ratio was significantly higher in the experimental group up to day seven after the race (Figure 3.5). The higher respiratory exchange ratio values were unexpected, especially when considered in relation to the known adaptive changes that occur in response to endurance events, and in response to exercise-induced muscle damage.

Muscle glycogen stores have been shown to be depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after a marathon[587]. The time taken to normalise muscle glycogen concentrations after a race is thought to be 10 days or longer[498]. Furthermore, an ongoing insulin resistance has been demonstrated for 48 hours after exercise-induced muscle damage[342].

A reduction in glucose transporter proteins 4 (GLUT-4) has also been found after exercise-induced muscle damage[242]. The prediction from these findings however would be that the respiratory exchange ratio would be reduced during recovery from prolonged exercise due to the development of a relative carbohydrate resistance.

The experimental design of this study did not provide for an explanation about the mechanisms of the increase in respiratory exchange ratio values after the ultramarathon race. The presence of the control subjects, who were tested at a similar time to the experimental subjects, eliminates the possibility of instrumentation error causing these findings. Without any other evidence, it may be postulated that the increase in respiratory exchange ratio after the race may be attributed to modifications in the normal muscle fibre recruitment pattern, with an increased relative contribution to force production from type II muscle fibres. This scenario would result in an increased reliance on carbohydrate oxidation. Further studies are needed to investigate this unexpected finding.

The rate of perceived exertion was significantly higher in the experimental group at day four after the race, and thereafter there was only a tendency for the rate of perceived exertion to be higher in the experimental group (Figure 3.7). This result is similar to findings previously reported following exercise-induced muscle damage[125;412;581]. However, the previous findings of an increase in the rate of perceived exertion linked with exercise-induced muscle damage have been associated with an increase in submaximal oxygen consumption following a 30-minute downhill run[125], a reduction in endurance running performance[412], or with no change in submaximal oxygen consumption at 70% of maximum oxygen consumption[581].

In this study there was a paradoxical finding, as the increase in the rate of perceived exertion was associated with a reduction in submaximal oxygen consumption. In addition, the rate of perceived exertion, together with plasma CK activity and muscle pain, had returned to pre-race values by day seven after the race. It has also been suggested that there is a relationship between the decrease in running performance associated with exercise-induced muscle damage, and an increase in the rate of perceived exertion[412].

Although running performance was not assessed in this study, cardiorespiratory, metabolic, and stride length changes persisted for up to 28 days after the race. From an anecdotal perspective, after comments from subjects, maximal running performance would have most certainly been impaired had it been measured during the study. Further studies should investigate the relationship between the time course of recovery, including running performance, following an endurance event.

There was no significant difference in heart rate values between the experimental and control groups in this study (Figure 3.6). This finding is contrary to that of a previous study, which used a field test and showed that the heart rate response to steady-state exercise after the Comrades marathon was elevated for up to 25 days after the race[120]. Additional research into the potential inter-relationships between heart rate, ventilation, and running economy in endurance exercise is needed[455].

Although the post-submaximal treadmill test blood lactate concentrations were significantly higher than pre-submaximal treadmill test values, there was no significant difference between groups over the time course of this study (Table 3.3). The higher post-submaximal treadmill test lactate concentrations possibly reflect a higher intra-muscular lactate concentration, and an increased relative contribution of the oxygen-independent glycolytic power system to ATP production. Previous research has shown that lactate production is increased during exercise following exercise-induced muscle damage[242]. However, the pre- and post-submaximal treadmill test blood lactate concentrations remained relatively constant in the experimental and control groups for the duration of the study, suggesting that no significant changes in lactate metabolism occurred in response to the muscle damage associated with the ultramarathon race.

In conclusion the main findings of this study are that a 90 km ultramarathon race induces moderate muscle damage, which causes pain for at least four days, and increases plasma CK activity for at least two days. The pain was not associated with changes in oxygen consumption, respiratory exchange ratio, and stride length during submaximal running. Furthermore, the race caused a reduction in submaximal oxygen consumption for 28 days. This was an unusual finding as conventionally, a reduction in submaximal oxygen consumption is associated with superior running performance.

A strong argument can be made that the running performance of these subjects would have been impaired in the recovery period after the race, in the presence of reduced submaximal oxygen consumption. This paradoxical finding challenges the validity of using running economy as a marker of running performance under these conditions, and shows that symptoms, other than just muscle pain and the rate of perceived exertion, should be used to define the recovery period following an ultramarathon race.

CHAPTER FOUR
STUDY TWO: CHANGES IN SUBMAXIMAL OXYGEN CONSUMPTION AND RUNNING KINEMATICS AFTER A 90 KM ULTRAMARATHON

4.1 INTRODUCTION

As discussed in Chapter 3, submaximal oxygen consumption was reduced for up to 28 days after a 90 km ultramarathon race. This finding is contrary to previous studies, where submaximal oxygen consumption either increased following running protocols[78;102;125;369;474;496;628;687], or remained unchanged following stretch shortening cycle[412] or resistance exercise protocols[510;581] that caused exercise-induced muscle damage.

The mechanism underlying this paradoxical response to exercise-induced muscle damage is unknown. The reduction in submaximal oxygen consumption appears to be dissociated from the increases in muscle pain, plasma CK activity, and the rate of perceived exertion, as all of these markers used to quantify exercise-induced muscle damage had returned to pre-race values by day seven after the race. However, a reduction in stride length persisted for up to 14 days after the ultramarathon race. The reduction in stride length after the race is also consistent with previous studies, where stride length was reduced after a marathon[369], and after a 30-minute downhill run[78].

It may be hypothesised that the reduction in stride length after the ultramarathon race is associated with a reduction in ground contact time, a reduced coupling time between stretch and shortening on the recoil of elastic energy, an increased utilisation of stored elastic energy, and a subsequent reduction in submaximal oxygen consumption[69;348].

Alternatively, it may be suggested that the reduction in stride length may be a compensatory mechanism due to alterations in neuromuscular function associated with fatigue[369], and that the reduction in stride length following exercise-induced muscle damage may be accompanied by changes in joint kinematics[194].

There is conflicting evidence regarding the effect of exercise-induced muscle damage on gait biomechanics. Changes in angular kinematics have been reported up to 48 hours after eccentric exercise[508], after a 30-minute downhill run[194], and after a marathon[474]. Conversely, little change in angular kinematics has been observed after a marathon[369], and after a prolonged maximal run[456].

The relationship between running economy and running mechanics is controversial. Although some kinematic variables, such as a low vertical oscillation of the centre of mass, and a smaller knee angle during toe-off, may be associated with improved running economy[8;571], changes in running economy following fatiguing exercise that causes muscle damage have yet to be fully explained by alterations in running mechanics[571].

Therefore, the aim of this study was to investigate the effects of exercise-induced muscle damage caused by a 90 km ultramarathon on submaximal oxygen consumption and running kinematics in experienced ultramarathon runners.

4.2 METHODS

4.2.1 SUBJECTS AND STUDY DESIGN

The study was granted ethical clearance by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town (Appendix III). Twenty-four experienced endurance runners, similar to those recruited for the first study (Chapter 3, Section 3.2.1, page 114), were selected to participate in this study, which had a quasi-experimental design. A schematic diagram of the research design is shown in Figure 4.1. Eleven runners, who participated in the 90 km ultramarathon, were assigned to the experimental group. Thirteen runners, who did not participate in the 90 km ultramarathon, formed the control group. The subjects were requested to avoid any medication, and strenuous training and racing, other than the ultramarathon race, for the duration of the study (± 42 days). Subjects were instructed to maintain the same diet and training regimen for 24 hours prior to the standard test. To facilitate adherence with instructions, subjects completed a training logbook for the duration of the study. In addition, subjects were questioned about their compliance with instructions prior to each laboratory test. Testing occurred at a similar time (to within one hour) for each subject for the duration of the study.

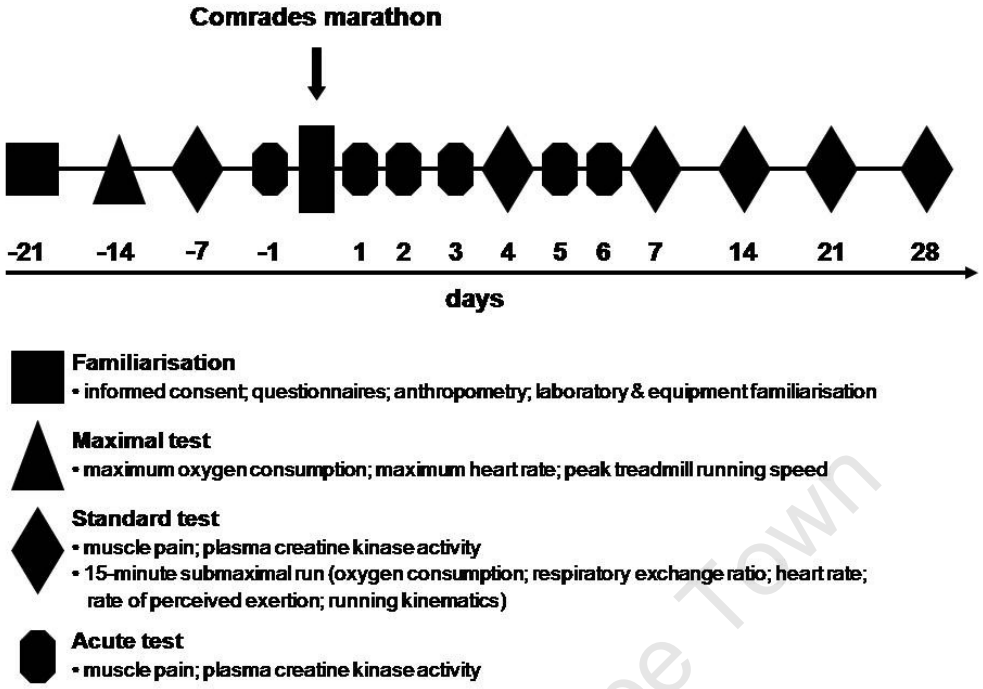

Figure 4.1: *Study design.*

4.2.2 FAMILIARISATION

During the first visit to the laboratory, three weeks before the ultramarathon race, subjects gave written consent after being informed about the demands of the study. The subjects completed questionnaires, and underwent an anthropometrical assessment, as described in Chapter 3 (Section 3.2.2, page 116).

The subjects were also familiarised with the laboratory equipment and testing protocols that would be used during the trial. This familiarisation process was conducted to reduce error associated with subjects performing unaccustomed exercise.

4.2.3 MAXIMAL TEST

Preliminary testing was conducted on all subjects two weeks before the ultramarathon race. A maximal treadmill test, as described in Chapter 3 (Section 3.2.2, page 116) was performed to determine maximum oxygen consumption (VO_{2max}), peak treadmill running speed (PTRS), and maximum heart rate (HR_{max}).

4.2.4 STANDARD TESTS

Each subject completed six standard tests. The first test was conducted seven days before the Comrades marathon. The standard test was repeated at 4, 7, 14, 21, and 28 days after the race, as described in Chapter 3 (Section 3.2.3, page 117). Laboratory conditions were standardised at a temperature of approximately 20 °C, and a relative humidity of approximately 60%.

Muscle pain was measured subjectively, where subjects rated lower limb "*pain at rest*" in the quadriceps muscle group of both legs according to a "rating of perceived pain" on a scale of 0 to 10, where 0 represents "*no pain*", and 10 represents "*maximal pain*", as previously described in Chapter 3 (Section 3.2.3, page 117).

A 5 ml blood sample was taken from the subject's antecubital vein before the submaximal treadmill test for the analysis of plasma CK activity. The methods of blood sampling and storage, and the analysis of plasma CK activity have been previously described in Chapter 3 (Section 3.2.3, page 117).

Fifteen retro-reflective markers were then positioned on the subjects at various sites, using the Running marker set[622]. Prior to taping the markers, the skin was cleaned with alcohol. The six-camera motion analysis system (Oxford Metrics Vicon System 370 Version 2.5, Oxford Metrics Ltd, Oxford, United Kingdom) was then calibrated with the subjects in a standing position. The treadmill was positioned in the centre of the gait laboratory, with the six cameras positioned equidistance (approximately 5 m) from the treadmill.

Subjects warmed up in a similar way for each standard submaximal treadmill test. The test started with the treadmill speed set at 10 $km.h^{-1}$ and a 1% elevation. This speed was maintained for two minutes, and was then increased to the speed that coincided with 75% of the peak treadmill running speed for each subject. Each subject maintained this speed for 15 minutes.

During the submaximal test, oxygen consumption (VO_2), respiratory exchange ratio (RER), and heart rate (HR) were recorded, as previously described in Chapter 3 (Section 3.2.3, page 118), at 3, 6, 9, 12, and 14.5 minutes. Subjects were also required to indicate their rate of perceived exertion (RPE), using a modified Borg scale[423], at 3, 6, 9, 12, and 14.5 minutes.

Kinematic data were recorded at 120 Hz, using fifteen retro-reflective markers from the Running marker set[622] and a six-camera motion analysis system (Oxford Metrics Vicon System 370 Version 2.5, Oxford Metrics Ltd, Oxford, United Kingdom), at 4 and 10 minutes during the submaximal test.

4.2.5 ULTRAMARATHON RACE

Subjects in the experimental group completed the 90 km Comrades ultramarathon race. In contrast to Chapter 3, this race started at an altitude of 650 m, in Pietermaritzburg, and finished at sea level, in Durban. The highest point of the race is 870 m above sea level. Anecdotally, this race is described as the "*down*" run[145]. A race profile of the "*down*" run is included in Appendix I. A comparison between the effects of the "*up*" run (Chapter 3) and the "*down*" run (Chapter 4) is described in detail in Appendix I.

Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at one-minute intervals for the duration of the ultramarathon race. Race heart rate data were averaged, and expressed as a percentage of maximum heart rate to provide an indication of exercise intensity during the ultramarathon race.

4.2.6 ACUTE TESTS

Daily muscle pain measurements and blood samples, for the analysis of plasma CK activity, were collected one day before, and for seven days after the Comrades marathon, to quantify muscle damage. These methods have been described in Chapter 3 (Section 3.2.5, page 118).

4.2.7 KINEMATIC DATA ANALYSIS

The kinematic data were visualised and processed into C3D files in Workstation (Oxford Metrics Ltd, Oxford, United Kingdom). Data from one stride length were then processed in Body Builder (Oxford Metrics Ltd, Oxford, United Kingdom), using the Running model[622]. The data were then exported as text files to Excel (Microsoft Corporation, Redmond, USA), where one stride length was normalised to 100% (0-100% gait cycle).

The kinematic variables that were analysed for this study are described in Table 4.1. In this study, as no marker was placed directly over the sacrum (S_1), vertical sacral displacement was determined by averaging the vertical displacement of the left and right posterior superior iliac spines.

Table 4.1: *Kinematic variables analysed in this study.*

VARIABLE	DESCRIPTION
Stride length…….	*Right heelstrike to right heelstrike*
Centre of mass……	*Average vertical sacral displacement*
Ankle angle at heelstrike……...	*Ankle dorsiflexion angle at heelstrike*
Knee angle at heelstrike……	*Knee flexion angle at heelstrike*
Hip angle at heelstrike……...	*Hip flexion angle at heelstrike*
Ankle angle at toe-off…….	*Ankle plantarflexion angle at toe-off*
Knee angle at toe-off……..	*Knee flexion angle at toe-off*
Hip angle at toe-off…….	*Hip extension angle at toe-off*
Maximum ankle angle (stance)……	*Maximum ankle dorsiflexion angle during stance phase*
Maximum knee angle (stance)…….	*Maximum knee flexion angle during stance phase*
Maximum hip angle (stance)……	*Maximum hip flexion angle during stance phase*
Ankle range of movement (ROM) (stance)……	*Ankle ROM during stance phase*
Knee ROM (stance)……..	*Knee ROM during stance phase*
Hip ROM (stance)……..	*Hip ROM during stance phase*
Maximum ankle angle (swing)..……	*Maximum ankle plantarflexion angle during swing phase*
Maximum knee angle (swing)..…….	*Maximum knee flexion angle during swing phase*
Maximum hip angle (swing)…..……	*Maximum hip extension angle during swing phase*
Ankle ROM (swing)……	*Ankle ROM during swing phase*
Knee ROM (swing)..……...	*Knee ROM during swing phase*
Hip ROM (swing)……..……..	*Hip ROM during swing phase*

4.2.8 STATISTICAL ANALYSES

Although data for submaximal oxygen consumption, respiratory exchange ratio, the rate of perceived exertion, and heart rate were analysed at 3, 6, 9, 12, and 14.5 minutes during the submaximal test, only the data at 3 and 12 minutes are shown in the results. These time points were selected to represent the warm-up (3 minutes) and steady-state (12 minutes) phases of the submaximal test respectively, and also complement the data analysis in Chapter 3.

In addition, although kinematic data were recorded at four and 10 minutes during the submaximal test, only the data at four minutes were analysed. It was not possible to analyse the 10-minute kinematic data, as many subjects had missing data points due to the loss of retro-reflective markers during the submaximal test. Subjects were excluded from the kinematic analysis if they had one data point missing, as data could not be processed using the Running model[622].

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in descriptive variables between the experimental and control groups were assessed using an independent t-test. Statistical significance for the two main effects of group and time, and the interaction (group x time) of all other variables were assessed using a two-way analysis of variance (ANOVA) with repeated measures. Tukey's *post hoc* comparisons were performed where necessary.

A Mann-Whitney U test was used to assess differences in the pain scores between groups. A Friedman's ANOVA and Kendall's concordance was used to assess differences in the pain scores within groups over time. A Pearson's product-moment correlation coefficient determined relationships between variables (vertical displacement of the centre of mass, oxygen consumption, changes in the vertical displacement of the centre of mass and oxygen consumption). The 95% confidence intervals of the correlation coefficients were calculated using a spreadsheet downloaded from www.newstats.org. All data are presented as the mean ± standard deviation (SD). Statistical significance was accepted as $p < 0.05$.

4.3 RESULTS

4.3.1 SUBJECTS

The descriptive characteristics of subjects are shown in Table 4.2, and the training and racing history of subjects are shown in Table 4.3. There were no significant differences between groups for any of these variables.

Table 4.2: *Descriptive characteristics of subjects in the experimental (n = 11) and control (n = 13) groups. Data are expressed as mean ± standard deviation (SD).*

VARIABLE	EXPERIMENTAL	CONTROL
Age (years)	41.0 ± 8.4	40.2 ± 11.1
Body mass (kg)	71.8 ± 11.6	77.1 ± 12.6
Height (cm)	177.2 ± 6.2	177.8 ± 7.9
Sum of skinfolds (mm)	74.9 ± 20.9	85.3 ± 25.9
Body fat (%)	19.6 ± 4.4	21.2 ± 4.7
Maximum heart rate ($b.min^{-1}$)	180 ± 15	178 ± 12
VO_2max ($ml.kg^{-1}.min^{-1}$)	57.8 ± 5.5	59.0 ± 7.0
Peak treadmill running speed (PTRS) ($km.h^{-1}$)	17.6 ± 1.7	17.5 ± 2.1

Table 4.3: *Training and racing history of subjects in the experimental (n = 11) and control (n = 13) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Total years running	10.5 ± 7.2	11.4 ± 7.4
Pre-competition training distance ($km.wk^{-1}$)[$]	72.7 ± 15.6	78.5 ± 26.2
Average training distance ($km.wk^{-1}$)	55.5 ± 11.7	63.7 ± 23.3
Number of standard marathons (42 km)	37 ± 26	20 ± 24
Personal best 10 km time (min)	37.9 ± 3.3	39.2 ± 5.5
Personal best 42 km time (min)	189.7 ± 23.1	199.3 ± 30.8

[$] *Average training distance in the 3 months preceding the race*

The subjects in the experimental group completed the 90 km race in 566.4 ± 64.5 minutes. The average intensity (% HR_{max}) during the race was 79 ± 2%.

4.3.2 MUSCLE PAIN

The subjects in the experimental group had painful muscles for 7 days after the race (Figure 4.2). The subjective pain scores were significantly higher in the experimental group compared to the control group on days 1, 2, 3, 4, 5, 6, and 7 after the ultramarathon ($p < 0.00004$) respectively. For the duration of the study thereafter, there were no differences between groups (Figure 4.2).

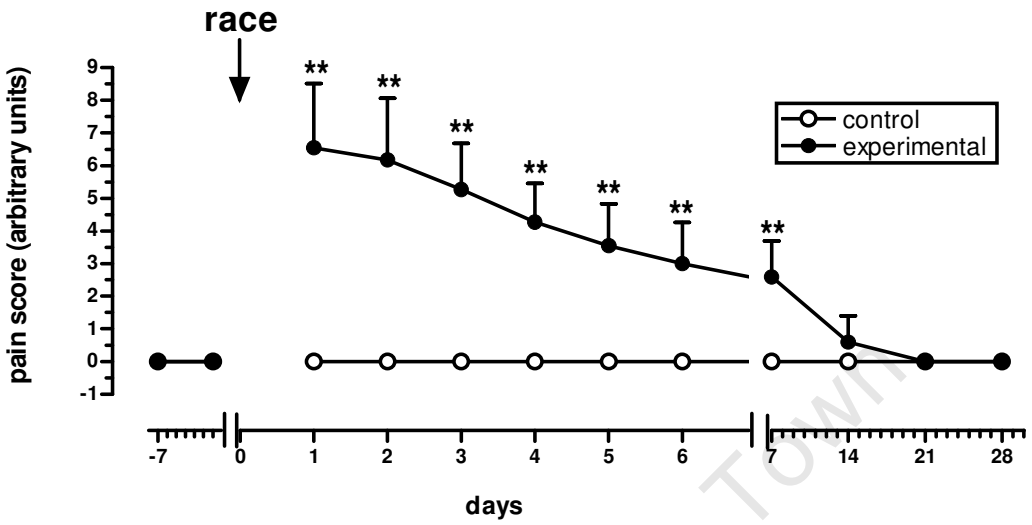

Figure 4.2: *Subjective pain (arbitrary units) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1, 2, 3, 4, 5, 6, and 7 vs. control days 1, 2, 3, 4, 5, 6, and 7 respectively ($p < 0.00004$)

4.3.3 PLASMA CREATINE KINASE ACTIVITY

There was a significant interaction between groups over time for plasma CK activity ($F_{(11, 242)} = 11.61$; $p < 0.0001$) (Figure 4.3). The plasma CK activity was significantly higher in the experimental group on days 1 and 2 ($p < 0.002$) after the ultramarathon. From day 3 onwards, for the duration of the experiment, there were no differences between groups (Figure 4.3).

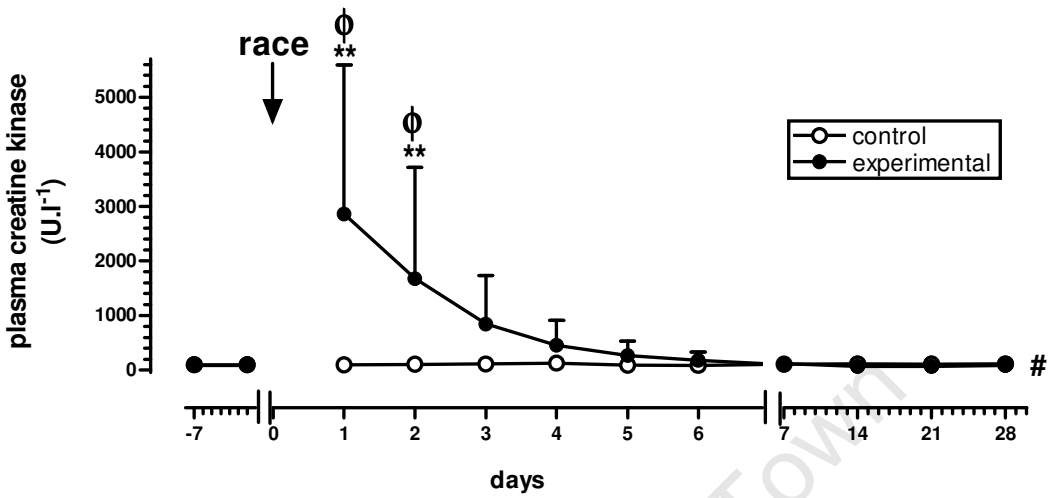

Figure 4.3: *Plasma creatine kinase activity (U.l^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1 and 2 vs. experimental days -7, -1, 3, 4, 5, 6, 7, 14, 21, and 28 ($p < 0.002$)

ϕ experimental days 1 and 2 vs. control days -7, -1, 1, 2, 3, 4, 5, 6, 7, 14, 21, and 28 ($p < 0.00004$)

interaction of group x time ($p < 0.0001$)

4.3.4 OXYGEN CONSUMPTION

The differences in oxygen consumption (VO_2) (ml.kg^{-1}.min^{-1}) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 4.4. There was a significant interaction between groups over time for oxygen consumption at 3 minutes ($F_{(5, 110)} = 3.79$; $p < 0.004$).

At 3 minutes, oxygen consumption was significantly decreased in the experimental group at days 7 ($p < 0.006$), 14 ($p < 0.001$), 21 ($p < 0.0002$), and 28 ($p < 0.02$), compared to pre-race values.

There was also a significant interaction between groups over time for oxygen consumption at 12 minutes ($F_{(5, 105)} = 5.93$; $p < 0.00008$). At 12 minutes, oxygen consumption was significantly decreased in the experimental group at days 7 ($p < 0.003$), 14 ($p < 0.0002$), 21 ($p < 0.0002$), and 28 ($p < 0.002$), compared to pre-race values.

4.3.5 RESPIRATORY EXCHANGE RATIO

The differences in respiratory exchange ratio (RER) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 4.5. There was no significant difference between groups at 3 minutes, however there was a significant difference in the measurement over time ($F_{(5, 110)} = 3.58$; $p < 0.005$). At 3 minutes, respiratory exchange ratio was significantly increased in the experimental group at day 4 ($p < 0.05$), compared to day 14, after the ultramarathon. There were no significant differences in respiratory exchange ratio between groups or over time at 12 minutes.

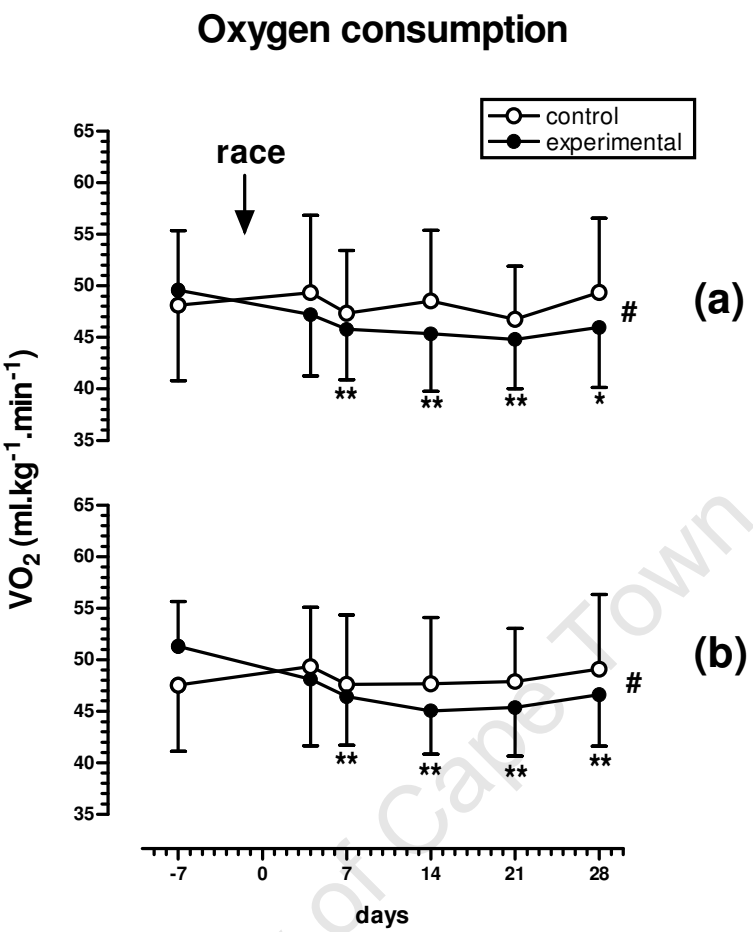

Figure 4.4: *Oxygen consumption (ml.kg^{-1}.min^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: ** experimental day -7 vs. days 7, 14, and 21 ($p < 0.006$)
* experimental day -7 vs. experimental day 28 ($p < 0.02$)
# interaction of group x time at 3 minutes ($p < 0.004$)

(b) 12 minutes: ** experimental day -7 vs. days 7, 14, 21, and 28 ($p < 0.003$)
interaction of group x time at 12 minutes ($p < 0.00008$)

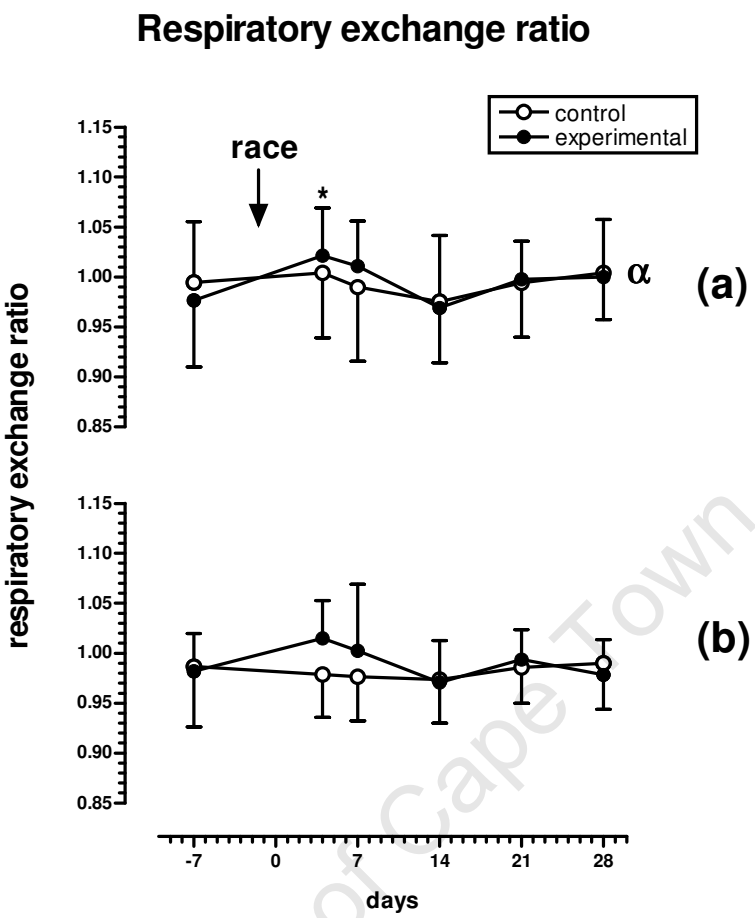

Figure 4.5: *Respiratory exchange ratio (RER) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: * experimental day 4 vs. experimental day 14 ($p < 0.05$)
α main effect of time at 3 minutes ($p < 0.005$)

4.3.6 HEART RATE

The differences in heart rate ($b.min^{-1}$) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 4.6. There were no significant differences between groups at 3 minutes or 12 minutes. However, there were significant differences in heart rate over time at 3 minutes ($F_{(5, 105)} = 10.16$; $p < 0.00001$), and at 12 minutes ($F_{(5, 110)} = 19.16$; $p < 0.00001$). At 3 minutes, heart rate was significantly decreased in the experimental group at days 14 ($p < 0.05$) and 21 ($p < 0.04$), compared to pre-race values.

At 12 minutes, heart rate was significantly increased in the experimental group at day 4 compared to days -7 ($p < 0.02$), 14 ($p < 0.0002$), 21 ($p < 0.0002$) and 28 ($p < 0.0008$). Heart rate was also significantly increased in the experimental group at day 7 compared to days 14 ($p < 0.02$) and 21 ($p < 0.003$). In addition, heart rate was significantly decreased in the control group on day 21 ($p < 0.03$), compared to pre-race values. Heart rate in the control group was also significantly decreased on days 14, 21, and 28 ($p < 0.008$), compared to day 4; and on day 21 ($p < 0.0009$), compared to day 7.

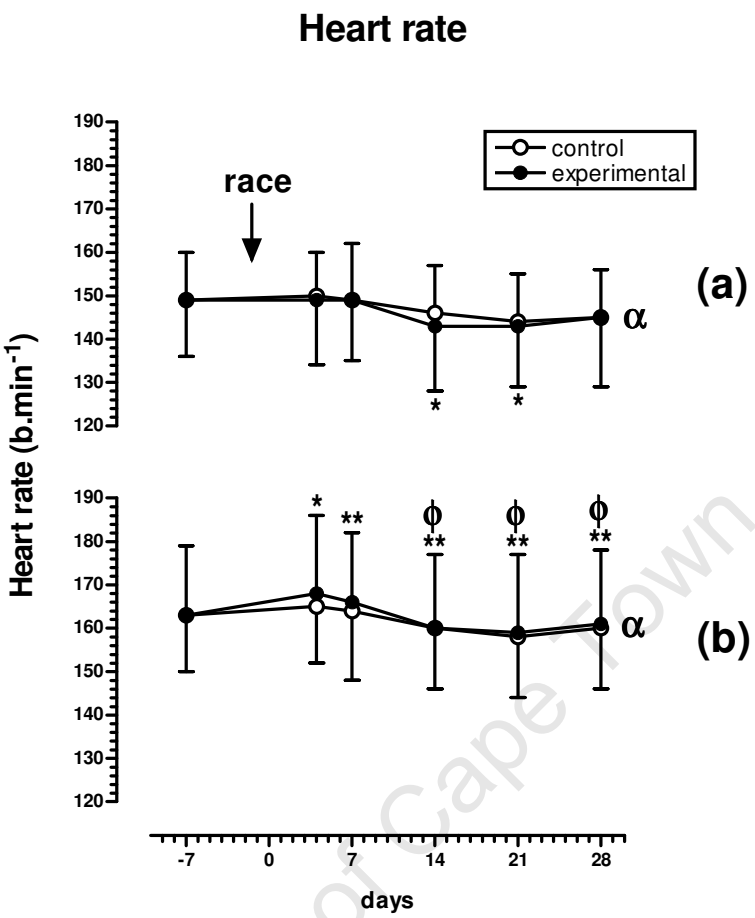

Figure 4.6: *Heart rate (b.min^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: * experimental day -7 vs. experimental days 14 and 21 ($p < 0.05$)
α main effect of time at 3 minutes ($p < 0.00001$)

(b) 12 minutes: * experimental day -7 vs. day 4 ($p < 0.02$)
** experimental day 4 vs. experimental days 14, 21, and 28 ($p < 0.0008$)
* experimental day 7 vs. experimental day 14 ($p < 0.02$)
** experimental day 7 vs. experimental day 21 ($p < 0.003$)
ϕ control day -7 vs. control day 21 ($p < 0.03$)
ϕ control day 4 vs. control days 14, 21, and 28 ($p < 0.008$)
ϕ control day 7 vs. control day 21 ($p < 0.0009$)
α main effect of time at 12 minutes ($p < 0.00001$)

4.3.7 RATE OF PERCEIVED EXERTION

The differences in the rate of perceived exertion (RPE) at 3 minutes and 12 minutes in the submaximal treadmill test between subjects in the experimental and control groups are shown in Figure 4.7. There were significant interactions between groups over time for the rate of perceived exertion at 3 minutes ($F_{(5, 110)} = 9.05$; $p < 0.00001$), and at 12 minutes ($F_{(5, 110)} = 11.94$; $p < 0.00001$). At 3 minutes, the rate of perceived exertion was significantly increased in the experimental group on days 4 ($p < 0.0002$), 7 ($p < 0.004$), 14 ($p < 0.0002$), 21 ($p < 0.002$), and 28 ($p < 0.04$), compared to pre-race values. In addition, the rate of perceived exertion pre-race values were significantly decreased in the experimental group ($p < 0.04$), compared to the control group.

At 12 minutes, the rate of perceived exertion was significantly increased in the experimental group on days 4 ($p < 0.0002$), 7 ($p < 0.0002$), 14 ($p < 0.0007$), and 21 ($p < 0.0007$), compared to pre-race values. The rate of perceived exertion was also significantly increased in the experimental group on day 4, compared to days -7 ($p < 0.0002$), 14 ($p < 0.005$), 21 ($p < 0.005$), and 28 ($p < 0.0002$).

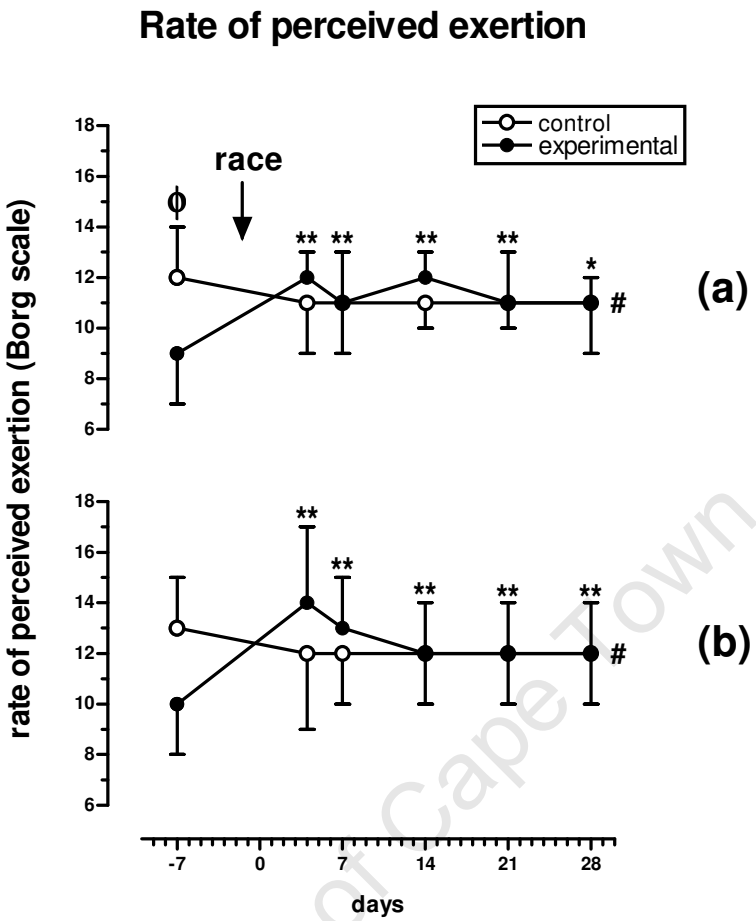

Figure 4.7: *Rate of perceived exertion (Borg scale) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) 3 minutes: ** experimental day -7 vs. experimental days 4, 7, 14, and 21 ($p < 0.004$)
* experimental day -7 vs. experimental day 28 ($p < 0.04$)
ϕ experimental day -7 vs. control day -7 ($p < 0.04$)
interaction of group x time at 3 minutes ($p < 0.00001$)

(b) 12 minutes: ** experimental day -7 vs. experimental days 4, 7, 14, and 21 ($p < 0.0007$)
** experimental day 4 vs. experimental days -7, 14, 21 and 28 ($p < 0.005$)
# interaction of group x time at 12 minutes ($p < 0.00001$)

4.3.8 RUNNING KINEMATICS

4.3.8.1 Stride length

The differences in stride length (m) of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.8. There was no difference between groups, whereas there was a significant difference in the measurement over time ($F_{(5, 105)} = 4.93$; $p < 0.0005$). Stride length was significantly increased in the experimental group on day 21 ($p < 0.01$), compared to pre-race values.

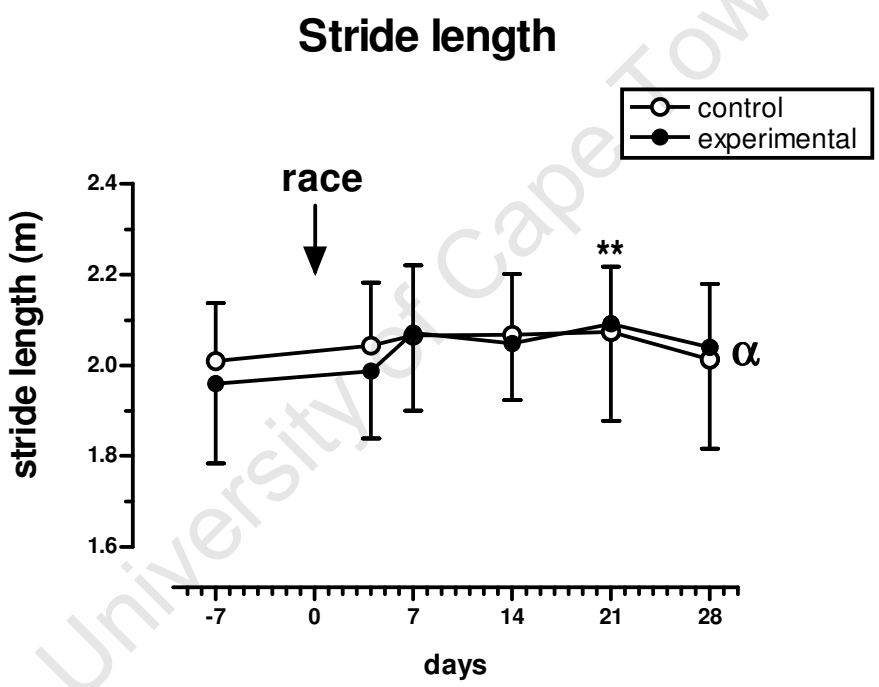

Figure 4.8: *Stride length (m) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental day -7 vs. experimental day 21 ($p < 0.01$)

α main effect of time ($p < 0.0005$)

4.3.8.2 Centre of mass

The average vertical sacral displacement (mm) of the centre of mass of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.4. There were no significant differences in the centre of mass either between groups or over time.

Table 4.4: *Vertical displacement of the centre of mass (mm) of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	7.8 ± 0.8	7.8 ± 1.1
4	7.7 ± 0.8	7.5 ± 1.4
7	7.7 ± 1.0	7.8 ± 0.7
14	7.8 ± 0.6	7.7 ± 0.9
21	8.2 ± 0.9	7.8 ± 0.7
28	7.9 ± 1.0	7.7 ± 0.8

4.3.8.2.1 Centre of mass and oxygen consumption

Figure 4.9 shows the correlation coefficients and 95% confidence intervals for the relationship between submaximal oxygen consumption and the vertical displacement of the centre of mass (COM) for the total group of subjects. There was a moderate association between submaximal oxygen consumption and the vertical displacement of the centre of mass before, and for up to 28 days after the ultramarathon race.

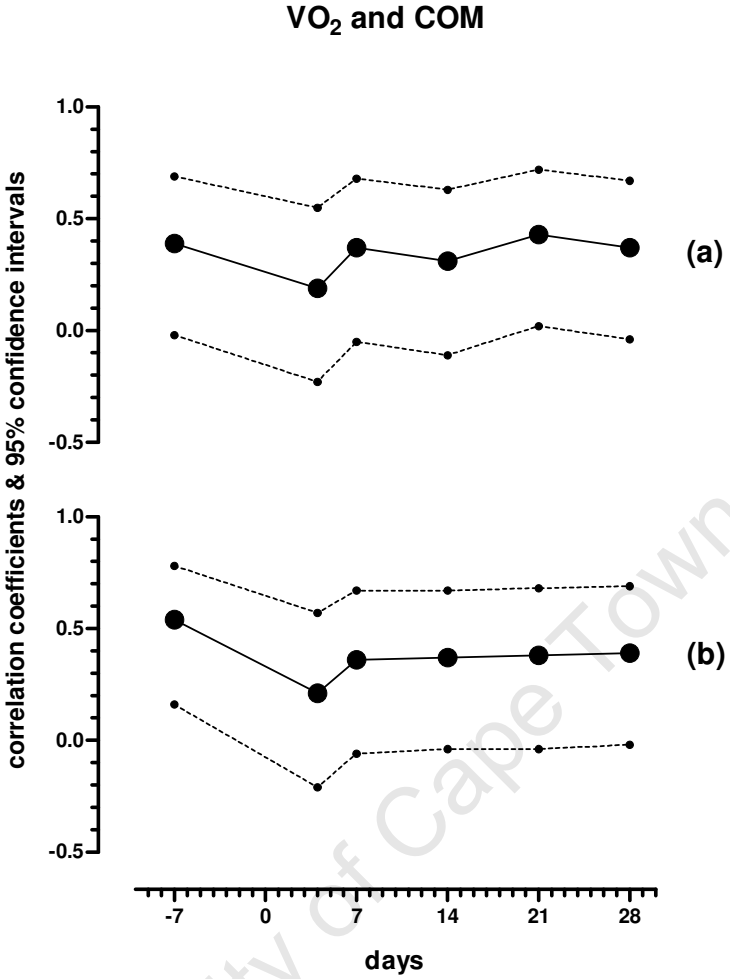

Figure 4.9: *Correlation coefficients (-●-) and 95% confidence intervals (--•--) for the relationship between submaximal oxygen consumption (VO_2) and the vertical displacement of the centre of mass (COM) for the total group of subjects (n = 24) at (a) 3 minutes and (b) 12 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race.*

4.3.8.2.2 Changes in centre of mass and oxygen consumption correlations

A further analysis of the relationship between changes in the vertical displacement of the centre of mass and oxygen consumption was performed. The analysis determined the difference between the pre-race and day 4 values, for the vertical displacement of the centre of mass and oxygen consumption respectively.

There were no significant correlations between the changes in the vertical displacement of the centre of mass and oxygen consumption for the total group at 3 minutes ($r = 0.004$; $p < 0.99$) or 12 minutes ($r = 0.08$; $p < 0.72$). There were also no significant correlations between these variables for the experimental group [at 3 minutes ($r = 0.13$; $p < 0.71$); or 12 minutes ($r = 0.35$; $p < 0.32$)], or the control group [at 3 minutes ($r = 0.09$; $p < 0.77$); or 12 minutes ($r = 0.09$; $p < 0.77$)], when data from these groups were analysed separately.

4.3.8.3 Ankle angle at heelstrike

The ankle dorsiflexion angle at heelstrike of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.10. There was no difference between groups, whereas there was a significant difference in the measurement over time ($F_{(5, 55)} = 3.09$; $p < 0.02$). The ankle angle at heelstrike was significantly increased in the experimental group on day 4 ($p < 0.05$), compared to pre-race values.

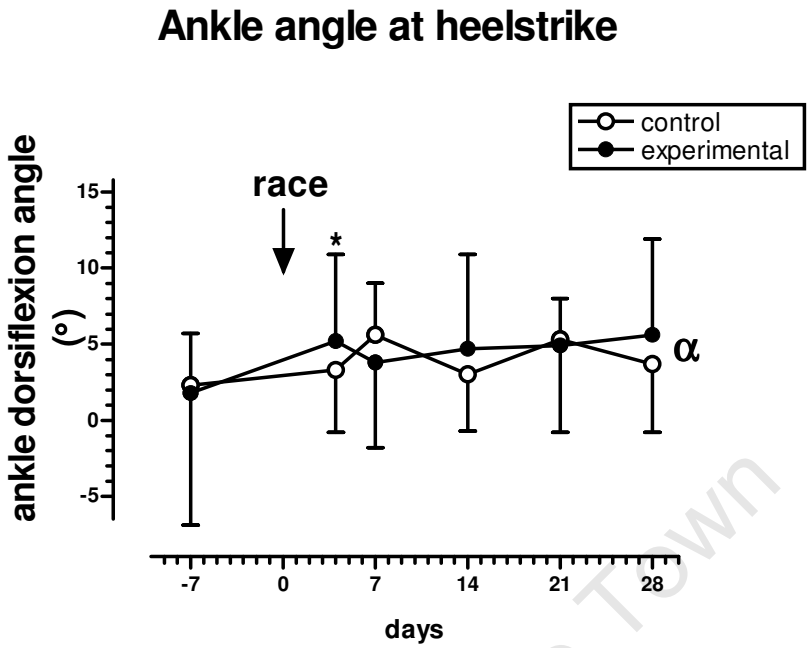

Figure 4.10: *Ankle dorsiflexion angle (°) at heelstrike of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

* experimental day -7 vs. experimental day 4 ($p < 0.05$)

α main effect of time ($p < 0.02$)

4.3.8.4 Knee angle at heelstrike

The knee flexion angle at heelstrike of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.11. There was a significant interaction between groups over time for the knee angle at heelstrike ($F_{(5, 65)} = 2.41$; $p < 0.05$). In addition, there was a significant difference between the experimental group and control group pre-race values, with the knee flexion angle at heelstrike being significantly higher in the experimental group ($p < 0.03$).

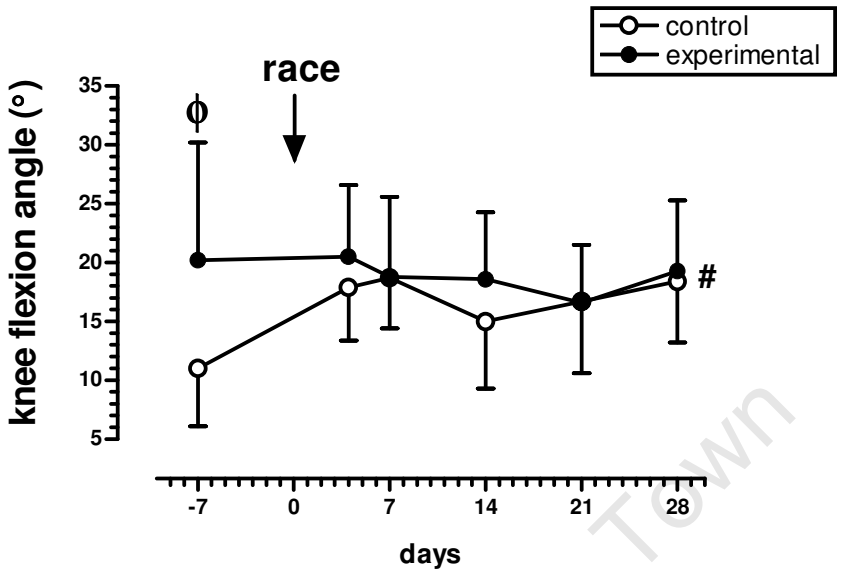

Figure 4.11: *Knee flexion angle (°) at heelstrike of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

ϕ experimental day -7 vs. control day -7 ($p < 0.03$)
interaction of group x time ($p < 0.05$)

4.3.8.5 Hip angle at heelstrike

The hip flexion angle at heelstrike of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.12. There was no difference between groups, whereas there was a significant difference in the measurement over time ($F_{(5, 65)} = 4.87$; $p < 0.0008$). The hip flexion angle at heelstrike was significantly increased in the control group on days 4 ($p < 0.005$), and 7 ($p < 0.003$), compared to pre-race values.

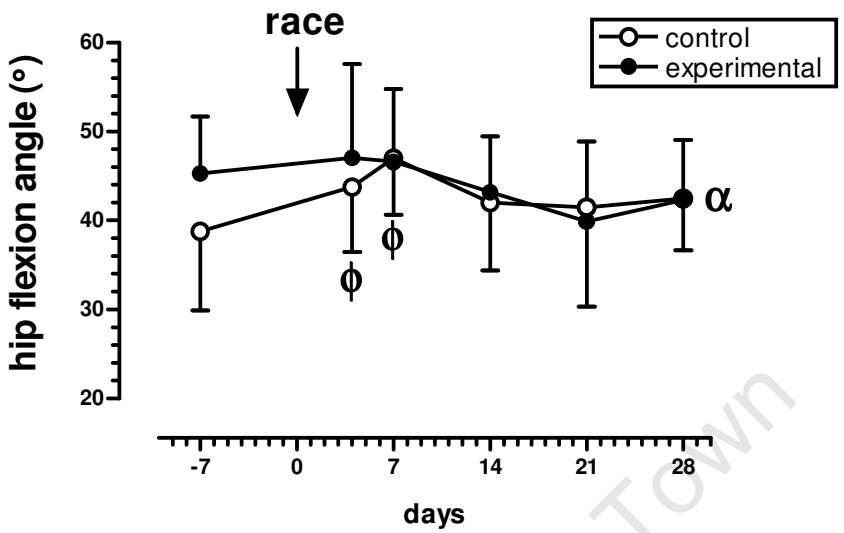

Figure 4.12: *Hip flexion angle (°) at heelstrike of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** control day -7 vs. control days 4 and 7 ($p < 0.005$)

α main effect of time ($p < 0.0008$)

4.3.8.6 Ankle angle at toe-off

The ankle plantarflexion angle at toe-off of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.13. There was no difference between groups, however there was a significant difference in the measurement over time ($F_{(5, 55)} = 4.34$; $p < 0.003$). Ankle plantarflexion at toe-off was significantly increased in the experimental group on days 7 ($p < 0.02$), and 21 ($p < 0.02$), compared to pre-race values.

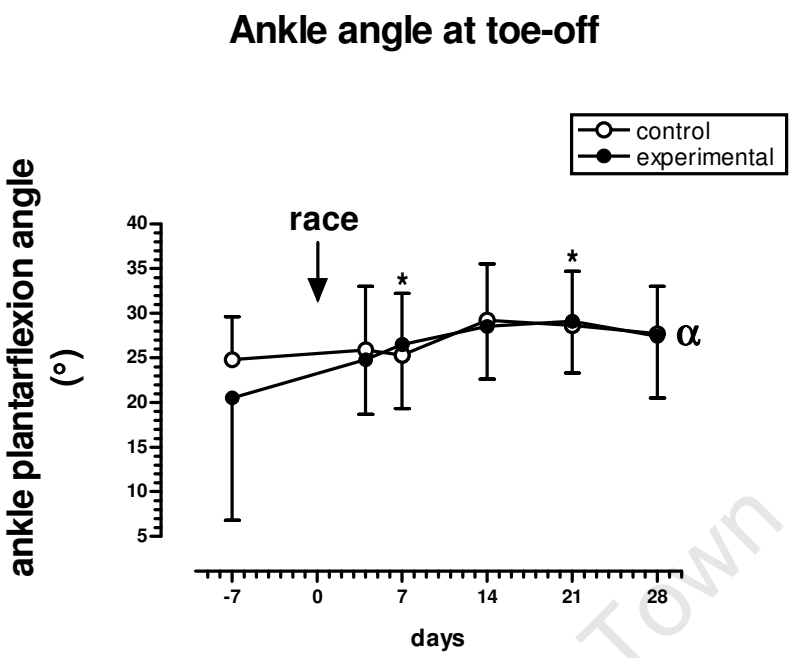

Figure 4.13: *Ankle plantarflexion angle (°) at toe-off of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

* experimental day -7 vs. experimental days 7 and 21 ($p < 0.02$)

α main effect of time ($p < 0.003$)

4.3.8.7 Knee angle at toe-off

The knee flexion angle at toe-off of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.5. There were no significant differences in the knee angle at toe-off either between groups or over time.

Table 4.5: *Knee flexion angle (°) at toe-off of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	14.6 ± 10.4	8.5 ± 5.3
4	12.9 ± 3.2	13.7 ± 6.0
7	14.1 ± 6.4	15.7 ± 4.4
14	12.8 ± 5.4	13.3 ± 7.7
21	12.7 ± 5.8	16.6 ± 8.3
28	14.1 ± 6.7	14.8 ± 5.8

4.3.8.8 Hip angle at toe-off

The hip extension angle at toe-off of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.6. There were no significant differences in the hip angle at toe-off either between groups or over time.

Table 4.6: *Hip extension angle (°) at toe-off of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	10.4 ± 3.7	12.7 ± 5.7
4	10.1 ± 4.3	11.8 ± 6.8
7	10.7 ± 9.7	8.9 ± 6.9
14	12.5 ± 4.6	10.0 ± 8.4
21	15.1 ± 7.1	10.2 ± 6.7
28	13.5 ± 4.4	11.0 ± 6.5

4.3.8.9 Stance phase kinematics

4.3.8.9.1 Maximum ankle angle

The maximum ankle dorsiflexion angle during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.7. There were no significant differences in the maximum ankle angle during stance phase either between groups or over time.

Table 4.7: *Maximum ankle dorsiflexion angle (°) during stance phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	19.0 ± 8.1	18.0 ± 2.7
4	20.9 ± 4.0	20.7 ± 6.9
7	22.1 ± 2.6	21.6 ± 7.4
14	19.9 ± 4.8	19.2 ± 7.3
21	20.0 ± 3.8	20.5 ± 4.4
28	19.6 ± 5.0	19.3 ± 3.6

4.3.8.9.2 Maximum knee angle

The maximum knee flexion angle during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.14. There was a significant difference in the measurement between groups ($F_{1, 15)} = 9.08$; $p < 0.009$), with experimental group maximum knee angles tending to be higher, however there was no significant difference in the measurement over time.

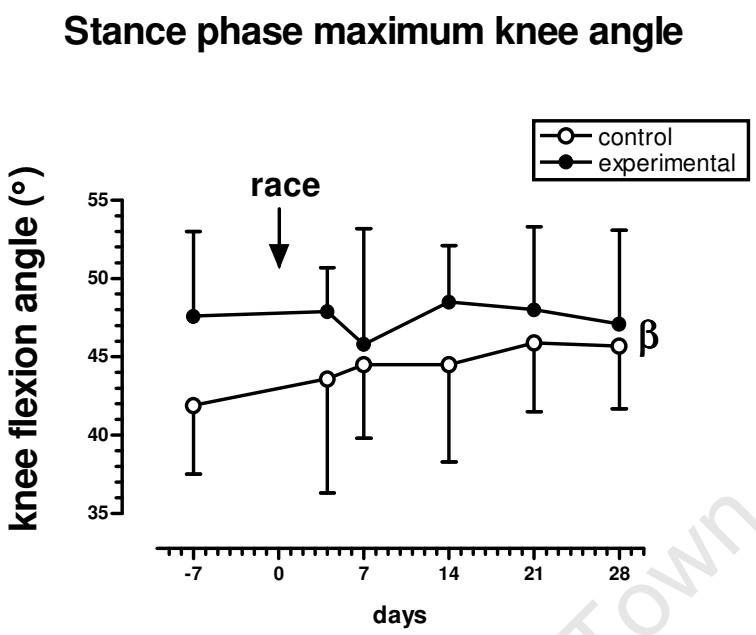

Figure 4.14: *Maximum knee flexion angle (°) during stance phase of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

β main effect of group ($p < 0.009$)

4.3.8.9.3 Maximum hip angle

The maximum hip flexion angle during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.15. There was no significant difference in the measurement between groups, whereas there was a significant difference in the measurement over time ($F_{(5, 85)} = 5.32$; $p < 0.0003$). The maximum hip flexion angle was significantly decreased in the experimental group on days 21 ($p < 0.02$) and 28 ($p < 0.05$), compared to day 4 values.

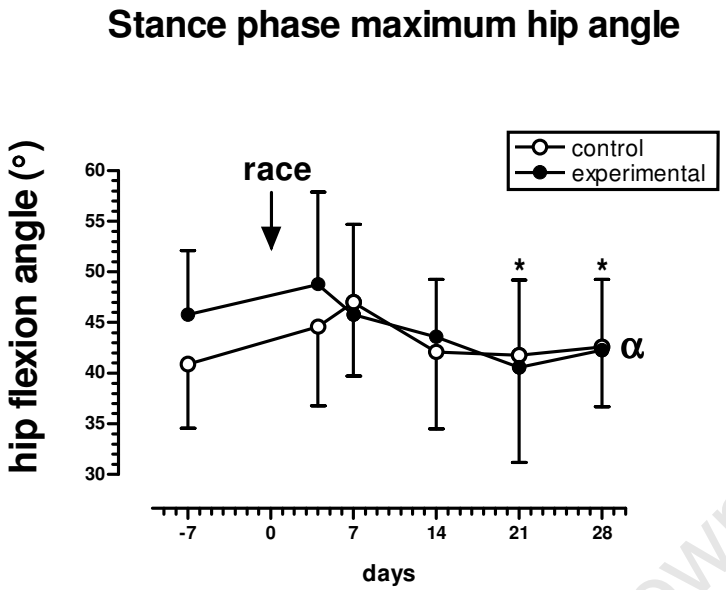

Figure 4.15: *Maximum hip flexion angle (°) during stance phase of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

* experimental day 4 vs. experimental days 21 and 28 ($p < 0.05$)

α main effect of time ($p < 0.0003$)

4.3.8.9.4 Ankle range of movement

The ankle range of movement (ROM) during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.16. There was no significant difference in the measurement between groups, however there was a significant difference in the measurement over time ($F_{(5, 75)} = 3.94$; $p < 0.004$), with the ankle ROM during stance phase tending to be higher in the experimental group.

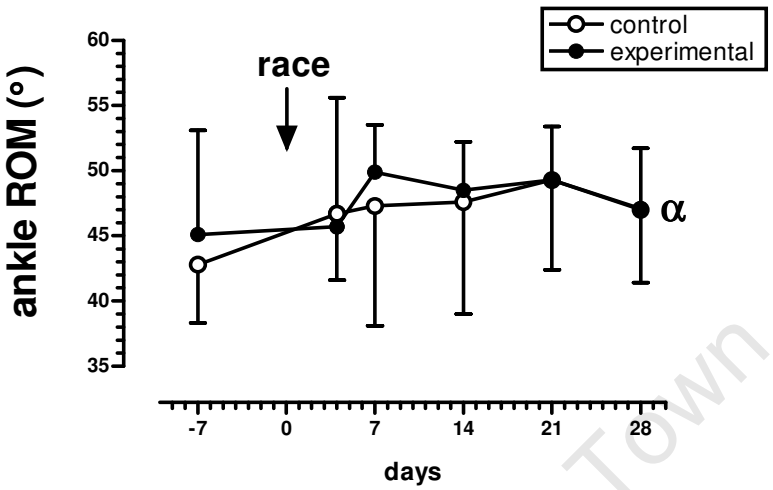

Figure 4.16: *Ankle range of movement (ROM) (°) during stance phase of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

α main effect of time ($p < 0.004$)

4.3.8.9.5 Knee range of movement

The knee range of movement (ROM) during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.8. There were no significant differences in the knee ROM during stance phase either between groups or over time.

Table 4.8: *Knee range of movement (°) during stance phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	38.4 ± 6.9	35.5 ± 4.3
4	35.8 ± 4.1	31.3 ± 7.2
7	34.0 ± 5.9	32.7 ± 3.2
14	38.8 ± 4.7	34.3 ± 6.6
21	38.3 ± 5.4	34.6 ± 6.3
28	36.6 ± 5.8	33.5 ± 5.0

4.3.8.9.6 Hip range of movement

The hip range of movement (ROM) during stance phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.9. There were no significant differences in the hip ROM during stance phase either between groups or over time.

Table 4.9: *Hip range of movement (°) during stance phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	56.6 ± 6.4	53.7 ± 3.1
4	59.1 ± 8.4	54.9 ± 5.4
7	57.6 ± 10.8	56.7 ± 4.4
14	56.3 ± 4.9	55.3 ± 6.4
21	55.8 ± 6.3	52.5 ± 4.3
28	56.1 ± 4.5	53.9 ± 3.5

4.3.8.10 Swing phase kinematics

4.3.8.10.1 Maximum ankle angle

The maximum ankle plantarflexion angle during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.17. There was a significant interaction between groups over time ($F_{(5, 85)} = 2.49$; $p < 0.04$), with the maximum ankle plantarflexion angle tending to be higher in the experimental group.

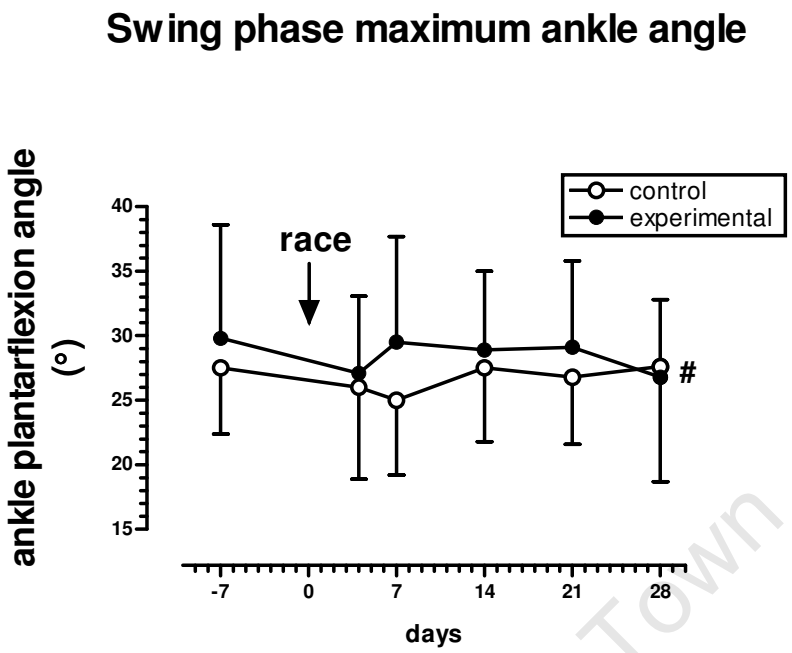

Figure 4.17: *Maximum ankle plantarflexion angle (°) during swing phase of subjects in the experimental (-•-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

interaction of group x time ($p < 0.04$)

4.3.8.10.2 Maximum knee angle

The maximum knee flexion angle during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.10. There were no significant differences in the maximum knee angle during swing phase either between groups or over time.

Table 4.10: *Maximum knee flexion angle (°) during swing phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	105.6 ± 12.7	98.4 ± 11.7
4	103.5 ± 11.7	98.7 ± 11.4
7	106.9 ± 11.5	100.5 ± 11.3
14	103.4 ± 11.3	99.0 ± 11.8
21	103.5 ± 13.5	100.8 ± 9.7
28	104.3 ± 13.5	100.3 ± 11.6

4.3.8.10.3 Maximum hip angle

The maximum hip extension angle during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.18. There was a significant interaction between groups over time ($F_{(5, 85)} = 2.53$; $p < 0.04$), with the maximum hip extension angle tending to be higher in the experimental group.

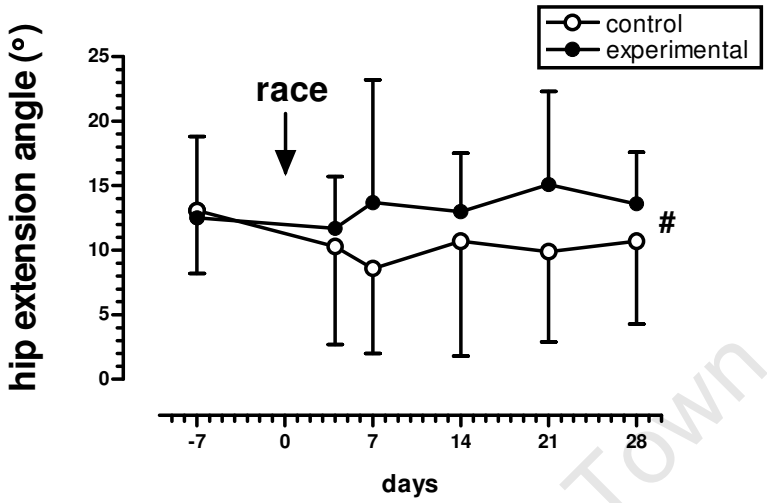

Figure 4.18: *Maximum hip extension angle (°) during swing phase of subjects in the experimental (-•-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

interaction of group x time ($p < 0.04$)

4.3.8.10.4 Ankle range of movement

The ankle range of movement (ROM) during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Figure 4.19. There was a significant interaction between groups over time ($F_{(5, 80)} = 3.42$; $p < 0.008$). The ankle ROM was significantly decreased in the experimental group on day 28 ($p < 0.05$), compared to day 7 values.

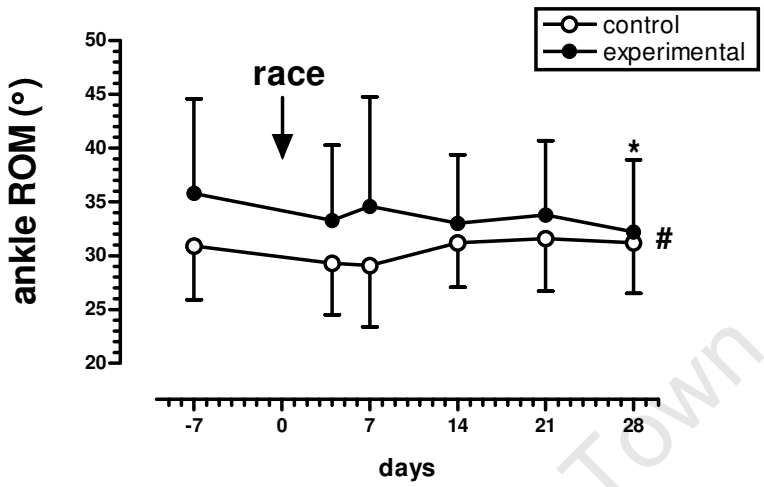

Figure 4.19: *Ankle range of movement (ROM) (°) during swing phase of subjects in the experimental (-•-) (n = 11) and control (-o-) (n = 10) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± SD.*

Significant differences:

* experimental day 7 vs. experimental day 28 ($p < 0.05$)

\# interaction of group x time ($p < 0.008$)

4.3.8.10.5 Knee range of movement

The knee range of movement (ROM) during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.11. There were no significant differences in the knee ROM during swing phase either between groups or over time.

Table 4.11: *Knee range of movement (°) during swing phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	92.0 ± 18.6	89.1 ± 15.8
4	86.9 ± 14.5	81.1 ± 11.3
7	91.4 ± 15.3	82.3 ± 13.0
14	88.0 ± 13.8	84.2 ± 14.2
21	89.6 ± 14.8	84.8 ± 11.8
28	87.8 ± 14.0	83.3 ± 12.5

4.3.8.10.6 Hip range of movement

The hip range of movement (ROM) during swing phase of subjects in the experimental and control groups at 4 minutes in the submaximal treadmill test are shown in Table 4.12. There were no significant differences in the hip ROM during swing phase either between groups or over time.

Table 4.12: *Hip range of movement (°) during swing phase of subjects in the experimental (n = 11) and control (n = 13) groups at 4 minutes during the submaximal bout of exercise. Tests were conducted 7 days before the race and at 4, 7, 14, 21 and 28 days after the race. Data are expressed as mean ± standard deviation.*

DAY	EXPERIMENTAL	CONTROL
-7	65.6 ± 7.1	61.4 ± 9.7
4	70.5 ± 11.8	62.1 ± 7.9
7	68.2 ± 11.5	63.0 ± 6.5
14	65.0 ± 6.3	62.0 ± 9.1
21	64.8 ± 7.2	61.1 ± 6.0
28	64.7 ± 6.8	62.7 ± 6.0

4.4 DISCUSSION

As previously demonstrated in Chapter 3, the 90 km ultramarathon race induced muscle pain in the experimental group consistent with delayed onset muscle soreness. However, in this study, muscle pain remained significantly elevated in the experimental group for seven days after the ultramarathon race (Figure 4.2), compared to four days in the previous study (Figure 3.2). Interestingly, the average exercise intensity during the race was similar in both studies. It may be suggested that the different pain response may be related to the difference in the race profile between the two studies. In this study, subjects descended approximately 650 m during the race, whereas in the previous study, subjects ascended approximately 650 m during the race (Appendix I).

It may be proposed that, although the duration of exercise was similar in both studies, the extent of lengthening muscle action, and subsequent exercise-induced muscle damage and delayed onset muscle soreness, would be greater in this study due to the greater proportion of downhill running during the ultramarathon race.

In addition, in the experimental group, subjective pain had returned to pre-race values by day 14 after the ultramarathon race. Studies have shown that although muscle pain associated with delayed onset muscle soreness usually dissipates within 96 hours after exercise[78;98;138], pain may persist for up to 10 days after exercise[135]. It is acknowledged that the exact time course of recovery of muscle pain in this study is unclear, as daily measurements of muscle pain were only recorded for seven days after the ultramarathon race.

Plasma CK activity was significantly higher in the experimental group at days one and two after the ultramarathon (Figure 4.3). This is consistent with findings previously demonstrated in Chapter 3, as well as with other studies that also reflect a rapid increase in plasma CK activity from 24 hours after a marathon[369;496]. In addition, although the magnitude of the increase in plasma CK activity, as well as the degree of intra-individual variability were excessively higher in this study, compared to the previous study, it is interesting to note that plasma CK activity still returned to pre-race values at day four after the ultramarathon race.

The main finding of this study was that a reduction in submaximal oxygen consumption, as described in Chapter 3, was again observed in the experimental group following the 90 km ultramarathon race (Figure 4.4). In this study, submaximal oxygen consumption was reduced for up to 28 days after the race, confirming the previously noted post-race reductions in oxygen consumption. Some of the possible underlying mechanisms that may explain the reduction in oxygen consumption following the ultramarathon race have been discussed in Chapter 3.

However, the contrary changes in submaximal oxygen consumption in this study, compared to previous studies, where submaximal oxygen consumption either increased following running protocols[78;102;125;369;474;628;687], or remained unchanged following stretch shortening cycle[412] or resistance exercise protocols[510;581], require further investigation.

Nicol et al[474] determined the effects of fatigue induced by a marathon on submaximal oxygen consumption. In this study, seven males and one female, all experienced endurance runners between 20 and 35 years of age, performed an individual and paced marathon run. The individual marathon speed was based on the subject's current training state and their last performance in a competition.

Submaximal oxygen consumption was assessed four days before the marathon, at 20 km during the marathon, and immediately after the marathon. Submaximal oxygen consumption was determined during a six-minute run. Subjects were required to run for three minutes at 75% of the individual marathon speed, for two minutes at 100% of the individual marathon speed, and for one minute at 125% of the individual marathon speed. Submaximal oxygen consumption was significantly increased immediately after the marathon at 75% and 100% of the individual marathon speed, compared to pre-marathon values. Changes in submaximal oxygen consumption at 125% of the marathon speed were not reported[474].

In addition, Hausswirth et al[268] showed that submaximal oxygen consumption was increased during and at the end of simulated triathlon and marathon runs in seven well-trained triathletes (31.0 ± 5.0 years of age; 5.5 ± 2.5 years of competition), when compared to values obtained during an isolated 45-minute run.

Other studies have also examined acute changes in submaximal oxygen consumption following an exercise bout. Thomas et al[628] demonstrated that, in recreational female runners (22.9 ± 4.8 years of age; approximately 24 km.wk^{-1} training volume), submaximal oxygen consumption increased during a 5 km run at 80% of maximum oxygen consumption.

Furthermore, both Sproule[605] and Xu and Montgomery[687] examined the effects of different exercise intensities on acute changes in submaximal oxygen consumption. It was demonstrated that submaximal oxygen consumption was increased in male subjects (23.0 ± 2.0 years of age) immediately after 60-minute runs at 70% and 80% of maximum oxygen consumption[605], and in male distance runners (31.6 ± 7.1 years of age; 64.6 ± 25.7 km.wk^{-1} training volume) after 90-minute runs at 65% and 85% of maximum oxygen consumption[687]. Both studies also reported greater increases in submaximal oxygen consumption at higher exercise intensities[605;687].

Additional studies have investigated the effects of exercise-induced muscle damage on submaximal oxygen consumption. Braun and Dutto[78] examined the effects of a 30-minute downhill run (-10% gradient) at 70% of peak oxygen consumption on nine experienced distance runners and triathletes (31.4 ± 5.4 years of age; 60.4 ± 23.4 km.wk^{-1} training volume).

Submaximal oxygen consumption was measured at 65%, 75%, and 85% of peak oxygen consumption before, and 48 hours after the downhill run. Submaximal oxygen consumption was increased by 3.2% at 48 hours after the downhill run, compared to baseline measurements[78].

Similarly, Chen et al[125] used a 30-minute downhill run (-15% gradient) at 70% of peak oxygen consumption to determine the effects of exercise-induced muscle damage on submaximal oxygen consumption in 10 male soccer players (20.5 ± 1.5 years of age; approximately 14 $h.wk^{-1}$ soccer training). Submaximal oxygen consumption was measured at 65%, 75%, and 85% of peak oxygen consumption before, immediately after, and daily for five days after the downhill run. Submaximal oxygen consumption was increased by between 4% and 7% up to three days after the downhill run, compared to baseline measurements.

Further, Kryöläinen et al[369] examined the effects of a marathon on submaximal oxygen consumption in seven experienced triathletes (29.0 ± 5.0 years of age; 160 ± 21 $km.month^{-1}$ running training). The marathon was individually run, and paced by a cyclist. The pace of the marathon was based on each subject's current training state. Submaximal oxygen consumption was assessed, in a five-minute submaximal run, one week before the marathon, at 0 km, 13 km, 26 km and 42 km during the marathon, two hours after the marathon, and at two, four, and six days after the marathon. The study showed that submaximal oxygen consumption was significantly increased at the end of the marathon (42 km), and two hours after the marathon. However, submaximal oxygen consumption had returned to pre-race values by day six after the marathon.

Changes in submaximal oxygen consumption following a duathlon were studied by Calbert et al[102]. Fifteen subjects (24.0 ± 1.3 years), who performed regular exercise but were not engaged in any systematic competitive training, participated in the study. Subjects performed a maximal test, followed by a duathlon (5 km run, 16 km cycle, 2 km run). This was followed by a six-week training programme, after which the duathlon was repeated. Submaximal oxygen consumption was assessed before the maximal test, and at two and seven days after the second duathlon. Subjects performed a submaximal bout of exercise, running at 58%, 63%, 67%, and 71% of peak treadmill running speed. Subjects ran at each speed for six minutes, with a three-minute rest between each speed increment. Submaximal oxygen consumption was recorded in the final two minutes of every six-minute exercise bout.

Two days after the second duathlon, submaximal oxygen consumption was approximately 8% higher than baseline values. However, seven days after the second duathlon, submaximal oxygen consumption was approximately 4.6% lower than day two values, and was similar to baseline values[102].

The above studies provide evidence that submaximal oxygen consumption is acutely increased following exercise that induces muscle damage and neuromuscular fatigue. The acute increases in submaximal oxygen consumption are evident immediately post-exercise[240;268;369;474;605;628;687], and for up to three days after the prolonged or damage-inducing exercise[78;102;125;369]. In addition, comparisons may be made between this study, and the aforementioned studies in terms of the age of subjects, training specificity of subjects, and the training volume and running experience of subjects. In this study, both the experimental and control group subjects were generally older, were all endurance runners, reported greater training volumes, and had greater levels of endurance running experience, when compared to subjects in the aforementioned studies.

Furthermore, although increases in submaximal oxygen consumption were observed for up to three days after exercise[78;102;125;369], certain studies monitored changes in submaximal oxygen consumption for up to seven days after a prolonged or damage-inducing exercise bout[102;125;369]. Interestingly, submaximal oxygen consumption had returned to pre-exercise values by day five after a 30-minute downhill run[125], by day six after a marathon[369], and by day seven after a duathlon[102]. In addition, Petersen et al[524] demonstrated significant reductions in energy expenditure on day two and day five after a marathon race. It may be hypothesised that the recovery of submaximal oxygen consumption to below pre-muscle damage values may reflect a sub-acute metabolic response to the neuromuscular changes associated with exercise-induced muscle damage or fatigue.

This study examined changes in submaximal oxygen consumption before, and between four days and 28 days after an ultramarathon race. While it is known that neuromuscular function is disturbed for up to 11 days after an ultramarathon race[120], Chapter 3 and Chapter 4 are the first studies to report changes in submaximal oxygen consumption beyond seven days after prolonged exercise, or exercise-induced muscle damage.

The initial reduction in oxygen consumption at day four after the ultramarathon race is contrary to the findings of the aforementioned studies. However, it may be theorised that the early reduction in submaximal oxygen consumption in this study may perhaps be related to the either the extent of exercise-induced muscle damage, or the type of neuromuscular fatigue induced by the ultramarathon event. In addition, it may be speculated that the training state or endurance running experience of the subjects in this study may result in a different metabolic response to exercise-induced muscle damage and endurance exercise.

The hypothesis that different metabolic responses may occur in relation to different types of neuromuscular fatigue may be supported by the findings of Marcora and Bosio[412]. No changes in submaximal oxygen consumption were observed during a 10-minute submaximal run at 70% of maximum oxygen consumption, following a 100-drop jump protocol designed to induced muscle damage in recreational runners. In addition, other studies have reported no changes in steady-state oxygen consumption at 55% and 75% of maximum oxygen consumption for five days after a 120-repetition maximum voluntary contraction protocol to induce muscle damage[510], or at approximately 70% of maximum oxygen consumption 24 to 30 hours after an exercise protocol that induced muscle damage using a series of lower extremity resistance exercises[581].

The theory that changes in submaximal oxygen consumption may be related to the extent of exercise-induced muscle damage may be substantiated by a study investigating changes in the oxygen cost of submaximal running and cycling in nine well-trained male athletes following a 65 km ultramarathon race. The oxygen cost of running, during a four-minute submaximal test at 11 $km.h^{-1}$ remained unchanged after the ultramarathon race compared to pre-race values. Interestingly however, the oxygen cost of cycling, during a four-minute submaximal test at 1.5 $W.kg^{-1}$, increased compared to pre-race values[442]. This also supports the hypothesis that the submaximal oxygen consumption response may be related to the training state or endurance experience of subjects.

Furthermore, Hamill et al[263] examined the effects of a 30-minute downhill run (-26% gradient) at 74% of maximum heart rate on recreational female runners. Submaximal oxygen consumption was measured before, and at 48 and 120 hours after the downhill run. There were no changes in the energy cost of running following the downhill run.

This finding is contrary to those of previous studies that showed an increase in submaximal oxygen consumption following downhill running at gradients of -10%[78] and -15%[125].

Gender differences of the subjects in the studies accounting for the varying results may be discounted, as previous studies have not observed gender-related differences in the response to downhill running[205;601]. It may be suggested that the difference in submaximal oxygen consumption response observed in these studies may be related to the differences in the exercise intensity of the downhill run between studies (% HR_{max} vs. % VO_{2peak}). Alternatively, it may be speculated that the differences in the training status of subjects may influence the submaximal oxygen consumption response to downhill running.

In addition, Westerlind et al[666] examined the effects of two 45-minute downhill runs (-10% gradient) at 50% of maximum oxygen consumption on recreational runners. The second downhill run was performed two weeks after the first downhill run. Although submaximal oxygen consumption increased during both downhill runs, it was observed that submaximal oxygen consumption was significantly increased during the first downhill run, compared to pre-exercise values. Interestingly, submaximal oxygen consumption was significantly reduced in the second downhill run, compared to both pre-exercise and the first downhill run values. The authors proposed that the reduction in submaximal oxygen consumption was due to a change in motor unit recruitment. It may also be theorised that the reduction in submaximal oxygen consumption reflects a metabolic adaptation associated with the repeated-bout effect.

It is also possible that environmental factors may influence the submaximal oxygen consumption response to exercise. Dressendorfer[191] reported no changes in submaximal oxygen consumption following a 21.1 km run completed in a mean time of 89.5 minutes, in temperatures ranging from 22 ºC to 27 ºC. This is contrary to the findings of Xu and Montgomery[687], who demonstrated increases in submaximal oxygen consumption after 90-minute runs at 65% and 85% of maximum oxygen consumption, in temperatures ranging from 1.3 ºC to 3.9 ºC. This theory is speculative and requires further investigation.

The later reduction in submaximal oxygen consumption, from day seven up to day 28 after the ultramarathon race (Figure 4.4), may reflect long-term metabolic adaptations during the recovery period after an ultramarathon race. This study did not provide mechanisms to determine whether the long-term reduction in submaximal oxygen consumption is associated with improvements in running performance. From an anecdotal perspective, after comments from the subjects, maximal running performance would have most certainly been impaired had it been measured during the study. This paradox requires further investigation.

An increase in respiratory exchange ratio, as described in Chapter 3, was observed in the experimental group following the 90 km ultramarathon race (Figure 4.5). In this study, the respiratory exchange ratio was significantly higher in the experimental group at day four after the race, confirming the previously noted post-race increases in respiratory exchange ratio. Increases in respiratory exchange ratio have been reported following downhill running protocols[78;125]. In addition, Calbert et al[102] showed an increase in respiratory exchange ratio at 7 days after a duathlon, compared to two days after the duathlon. Conversely, Kryöläinen et al[369] reported a significant reduction in respiratory exchange ratio two hours after a marathon. However, the respiratory exchange ratio showed a tendency to be increased above pre-race values up to day six after the marathon.

Although the time taken to normalise muscle glycogen concentrations after a race is thought to be 10 days or longer[498], it may be speculated that the higher respiratory exchange ratio values may be associated with a progressive increased utilisation of muscle glycogen during the recovery period after the race[102]. However, this study did not provide mechanisms to determine the potential underlying causes of the increase in respiratory exchange ratio values after the ultramarathon race, and further investigation is required.

Significant changes in heart rate values were noted in both the experimental and control groups (Figure 4.6). Nevertheless, it may be maintained that the significant changes in heart rate observed in this study do not reflect a meaningful difference in heart rate. Lamberts et al[381] established the average day-to-day variation of heart rate was 5 to 8 $b.min^{-1}$. This average day-to-day variation in heart rate was observed during constant levels of training, and without changes in the levels of muscle soreness and fatigue.

In this study, although changes in heart rate in the experimental group occurred at some stages in the presence of increased muscle pain, the variation in heart rate values in both the experimental and control groups was less than 5 to 8 $b.min^{-1}$ for the duration of the study. Therefore, it may be proposed that no meaningful changes in heart rate occurred in this study.

The rate of perceived exertion was significantly higher in the experimental group for up to 28 days after the ultramarathon race (Figure 4.7). Interestingly, the elevated levels of the rate of perceived exertion persisted for much longer after the ultramarathon race in this study, compared to the previous study.

It may be proposed that the prolonged increase in the rate of perceived exertion noted in this study may be linked to the increased levels of muscle pain and plasma CK activity, and potential extent of exercise-induced muscle damage, when compared to the previous study.

Alternatively, the experimental group pre-race rate of perceived exertion tended to be reduced, when compared to the control group values. It may be suggested that this pre-race reduction in the rate of perceived exertion in the experimental group may be associated with the pre-race taper. It is acknowledged that numerous physiological and psychological factors may influence the rate of perceived exertion. Exercise training is recognised to reduce the rate of perceived exertion at submaximal workloads. It may therefore be hypothesised that the pre-race reduction in the rate of perceived exertion in the experimental group may be as result of the combined effects of training, tapering, and psychological preparation for the ultramarathon race. However, this theory is speculative and requires further investigation.

In this study, stride length was significantly increased at day 21 after the race, compared to pre-race values (Figure 4.8). This finding is contrary to the previous study (Chapter 3), where stride length was reduced for 14 days after the ultramarathon race, as well as other studies, where reductions in stride length were observed after a marathon[369], and after 30 minutes of downhill running[78;125]. The difference in stride length observations between this study and the previous study may perhaps be explained by the different methods used to determine stride length. In this study, the method of recording stride length, using the six-camera motion analysis system (Oxford Metrics Vicon System 370 Version 2.5, Oxford Metrics Ltd, Oxford, United Kingdom), may be considered more accurate than the previous study Figure 3.8), where stride frequency was manually counted.

However, in this study, only one stride was analysed at four minutes during the submaximal run, whereas in the previous study, stride frequency was counted for 30 seconds at 4, 9, and 14 minutes during the submaximal run. It is suggested that future studies should assess stride length using the six-camera motion analysis system (Oxford Metrics Vicon System 370 Version 2.5, Oxford Metrics Ltd, Oxford, United Kingdom), and that stride length should be examined for 30 second periods at numerous time points during a submaximal run.

Further, Hunter and Smith[306] reported a decrease in stride frequency during a one-hour high intensity run. Interestingly, stride frequency showed a considerable inter-individual response to fatigue, and there was no relationship between changes in steady-state oxygen consumption and stride frequency. It was proposed that the variability in stride frequency may reflect the selection of a self-optimal stride frequency during exercise and fatigue, and that the optimisation of stride frequency may indicate a balance between the elastic storage of energy and the energy cost of accelerating limbs.

In addition, other studies have suggested that, at every running speed, an individual optimal stride length exists at which oxygen consumption is minimised[81;119;457;480]. Therefore, the stride length alterations observed in this study may reflect the optimisation of stride length during the recovery period after the ultramarathon race.

There were no significant differences in the vertical displacement of the centre of mass between the experimental and control groups in this study (Table 4.4). There was however a moderate association between submaximal oxygen consumption and the vertical displacement of the centre of mass before, and for up to 28 days after the ultramarathon race (Figure 4.9).

Conversely, during the acute period after the ultramarathon race there were no significant correlations between the changes in the vertical displacement of the centre of mass and oxygen consumption. The vertical displacement of the centre of mass has been related to energy changes that occur in the body during running[595], and has been found to be correlated with oxygen consumption in normal cardiopulmonary conditions[337;675], and performance in a 10 km run[676]. It is also recognised that treadmill running is associated with a lower and less variable centre of mass, when compared to overground running[463].

However, in this study, the vertical displacement of the centre of mass remained relatively unchanged in the presence of delayed onset muscle soreness, and thereafter in the recovery period following the ultramarathon race. In addition, changes in the vertical displacement of the centre of mass occurred independently to changes in submaximal oxygen consumption in the presence of muscle pain. Thus, the vertical displacement of the centre of mass does not seem to suggest a more efficient biomechanical motion for the experimental group, and therefore probably does not account for the reduced submaximal oxygen consumption in this study.

The significant changes in kinematic variables observed in the experimental group in this study included increased ankle dorsiflexion, knee flexion, and hip flexion angles at heelstrike, and an increased ankle plantarflexion angle at toe-off (Figures 4.10 – 4.13). Significant stance phase alterations in the experimental group included increased maximum knee flexion angles, decreased maximum hip flexion angles, and increased ankle range of movement. In addition, the experimental group demonstrated tendencies for the swing phase maximum ankle and hip angles, and ankle range of movement to be increased, compared to control group values.

This is the first study that has examined changes in running kinematics before and after an ultramarathon, and over an extended recovery period. Previous studies investigating the effects of delayed onset muscle soreness on running kinematics have provided varied results[127]. Hamill et al[263] reported increased maximum ankle dorsiflexion during stance phase, a reduction in maximum knee flexion during stance and swing phase, and decreased maximum hip flexion at heelstrike following a 30-minute downhill run. Further studies reported a reduction in ankle and knee range of movement for 48 to 72 hours after a 30-minute downhill run[125;194].

Conversely, no distinct changes in running kinematics were observed after a marathon[369]. In addition, large inter-individual variations in running kinematics were associated with marathon fatigue[474].

It may be postulated that the changes in running kinematics observed in this study may be compensatory adaptations to alterations in motor unit activation, the reduction in range of movement, and, at some stages, the muscle pain associated with delayed onset muscle soreness[78;125;127;263]. Mann and Hagy[410] also proposed that increased hip and knee flexion, and ankle dorsiflexion is related to a lower centre of mass, indicating that a possible reduction in energy cost of running may be associated with the kinematic changes observed in this study.

In addition, the increased ankle dorsiflexion and knee flexion angles at heelstrike may be a further compensatory mechanism to increase shock attenuation during the initial stance phase[263;435]. Alternatively, increased impact acceleration of the tibia, associated with an imbalance between the ankle dorsiflexors and plantarflexors, has been noted during fatigue[195], suggesting that the changes in ankle angles during heelstrike and toe-off may not be advantageous in a fatigued state.

It is unclear whether the changes in the discrete kinematic variables assessed in this study may be associated with the reduction in submaximal oxygen consumption. The underlying mechanisms of the alterations in running kinematics are not well understood. In addition, the timing of changes in running kinematics varied throughout the recovery period from the ultramarathon race. It is recommended that future studies investigate segmental and whole body energy changes in an attempt to explain the reductions in submaximal oxygen consumption.

In conclusion the main findings of this study are that a 90 km ultramarathon race induces severe muscle damage, which causes pain and increases in plasma CK activity for at least seven and four days respectively. The race caused a reduction in submaximal oxygen consumption for 28 days. This confirms the previous finding of a post-race reduction in oxygen consumption. It may be proposed that this submaximal oxygen consumption response to an ultramarathon may be related to the training state or endurance experience of subjects.

Alternatively, it may be theorised that the reduction in submaximal oxygen consumption may reflect sub-acute or long-term metabolic adaptations, or changes in motor unit recruitment during the recovery period after an ultramarathon race. In addition, although discrete alterations in running kinematics were observed for up to 28 days after the race, the findings of this study strongly suggest that the changes in running kinematics do not account for the reduction in submaximal oxygen consumption. It is recommended that further studies should investigate the potential metabolic adaptations underlying changes in submaximal oxygen consumption after an ultramarathon race. In addition, it should be established whether the long-term reduction in submaximal oxygen consumption is associated with improvements in running performance.

CHAPTER FIVE
LITERATURE REVIEW: NEUROMUSCULAR CHARACTERISTICS AND STRETCH SHORTENING CYCLE FATIGUE DURING RUNNING

5.1 INTRODUCTION

Running economy and the factors associated with running economy were discussed in detail in Chapter 2. Traditionally, measurements of cardiorespiratory fitness, including running economy, maximal oxygen consumption, and the rate of blood lactate accumulation have been considered to be the most appropriate measurements that may predict endurance running performance, based on the assumption that exercise performance may be exclusively related to cardiorespiratory and skeletal muscle factors[44;155;214]. However, this model of exercise performance does not consider the potential role of the central nervous system in modulating endurance running performance by altering muscle recruitment patterns[234;479].

The results of the previous studies (Chapter 3 and Chapter 4) have shown reductions in submaximal oxygen consumption for up to 28 days after an ultramarathon race. This is a seemingly paradoxical finding as anecdotal evidence suggests that running performance would have been impaired in the recovery period after the race. It may be theorised that alterations in neuromuscular function may contribute to changes in submaximal oxygen consumption in the recovery period after the ultramarathon race. Indeed, Komi[351] and Paavolainen et al[504-506] have demonstrated that neuromuscular characteristics and muscle power may be related to endurance running performance.

In addition, the effective storage and utilisation of elastic energy through the stretch shortening cycle contributes to the production of muscular force and mechanical effectiveness[19;64;70;112;201;311;348;351;472;631]. The repetitive stretch shortening cycling that occurs during endurance running may be associated with alterations in muscle elasticity and stiffness regulation[475;476].

It has also been proposed that there may be a limit to the number of times these shock absorbing mechanisms may be damaged, where after the central nervous system may alter the neuromuscular recruitment patterns as a compensatory mechanism to protect the body from further damage[480]. However, the recovery pattern after prolonged running has not been studied extensively[524], and thus the complex interactions between fatigue, exercise-induced muscle damage, and performance require further investigation.

Therefore, this review will examine the contribution of neural, mechanical, and structural factors to running performance, and the interaction of these factors to produce an efficient running gait cycle. Specifically, the stretch shortening cycle and the role of muscle preactivation will be highlighted. The review will also consider the effects of fatigue, muscle damage, and training on neuromuscular characteristics and endurance running performance.

5.2 THE STRETCH SHORTENING CYCLE

Human movement seldom involves pure forms of isolated shortening, lengthening or isometric muscle actions. Body segments are periodically subjected to impact or lengthening forces. For example, during running, walking, and hopping, gravity acts as an external force to lengthen the muscle. The stretch shortening cycle occurs during functional activities, and describes the sequence of an active lengthening or eccentric muscle action followed by an active shortening or concentric muscle action. These integrated muscle actions are linked to performance enhancement, compared to an isolated shortening muscle action[348;351;472;617]. Lengthening muscle actions actively contribute to the stretch shortening cycle. During a lengthening muscle action, there is active lengthening of the skeletal muscle with simultaneous force resistance[332;490].

Muscle elasticity has an important role in human locomotion by improving the power output in maximal effort[19;111;352;632], and attenuating high impact forces. The effective storage and release of this elastic energy during stretch shortening cycle exercise contributes to the production of muscular force and mechanical effectiveness, resulting in a movement that is more efficient than isolated shortening or lengthening muscle actions[19;64;70;112;201;311;348;351;472;631].

5.2.1 THE STRETCH SHORTENING CYCLE AND MECHANICAL EFFICIENCY

The stretch shortening cycle results in improvements in the force, speed and power of movement, and therefore similar improvements in the mechanical efficiency of muscular work should also occur. Mechanical efficiency of a given task may be defined as "the ratio of produced mechanical work to the energy expenditure above that of the resting condition"[347]. The positive contribution of the stretch shortening cycle to mechanical efficiency may be related to the mechanical and neural properties of skeletal muscle.

During the active prestretch, or the lengthening phase of the stretch shortening cycle, the elastic characteristics of the muscle are temporarily altered[110;111], allowing for the storage of potential energy. The stored potential energy may be partly recovered during the subsequent shortening phase of the stretch shortening cycle[352]. A component of the positive work produced during the shortening muscle action is therefore delivered, at no energy cost, from the recoil of previously stretched elastic elements[68]. In addition, segmental reflex activity may also reduce the energy cost during stretch shortening cycle exercise[64;70].

A continual interaction between mechanical and neural factors may contribute to stretch shortening cycle efficiency. These factors include muscle preactivation, prestretch intensity, and the transition time between initial muscle lengthening and subsequent muscle shortening[351;472]. In addition, Bosco et al[70] proposed that type I and type II muscle fibres may have different viscoelastic properties. There is also some evidence indicating that muscle fibre content may contribute to alterations in electromyographic (EMG) activity during fatiguing exercise[649]. It may therefore be theorised that skeletal muscle structural components may contribute to the interactive processes between neural control and mechanical responses during running.

5.2.1.1 Muscle preactivation

Muscle preactivation is essentially a centrally regulated, feed-forward, anticipatory mechanism[25;186;245-247;252;255;297;460], initiated by the brain[387]. Widespread regions of the cortex are involved in the planning and execution of self-initiated movements, illustrated by pre-movement brain potentials[387], and onto which a reflex activity is imposed[33;186;434;460].

Muscle preactivation functions to prepare the lower limb muscles for landing by increasing the neural activity in the appropriate muscle before the foot makes contact with the ground[4;25;33;186;202;436]. Muscle preactivation regulates muscle stiffness, and the transition time between the prestretch and shortening components of the stretch shortening cycle[247;252;255], as a high pre-landing stiffness is directly responsible for a high post-landing stiffness[294;650].

Preactivation during running is calculated from EMG activity recorded 100 milliseconds (ms) before heelstrike[506]. Preactivation has a significant contribution to the effective utilisation of elastic energy[25;26;288;471;619]. An increase in muscle preactivation is associated with a reduction in ground contact time, due to improvements in muscle stiffness[288;471] and muscle recoil capacity[25;26;619].

In addition, muscle preactivation also accommodates high initial ground reaction force peaks that occur on landing[245;247]. It has been demonstrated that, with the onset of fatigue following repeated stretch shortening cycle exercise, the initial force peaks upon impact are higher, and contraction times for both lengthening and shortening phases are increased. These findings occur together with a reduction in force production[247].

Current literature provides evidence for the central nervous system regulation of muscle preactivation, through both central and reflex-induced activation. Prochazka et al[541] demonstrated that a fast stretch of an active muscle leads to the enhancement of stretch reflexes via Ia-afferents from the muscle spindle. This reflex potentiation, together with an increase in motorneurone activity to the contracting muscles, would result in an increase in force at the end of the lengthening phase, resulting in increased muscle stiffness[30;67;471;648].

5.2.1.1.1 Stretch reflexes

Bosco et al[64;70] determined that centrally pre-programmed activation and segmental reflex activity were important factors in the utilisation of elastic energy[252], and the enhancement of stretch shortening cycle performance.

It has been demonstrated that muscle stiffness represents the actual state in the contractile mechanisms of the muscle, with the filament overlap between actin and myosin, which is closely related to force production. The compensation in stiffness that occurs after stretching is thought to be associated with a corresponding change in muscle mechanical behaviour, such as power production. Therefore, the stretch reflex during the lengthening phase of the stretch shortening cycle may be an important factor in the regulation of subsequent muscle stiffness, which will affect the enhancement of performance during the shortening phase of the stretch shortening cycle[293].

Numerous studies have identified an increase in segmental reflex activity prior to ground contact[247;252;351;471]. However, Aura and Komi[25] theorised that there may be an upper limit to the improvements in muscle stiffness characteristics, and proposed that this limit may be related to the activation and chemo-mechanical behaviour of skeletal muscle cross-bridges.

Prolonged periods of repetitive stretch shortening cycle exercise, for example, in arm exercise[245;246] or marathon running[475;476], are associated with reductions in reflex activation, which may be related to reductions in elastic energy potential and stiffness regulation, coupled with alterations in muscle spindle and Golgi tendon organ sensitivity. The reduction in muscle activation may also protect the fatigued muscle from excessive stretch loads[245]. It is therefore evident that stretch shortening cycle efficiency may be influenced by neural and reflex activation strategies.

5.2.1.1.2 Prestretch intensity

The enhancement of performance through prestretching may be seen in isolated voluntary muscle, both in force-length and force-velocity curves[111]. When the force-velocity curve was measured during vertical jump tests, prestretching resulted in substantial displacement of the force-velocity curve to the right, thereby enabling the leg extensor muscles to exert higher forces at any knee angular velocity during the shortening phase of the stretch shortening cycle[65].

Skeletal muscle length and velocity during the initial lengthening muscle action are important contributing factors to the mechanical efficiency of the subsequent shortening muscle action[25;67;70;111;326]. Prestretch intensity increases with an increase in the velocity of movement, thereby leading to a subsequent increase in concentric work production[25;326].

In addition, as elastic energy is partly stored in the contractile components in the series of elastic compartments, any increase in cross-bridge activation may be associated with an increased capacity of elastic energy storage available for use during the shortening phase of the stretch shortening cycle[619].

5.2.1.2 Transition time

Bosco and Rusko[69] investigated the effect of increasing the transition time between stretch and shortening on the recoil of elastic energy and energy expenditure at different running speeds. The transition time was increased by the subjects wearing special soft shoes in comparison to normal soft shoes while running on a treadmill. The results indicated that an increased transition time was associated with greater energy requirements and a reduction in stretch shortening cycle efficiency.

Therefore, the time interval between breaking and push-off phases needs to be short[64;67;71;111;351;475], as a delay in the transition time leads to a loss of the stored elastic energy[111], and a subsequent reduction in movement efficiency[67;112].

5.2.1.3 Muscle fibre type and elastic energy storage

The elastic properties of the musculoskeletal system facilitate the storage of elastic energy, and thereby the enhancement of performance through the stretch shortening cycle[7;347;348;352;632]. The elastic properties of muscle are related to the mechanical structure of the tissue, which primarily consists of contractile and viscoelastic components. The viscoelastic components of skeletal muscle may be classified into parallel elastic components (PEC) and series elastic components (SEC), according to whether the viscoelastic components are in parallel or in series with the contractile components of the muscle[348].

The PEC is comprised of the sarcolemma, endomysium, perimysium and epimysium. It is theorised that the PEC provides passive muscle tension during a stretch[348]. The SEC may be partially situated in tendon tissue[3], as well as in the cross-bridges between actin and myosin[65]. The SEC is thought to contribute to the storage of elastic energy during the lengthening phase of the stretch shortening cycle[348;632].

The utilisation of the stored elastic energy will be maximised if the stretch itself, as well as the transition time, are of a short duration. The lengthened cross-bridges will be detached if the stretch position is maintained for too long[110], or may result in sarcomere "popping"[449] and damage if the range of the stretch is too large[220], and the elastic potential of the respective cross-bridges will not be utilised. This provides further evidence that a short transition time between lengthening and shortening phases improves stretch shortening cycle efficiency[65;66].

Bosco et al[72] suggested that type I and type II muscle fibres are characterised by different viscoelastic properties, and therefore the response to stretch shortening cycle exercise may be influenced by the muscle fibre type distribution. During vertical jump tests, subjects with a high percentage of type II muscle fibres performed better when executing the lengthening phase at higher speeds, and with smaller angular displacements. In contrast, subjects with a high percentage of type I muscle fibres performed better with increased transition times between the lengthening and shortening phases, and with larger angular displacements.

It was proposed that these differences might be related to differences in cross-bridge lifetime between type I and type II muscle fibres. Small amplitude jumps are characterised by a short transient period between the lengthening and shortening phases, and therefore subjects with a greater proportion of type II muscle fibres would be at an advantage. In contrast, large amplitude jumps have a significantly longer transient period between the lengthening and shortening phases, which would provide subjects with a greater percentage of type I muscle fibres with an extended period for additional motor unit recruitment. It was theorised that longer transition times facilitated the storage of elastic energy in type I muscle fibres for a longer time period without cross-bridge detachment[70].

In addition, the limiting effect of transition time on the storage and recoil of elastic energy may be greater in type II muscle fibres, compared to type I muscle fibres[68-70;625]. Type II muscle fibres have a significantly shorter cross-bridge lifetime cycle, and therefore if the transition time is longer than a few milliseconds, some of the cross-bridges will be detached and will lose elastic potential. This may provide an explanation for the increased mechanical efficiency during submaximal tasks in subjects with predominantly type I muscle fibres, compared to subjects with predominantly type II muscle fibres[70;625].

Furthermore, Moritani et al[460] demonstrated that the gastrocnemius muscle, with a higher proportion of type II muscle fibres were less resistant to fatigue during a hopping task to exhaustion, compared to the soleus muscle, with a higher proportion of type I muscle fibres. The level of fatigue-resistance may be associated with differences in the preactivation and lengthening phases of the stretch shortening cycle between the two muscle groups. It was proposed that the metabolic profile of the different muscle fibre types may have an important role in the regulation of muscle membrane excitability, and the response to stretch shortening cycle fatigue.

It is therefore evident that neural, mechanical, and muscular factors may contribute to improved stretch shortening cycle efficiency, which may be associated with improvements in performance. There is also much evidence to suggest that increased fatigue-resistance may facilitate improvements in endurance running performance.

5.3 NEUROMUSCULAR FATIGUE

Muscle fatigue is a complex phenomenon, and may be broadly defined as the inability to maintain the required or expected force or power output[41;203;330;480], or as a decrease in muscle performance[41;330;480]. The causes of fatigue may originate at locations proximal or distal to the neuromuscular junction. The manifestation of symptoms has lead to the definition of "central" and "peripheral" fatigue.

Central fatigue may be defined as a reduction in neural drive or motor command to the muscle, leading to a decrease in force or tension development. Peripheral fatigue may be defined as a reduction in the force-generating capacity of the skeletal muscle, due to action potential failure, excitation-contraction coupling failure, or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive[330;480].

Fatigue may be associated with alterations in the amplitude of EMG signals[212], a shift in the EMG power spectra towards lower frequencies[325], reductions in muscle force-generating capacity and relaxation time[447], and a delayed transition time between the lengthening and shortening phases of the stretch shortening cycle[475].

It is generally accepted that fatigue that occurs as a result of short-duration exercise is predominantly due to peripheral fatigue mechanisms, in particular metabolic factors or exercise-induced muscle damage[444]. Numerous studies have identified a close relationship between changes in intracellular metabolites and force production during sustained maximal isometric contractions[100;199;441;664].

Bigland-Ritchie et al[53] and Kent-Braun[333] demonstrated that, during a sustained isometric maximal voluntary contraction, central activation failure contributes to approximately 20% of the total fatigue. The remainder of the performance decrement was attributed to intramuscular mechanisms, primarily an increase in hydrogen ions. In contrast, Baker et al[36] determined that during short-duration exercise, the majority of the fatigue was due to a metabolic inhibition of contraction. However, long-duration exercise was associated with a non-metabolic component of fatigue acting beyond the cell membrane, at the level of the excitation-contraction coupling mechanism.

During endurance exercise, the aetiology of muscle fatigue is thought to be multi-faceted, and the relative contribution of central and peripheral fatigue mechanisms has yet to be determined[444]. Certain limitations have been identified relating to endurance exercise and the peripheral model of fatigue. For example, an exclusively peripheral model of fatigue cannot explain how muscle fatigue may develop during prolonged voluntary exercise when motor unit recruitment is never maximal[235;608]. In addition, the peripheral model of fatigue also fails to provide an explanation for the observed increase in exercise intensity towards the end of a competitive event, exactly when metabolic accumulation or depletion should result in a reduction in exercise intensity[479].

Noakes et al[481] postulated that during self-paced exercise, the central nervous system continuously modifies the pace by altering skeletal muscle recruitment through a complex non-linear dynamic model. The central nervous system therefore regulates skeletal muscle recruitment, preventing absolute fatigue or “catastrophe”. In support of this theory, Kay et al[331] demonstrated that, during a 30-minute time trial in the heat, there is an initial decline in neuromuscular activity and power output. However, subsequent increases in both neuromuscular activity and power output were observed as subjects approached the known endpoint of the time trial. In addition, St Clair Gibson et al[610] showed that, during a 100 km cycle time trial, only approximately 20% of the available motor units were recruited at any point during the time trial.

It is theorised that central fatigue may develop during prolonged exercise[177;479], and that metabolic and structural changes may be involved in muscle fatigue following endurance exercise[369;502]. Metabolic activity in the active skeletal muscle could partially control motor unit recruitment through afferent feedback to the central nervous system. Lambert et al[378] reviewed the possible peripheral regulation of metabolic activity within central regulatory centres, and proposed an integrated model of fatigue regulated by a homeostat.

Further, Ulmer[647] proposed a complex teleoanticipatory model of fatigue. It was theorised that central efferent signals are sent to the active skeletal muscles, thereby determining exercise intensity and force output. The feed-forward mechanism described in this model includes previous experience, environmental conditions, training status, muscle reserve, and metabolic status.

It may therefore be theorised that both central and peripheral factors contribute to the development of fatigue[444;479]. There may be a constant feedback loop between central and peripheral factors during prolonged or fatiguing exercise, thereby providing a direct link between intramuscular metabolism and central motor drive[333].

5.4 STRETCH SHORTENING CYCLE FATIGUE

Fatigue has been extensively examined in isolated forms of isometric, shortening or lengthening muscle actions. From a structural perspective, fatigue during stretch shortening cycle exercise corresponds to that observed after fatiguing eccentric exercise. Functionally however, stretch shortening cycle fatigue appears to be more complex[350;617].

Due to the important lengthening phase of the stretch shortening cycle, it is evident that fatiguing stretch shortening cycle exercise may be associated with structural muscle damage and associated delayed onset muscle soreness[350;351]. Kyröläinen et al[370] demonstrated acute elevations in the levels of serum creatine kinase, carbonic anhydrase III and serum myoglobin following a series of repetitive and strenuous stretch shortening cycle exercises performed by power- and endurance-trained athletes. However, in comparison to the pure eccentric loading used in many studies investigating exercise-induced muscle damage, the lengthening phase of the stretch shortening usually takes place quite rapidly, with a relatively high initial stretch velocity.

Consequently, as an example, submaximal hopping may load the triceps surae muscle up to two times more than maximal squatting jumps[349]. Thus, the relative contribution of the reflex loops is of importance in the stretch shortening cycle, where stretching loads are high, and muscle stiffness must be well regulated to meet the external loading conditions. This is the main reason for stretch shortening cycle exercise, with the high velocity and short duration lengthening phase, having more functional consequences than isolated eccentric exercise[351].

A special sledge apparatus with a force plate has been used to induce stretch shortening cycle fatigue in many studies. Gollhofer et al[245;246] used the apparatus to perform fatiguing arm exercises. Fatigue during submaximal stretch shortening cycle exercise was characterised by reductions in movement efficiency and maximal isometric force, and increasing contact times in both the lengthening and shortening phases of the stretch shortening cycle. The force-time curves were also influenced by fatigue, with the initial force peak becoming higher, and the subsequent drop in force becoming more pronounced towards the end of the exercise bout. Therefore, as the muscles became progressively more fatigued, the reflex contribution to sustain the repeated stretch loads was enhanced[245;246;350].

In a non-fatigued state, the muscles were able to dampen the impact in the stretch shortening cycle by a smooth increase in force, and by a smooth joint motion. However, repeated dampening (eccentric) actions followed by shortening actions may have become so fatiguing that the neuromuscular system changed its "stiffness" regulation. This change was characterised especially by a high impact force peak followed by a temporary decline in force. The stretch reflex contribution during fatigue could be interpreted as an attempt by the nervous system to compensate, by increasing activation, for the loss of the muscles contractile force to resist impact loads[245;246;350].

In a similar study, Horita et al[293] performed repeated submaximal leg stretch shortening cycle exercise to fatigue. The results indicated a possible coupling between the performance reduction in the stretch shortening cycle and the inflammatory process resulting from muscle damage. In addition, knee joint stiffness changes were related to changes in short-latency reflex components. It was concluded that an immediate reduction and delayed recovery of the stretch reflex loop sensitivity occurs after exhaustive stretch shortening cycle exercise. These results are therefore contrary to the findings of Gollhofer et al[246].

It was proposed that the neuromuscular system may adapt differently, according to the fatigue levels, and to the imposed demands[472]. The reductions in the stretch reflex loop sensitivity may have been due to either a reduction of the excitatory input from the muscle spindles[400], or to an increased inhibition originating from the sensitisation of small-diameter muscle afferents[237].

Effects on the neuromuscular function have also been reported in less intensive, but long-lasting stretch shortening cycle exercise, for example, marathon running[474-476]. These studies confirm the observations of laboratory tests which show that the ground reaction force curves, both during running and in special drop jump tests, imply reduced tolerance to stretch loads, as well as loss in the recoil characteristics of the muscles[350].

Nicol et al[476] demonstrated that the loss in maximal force of the quadriceps muscle group was accompanied by a clear decline in the ability to maintain a 60% submaximal isometric level of force during a fatigue test. The EMG analysis revealed a large decrease in maximal activity, as well as the need for an initial increase of the neural activation at a submaximal force level, suggesting a decline in muscle function. The results support previous observations that various modifications of the neural activation may take place to compensate for the exercise-induced contractile fatigue[476]. Gollhofer et al[245;246] proposed that the results indicate a facilitation of force production at submaximal levels, and an inhibition of force production at maximal levels.

Similar reductions in force production have been reported during long duration skiing[355;444], and long[475;476] and short[494;505;506] duration running. Millet et al[445] also reported a reduction in maximal voluntary activation resulting in a reduction in maximal force production of the knee extensor and ankle plantarflexor muscles following a 65 km ultramarathon race.

In addition, pre- and post-marathon comparison of the ground reaction force-time curves revealed a drop in the vertical force after the impact peak, with a concomitant increase in ground contact time[246;475;476]. Ground contact was also made with a more extended leg, with a subsequent greater degree of knee flexion during stance phase. The natural consequence of these alterations in the gait pattern would be a longer push-off phase[293;475;476].

Two primary mechanisms have been proposed to explain the reduction in muscle function following fatiguing stretch shortening cycle exercise. Firstly, the failure of maximal muscle functioning may be due to impaired peripheral mechanisms[219]. Secondly, as indicated by the reduction in EMG activity, there may be a decrease in the neural input to the muscle, which may indicate impaired central mechanisms[29;30;235;479] that may include supraspinal fatigue[77;235], peripheral inhibition[236;237], and disfacilitation of the alpha-motorneurone pool[60].

5.4.1 PERIPHERAL MECHANISMS

Gollhofer et al[246] and Viitasalo and Komi[649] proposed that the reduced contractile characteristics of muscle may be associated with a reduction in calcium transport following fatiguing stretch shortening cycle exercise. An inability to sustain calcium release from the sarcoplasmic reticulum would result in lower activation levels, while a reduction in the time taken to remove calcium from the cytosol would prolong the dissociation of actin and myosin, and reduce the relaxation of the muscle during the recovery phase[5;625].

Furthermore, a reduction in calcium transport may be associated with an accumulation of hydrogen ions, as there is evidence to suggest that the sarcoplasmic reticulum binds more calcium with an increase in muscle acidity[14;246;437;625;633]. As the pH is reduced, there is an increased requirement of calcium to produce tension. In addition, the increased hydrogen concentration may reduce the effect of calcium on troponin[507], and may therefore directly impact on the contractile process[625].

Strojnik and Komi[617] investigated the fatigue response to maximal stretch shortening cycle exercise using maximal drop jumps on an inclined sledge apparatus, and observed a reduction in force production following the exercise bout. It was proposed that the reduction in force was associated with impairments in contractile mechanics that may include a decrease in calcium release from the sarcoplasmic reticulum, and a reduction in strong binding of cross-bridges[617]. Alterations in calcium regulation and calcium sensitivity have been related to changes in the contractile function of the actin and myosin components[437;507;617;625].

5.4.2 CENTRAL MECHANISMS

During and after fatiguing stretch shortening cycle exercise, neural adaptations or failure may affect the activation pathways at different levels. These potential sites include excitatory input to supraspinal motor centres, excitatory drive to alpha-motorneurones, modulation of interneuronal circuits, motorneurone excitability, peripheral reflex activity from small diameter afferents, and muscle spindle activity[51;393]. If these neural adaptations lead to a reduction in neural drive, the development of central fatigue exists. The relative contribution of central and reflex neural adjustments to stretch shortening cycle fatigue may vary, and appears to be task-dependent[472].

These neural adaptations are thought to compensate for the contractile failure[245], enhance the neural drive in proportion to the contractile failure[52], and induce contractile failure with inadequate neural drive[234]. Alterations in motor unit activation, stretch reflexes, and stiffness regulation have also been shown to contribute to the decline in force production associated with stretch shortening cycle fatigue[351]. Although the relationship between force-generating capacity and limitations in neural drive is not well understood, it is theorised that, in a fatiguing exercise where muscle damage has occurred, inadequate neural drive may be an attempt of the neuromuscular system to protect the musculotendinous unit from further damage[552;618].

In support of this theory, Nicol et al[476] demonstrated a 26% reduction in maximal torque production with a 36% reduction in EMG activity during a maximal voluntary contraction after a marathon race. It was proposed that the progressive reduction in motor unit activation during contractions at high force levels may be a protective mechanism to minimise fatigue by avoiding neuromuscular transmission failure[203;232;235]. Viitasalo and Komi[649] reported similar reductions in maximal force, reflex and voluntary reaction time, and EMG mean power frequency following 100 maximal isometric leg extensions. These findings provide evidence to suggest that a reduction in neural input contributes to the loss of maximal force production following intense stretch shortening cycle exercise[245].

Stretch shortening cycle fatigue may also be associated with changes in centrally mediated preactivation[29;245;460;494]. A reduction in muscle preactivation and inadequate neural drive to the muscle may be related to a decline in the efficiency of contractile mechanisms[29;245;246;460]. This results in longer ground contact times, and reductions in ground reaction forces. The transition time between the lengthening and shortening phases of the stretch shortening cycle therefore increases, indicating a decrease in the ability to store and utilise elastic energy, thereby decreasing mechanical efficiency[67;112].

In addition, it has also been proposed that alterations in stiffness regulation may also be associated with the reduction in muscle force and power production during and after fatiguing exercise[29]. Avela et al[29] determined the effects of a marathon on neuromuscular function in endurance runners. Neuromuscular function was assessed before and after the marathon during maximal stretch shortening cycle exercises using a sledge ergometer. Marathon running resulted in a significant reduction in the ability to perform maximal stretch shortening cycle exercise. There were significant reductions in average eccentric and concentric forces, take-off velocity, muscle stiffness, and EMG activity of the vastus medialis and soleus muscles. The reduction in EMG activity was more pronounced in the preactivation and lengthening phases of the stretch shortening cycle, compared to the shortening phase. Stretch reflex sensitivity was also significantly decreased after the marathon.

Several mechanisms were proposed to explain the reduction in muscle function following the marathon. The reduction in neural input may be due to the occurrence of central fatigue, supraspinal fatigue, peripheral inhibition, disfacilitation of the alpha-motorneurone pool, or impairment of peripheral mechanisms. In addition, the reduced stretch reflex sensitivity was associated with decreased muscle stiffness. It was theorised that the reduced muscle stiffness may be related to the reduction in muscle function, leading to an impaired utilisation of elastic energy[29;32].

Furthermore, Avela et al[31] observed acute reductions in the stretch-resisting force of the triceps surae muscle following long-lasting stretch shortening cycle exercise. Avela et al[27] also determined reductions in stretch reflex peak-to-peak amplitude and H-reflex after repeated passive muscle stretching of a one-hour duration.

These findings suggest that increased compliance of the muscle may be associated with a reduced mechanical response of the muscle spindle, leading to a reduction in Ia-afferent activity, and ultimately to disfacilitation of the alpha-motorneurone pool. The secondary decline of performance following stretch shortening cycle fatigue may also be related to prolonged activation of group III and IV muscle afferents by the inflammatory process associated with exercise-induced muscle damage. These small muscle afferents may have an important role in presynaptic inhibition, leading to a subsequent reduction in the stretch reflex response. However, this theory requires further investigation in relation to human locomotion[472].

Moreover, Komi[351] proposed that repetitive impact loading may be associated with a reduction in the ability of the leg extensor muscles to sustain impact loads. As the enhancement of the stretch shortening cycle depends on the ability to tolerate and utilise stretch loads, a reduction in the capacity to tolerate impact forces may negatively influence endurance performance.

In summary, the relative contribution of peripheral and central mechanisms to stretch shortening cycle fatigue during and following endurance exercise remains unclear. In addition to the neuromuscular adaptations associated with fatigue, it may be proposed that the reductions in performance capacity may also be related to exercise-induced muscle damage[444;472]. Further studies should examine the complex relationship between stretch shortening cycle fatigue and exercise-induced muscle damage.

5.4.3 RECOVERY FROM STRETCH SHORTENING CYCLE FATIGUE

The recovery from stretch shortening cycle fatigue is a delayed process, follows a bimodal pattern, and occurs in parallel with the recovery of maximal EMG activation and maximal force[28;216;294;351;472;473].

The bimodal pattern of recovery is characterised by a dramatic reduction in performance immediately after exercise. This initial decline in performance is followed by a short-duration recovery, and a subsequent secondary reduction in performance[294;351;401;472]. The second performance decrement usually peaks between 48 and 72 hours after the fatiguing exercise bout[28;30;111;294;473;475].

The immediate reduction in performance may be related to mechanical injury, specifically myofibrillar disruptions[216;402], or metabolic disturbances[216]. The secondary decline in performance may be associated with inflammatory responses related to exercise-induced muscle damage[216;351].

In addition, sensitivity of the stretch reflex to passive perturbation is also reduced during and after fatiguing stretch shortening cycle exercise[28;30;293;473]. The recovery follows a bimodal pattern, and occurs in parallel with mechanical parameters. These findings infer that stiffness regulation mechanisms may require an extended recovery period following fatiguing stretch shortening cycle exercise and exercise-induced muscle damage before returning to optimal function[29;30].

5.5 THE EFFECTS OF EXERCISE-INDUCED MUSCLE DAMAGE ON MUSCLE PREACTIVATION AND STIFFNESS REGULATION

Prolonged and intense stretch shortening cycle exercise usually results in reversible neural, structural, and mechanical disturbances, the severity and duration of which are dependent on the nature of the stretch shortening cycle exercise[472]. Exercise-induced muscle damage following intense or repetitive stretch shortening exercise is associated with prolonged reductions in maximal force and EMG activity, ground reaction forces, stretch reflex sensitivity, muscle and joint stiffness regulation, and vertical jump performance[32;294;475;476]. In addition, structural damage has been observed following marathon running[120;284;372;592;609;656], indicating that there may also be potential impairments in muscle fibre function[476], and contractile elements associated with muscle damage[13;15;36;46;58;96;137;202;205;231;384;468;476].

Horita et al[293] determined that stiffness regulation in the knee joint during drop jumps was significantly impaired following repetitive stretch shortening cycle exercise. It was proposed that myofibrillar disruption and connective tissue injury may be the underlying mechanisms affecting the stiffness regulation of the musculotendinous complex[294].

Horita et al[294] also demonstrated significant reductions in preactivation of the vastus lateralis muscle during drop jumps immediately after fatiguing stretch shortening cycle exercise. Further reductions in preactivation were observed two and four days post-exercise. These findings suggest the presence of a neural compensatory mechanism, to protect the muscle from further damage. It was theorised that mechanical behaviour may be influenced by modified motor control, pre-landing, in response to exercise-induced muscle damage.

Nicol et al[475;476] demonstrated changes in neuromuscular function after a marathon race that included reductions in maximal isometric knee extension torque, maximal integrated electromyographic activity (iEMG) of the vastus lateralis and vastus medialis, and drop jump performance. Avela et al[29;32] determined that marathon running resulted in significant reductions in average eccentric and concentric forces, take-off velocity, and EMG activity of the vastus medialis and soleus muscles. The reduction in EMG activity was more pronounced in the preactivation and lengthening phases of the stretch shortening cycle, compared to the shortening phase. Stretch reflex sensitivity was also significantly decreased after the marathon.

Several mechanisms were proposed to explain the reduction in muscle function following the marathon. The reduction in neural input may be due to the occurrence of central fatigue, supraspinal fatigue, peripheral inhibition, disfacilitation of the alpha-motorneurone pool, or impairment of peripheral mechanisms. In addition, the reduced stretch reflex sensitivity was associated with decreased muscle stiffness. It was theorised that the reduced muscle stiffness may be related to the reduction in muscle function, leading to an impaired utilisation of elastic energy[29;32].

In addition, a reduction in neuromuscular efficiency of the knee extensors, exhibited as a decrease in the force: iEMG activity ratio, has also been observed following eccentric exercise[98;183;356]. Impairments in proprioception have also recently been observed after exercise-induced muscle damage[439;576]. These studies collectively demonstrate that the force-generating capacity of muscle and motor control may be affected by a damaging bout of eccentric exercise[98].

Conversely, some studies have observed no changes in EMG activity following eccentric exercise that resulted in muscle damage, suggesting that normal motor unit activation may be maintained, despite symptoms of exercise-induced muscle damage[46;427].

Further, Saxton and Donnelly[577] demonstrated that strength loss following eccentric exercise was unaffected by superimposing supramaximal stimulation during maximal voluntary isometric exercise.

Komi[351] proposed two hypotheses to explain the reduction in stretch shortening cycle performance associated with exercise-induced muscle damage. Firstly, as a consequence of exercise-induced muscle damage, there may be a reduction in stretch reflex sensitivity, resulting in disturbances in the stiffness regulatory mechanisms, leading to a reduction in the efficiency of the stretch shortening cycle. Secondly, as a result of the decline in muscle function associated with exercise-induced muscle damage, there may be reductions in the tolerance for high impact loads, muscle preactivation, and the elastic energy potential. The combined effect of these alterations results in an increase in the work required during the shortening phase of the stretch shortening cycle, thereby leading to a reduction in the efficiency of the stretch shortening cycle.

Alternatively, there is evidence to support the existence of neural compensatory mechanisms during and after lengthening muscle actions. Hortobágyi et al[296;298] demonstrated that the decline in muscle force following voluntary exercise was attenuated after lengthening muscle actions, compared to shortening or isometric muscle actions.

Furthermore, Chambers et al[120] investigated the effects of a 90 km ultramarathon on the vertical jump performance with (drop jump and counter-movement jump) and without (squat jump) the activation of the stretch shortening cycle. The runners performed the vertical jump tests before the race, immediately after the race, daily for five days after the race and thereafter, weekly for a further four weeks after the race. Vertical jump performance was significantly reduced immediately after the ultramarathon race, both with and without the use of the stretch shortening cycle. Drop jump, counter-movement jump, and squat jump heights were significantly reduced for 3, 11, and 18 days after the ultramarathon respectively, when compared to pre-race values.

These results suggest that the stretch shortening cycle may possibly attenuate the decrement in performance associated with exercise-induced muscle damage[98]. However, further studies are required to investigate potential neural compensatory mechanisms associated with exercise-induced muscle damage, and to determine the role of muscle preactivation following damaging stretch shortening cycle exercise.

5.6 THE EFFECTS OF TRAINING ON MUSCLE PREACTIVATION AND STIFFNESS REGULATION

Endurance training may be associated with neuromuscular adaptations that include an increased recruitment of muscle fibres and therefore a large, active muscle mass[272]. Noakes[480] proposed that improved performance following endurance training may be related to an increased ability of the brain to recruit a larger muscle mass for extended periods[260;262]. These training-induced neural adaptations may account for increased force and power production within the first eight weeks of training[260;674].

In addition, Paavolainen et al[505] demonstrated that the capacity of individual cross-bridges to generate force is closely related to running performance. Noakes[480] theorised that regular endurance training may facilitate changes in muscle cross-bridge activity. Alterations in muscle cross-bridge activity may also positively influence running economy[582], and may therefore improve running performance.

Häkkinen et al[259] examined the effects of a combined strength and endurance training, compared to a strength training programme alone on functional and structural neuromuscular adaptations. Both groups demonstrated similar improvements in the one-repetition maximum load, maximum isometric force, maximum integrated electromyographic activity of the vastus lateralis muscle, cross-sectional area of the quadriceps femoris muscle group, and mean fibre areas of type I, IIa and IIb muscle fibres. However, an improvement in the rate of force development only occurred in the strength training group. It was theorised that improved power development may be partially mediated by more rapid voluntary neural activation of the trained muscles.

Saunders et al[569] observed the effects of endurance training in cyclists. Endurance training was associated with a reduction in quadriceps muscle activity, potentially due to the decreased oxygen demand of a bout of high-intensity submaximal exercise. However, the underlying mechanism for the attenuation of end-exercise muscle activity is unclear.

It was proposed that the training-induced increase in muscle mitochondrial content and oxidative capacity may be associated with a decreased reliance on anaerobic energy supply, which therefore extends the time to fatigue of the muscle fibres. Subsequently, less additional muscle fibres will be recruited to replace the fatigued fibres, therefore decreasing the end-exercise active muscle and oxygen consumption[569].

Moreover, Widrick et al[673] compared the force-velocity and power-velocity properties of single muscle fibres between endurance-trained and sedentary subjects. The endurance-trained group showed significant reductions in type I and type IIa muscle fibre diameter, single fibre peak power output, and absolute force production, compared to the control group. The endurance-trained group also had significantly higher maximum shortening velocities, compared to the control group. It was proposed that, although the ability to produce force was reduced in the endurance-trained group, the increased shortening velocity enabled the muscle fibres to maintain a higher level of force production. Thus, there was an increased relative contribution of type I muscle fibres to the total power output, and a decreased reliance on the more fatigable type IIa muscle fibres[673].

Noakes[480] hypothesised that runners with poor economy may have muscles with a reduced ability to utilise the impact energy produced as they absorb the force of landing. The relative stiffness of the musculotendinous system may be associated with the ability to store and utilise elastic energy[680].

Explosive-strength or plyometric training induces neuromuscular adaptations that may facilitate improvements in running economy. Plyometric training enhances the muscles' ability to generate power by stimulating the stretch shortening cycle with activities such as jumping, hopping, and bounding[645].

The proposed adaptations to plyometric training include increased activation of motor units with less muscle hypertrophy than resistance training[261], increased stiffness of the musculotendinous system[606], and modifications of the contractile component, the series elastic component, and the parallel elastic component[153].

Spurrs et al[606] examined changes in performance following a six-week plyometric training programme performed in conjunction with normal running training in moderately trained male runners. The experimental group showed significant improvements in running economy of between 4.1% and 6.7% following the plyometric training programme. The experimental group also showed a 2.7% improvement in 3 km running performance, and improved muscle-tendon stiffness and the rate of force development following the training programme. However, this result may have been different had the runners been better trained.

Paavolainen et al[503] investigated the effects of a nine-week plyometric and endurance training programme in male cross-country runners. Neuromuscular characteristics were evaluated using a 20 m sprint test, and a five-jump test. The experimental group demonstrated a 2.8% improvement in 5 km running performance, a 7.8% improvement in running economy, and improved neuromuscular characteristics. No significant changes were measured in the control group. It was theorised that plyometric training may induce alterations in motor control that would enable a muscle to resist an imposed stretch more efficiently, and therefore result in an increased accumulation of elastic energy by the musculotendinous complex.

Furthermore, Viitasalo et al[650] determined that athletes with specific jump training have increased muscle preactivation earlier before landing, compared to an untrained control group. The neuromuscular system of the jumping athletes was also more able to resist high muscle lengthening and ground reaction forces, demonstrated by increased force production in the propulsion phase, and increased vertical jump height. Similarly, Kryöläinen et al[368] and Kryöläinen and Komi[366] demonstrated that specific stretch shortening cycle training may be associated with improvements in mechanical efficiency, and the rate of EMG development during the preactivation phase of the stretch shortening cycle.

5.7 SUMMARY OF THE LITERATURE

The functioning of the stretch shortening cycle is thus an important consideration for endurance running performance. The effective storage and release of elastic energy during exercise involving the stretch shortening cycle contributes to force production and mechanical efficiency during running[19;70;201;311;632].

It is evident that muscle preactivation has an essential role in enhancing the efficiency of the stretch shortening cycle, and in attenuating high impact forces on landing during running. However, in the presence of neuromuscular fatigue, the regulation of muscle stiffness and impact loading may be altered. As a result, neuromuscular characteristics are well regulated by the central nervous system to protect skeletal muscle from chronic overuse damage and injury. These characteristics may also be modified through training interventions that may improve muscle stiffness and mechanical efficiency, through the effective utilisation of stored elastic energy during the muscle lengthening phase of the stretch shortening cycle[351;472].

Although it has been established that neuromuscular function is disturbed for 11 days after an ultramarathon[120], little is known regarding the relationship between neuromuscular fatigue, exercise-induced muscle damage, and running performance, particularly in the recovery period following endurance running[351;472;524]. In addition, relatively few studies have investigated the response of direct measurements of endurance performance, such as time to exhaustion at a fixed workload or time trial performance, to exercise-induced muscle damage[412].

Therefore, the aim of the next study was to determine the effects of exercise-induced muscle damage and fatigue, induced by an ultramarathon, on neural regulation and running performance in experienced ultramarathon runners.

CHAPTER SIX
STUDY THREE: CHANGES IN MUSCLE PREACTIVATION AND EXERCISE PERFORMANCE AFTER A 90 KM ULTRAMARATHON

6.1 INTRODUCTION

Traditionally, a reduction in oxygen consumption during running at a specific submaximal velocity is thought to be associated with an improvement in running economy, and running performance[146;166;480;582;591]. The results of the previous studies (Chapter 3 and Chapter 4) have shown reductions in submaximal oxygen consumption for up to 28 days after an ultramarathon race. This is a seemingly paradoxical finding as anecdotal evidence suggests that running performance would have been impaired during the recovery period after the race. However, the relative contribution of peripheral and central mechanisms to stretch shortening cycle fatigue during and following endurance exercise remains unclear. In addition, the potential role of the central nervous system in skeletal muscle recruitment[481], and the neuromuscular characteristics that are also related to running performance[505;506] may influence the relationship between running economy and performance, particularly in the presence of muscle damage and fatigue after an endurance event. It follows that this is an area that requires further investigation.

The functioning of the stretch shortening cycle is an important consideration for endurance running performance. The effective storage and release of elastic energy during exercise involving the stretch shortening cycle contributes to force production and mechanical efficiency during running[19;70;201;311;632], and may positively influence running economy. The efficiency of the stretch shortening cycle is related to muscle preactivation. Muscle preactivation is a centrally regulated, feed-forward, anticipatory mechanism[25;186;245-247;297;460] that is initiated in the brain[387]. During running, muscle preactivation is observed in the 100 ms period before heelstrike[506], and functions to prepare the lower limb for ground contact by regulating muscle stiffness.

The stiffness characteristics of the muscle influence the shock absorption during landing[4;25;33;186;245;247;436]. In addition, muscle preactivation regulates the transition time between the prestretch and shortening component of the stretch shortening cycle, and is therefore important in ensuring effective utilisation of elastic energy[247]. Therefore, a decrease in muscle preactivation may result in alterations in stiffness regulation and shock absorption, which may lead to a reduction in force production[32;295], and a decrease in mechanical efficiency[505].

Although it has been shown that reduced muscle preactivation is a sensitive indicator of muscle fatigue[505;506;584], the complex relationship between muscle damage, fatigue, and preactivation is not well understood. Chambers et al[120] showed that the decrement in vertical jump performance following an ultramarathon was attenuated in movements that utilised the stretch shortening cycle and muscle preactivation, indicating a potential adaptation in neuromuscular function. This raises the question of whether altered muscle preactivation may possibly moderate the decrement in stretch shortening cycle function that is associated with exercise-induced muscle damage[98].

Furthermore, numerous physiological findings suggest that endurance performance will decrease following exercise-induced muscle damage. However, relatively few studies on exercise-induced muscle damage have investigated the response of direct measurements of endurance performance, such as time to exhaustion at a fixed workload or time trial performance[412].

Therefore, the aim of this study was to investigate the effects of exercise-induced muscle damage and fatigue, induced by an ultramarathon, on muscle preactivation and running performance in experienced ultramarathon runners.

Based on the results of Chapter 3 and Chapter 4, all tests after the ultramarathon race were conducted nine to 11 days later, to coincide with the time when the runners had expected reduced submaximal oxygen consumption, and in the absence of muscle pain and elevated plasma CK activity.

6.2 METHODS

6.2.1 SUBJECTS AND STUDY DESIGN

Twenty-three experienced endurance runners, similar to those recruited for the first study (Chapter 3, Section 3.2.1, page 114), were selected to participate in this study, which had a quasi-experimental design.

A schematic diagram of the research design is shown in Figure 6.1. Due to the duration of the testing procedures for the familiarisation, maximal test, and track test, it was not possible to test all subjects on a single day. These tests were therefore conducted over a three-day period. The time stamps for the familiarisation, maximal test, and track tests shown in Figure 6.1 reflect the midpoint of each testing period respectively. In addition, based on the data from the previous studies (Chapter 3 and Chapter 4), the track test was conducted between days 9 to 11 following the ultramarathon race. This testing period was referred to as day 10 in the following sections.

Eleven runners, who participated in the Comrades marathon, were assigned to the experimental group. Twelve runners, who did not participate in the Comrades marathon, formed the control group. The study was granted ethical clearance by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town.

The subjects were requested to avoid any medication, and strenuous training and racing, other than the ultramarathon race, for the duration of the study (± 32 days). Subjects were instructed to maintain the same diet and training regimen for 24 hours prior to testing. To facilitate adherence with instructions, subjects completed a training logbook for the duration of the study. In addition, subjects were questioned about their compliance with instructions prior to each laboratory test. Testing occurred at a similar time (to within one hour) for each subject for the duration of the study.

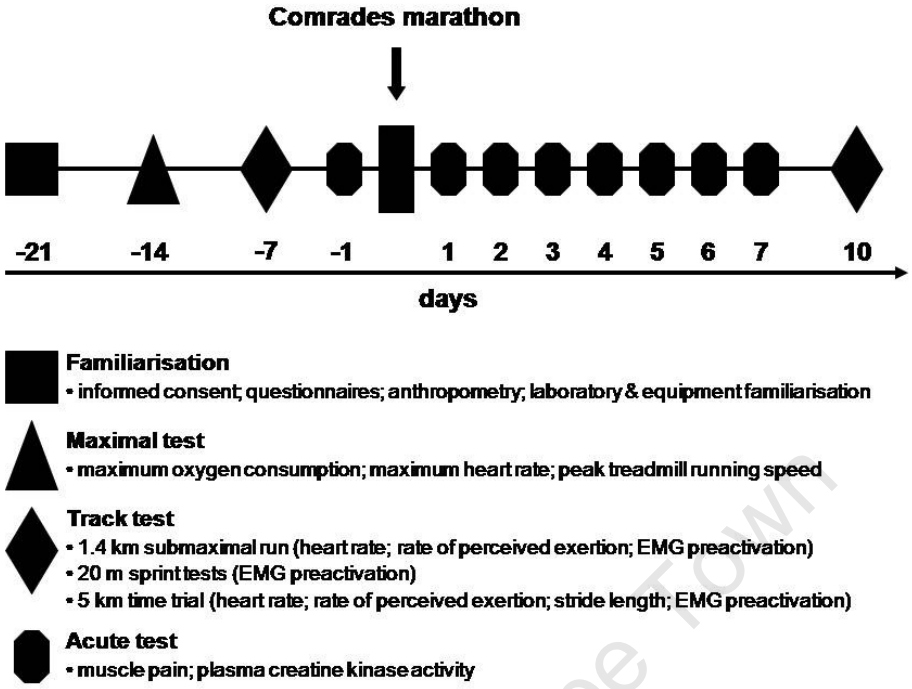

Figure 6.1: *Study design.*

6.2.2 FAMILIARISATION

During the first visit to the laboratory, 3 weeks before the ultramarathon race, subjects gave written consent after being informed about the demands of the study. The subjects completed questionnaires, and underwent an anthropometrical assessment, as described in Chapter 3 (Section 3.2.2, page 116).

The subjects were also familiarised with the laboratory equipment and testing protocols that would be used during the trial. This familiarisation process was conducted to reduce error associated with subjects performing unaccustomed exercise.

6.2.3 MAXIMAL TEST

Preliminary testing was conducted on all subjects two weeks before the ultramarathon race. A maximal treadmill test, as described in Chapter 3 (Section 3.2.2, page 116) was performed to determine maximum oxygen consumption (VO_{2max}), peak treadmill running speed (PTRS), and maximum heart rate (HR_{max}).

6.2.4 TRACK TEST

The track test was conducted seven days before the ultramarathon race, and was repeated 10 days after the ultramarathon race. The track test included a 1.4 km submaximal run, 20 m sprint tests, a 5 km time trial run, and the measurement of muscle pain and plasma CK activity.

6.2.4.1 1.4 km submaximal run

Subjects performed a 1.4 km submaximal run around an indoor tartan track at 70% of peak treadmill running speed. The circumference of the indoor track was 140 m. A light pacing system was used to pace the subjects for 10 laps at a submaximal velocity equivalent to 70% of the individual peak treadmill running speed. The light pacing system was custom-built by the Department of Human Biology, University of Cape Town. The rate of perceived exertion (RPE), heart rate, surface electromyographic (EMG) activity, and 20 m running time were recorded during laps 6 (840 m), 8 (1120 m), and 10 (1400 m) of the submaximal run.

The 20 m running time was recorded using two single-beam photocell gates connected to an electronic timer (Newtest Ltd., Oulu, Finland). The photocell gates were placed 20 m apart over a straight section of the indoor track, to prevent any abnormal gait patterns that could occur from running over the corner stretch of the track. Electromyographic activity was recorded over 20 m between the photocell gates. Electromyographic activity recordings were manually synchronised with the timing gates. An investigator was positioned at the first timing gate, and the EMG recordings were commenced as subjects crossed the 0 m line at the start of the 20 m section. The rate of perceived exertion and heart rate were recorded at 840 m, 1120 m, and 1140 m splits during the submaximal run.

6.2.4.2 20 m sprint tests

A 10-minute rest period separated the submaximal run and the sprint tests. Subjects performed three 20 m sprint tests on the indoor running track prior to the 5 km time trial. Subjects were required to sprint at 130% of peak treadmill running speed. A constant velocity over the 20 m sprint test was achieved using the light pacing system that was set at a maximal velocity equivalent to 130% of the individual peak treadmill running speed. Subjects were given a running start of 60 m to ensure a normal and maximal running gait through the 20 m, and to exclude gait changes associated with acceleration during the sprint. Each 20 m sprint was separated by a brief recovery period, during which subjects returned to the start of the sprint course. The 20 m running time was recorded using two single-beam photocell gates connected to an electronic timer (Newtest Ltd., Oulu, Finland).

The photocell gates were placed 20 m apart over a straight section of the indoor track. Electromyographic activity was recorded over 20 m between the photocell gates. The pre- 5 km time trial sprint test data were averaged, and represented the non-fatigued pre- 5 km time trial values. In addition, during the final lap of the 5 km time trial subjects were required to repeat the 20 m sprint test, to determine fatigued sprint performance. This represented the post- 5 km time trial sprint value. Subjects were required to sprint the final lap of the 5 km time trial at 130% of peak treadmill running speed. Constant velocity during the sprint was again controlled using the light pacing system.

6.2.4.3 5 km time trial

A 10-minute rest period separated the sprint tests and the 5 km time trial. Subjects performed a 5 km time trial on the 140 m indoor track. Subjects were instructed to run “as fast as possible”, and were provided with standardised verbal encouragement during the run. Subjects were provided with split times and distance covered at every kilometer.

Subjects were required to indicate their rate of perceived exertion, using a modified Borg scale[423] at every kilometer split. Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at five-second intervals throughout the 5 km time trial.

Electromyographic activity and 20 m running time were recorded during the final lap of kilometer one to four of the 5 km time trial. Electromyographic activity and 20 m running time for kilometer five were recorded during the second last lap of the fifth kilometer split (4860 m), as the final lap of the 5 km time trial was the post- time trial sprint. The 20 m running time was recorded using two photocell gates connected to an electronic timer (Newtest Ltd., Oulu, Finland). Electromyographic activity was recorded over 20 m between the photocell gates. Stride length was calculated using successive heelstrike data (ground contact times) to determine cadence, and running speed ($m.min^{-1}$) over 20 m. Stride length was derived according to the following calculation:

$$\textit{Stride length} = \frac{\textit{running velocity}}{\textit{cadence}} \times 2$$

6.2.4.4 Muscle pain

Muscle pain was assessed before the 1.4 km submaximal run. Muscle pain was assessed subjectively using a multidimensional visual analogue pain scale. Subjects were required to rate the pain in the quadriceps, hamstrings, and gastrocnemius muscles according to "*general pain at rest*", "*pain during activities of daily living*", "*pain during a passive stretch*", and "*pain when pressure was applied to the mid-belly of the muscle*". For pressure pain, digital pressure was applied to the mid-belly of the muscle until moderate tissue resistance was felt. Subjects were required to rate the pain in each of the aforementioned categories for each muscle by drawing a vertical line on a 10 cm pain rating scale, where 0 cm represents "*no pain*", and 10 cm represents "*maximal pain*". The distance along the pain rating scale to the vertical line drawn by the subject was measured in millimetres (mm), and the pain score for each condition was recorded.

Muscle pain was measured using a different method of assessment compared to the previous studies (Chapter 3 and Chapter 4). The reason for changing the assessment technique was because no significant differences have been reported between pain measurements using uni-dimensional pain scales, such as the visual analogue scale for pain (VAS) used in the previous studies, and multidimensional pain scales[139].

However, Cleather et al[139] established that multidimensional pain scales provide a clearer description of delayed onset muscle soreness, and may assist in distinguishing the pain associated with delayed onset muscle soreness from other sources of pain.

6.2.4.5 Plasma creatine kinase activity

A 5 ml blood sample was taken from the subject's antecubital vein before the 1.4 km submaximal run for the analysis of plasma CK activity. The methods of blood sampling and storage, and the analysis of plasma CK activity have been previously described in Chapter 3 (Section 3.2.3, page 117).

6.2.4.6 Electromyographic (EMG) activity measurements

In preparation for EMG measurement the hair on the subject's right leg was removed by shaving the sites of electrode placement with a disposable razor. The outer layer of epidermal cells was then removed with industrial sand paper, and finally all dirt and oil was removed from the site using alcohol swabs. The electrode positions were standardised and positioned longitudinally on the belly of the vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), and medial gastrocnemius (MG) muscles. The ground electrode was positioned over the tibial tuberosity of the right lower limb. Each subject was fitted with bipolar EMG electrodes (Blue sensor, Ambu skin electrodes SP-00-S, Medicotest A/S, Denmark). Electrodes were secured using 50 mm Elastoplast adhesive tape. All EMG data were amplified and recorded telemetrically (Noraxon, Telemyo, Scottsdale, Arizona, USA). Electromyographic activity was recorded during the 1.4 km submaximal run, the 20 m sprint tests, and the 5 km time trial run.

6.2.4.7 Accelerometer placement

A dual axis accelerometer (MMA6233Q, Freescale Semiconductor Incorporated, Chandler, Arizona, USA) was placed on the dorsal surface of the right foot at the 3rd metatarsophalangeal joint. The accelerometer was secured to the right shoe using 50 mm Elastoplast adhesive tape. Data from the accelerometer were recorded simultaneously with the EMG signals (Noraxon, Telemyo, Scottsdale, Arizona, USA).

The accelerometer was used to determine the period of preactivation (100 ms before heelstrike)[506] during running. A pilot study was conducted to determine the validity of the accelerometer, using a 1000 Hz force plate (Advanced Mechanical Technology Incorporated (AMTI®), Newton, MA, USA) as the "gold standard" for the determination of ground contact time (Appendix II).

6.2.5 ULTRAMARATHON RACE

Subjects in the experimental group completed a 90 km ultramarathon race. In this study, subjects completed the "*down*" run[145]. A race profile of the "*down*" run is included in Appendix I. Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at one-minute intervals for the duration of the ultramarathon race. Race heart rate data were averaged, and expressed as a percentage of maximum heart rate to provide an indication of exercise intensity during the ultramarathon race.

6.2.6 ACUTE TESTS

Daily muscle pain measurements, as described for the track test, and blood samples, for the analysis of plasma CK activity, were collected for one day before, and for seven days after the ultramarathon race as an estimate of muscle damage. The methods for the determination of plasma CK activity and muscle pain have been described in Chapter 3 (Section 3.2.5, page 118) and Chapter 6 (Section 6.2.4.4, page 220) respectively.

6.2.7 EMG DATA ANALYSIS

Electromyographic raw data activity was sampled at 2000 Hz, and was amplified and recorded telemetrically (Noraxon, Telemyo, Scottsdale, Arizona, USA). The raw EMG signal was filtered using a RJ-50 filter, followed by a 15-500 band pass filter. All data were then smoothed by taking the root mean square of the signal over 50 ms periods. The amount of EMG activity was quantified by determining the area under the curve for EMG (μV) vs. time (s), resulting in an integrated EMG (iEMG) measurement. Electromyographic data from a minimum of 10 strides obtained during the 20 m of the submaximal, sprint, and 5 km time trial tests were averaged.

The iEMG value during preactivation for each of the four muscle groups was normalised to the iEMG value obtained from the 6th lap (840 m) during the 1.4 km submaximal run. During running, the normalisation to the EMG obtained during a standardised submaximal run has been shown to be the most appropriate method of normalisation of iEMG[2]. In addition, 20 m running speeds during the submaximal and sprint tests were analysed to ensure consistency with 70% and 130% of peak treadmill running speed respectively. A 5% variability in running speeds was accepted. Data with greater than 5% variance from the predetermined submaximal and maximal running speeds were excluded from the statistical analyses.

6.2.8 STATISTICAL ANALYSES

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in descriptive variables between the experimental and control groups were assessed using an independent t-test. Statistical significance for the two main effects of group and time, and the interaction (group x time) of all other variables were assessed using a two-way analysis of variance (ANOVA) with repeated measures. Tukey's *post hoc* comparisons were performed where necessary.

A Mann-Whitney U test was used to assess differences in the pain scores between groups. A Friedman's ANOVA and Kendall's concordance was used to assess differences in the pain scores within groups over time. A Pearson's product-moment correlation coefficient determined relationships between variables (change in 5 km time trial times, and running history and personal best times). All data are presented as the mean ± standard deviation. Statistical significance was accepted as $p < 0.05$.

6.3 RESULTS

6.3.1 SUBJECTS

The descriptive characteristics of subjects are shown in Table 6.1, and the training and racing history of subjects are shown in Table 6.2. There were no significant differences between groups for any of these variables. The subjects in this study were similar to those in the previous studies (Chapter 3, page 120 and Chapter 4, page 147), based on their general characteristics, and training and racing history.

Table 6.1: *Descriptive characteristics of subjects in the experimental (n = 11) and control (n = 12) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Age (years)	42.2 ± 6.1	37.5 ± 5.9
Weight (kg)	77.4 ± 4.6	74.2 ± 14.9
Height (cm)	176.8 ± 7.0	177.9 ± 8.4
Sum of skinfolds (mm)	70.6 ± 13.6	68.8 ± 27.0
Body fat (%)	20.6 ± 3.2	18.5 ± 3.7
Maximum heart rate ($b.min^{-1}$)	180 ± 10	181 ± 10
VO_2max ($ml.kg^{-1}.min^{-1}$)	60.6 ± 5.2	63.0 ± 6.9
Peak treadmill running speed (PTRS) ($km.h^{-1}$)	18.0 ± 1.1	18.9 ± 1.4

Table 6.2: *Training and racing history of subjects in the experimental (n = 11) and control (n = 12) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Total years running	13.9 ± 7.3	12.5 ± 6.8
Pre-competition training distance ($km.wk^{-1}$)[$]	75.9 ± 7.4	66.7 ± 17.5
Average training distance ($km.wk^{-1}$)	51.4 ± 14.7	43.4 ± 14.7
Number of standard marathons (42 km)	21 ± 10	12 ± 17
Personal best 10 km time (min)	40.8 ± 3.5	39.5 ± 5.5
Personal best 42 km time (min)	201.4 ± 18.9	197.8 ± 25.5

[$] *Average training distance in the 3 months preceding the race*

The subjects in the experimental group completed the 90 km race in 602.5 ± 90.9 minutes. The average intensity (% HR_{max}) during the race was 80 ± 2%. Although this group displayed a relatively wide range of finishing times for the ultramarathon race, compared to the previous studies, the average race times and the intensity (% HR_{max}) during the race were similar to those reported in the previous studies (Chapter 3, page 121 and Chapter 4, page 148).

6.3.2 MUSCLE PAIN

Subjective pain scores of "*general pain at rest*" and "*pain during activities of daily living*" are shown in Figure 6.2. Pain scores "*during a static stretch*", and "*pressure pain*" are shown in Figure 6.3. "*General pain*" was significantly higher in the experimental group compared to the control group in the quadriceps ($p < 0.002$) and hamstrings ($p < 0.04$) on day 1, and in gastrocnemius ($p < 0.04$) on days 2 and 3 after the ultramarathon.

"*Daily living pain*" was significantly higher in the experimental group compared to the control group in the quadriceps on days 1, 2 ($p < 0.004$), and 3 ($p < 0.03$), and gastrocnemius on days 2 and 3 ($p < 0.05$) after the ultramarathon (Figure 6.2).

"*Stretch pain*" was significantly higher in the experimental group compared to the control group in the quadriceps on days 1 ($p < 0.004$) and 2 ($p < 0.04$) after the ultramarathon. "*Pressure pain*" was also significantly higher in the experimental group compared to the control group in the quadriceps on days 1 and 2 ($p < 0.01$), and gastrocnemius ($p < 0.04$) on day 1 after the ultramarathon (Figure 6.3). From day 4 onwards, for the duration of the experiment, there were no differences between groups (Figures 6.2 and 6.3).

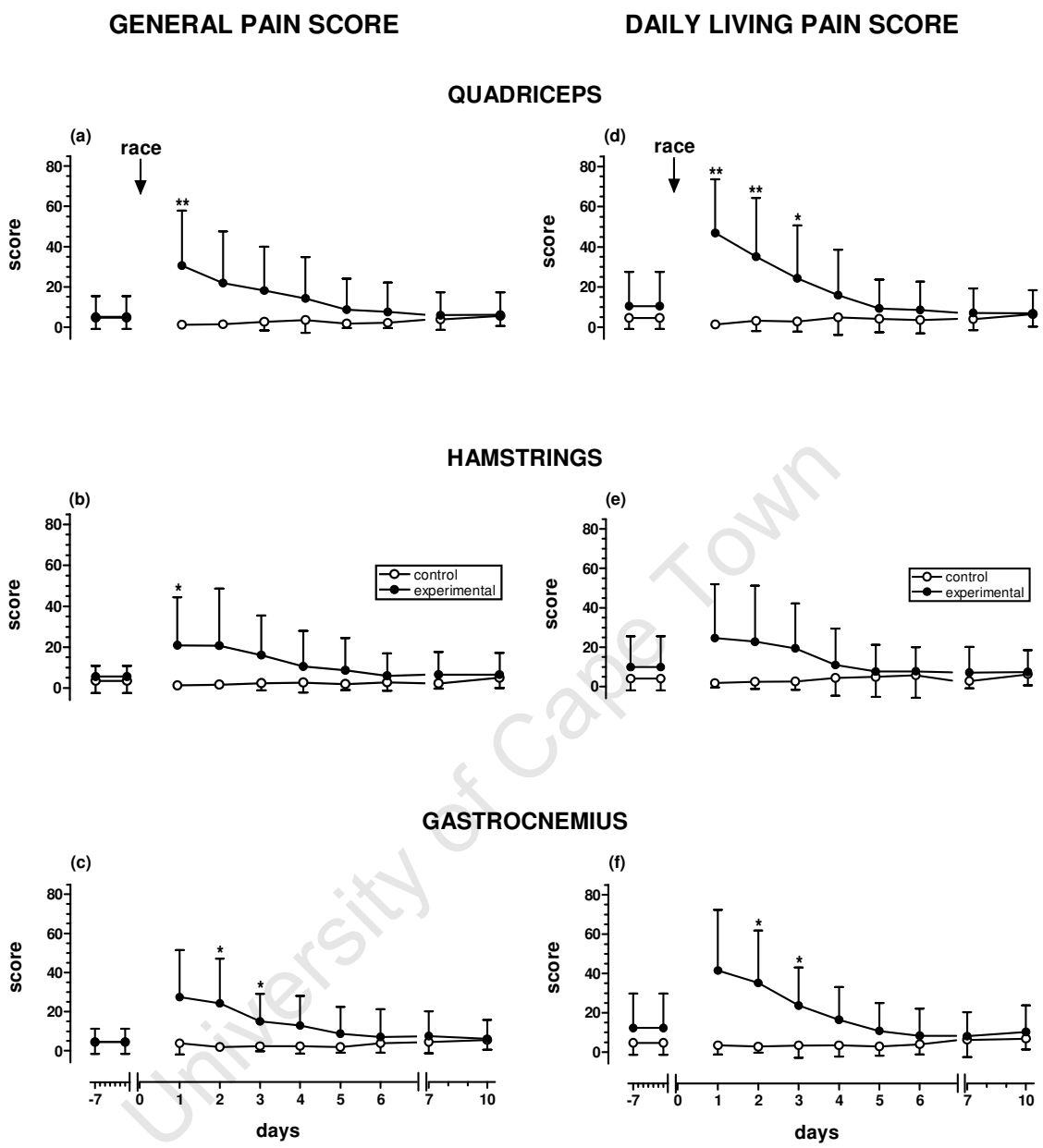

Figure 6.2: *Pain scores of subjects in the experimental (-●-) (n = 11) and control (-○-) (n = 12) groups. General pain scores in the (a) quadriceps, (b) hamstrings, and (c) gastrocnemius muscles, and daily living pain scores in the (d) quadriceps, (e) hamstrings, and (f) gastrocnemius muscles. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences (continued on next page).

Significant differences:

General pain:

(a) Quadriceps: ** experimental day 1 vs. control day 1 ($p < 0.002$)
(b) Hamstrings: * experimental day 1 vs. control day 1 ($p < 0.04$)
(c) Gastrocnemius: * experimental days 2 and 3 vs. control days 2 and 3 respectively ($p < 0.04$)

Daily living pain:

(d) Quadriceps: ** experimental days 1 and 2 vs. control days 1 and 2 respectively ($p < 0.004$)
* experimental day 3 vs. control day 3 ($p < 0.03$)
(f) Gastrocnemius: * experimental days 2 and 3 vs. control days 2 and 3 respectively ($p < 0.05$)

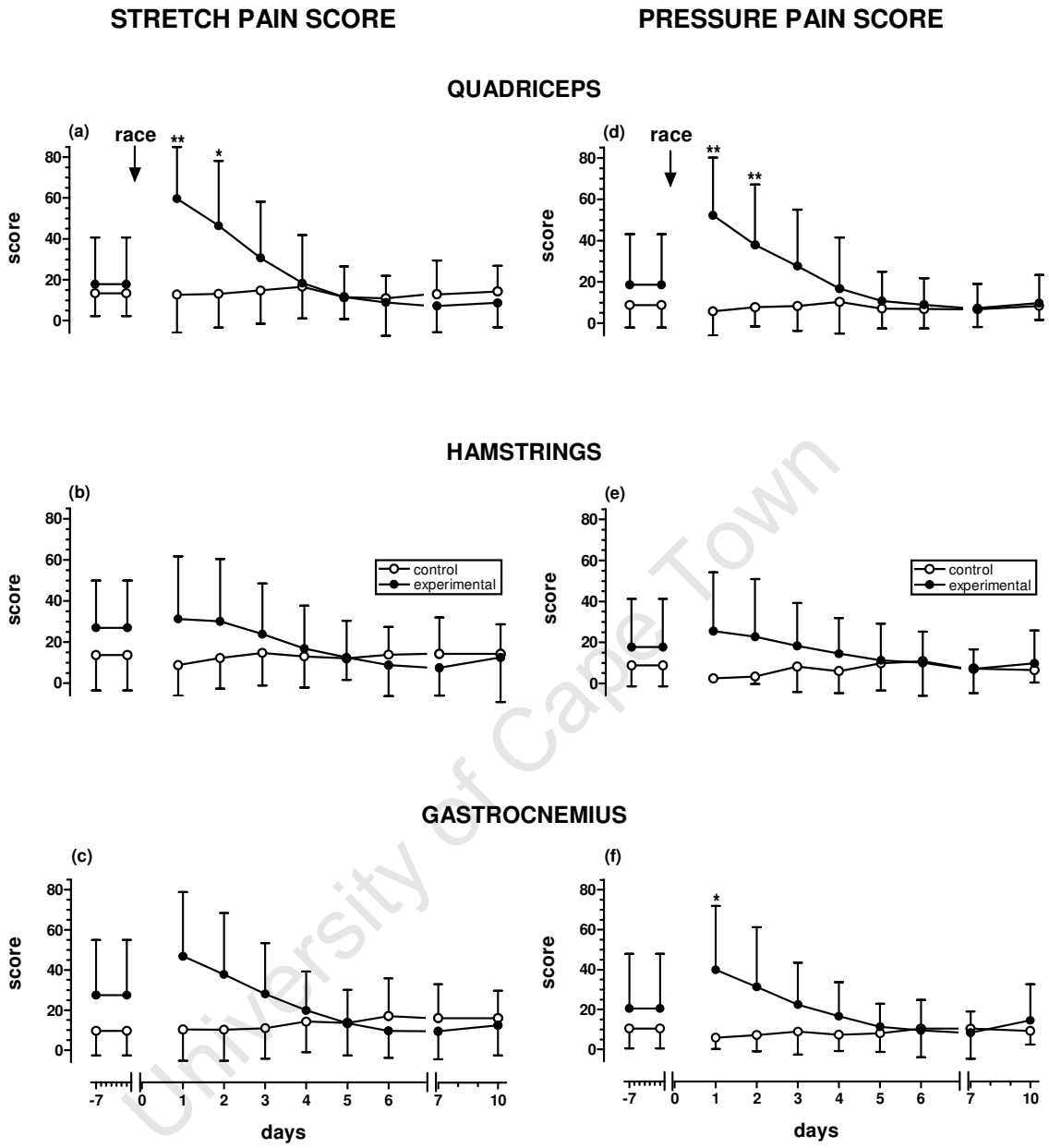

Figure 6.3: *Pain scores of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 12) groups. Stretch pain scores in the (a) quadriceps, (b) hamstrings, and (c) gastrocnemius muscles, and pressure pain scores in the (d) quadriceps, (e) hamstrings, and (f) gastrocnemius muscles. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences (continued on next page).

Significant differences:

Stretch pain:

(a) Quadriceps: ** experimental day 1 vs. control day 1 ($p < 0.004$)
* experimental day 2 vs. control day 2 ($p < 0.04$)

Pressure pain:

(d) Quadriceps: ** experimental days 1 and 2 vs. control days 1 and 2 respectively ($p < 0.01$)

(f) Gastrocnemius: * experimental day 1 vs. control day 1 ($p < 0.04$)

6.3.3 PLASMA CREATINE KINASE ACTIVITY

There was a significant interaction between groups over time for plasma CK activity ($F_{(8, 168)} = 16.25$; $p < 0.00009$) (Figure 6.4). The plasma CK activity was significantly higher in the experimental group on days 1, 2, 3, and 4 ($p < 0.006$) after the ultramarathon. From day 5 onwards, for the duration of the study thereafter, there were no differences between groups (Figure 6.4).

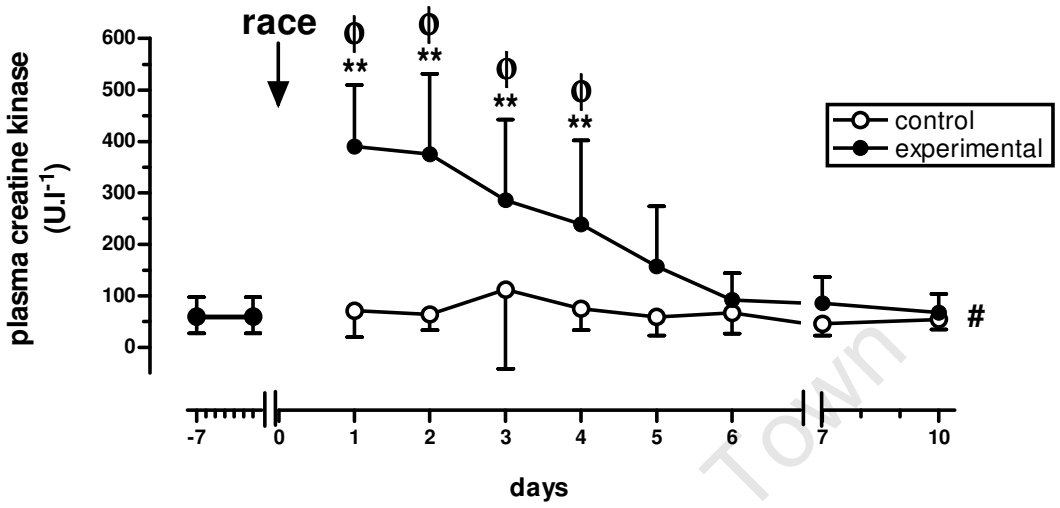

Figure 6.4: *Plasma creatine kinase (U.l^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 12) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1, 2, and 3 vs. experimental days -7, -1, 4, 5, 6, 7, and 10 ($p < 0.006$)

** experimental day 4 vs. experimental days -7, -1, 6, 7, and 10 ($p < 0.003$)

ϕ experimental days 1, 2, and 3 vs. control days -7, -1, 1, 2, 3, 4, 5, 6, 7, and 10 ($p < 0.002$)

ϕ experimental day 4 vs. control days -7, -1, 1, 2, 4, 5, 6, 7, and 10 ($p < 0.003$)

interaction of group x time ($p < 0.00009$)

6.3.4 PERFORMANCE

The differences in running speed ($m.s^{-1}$) during the 5 km time trial pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.5. There were no significant differences in running speed between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(4, 84)} = 34.25$; $p < 0.00001$).

In the experimental group, there were significant differences between pre-race km 1 and post-race km 3 and 4 running speeds ($p < 0.009$), and between post-race km 1 and pre-race km 3 and 4 running speeds ($p < 0.002$). There was a tendency for running speed to be increased at km 1 and 4 post-race, compared to km 1 and 4 pre-race values respectively (Figure 6.5).

In the control group, there were significant differences between pre-race km 1 and post-race km 3 and 4 running speeds ($p < 0.008$), and between post-race km 1 and pre-race km 2, 3, and 4 running speeds ($p < 0.01$). There was a tendency for running speed to be increased at km 4 post-race, compared to km 4 pre-race values (Figure 6.5).

In addition, there were no significant differences in the total 5 km time trial time between groups, or pre-post the ultramarathon race. Pre-race 5 km time trial times were 21.5 ± 1.5 minutes and 20.8 ± 2.3 minutes for the experimental and control groups respectively. Post-race 5 km time trial times were 21.5 ± 1.6 minutes and 20.7 ± 2.3 minutes for the experimental and control groups respectively. The pre-race and post-race 5 km time trial times remained relatively unchanged in both the experimental and control groups.

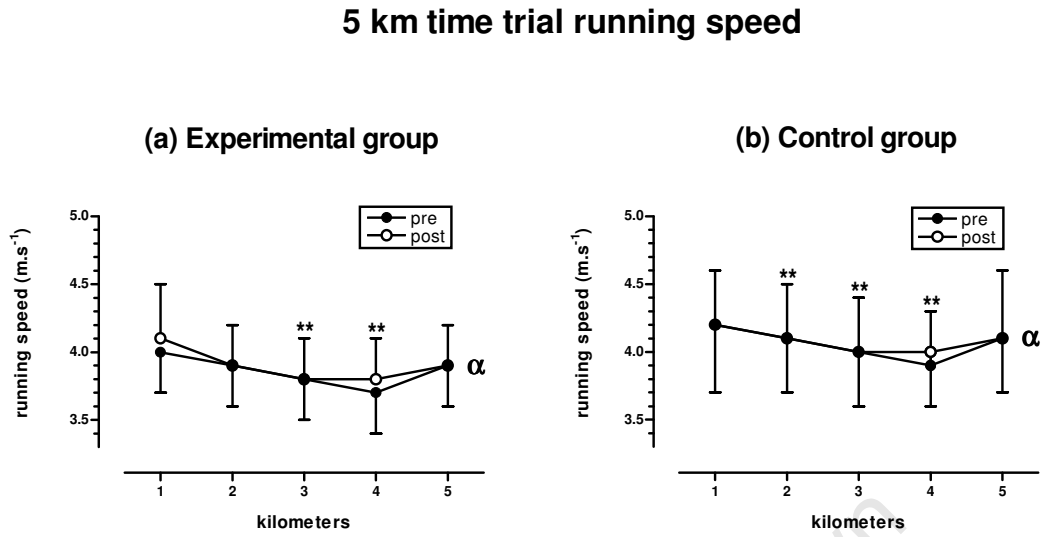

Figure 6.5: *Running speed ($m.s^{-1}$) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at kilometers 1 to 5 during the 5 km time trial, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre km 1 vs. post km 3 and 4 ($p < 0.009$)
** post km 1 vs. pre km 3 and 4 ($p < 0.002$)
α main effect of time ($p < 0.00001$)

(b) Control group: ** pre km 1 vs. post km 3 and 4 ($p < 0.008$)
** post km 1 vs. pre km 2, 3, and 4 ($p < 0.01$)
** pre km 4 vs. post km 2 and 5 ($p < 0.005$)
α main effect of time ($p < 0.00001$)

6.3.5 RATE OF PERCEIVED EXERTION

6.3.5.1 Submaximal run

The differences in the rate of perceived exertion (RPE) during the 1.4 km submaximal run pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.6. There were no significant differences in the rate of perceived exertion between groups.

However, there were significant differences in the rate of perceived exertion pre-post the ultramarathon race ($F_{(1, 21)} = 4.86$; $p < 0.04$) and over time ($F_{(2, 42)} = 9.84$; $p < 0.0004$). In the experimental group, the rate of perceived exertion was significantly increased at 840 m, 1120 m, and 1400 m during the post-race submaximal run, compared to pre-race values ($p < 0.03$).

6.3.5.2 5 km time trial

The differences in the rate of perceived exertion during the 5 km time trial pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.7. There were no significant differences in the rate of perceived exertion between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(4, 84)} = 89.98$; $p < 0.00009$).

In the experimental group, the rate of perceived exertion was significantly increased at post-race km 2, 3, 4, and 5 compared to pre-race km 1 ($p < 0.0002$), at post-race km 3, 4, and 5 compared to pre-race km 2 ($p < 0.0003$), at post-race km 4 and 5 compared to pre-race km 3 ($p < 0.0006$), and at post-race km 5 compared to pre-race km 4 ($p < 0.002$). In the control group, the rate of perceived exertion was significantly increased at post-race km 2, 3, 4, and 5 compared to pre-race km 1 ($p < 0.009$), at post-race km 1, 4, and 5 compared to pre-race km 2 ($p < 0.009$), at post-race km 1 and 5 compared to pre-race km 3 ($p < 0.0002$) (Figure 6.7).

In addition, in both the experimental and control groups pre- and post- the ultramarathon race, the rate of perceived exertion significantly increased during the 5 km time trial. The rate of perceived exertion was significantly increased pre- and post- the ultramarathon race at km 3, 4, and 5, compared to km 1 ($p < 0.002$).

Submaximal RPE

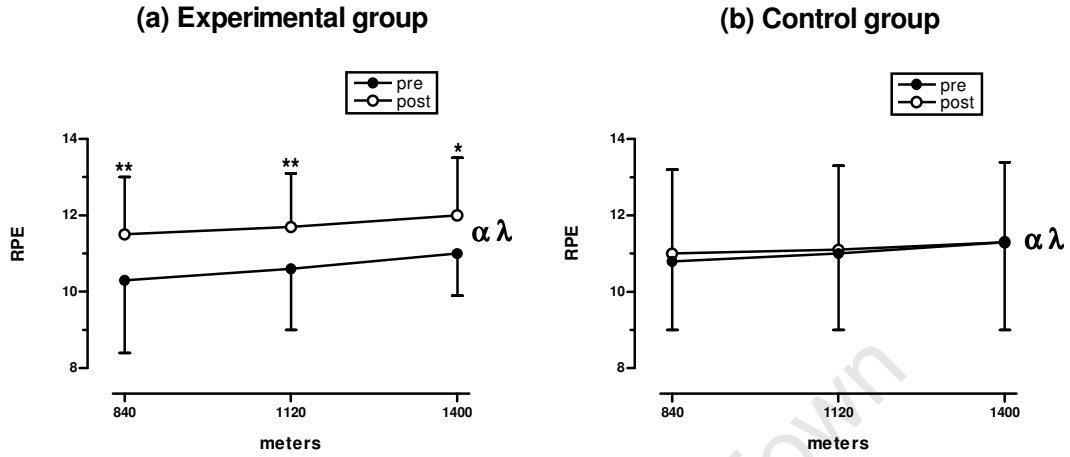

Figure 6.6: *Rate of perceived exertion (Borg scale) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 840 m, 1120 m, and 1400 m during the submaximal run, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre 840 m vs. post 840 m, 1120 m, and 1400 m ($p < 0.002$)
** pre 1120 m vs. post 1120 m and 1400 m ($p < 0.01$)
* pre 1400 m vs. post 1400 m ($p < 0.03$)
α main effect of time ($p < 0.0004$)
λ main effect of pre-post ($p < 0.04$)

(b) Control group: α main effect of time ($p < 0.0004$)
λ main effect of pre-post ($p < 0.04$)

5 km time trial RPE

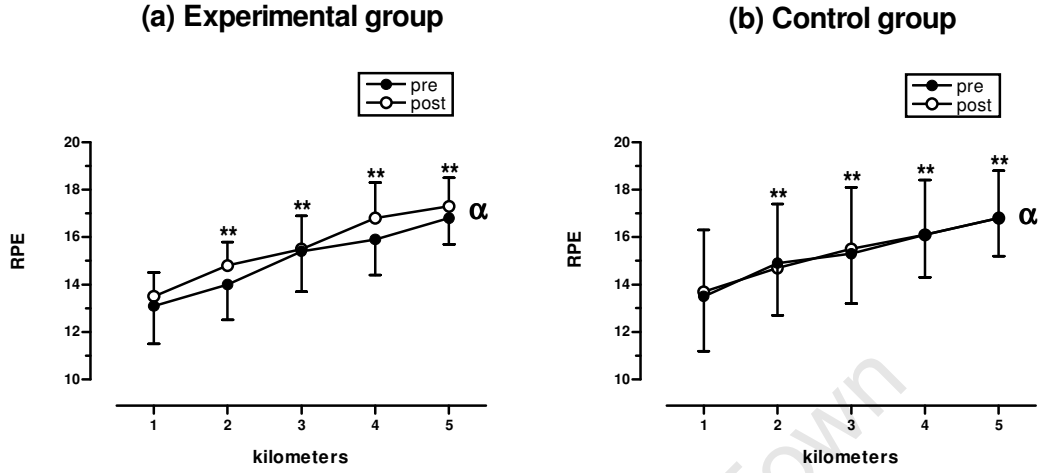

Figure 6.7: *Rate of perceived exertion (Borg scale) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at kilometers 1 to 5 during the 5 km time trial, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre km 1 vs. post km 2, 3, 4, and 5 ($p < 0.0002$)
** pre km 2 vs. post km 3, 4, and 5 ($p < 0.0003$)
** pre km 3 vs. post km 4 and 5 ($p < 0.0006$)
** pre km 4 vs. post km 5 ($p < 0.002$)
α main effect of time ($p < 0.00009$)

(b) Control group: ** pre km 1 vs. post km 2, 3, 4, and 5 ($p < 0.009$)
** pre km 2 vs. post km 1, 4, and 5 ($p < 0.009$)
** pre km 3 vs. post km 1 and 5 ($p < 0.0002$)
α main effect of time ($p < 0.00009$)

6.3.6 HEART RATE

6.3.6.1 Submaximal run

The differences in heart rate ($b.min^{-1}$) during the 1.4 km submaximal run pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.8. There were no significant differences in heart rate between groups. However, there were significant differences in heart rate pre-post the ultramarathon race ($F_{(1, 19)} = 7.24$; $p < 0.02$) and over time ($F_{(2, 38)} = 22.34$; $p < 0.00001$). In the experimental group, heart rate was significantly decreased at post-race 840 m compared to pre-race 840 m ($p < 0.008$), and at post-race 840 m and 1120 m, compared to pre-race 1120 m and 1400 m ($p < 0.0007$). In the control group, heart rate was significantly decreased at 840 m, 1120 m, and 1400 m during the post-race submaximal run, compared to pre-race values ($p < 0.04$).

6.3.6.2 5 km time trial

There was a significant interaction between groups over time pre-post the ultramarathon race for heart rate during the 5 km time trial ($F_{(4, 84)} = 2.56$; $p < 0.05$) (Figure 6.9). In the experimental group, heart rate was significantly increased at post-race km 3, 4, and 5 compared to pre-race km 1 ($p < 0.02$), and at post-race km 5 compared to pre-race km 2, 3, 4, and 5 ($p < 0.03$). In the control group, heart rate was significantly increased at post-race km 2, 3, 4, and 5 compared to pre-race km 1 ($p < 0.01$), and at pre-race km 5 compared to post-race km 1 ($p < 0.005$). In addition, in both the experimental and control groups pre- and post- the ultramarathon race, there was heart rate was significantly increased at km 3, 4, and 5, compared to km 1 ($p < 0.05$).

Submaximal heart rate

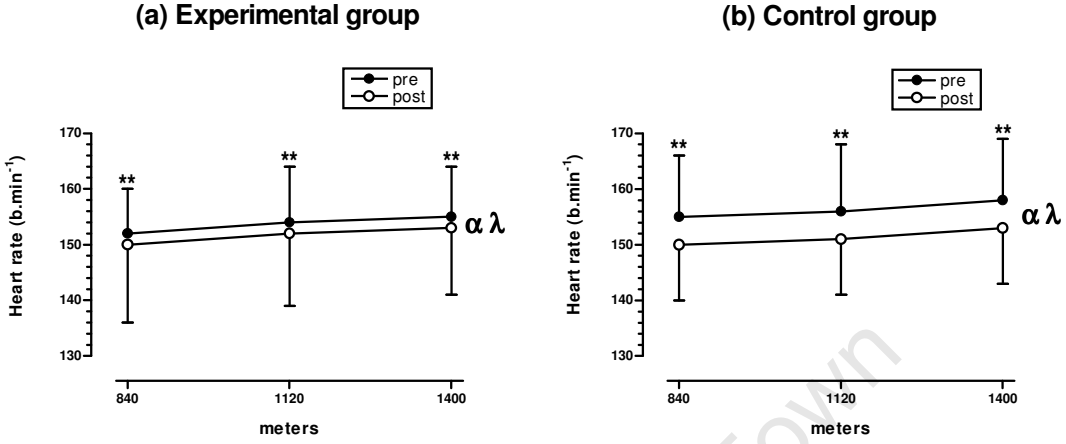

Figure 6.8: *Heart rate (b.min^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 840 m, 1120 m, and 1400 m during the submaximal run, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre 840 m vs. post 840 m ($p < 0.008$)
** pre 1120 m vs. post 840 m and 1120 m ($p < 0.0007$)
* pre 1400 m vs. post 840 m and 1120 m ($p < 0.0002$)
α main effect of time ($p < 0.00001$)
λ main effect of pre-post ($p < 0.02$)

(b) Control group: ** pre 840 m vs. post 840 m and 1120 m ($p < 0.0002$), and 1400 m ($p < 0.04$)
** pre 1120 m vs. post 840, 1120, and 1400 m ($p < 0.0009$)
** pre 1400 m vs. post 840, 1120, and 1400 m ($p < 0.0002$)
α main effect of time ($p < 0.00001$)
λ main effect of pre-post ($p < 0.02$)

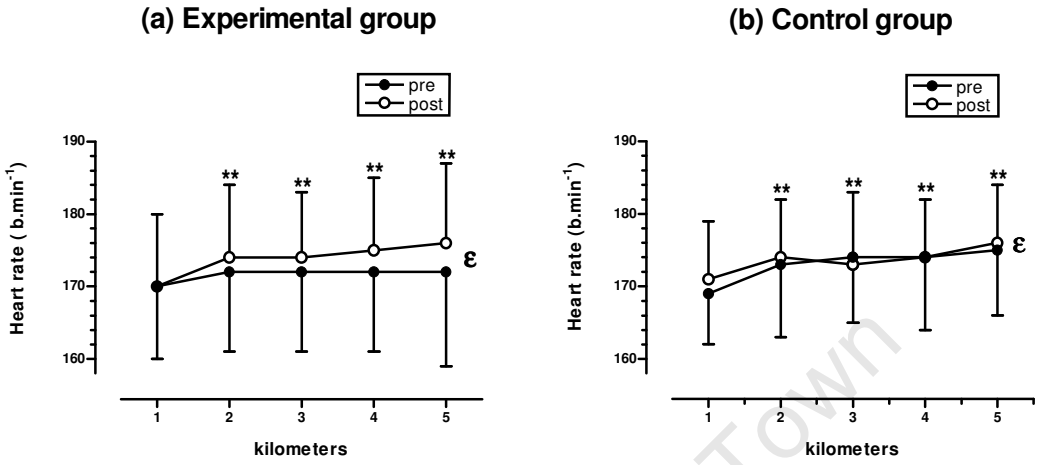

Figure 6.9: *Heart rate (b.min^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at kilometers 1 to 5 during the 5 km time trial, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre km 1 vs. post km 3 ($p < 0.02$), 4, and 5 ($p < 0.0006$)
** post km 5 vs. pre km 2, 3, 4 ($p < 0.004$), and 5 ($p < 0.03$)
ε interaction of pre-post x time x group ($p < 0.05$)

(b) Control group: ** pre km 1 vs. post km 2, 3, 4, and 5 ($p < 0.01$)
** pre km 5 vs. post km 1 ($p < 0.005$)
ε interaction of pre-post x time x group ($p < 0.05$)

6.3.7 STRIDE LENGTH

The differences in stride length (m) during the 5 km time trial pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.10. There were no significant differences in stride length pre-post the ultramarathon race. However, there was a significant interaction between groups over time for stride length ($F_{(4, 76)} = 3.92$; $p < 0.006$). In the control group, stride length was significantly decreased at pre-race km 3 and 4, compared to post-race km 1 ($p < 0.0004$).

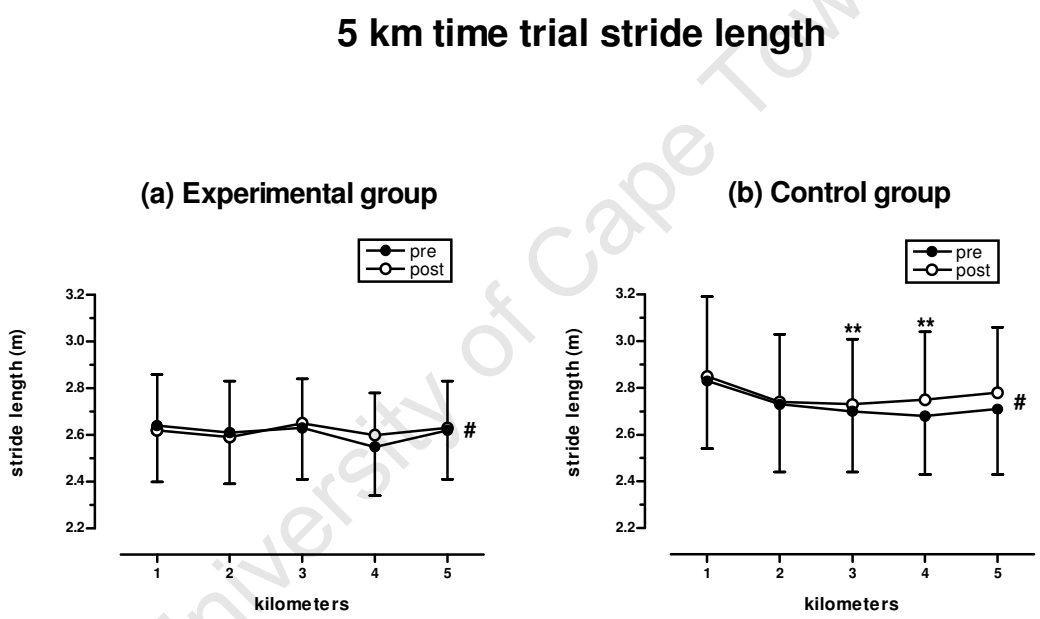

Figure 6.10: *Stride length (m) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at kilometers 1 to 5 during the 5 km time trial, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: # interaction of group x time ($p < 0.006$)

(b) Control group: ** post km 1 vs. pre km 3 and 4 ($p < 0.0004$)
interaction of group x time ($p < 0.006$)

6.3.8 EMG PREACTIVATION

6.3.8.1 Submaximal run

The differences in EMG preactivation (EMG %) in the vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), and medial gastrocnemius (MG) muscles during the 1.4 km submaximal run pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.11. There were significant differences in EMG preactivation over time for VL ($F_{(1, 14)} = 7.39$; $p < 0.02$) and MG ($F_{(1, 14)} = 7.43$; $p < 0.02$), with EMG preactivation tending to decrease during the submaximal run. There were however no significant differences in EMG preactivation for VL or MG either between groups, or pre-post the ultramarathon race. In addition, there were no significant differences in EMG preactivation for VM or BF between groups, pre-post the ultramarathon race, or over time.

6.3.8.2 5 km time trial

The differences in EMG preactivation (EMG %) in the VM, VL, BF, and MG muscles during the 5 km time trial pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 6.12. There were no significant differences in preactivation for VM or VL between groups, pre-post the ultramarathon race, or over time. There were no significant differences in preactivation for BF pre-post the ultramarathon race, however there was a significant interaction between groups over time ($F_{(4, 52)} = 4.23$; $p < 0.005$). There was a significant difference in preactivation over time for MG ($F_{(4, 52)} = 3.65$; $p < 0.02$). There were no significant differences in MG preactivation between groups or pre-post the ultramarathon race.

In the experimental group, BF preactivation was significantly reduced at post-race km 1, compared to pre-race km 1, 2, and 3 ($p < 0.05$). During the post-race 5 km time trial, BF preactivation was also significantly reduced at km 1, compared to km 2 ($p < 0.04$). MG preactivation was significantly reduced at post-race km 2 and 4, compared to pre-race km 1 ($p < 0.04$) (Figure 6.12).

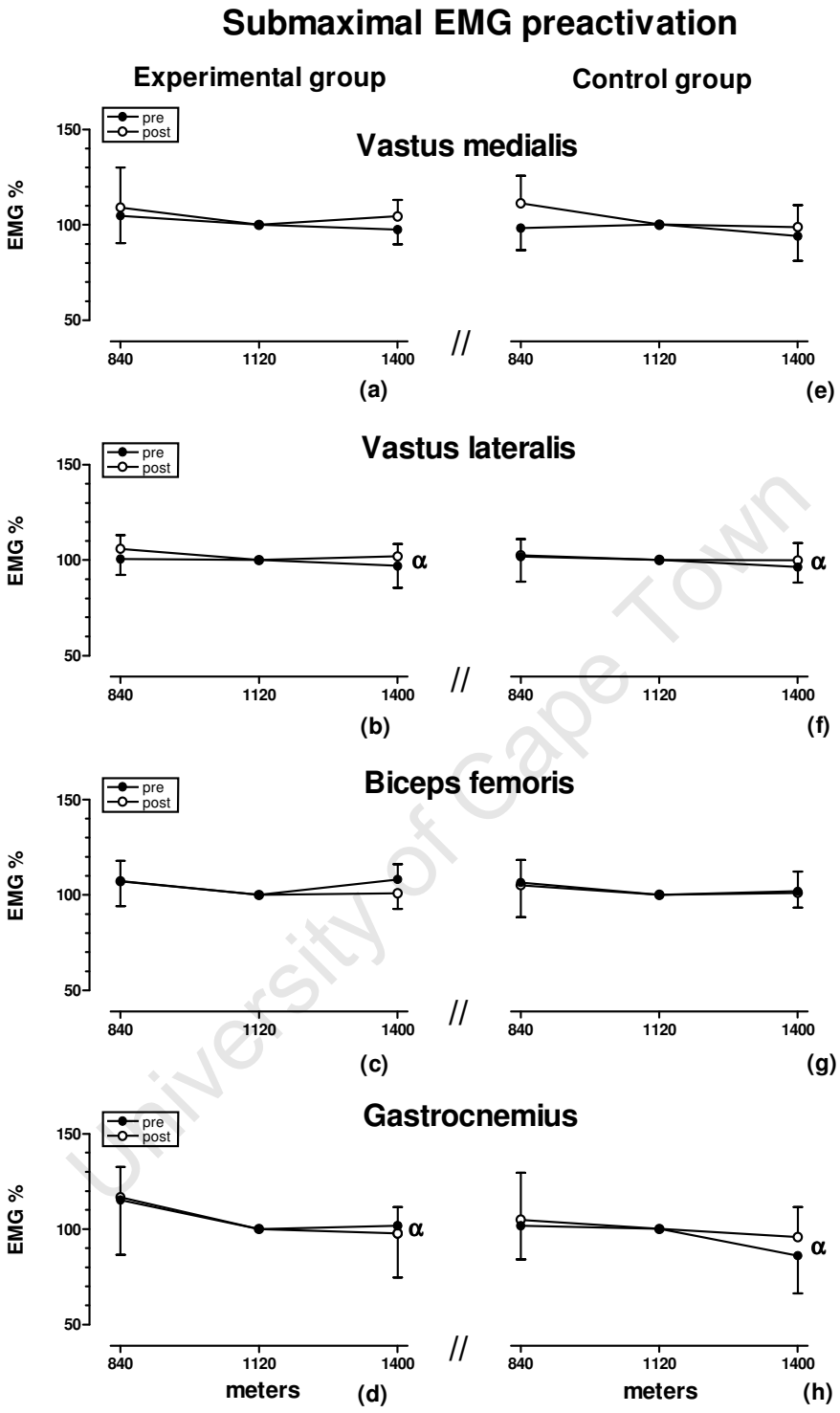

Figure 6.11: *Preactivation (EMG %) during the submaximal run (continued on next page).*

Figure 6.11: *Preactivation (EMG %) of four muscles of subjects in the experimental (n = 11) and control (n = 12) groups at 840 m, 1120 m, and 1400 m during the submaximal run, pre (-●-) and post (-o-) the ultramarathon race. Experimental group preactivation in the (a) vastus medialis (VM), (b) vastus lateralis (VL), (c) biceps femoris (BF), and (d) medial gastrocnemius (MG) muscles. Control group preactivation in the (e) VM, (f) VL, (g) BF, and (h) MG muscles. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

Experimental group:
(b) Vastus lateralis: α main effect of time ($p < 0.02$)
(d) Medial gastrocnemius: α main effect of time ($p < 0.02$)

Control group:
(f) Vastus lateralis: α main effect of time ($p < 0.02$)
(h) Medial gastrocnemius: α main effect of time ($p < 0.02$)

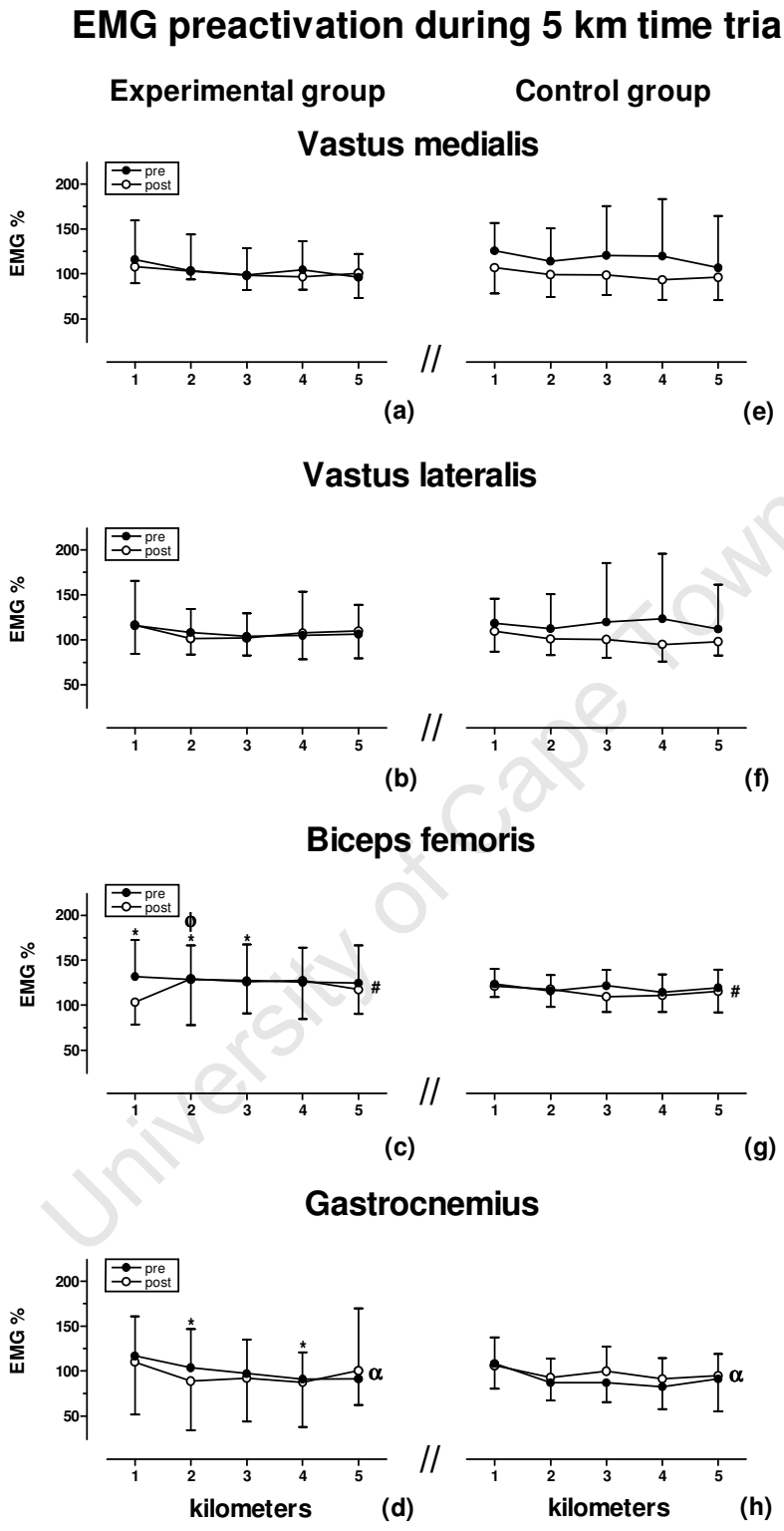

Figure 6.12: *Preactivation (EMG %) during the 5 km time trial (continued on next page).*

Figure 6.12: *Preactivation (EMG %) of four muscles of subjects in the experimental (n = 11) and control (n = 12) groups at kilometers 1 to 5 during the 5 km time trial, pre (-●-) and post (-o-) the ultramarathon race. Experimental group preactivation in the (a) vastus medialis (VM), (b) vastus lateralis (VL), (c) biceps femoris (BF), and (d) medial gastrocnemius (MG) muscles. Control group preactivation in the (e) VM, (f) VL, (g) BF, and (h) MG muscles. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

Experimental group:

(c) Biceps femoris: * post km 1 vs. pre km 1, 2, and 3 ($p < 0.05$)
ϕ post km 1 vs. post km 2 ($p < 0.04$)
interaction of group x time ($p < 0.005$)

(d) Medial gastrocnemius: * pre km 1 vs. post km 2 and 4 ($p < 0.04$)
α main effect of time ($p < 0.02$)

Control group:

(g) Biceps femoris: # interaction of group x time ($p < 0.005$)

(h) Medial gastrocnemius: α main effect of time ($p < 0.02$)

6.3.8.3 20 m sprint tests

The change in EMG preactivation (EMG %) between the pre- and post-5 km time trial 20 m sprint tests for subjects in the experimental and control groups pre- and post- the ultramarathon race are shown in Figure 6.13. There were no significant differences in the change in EMG preactivation either between groups or pre-post the ultramarathon race.

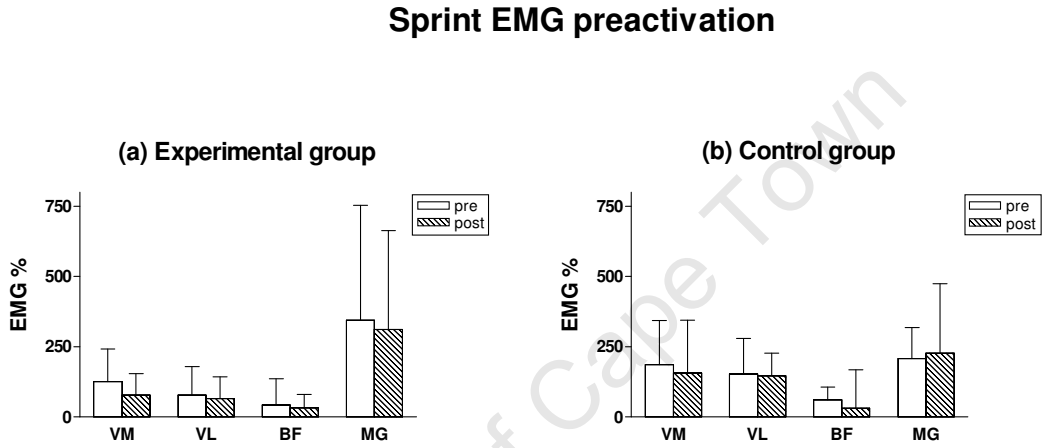

Figure 6.13: *Change in preactivation (EMG %) between the pre- and post-5 km time trial 20 m sprint tests of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups, pre- and post- the ultramarathon race, in the vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), and medial gastrocnemius (MG) muscles. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

6.3.9 CHANGE IN 5 KM TIME TRIAL TIME AND RUNNING HISTORY CORRELATIONS

Figure 6.14 shows the relationship between the change in 5 km time trial time and the total years of running, the number of marathons, and the number of ultramarathon races for the experimental group. There were significant negative correlations between the change in time trial time and the total years of running ($r = -0.61$; CI: -0.89 to -0.02; $p < 0.05$), the number of marathons ($r = -0.76$; CI: -0.93 to -0.30; $p < 0.007$), and the number of ultramarathon races ($r = -0.77$; CI: -0.94 to -0.31; $p < 0.006$) for the experimental group. There were no significant correlations between any variables for the total group, or for the control group, when data from these groups were analysed separately.

There were significant positive correlations between the change in 5 km time trial time and 10 km personal best (PB) time ($r = 0.66$; CI: 0.09 to 0.90; $p < 0.03$), and 42 km PB time ($r = 0.65$; CI: 0.08 to 0.90; $p < 0.04$) for the experimental group (Figure 6.15). There were no significant correlations between any variables for the total group, or for the control group, when data from these groups were analysed separately.

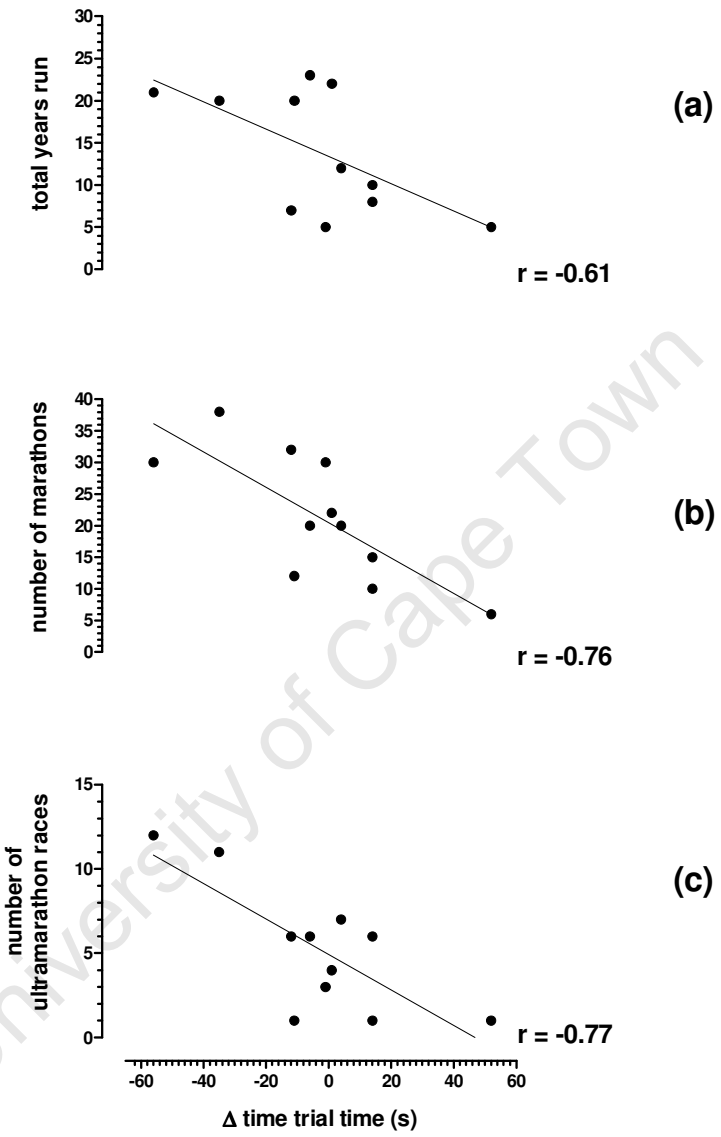

Figure 6.14: *Relationships between the change in time trial time (s) and (a) the total years run, (b) the number of marathons, and (c) the number of ultramarathon races for the experimental group (n = 11). Note that a positive change in time trial time indicates a decrease in performance.*

Personal best 10 km and 42 km times and Δ time trial time

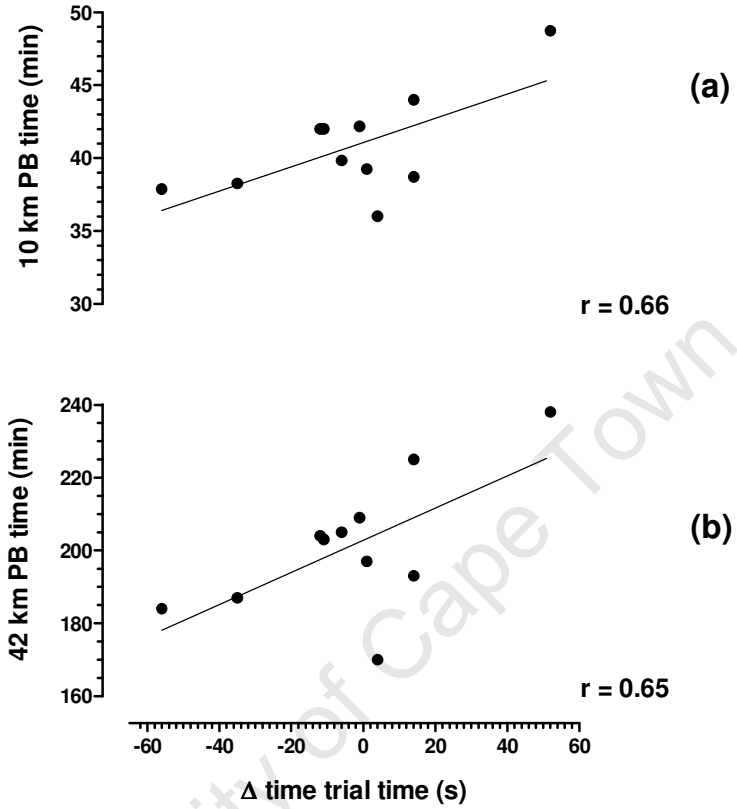

Figure 6.15: *Relationships between the change in time trial time (s) and (a) 10 km personal best (PB), and (b) 42 km PB time for the experimental group (n = 11). Note that a positive change in time trial time indicates a decrease in performance.*

6.4 DISCUSSION

As previously described in Chapter 3 and Chapter 4, the 90 km ultramarathon race induced muscle pain in the experimental group consistent with delayed onset muscle soreness. In this study, muscle pain remained significantly elevated in the experimental group for three days after the ultramarathon race, and plasma CK activity was significantly higher in the experimental group for four days after the ultramarathon race (Figures 6.2 – 6.4).

This is one of the first studies to investigate the effect of exercise-induced muscle damage induced by an ultramarathon race on endurance running performance. Interestingly, time trial performance remained relatively unchanged in both the experimental and control groups after the ultramarathon race, compared to pre-race performances (Figure 6.5), suggesting that exercise-induced muscle damage did not have a detrimental effect on endurance running performance. This finding is contrary to previous animal[106] and human studies[412], where running performance following damaging exercise protocols was reduced by 65%[106] and 4%[412] respectively.

These conflicting findings may potentially be explained by differences in the eccentric exercise protocols used to induce muscle damage, and the endurance performance tests. Carmichael et al[106] used a 130-minute to 150-minute downhill running protocol to determine the effects of exercise-induced muscle damage on running time to exhaustion in mice. A 65% reduction in running time to exhaustion was observed after the downhill run. Marcora and Bosio[412] used a 100-drop jump protocol to induce muscle damage in recreational runners. Endurance running performance was measured during a 30-minute self-paced time trial on a treadmill. There was a mean 4% reduction in time trial performance in the experimental group following the muscle damage protocol, compared to control group values. In this study, the ultramarathon race was used to induce muscle damage in trained distance runners. The average duration of the race was 602.5 ± 90.9 minutes.

There are also differences in the timing of performance testing following exercise-induced muscle damage. Marcora and Bosio[412] performed the 30-minute time trial 48 hours after the 100-drop jump protocol, while plasma CK activity and muscle pain were still elevated following exercise-induced muscle damage.

In this study, the 5 km time trial was performed between nine and 11 days after the ultramarathon race, and both plasma CK activity and muscle pain had returned to pre-race values.

Similar increases in the rating of perceived exertion at a fixed submaximal workload after exercise-induced muscle damage were observed by the study of Marcora and Bosio[412] and in this study (Figures 6.6 and 6.7), and therefore the contrasting changes in endurance running performance both occurred in the presence of an increased perception of effort. It is well documented that exercise-induced muscle damage is associated with an increased rate of perceived exertion during stretch shortening cycle exercise[107;544;663]. Factors that may contribute to an increased perception of effort associated with exercise-induced muscle damage include a higher central motor command to produce the same exercise intensity due to the force loss associated with exercise-induced muscle damage[544], the contribution of muscle pain to the rate of perceived exertion[61;544], and alterations in glycogen metabolism and availability[20;37]. However, further research is required to determine the peripheral and central mechanisms associated with the perception of effort during performance testing.

An important finding from this study was that the change in time trial performance was related to running history and personal best performances over 10 km and 42 km distances (Figures 6.14 and 6.15). In the experimental group, runners with a greater amount of endurance training experience, reflected by the number of years of endurance running, and racing experience, reflected by the number of marathon and ultramarathon races, demonstrated improvements in 5 km time trial performance following the ultramarathon race. In addition, there was a positive association between personal best performances over 10 km and 42 km distances and the change in time trial performance. In contrast, Marcora and Bosio[412] reported no differences in the susceptibility to exercise-induced muscle damage, and therefore a change in endurance running performance between more and less trained subjects.

However, previous studies[367;370;374] have reported that training may modify muscle activity patterns in stretch shortening cycle activity. Modifications include increased activation in the braking phase relative to the push-off phase. It is theorised that these training adaptations may be associated with an increase in muscle stiffness and elastic potentiation in stretch shortening cycle activity[367;370;374]. It is recognised that these findings were related to power trained athletes, and therefore the significance of these findings to endurance running has yet to be determined.

The dissociation in the change in time trial performance may possibly be explained by alterations in firing rates through "muscle wisdom" or central pathways controlling neural input to the muscle fibres. It has been proposed that muscle wisdom may be related to either the available percentage of type II muscle fibres, and exists to protect these fibres from damage associated with metabolite accumulation, or to selectively recruit type I muscle fibres that are more fatigue resistant, thereby maintaining levels of force production[584]. In addition, it is thought that prior experience may be an important factor in regulating efferent neural commands sent to the central pattern generators, based on afferent input from current metabolic activity, and the teleoanticipation-generated current level of activity. Therefore, in runners with greater distances in training and racing, prior experience and muscle wisdom changes in firing frequency may potentially be associated with improvements in time trial performance due to alterations in muscle recruitment patterns[607].

In addition, there is much evidence to suggest that exercise-induced muscle damage is associated with selective fibre type damage[80;95;211;227;229;231;324;384;388;427;651;652]. It may be theorised that runners with better 10 km and 42 km performances may have a greater percentage of type II muscle fibres, and may therefore have an improved inherent ability to sustain levels of force production and performance during a 5 km time trial. However, this theory is speculative and does not consider the chronic adaptations associated with endurance training.

Significant changes in heart rate values were noted in both the experimental and control groups (Figures 6.8 and 6.9). However, the variation in heart rate values in both the experimental and control groups was less than 5 to 8 $b.min^{-1}$ for the duration of the study. As previously discussed, the average day-to-day variation of heart rate is 5 to 8 $b.min^{-1}$ [381] in the absence of muscle pain and fatigue, and with constant levels of training. Therefore, it may be suggested that the significant changes in heart rate observed in this study do not reflect a meaningful difference in heart rate.

In this study, stride length remain relatively constant over the duration of the 5 km time trial in both the experimental and control groups (Figure 6.10). However, some differences in post-race stride length were observed in the control group, compared to pre-race values. Previous studies have determined considerable inter-individual variation in stride frequency in response to fatigue. This variability may indicate the selection of an optimal stride length during exercise and fatigue, reflecting a balance between energy cost and energy storage[306].

This study identified reductions in EMG preactivation in the experimental group biceps femoris and medial gastrocnemius muscles during the 5 km time trial (Figure 6.12). In addition, reductions in submaximal EMG preactivation were observed in both the experimental and control group vastus lateralis and medial gastrocnemius muscles over the duration of the submaximal run (Figure 6.11). Interestingly, there were no differences in the change in sprint EMG preactivation between groups, or following the ultramarathon race (Figure 6.13).

The gastrocnemius muscle has an important role in the regulation of the reaction force at ground contact in stretch shortening cycle exercise[186;353], and in the transmission of power from a proximal segment to a distal segment[59]. In addition, studies have demonstrated changes in ankle and knee kinematics following exercise-induced muscle damage[78;125;127;263]. The reductions in EMG preactivation in the biceps femoris and medial gastrocnemius muscles may therefore be a further compensatory mechanism to increase shock attenuation during the stance phase of running[263;435].

Previous studies have also demonstrated reductions in EMG preactivation after a 400 m sprint[494], a 10 km time trial[506], a 5 km time trial[584], and a marathon[476]. It is recognised that the majority of these studies have used exercise protocols of different intensities and durations to induce fatigue. Although there would be variations in the metabolic profiles associated with fatigue following the different exercise protocols[479], there are similarities in the alterations in EMG activity associated with fatigue[29;476;494;506].

It may be proposed that a reduction in preactivation of lower limb muscles may be associated with a reduction in muscle stiffness, and an increase in the duration of the transition between the lengthening and shortening phases of the stretch shortening cycle[67;348]. However, these alterations may be related to an increase in ground contact time, and an increase in the energy requirement during the propulsion phase of the running gait[67], and may lead to a decrement in performance.

Alternatively, it may be theorised that a reduction in preactivation may reflect a neural protective mechanism that prevents further damage to the muscle[29;292]. In support of this theory, Chambers et al[120] investigated the effects of a 90 km ultramarathon on the vertical jump performance with (drop jump and counter-movement jump) and without (squat jump) the use of the stretch shortening cycle. The vertical jump performance provides an indirect assessment of the ability to utilise stored elastic energy in the quadriceps muscle. The runners performed the vertical jump tests before the race, immediately after the race, daily for five days after the race and thereafter, weekly for a further four weeks after the race.

Vertical jump performance was significantly reduced immediately after the ultramarathon race, both with and without the use of the stretch shortening cycle. Drop jump, counter-movement jump, and squat jump heights were significantly reduced for 3,11, and 18 days after the ultramarathon respectively, when compared to pre-race values[120]. These results suggest that the stretch shortening cycle may possibly attenuate the decrement in performance associated with exercise-induced muscle damage[98].

In addition, the optimum angle for torque generation shifts to the right following lengthening muscle actions, indicating a shift in the length-tension relationship towards longer muscle lengths for maximal force generation[322;669]. In terms of neuromuscular function, a more compliant musculotendinous unit has an increased ability to store elastic energy, whereas a stiffer musculotendinous unit is capable of producing a faster rate of power output. During stretch shortening cycle exercise, increased compliance at the beginning of the stretch may be associated with improved storage of elastic energy. In addition, increased stiffness towards the end of the stretch shortening cycle may be related to improvements in the amount and rate of energy released. These adaptations may therefore also enhance the action of the stretch shortening cycle following exercise-induced muscle damage[87].

However, it is recognised that numerous factors may influence the development of stretch shortening cycle fatigue. Nicol et al[472] emphasises the flexibility of neural adjustments in order to meet functional requirements. Alterations in neuromuscular function following exercise that causes fatigue and muscle damage may be related to both peripheral mechanisms, such as disorganisation of the contractile machinery and calcium regulation, excitation-contraction coupling failure, redistribution of sarcomere lengths, and selective muscle fibre damage[46;98;384;450;545;658], as well as central mechanisms[98].

It may be theorised that continual interaction between central and peripheral factors may regulate the changes in muscle function associated with exercise-induced muscle damage and fatigue. Further studies are required to understand this complex interaction.

In conclusion, this study demonstrated that endurance running performance remained relatively unchanged in the recovery period 10 days after a 90 km ultramarathon. In addition, training and racing experience may affect the performance response following exercise-induced muscle damage. These findings, together with the reduction in EMG preactivation of the biceps femoris and medial gastrocnemius muscles, may indicate that neuromuscular adaptations may act as a protective mechanism following exercise-induced muscle damage and fatigue. It is recommended that further studies should investigate the metabolic adaptations in the recovery period after an ultramarathon race.

CHAPTER SEVEN
LITERATURE REVIEW: METABOLIC ADAPTATIONS ASSOCIATED WITH EXERCISE-INDUCED MUSCLE DAMAGE

7.1 INTRODUCTION

Exercise-induced muscle damage is a common occurrence following unaccustomed exercise, or increased exercise intensity or duration, and is characterised by a complex interaction of central and peripheral adaptations[98;133;196]. It has previously been established that lengthening muscle actions are associated with greater evidence of exercise-induced muscle damage than isometric or shortening muscle actions[244;325;356;467;468]. The conventional model that describes the mechanisms underlying exercise-induced muscle damage therefore emphasises the mechanical factors that contribute to the development of exercise-induced muscle damage.

The mechanical theory includes adaptations at the levels of the whole muscle and the muscle fibre, as well as at the myofibrillar level, specifically in the cytoskeleton. However, this model of exercise-induced muscle damage does not consider the potential role of metabolic factors in the development of exercise-induced muscle damage. Examples of metabolic factors include alterations in calcium concentrations, muscle temperature and pH, insufficient mitochondrial respiration, and oxygen free radical production[332;428].

The cellular, mechanical, and neural mechanisms of exercise-induced muscle damage were discussed in detail in Chapter 2. However, the results of the previous studies (Chapter 3 and Chapter 4) have demonstrated increases in the respiratory exchange ratio during submaximal exercise after an ultramarathon race. These findings are contrary to studies that have reported reductions in insulin sensitivity and glucose oxidation following eccentric exercise protocols[20;339;342].

The metabolic adaptations associated with prolonged running have not been studied extensively, and the complex interactions between muscle metabolism and exercise-induced muscle damage require further investigation. Therefore, this review will discuss the metabolic adaptations associated with endurance running, endurance training, and exercise-induced muscle damage.

7.2 METABOLIC EFFECTS OF ENDURANCE RUNNING

Several studies have observed metabolic adaptations in response to endurance running[22;23;284;342;587;642;656]. Warhol et al[656] examined skeletal muscle injury and repair in 40 male distance runners following a marathon. Gastrocnemius muscle biopsy samples were obtained immediately after the marathon, and on days 1, 2, 3, 5, 7, 10, 14, 21, 28, 42, 56, 70, and 84 after the race. There was evidence of cell injury, including interstitial collagen deposition and thickened capillary basal lamina, before the marathon. It was proposed that these changes may be associated with the training involved in the preparation for the race.

After the marathon up to 25% of the muscle fibres of runners exhibited areas of myofibrillar loss. The myofibrillar loss was extremely patchy, and was not greater than 10% of the fibre length. Other ultrastructural changes in the muscle biopsy samples included intra- and extracellular oedema with endothelial injury, myofibrillar lysis, dilation and disruption of the t-tubule system, and mitochondrial damage which was manifested by dissolution of cristae and loss of mitochondrial matrix. It was determined that the myofibrillar alterations occurred in muscle fibres depleted of glycogen and lipid. In addition, glycogen repletion correlated with the restoration of mitochondrial architecture and the repair of sarcomere damage[656].

Sherman et al[587] examined the effects of a marathon race, and subsequent rest or exercise on muscle glycogen, glycogen synthase, hexokinase, and the activity of hexose monophosphate pathway enzymes during a seven-day recovery period after the marathon. Ten male runners were randomly assigned to a post-marathon rest group or a post-marathon exercise group. Subjects in the exercise group ran for 20 minutes at the highest individual volitional intensity 24 hours after the marathon.

Thereafter, the running exercise was increased by five minutes per day for the duration of the seven-day recovery period. Muscle biopsy samples were obtained from the lateral head of the gastrocnemius muscle before the marathon, 15 minutes after the marathon, and at one, three, five, and seven days after the marathon. It was established that muscle glycogen stores were depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after the marathon. However, the muscle glycogen stores that remained after the marathon were predominantly located in type II muscle fibres. Glycogen synthase activity was significantly elevated immediately after the marathon[587].

Five days later, muscle glycogen concentrations were still below the pre-race values, although glycogen synthase activity had returned to normal. Hexokinase activity was significantly elevated for up to five days after the marathon compared to pre-race values, whereas hexose monophosphate pathway enzyme activity was significantly reduced for up to seven days after the marathon compared to pre-race values. The decrease in hexose monophosphate pathway enzyme activity may be associated with the alterations in glycogen synthase and hexokinase activity in an attempt to normalise muscle glycogen stores. In addition, no differences were observed between the post-marathon exercise and rest groups. The time taken to normalise muscle glycogen concentrations is not well known, but is thought to be ten days or longer[498].

The muscle glucose transporter GLUT-4 has been examined as a potential source of impaired glycogen resynthesis following exercise-induced muscle damage. Asp et al[23] observed the effects of a marathon race on GLUT-4 content. Seven well-trained male runners participated in a marathon race. Muscle biopsy samples were obtained from the lateral head of the gastrocnemius muscle before the marathon, 15 minutes after the marathon, and at one, two, and seven days after the marathon. Plasma CK activity peaked 24 hours after the marathon, and was significantly elevated 48 hours after the marathon, compared to pre-race values. The muscle glycogen concentration was significantly reduced immediately after the marathon race, and for up to two days after the marathon. However, GLUT-4 content remained unchanged during the recovery period after the marathon, compared to pre-race values. The slow recovery of muscle glycogen stores could therefore not be attributed to changes in GLUT-4 content.

It is recognised that this finding is contrary to a previous study that investigated the effects of an eccentric exercise protocol on GLUT-4 content[21]. Asp et al[21] showed a reduction in GLUT-4 content, indicating the potential role of GLUT-4 content in glycogen resynthesis following exercise-induced muscle damage. However, the contrasting methods used to induce muscle damage, mainly lengthening muscle actions in untrained males[21] compared to marathon running in well-trained males[23], may contribute to the equivocal evidence relating to GLUT-4 content and glycogen resynthesis.

Furthermore, Asp et al[22] determined the effects of a marathon race on two forms of glycogen, acid-soluble macroglycogen and acid-insoluble proglycogen. The study also examined the glycogen accumulation pattern in different types of muscle fibres. Six well-trained male runners participated in a marathon race. Muscle biopsy samples were obtained from the vastus lateralis muscle before the marathon, 15 minutes after the marathon, and at one, two, and seven days after the marathon. Muscle glycogen and macroglycogen concentrations were significantly reduced immediately after the marathon race, and remained so for up to two days after the marathon. Proglycogen concentration was significantly reduced immediately after the marathon race, and for 24 hours after the marathon. Muscle glycogen, macroglycogen, and proglycogen concentrations had all returned to pre-race values by day seven after the marathon. These findings suggest that a greater fraction of macroglycogen was utilised during the marathon, compared to proglycogen.

In addition, glycogen accumulation patterns revealed selective glycogen depletion in type I and type IIa muscle fibres, compared to type IIb muscle fibres. It was hypothesised that the primary reliance and metabolic demand on type I and type IIa muscle fibres during the marathon may be associated with calcium (Ca^{2+}) accumulation within the muscle cells, both during and after the marathon race. Increased cytoplasmic concentrations of calcium may stimulate glycogen phosphorylase activity, thereby increasing glycogen catabolism[22].

Tuominen et al[642] determined the effects of a marathon run on the insulin sensitivity and lipid oxidation in 19 male runners. It was established that there was a 12% reduction in glucose disposal, and a 43% reduction in the rate of glucose oxidation after the marathon run and 24 hours after the marathon run, compared to control group values. Muscle glycogen content was 37% lower, glycogen synthase fractional activity was increased by 56%, and there was a 55% increase in lipid oxidation, compared to control group values.

In addition, during euglycemic-hyperinsulinemic clamp, whole body glucose disposal was decreased by 12%, there was a 36% reduction in glucose oxidation rate, and the rate of lipid oxidation was 10-fold greater, compared to control group values. After the marathon, significant positive correlations were observed between muscle glycogen content and lipid oxidation, between muscle glycogen content and maximal aerobic power, and between basal lipid oxidation and maximal aerobic power[642].

Therefore, after the marathon the reduction in the glucose oxidation rate was associated with a reduction in oxidative glucose metabolism, compared to non-oxidative glucose metabolism. Furthermore, the contribution of lipid oxidation in energy expenditure appeared to increase in proportion to the level of physical fitness. It was theorised that these adaptations of fuel homeostasis may contribute to the maintenance of physical performance after prolonged exercise[642].

Kirwan et al[342] investigated the effects of an eccentric exercise bout, consisting of a 30-minute downhill run (-17% gradient) at approximately 60% of maximum oxygen consumption, on insulin resistance in untrained male and female volunteers. Insulin resistance was also assessed during a concentric exercise bout, consisting of a 30-minute cycle at approximately 60% of maximum oxygen consumption, and a control session, where no exercise was performed. An ongoing insulin resistance was observed for up to 48 hours after the eccentric exercise bout, with a 37% reduction in insulin-mediated whole body glucose disposal.

It was postulated that the decreased glucose uptake following exercise-induced muscle damage may be related to decreased insulin binding to skeletal muscle, and altered glucose transporter translocation in the plasma membrane. The low muscle glycogen concentrations during the recovery period were attributed to either a decreased uptake of glucose through the disrupted sarcolemma in the damaged cells, or to an increased insulin resistance[339].

An alternative suggestion is that exercise-induced muscle damage results in an infiltration of inflammatory cells to the damaged muscle. The inflammatory cells have a large affinity for glucose oxidation, and release a factor that stimulates glucose oxidation and lactate production by the surrounding muscle cells. These processes appear to result in a competition between the inflammatory cells and the glycogen-depleted muscle fibres for blood glucose[156]. However, this theory is speculative, and requires further investigation.

Two different hypotheses have been proposed to explain the initial events in exercise-induced muscle damage. The mechanical stress model is based on mechanical disruption of the muscle cell initiating exercise-induced muscle damage, whereas the metabolic stress model is based on the disturbance of metabolic function during the initial events in exercise-induced muscle damage. Following exercise-induced muscle damage, disordered mechanical or metabolic function may be associated with a loss of calcium homeostasis, leading to increased calcium concentrations, and the activation of numerous calcium-dependent proteolytic and phospholipolytic pathways, resulting in exercise-induced muscle damage[371]. The potential mechanisms underlying the mechanical stress model have been discussed in Chapter 2. This review will therefore focus on the metabolic stress model, and the metabolic effects of exercise-induced muscle damage.

7.3 METABOLIC STRESS MODEL

The metabolic stress model proposes that the initial events in exercise-induced muscle damage may be related to metabolic deficiencies in the active muscle. In addition, these metabolic deficiencies may be associated with an increased susceptibility to mechanical stress[17;371;626].

The findings of Warhol et al[656] support the theory that the mechanism of exercise-induced muscle damage during marathon running may be predominantly metabolic, rather than mechanical. In particular, myofibrillar alterations occurred in muscle fibres depleted of glycogen and lipid. In addition, glycogen repletion correlated with the restoration of mitochondrial architecture and the repair of sarcomere damage.

Furthermore, there are equivocal findings relating to GLUT-4 content and glycogen resynthesis. GLUT-4 content was decreased following lengthening muscle actions in untrained males[21], whereas GLUT-4 content was not disturbed following marathon running in well-trained males[23]. These findings support potential differences in the metabolic effects of exercise-induced muscle damage in relation to mechanical and metabolic stress[626].

There is also some evidence to suggest that supplementation during exercise, specifically the use of beverages containing a mixture of carbohydrate and protein, may assist in the prevention of exercise-induced muscle damage. It is theorised that these supplements may increase the amount and availability of carbohydrate and protein to the active muscle, thereby potentially reducing some of the metabolic stress experienced during the damaging bout of exercise[570].

The main argument against the metabolic stress model is the fact that exercise-induced muscle damage is more commonly associated with lengthening muscle actions, compared to shortening muscle actions. Lengthening muscle actions are characterised by a reduction in motor unit recruitment[54] and an increase in force production, compared to shortening muscle actions[215]. Therefore, the individual muscle fibres may be subjected to increased mechanical stress during lengthening muscle actions, which may result in cross-bridge failure and mechanical disruption. In addition, the metabolic cost of lengthening muscle actions is less than that of isometric and shortening muscle actions[17].

However, the mechanical stress model cannot provide an explanation for the occurrence of exercise-induced muscle damage in endurance cyclists, where exercise consists of predominantly shortening muscle actions[346;570;626]. In addition, similar structural muscle damage has been observed in metabolic disorders. These findings suggest that muscle damage may occur independently to mechanical overload[17].

7.3.1 DELAYED ONSET MUSCLE SORENESS AND PLASMA CREATINE KINASE ACTIVITY

The experimental protocols predominantly used to induce muscle damage may be categorised according to primarily mechanical stress (high-force eccentric protocols such as maximal contraction of the elbow flexors, drop jumps, and bench stepping)[20;21;156;342;482;498], or metabolic stress (for example, downhill running, and endurance running and cycling)[22;23;284;587;642;656]. These mechanical and metabolic stress protocols demonstrate very different patterns of plasma CK activity. For example, after downhill running, where the stress in primarily metabolic, plasma CK activity usually peaks between 12 to 24 hours after exercise[78;99;125;133].

Conversely, after high-force eccentric exercise protocols, such as maximal contraction of the elbow flexors, where the stress is predominantly mechanical, the increase in plasma CK activity does not begin until approximately 48 hours after exercise, with peak plasma CK activity occurring only between four to six days following the eccentric exercise bout[133;135;482;483;489].

Differences have also been observed in the pattern of delayed onset muscle soreness after exercise-induced muscle damage. Following mechanical stress exercise protocols, delayed onset muscle soreness generally peaks between 24 and 48 hours after exercise[482;485;489], and may remain elevated for up to nine days after the damaging bout of exercise. In contrast, following metabolic stress exercise protocols, delayed onset muscle soreness usually peaks 24 hours after exercise, and subsides within seven days after the exercise bout[78;125].

It may be hypothesised that the differences in plasma CK activity and delayed onset muscle soreness in response to exercise-induced muscle damage may be related to differences in the training status of subjects and the repeated bout effect[151;428;429]. It may also be proposed that alterations in the neural, mechanical, and cellular properties of the musculoskeletal system may be related to the protective adaptations of the repeated bout effect[428;429].

7.3.2 REPEATED BOUT EFFECT

Neural adaptations associated with the repeated bout effect may include a more efficient recruitment of motor units, increased recruitment of type I muscle fibres, activation of a larger motor unit pool, a more even distribution of workload over the active fibres, increased motor unit synchronisation, and improved use of synergist muscles[244;428;429;431;657].

Mechanical adaptations may occur at the level of the cytoskeleton and myofibril, the muscle fibre, and the whole muscle[398;402;428;429;612], and include increases in passive and dynamic stiffness[539;553]. The alterations in stiffness have been attributed to increased tendon or cross-bridge stiffness[539], or cytoskeletal adaptations in order to maintain sarcomere alignment and structure[553].

In addition, it is theorised that cellular adaptations associated with the repeated bout effect may include strengthening of the cell membrane[137], removal of select populations of weak fibres or sarcomeres following the initial muscle damage[16;99;407], and the longitudinal addition of sarcomeres[397].

Morgan[449] theorised that the longitudinal addition of sarcomeres following an initial bout of eccentric exercise would be associated with a reduction in sarcomere strain. A decrease in sarcomere strain would facilitate the overlapping of myofilaments, thereby reducing the extent of sarcomere "popping", and limiting the subsequent cellular disruption. Furthermore, Clarkson and Tremblay[137] proposed that strengthening of the sarcolemma or the sarcoplasmic reticulum may decrease the extent of sarcolemmal disruption following eccentric exercise, preventing the calcium influx, and thus minimising the subsequent loss of calcium homeostasis and cellular disturbance.

It may therefore be suggested that the repeated bout effect may be associated with neural, mechanical, and cellular adaptations that limit the mechanical stress of exercise-induced muscle damage, but that do not provide protection from the metabolic stress of exercise-induced muscle damage. However, this theory is speculative, and requires further investigation.

7.3.3 PROPOSED MECHANISMS FOR ALTERED METABOLIC FUNCTION FOLLOWING EXERCISE-INDUCED MUSCLE DAMAGE

7.3.3.1 Calcium concentrations

A disturbance in calcium homeostasis occurs during the initial phase of exercise-induced muscle damage, through the disruption of the sarcoplasmic reticulum release and reuptake of calcium[47;603]. A reduction in the action of calcium-activated adenosine triphosphatase (Ca^{2+}-ATPase) in the sarcoplasmic reticulum or sarcolemma may be a potential mechanism for metabolic muscle damage. This would compromise the removal of calcium, resulting in the elevation of cytosolic concentrations of calcium, leading to a cascade of metabolic events resulting in muscle fibre degeneration[17]. In support of this theory, Duncan[192] demonstrated that Ca^{2+}-ATPase inhibition was associated with rapid ultrastructural muscle damage.

The subsequent increases in intracellular calcium concentrations are thought to contribute to the progression of exercise-induced muscle damage. Increased calcium stimulates calcium-sensitive phospholipase A_2, which leads to an alteration in the permeability of the sarcolemma, through the production of leukotrienes and prostaglandins. This results in the leakage of intramuscular enzymes, such as creatine kinase[15;239].

In addition, the activated phospholipase A_2 may attack mitochondrial and other membrane phospholipids, giving rise to lysophospholipids and free fatty acids. Lysophospholipids will disrupt membrane lipid organisation, and free fatty acids may have a detergent action, leading to membrane damage. Arachidonic acid may be among the free fatty acids liberated during this process, and this may promote the production of reactive oxygen species by the mitochondria[239].

Increased calcium concentrations may also activate the non-lysosomal cysteine protease calpain[47]. It is theorised that calpain may initiate skeletal muscle protein breakdown, inflammation, and regeneration following exercise-induced muscle damage[603]. Specifically, calpain is thought to be involved in proteolysis, and cleaves a variety of protein substrates, including cytoskeletal and myofibrillar proteins[47], such as desmin[47;94;284]. Calpain may also be involved in the disturbance of mitochondrial function[609].

Furthermore, increased calcium concentrations and the subsequent inflammatory cascade may also be linked to increased production of reactive oxygen species and the release of lysphospholipids, leading to lipid peroxidation[15]. Elevated calcium concentrations may also be associated with a disruption of the excitation-contraction coupling process, potentially reducing the maximal isometric force. Increased calcium also results in a transient shortening of the muscle fibres, with a subsequent increase in resting tension[254].

7.3.3.2 Muscle temperature, pH, and adenosine triphosphate (ATP) concentrations

Lengthening muscle actions are associated with higher local muscle temperatures, compared to shortening muscle actions[173;178]. Increased temperature, particularly above 38 ºC, is associated with uncoupling of the calcium-activated ATPase activity from calcium transport by the sarcoplasmic reticulum, and may also be related to alterations in the fluidity of the lipid membrane surrounding the ATPase pump. These factors may both limit the reuptake of calcium by the sarcoplasmic reticulum[94].

The increase in hydrogen ions (H^+), or the reduction in pH that occurs during fatiguing exercise also influences the reuptake of calcium by the sarcoplasmic reticulum. It is theorised that the hydrogen ions may compete with the calcium ions for the calcium binding site on the ATPase pump[94;386]. This may reduce the capacity for calcium release from the cell through ATPase pumps[14;633]. Furthermore, a reduction in the rate of calcium pumping by the sarcoplasmic reticulum may occur as a result of reductions in local ATP concentrations, or the free energy from ATP hydrolysis due to increased adenosine diphosphate (ADP) concentrations[94].

In addition, during physical activity, metabolic flux through the glycolytic and oxidative pathways is increased to match the rate of ATP synthesis to the rate of ATP hydrolysis. However, muscle activity may be associated with some reductions in the concentration of ATP. It may be hypothesised that extremely low concentrations of ATP may the related to the development of exercise-induced muscle damage, particularly in the presence of severe glycogen depletion[363].

Therefore, further elucidation regarding the proposed underlying mechanisms for altered metabolic function following exercise-induced muscle damage is necessary. The alterations in biomechanical and neuromuscular function associated with endurance training and exercise-induced muscle damage have been reviewed in Chapter 2. This review will now consider the metabolic consequences of endurance training and exercise-induced muscle damage.

7.4 ALTERATIONS IN METABOLIC FUNCTION ASSOCIATED WITH ENDURANCE TRAINING

7.4.1 SUBSTRATE METABOLISM

Endurance-trained athletes have a slower rate of depletion of muscle glycogen stores during submaximal exercise, compared to untrained subjects[271]. Endurance training is also associated with a reduction in the production, uptake, and oxidation of plasma glucose during moderate and intense exercise[142;143]. The reduction in carbohydrate utilisation is linked to a proportional increase in fat oxidation[271].

The early training-induced shift in substrate selection may be related to an improved muscle respiratory capacity that results from increased mitochondrial density[159]. Mitochondria from endurance-trained muscle also have an increased ability to produce energy at higher concentrations of free fatty acids.

Therefore, at specific exercise intensities, trained muscles are less dependent on carbohydrate metabolism, compared to untrained muscles. Subsequently, fat is more readily available as a source of fuel at higher exercise intensities. There is also a corresponding reduction in hydrogen ions, a by-product of carbohydrate metabolism[316;334], and muscle contractility is preserved[313;316;418]. In addition, muscle glycogen stores are conserved[109;418].

However, other factors such as a greater supply of fat due to an increase in intramuscular triglyceride concentration[271], or morphological adaptations such as an increased recruitment of active muscle mass[157], may be associated with subsequent adaptations in substrate utilisation following intensified training in well-trained athletes[271].

7.4.2 OXIDATIVE AND GLYCOLYTIC ENZYMES

Many of the adaptations associated with endurance training may be related to alterations in skeletal muscle oxidative capacity[303;527]. There are significant increases in the size and number of skeletal muscle mitochondria following endurance training[338].

There is also a simultaneous increase in mitochondrial enzyme content, particularly in those enzymes associated with fatty acid metabolism, and the shuttle systems that transport hydrogen ions into the mitochondria for utilisation in the respiratory chain[316;643]. These changes occur in the presence of increased ATP demand and supply during exercise. Other training-related adaptations include an increased maximum rate of ATP production, and improved ATP-adenosine diphosphate (ADP) homeostasis. It is theorised that the activation of different components of the oxidative phosphorylation system may be related to the behaviour of calcium ions[358].

Activation of the mitogen-activated protein kinase (MAPK) signalling cascade may be associated with the regulation of many of the exercise-induced adaptations in skeletal muscle[689]. Adenosine monophosphate (AMP)-activated protein kinase (AMPK) may also down-regulate genes involved in the glucose-signalling system in hepatocytes[685], and up-regulate genes associated with glucose uptake and substrate metabolism in skeletal muscle[682]. AMPK may also be related to the acute increase in GLUT-4 translocation following exercise, and the chronic increase in mitochondrial enzyme activity following exercise[681;682].

Furthermore, peroxisome proliferator receptor-γ co-activator-1α (PGC-1α) has been linked to the coactivation of multiple mitochondrial transcription factors[291], and therefore may be an important regulator of mitochondrial content in skeletal muscle. PGC-1α may also be associated with the regulation of aerobic metabolism, mitochondrial architecture, and type II to type I muscle fibre transformation[141;531;532;627]. The exercise-induced up-regulation of PGC-1α appears to occur in response to endurance training, but not to resistance training in skeletal muscle[140;531].

Endurance training also results in increased gene expression of metabolic proteins, including genes encoding enzymes and transporters involved in carbohydrate and fat metabolism, such as hexokinase and lipoprotein lipase. Moreover, the post-exercise recovery period is associated with increased mRNA abundance and transcription of various metabolic genes. The up-regulation of metabolic genes peaks in the initial hours following endurance exercise, and generally returns to resting levels within 24 hours after exercise[531;688].

7.4.3 ACID-BASE STATUS

The ability to transport lactate across the sarcolemma is significantly higher in endurance-trained subjects, compared to untrained subjects[529]. There also appears to be a positive relationship between the intensity of training, and lactate transporter values[530]. In addition, the relative increase in the proportion of type I muscle fibres that is observed in endurance-trained athletes, is also associated with a relative increase in lactate transport capacity[533].

7.5 ALTERATIONS IN METABOLIC FUNCTION ASSOCIATED WITH EXERCISE-INDUCED MUSCLE DAMAGE

7.5.1 INSULIN SENSITIVITY

GLUT-4 is a primary glucose transporter protein, and is stored in intracellular vesicles that are translocated to the cell membrane when additional glucose uptake is required. Translocation occurs in response to insulin secretion or muscle contraction[82]. Insulin secretion stimulates GLUT-4 translocation through the phosphatidylinositol 3-kinase pathway[250], whereas contraction-induced stimulation of GLUT-4 translocation may occur through the adenosine monophosphate-kinase pathway[250;626].

A single session of exercise may be associated with an increase in insulin sensitivity that may persist for several hours or days after the exercise bout[108], provided that the exercise bout does not induce muscle damage[342]. It is theorised that the enhanced insulin sensitivity following an exercise bout may be related to a reduction in muscle glycogen concentration[108].

Current literature provides equivocal evidence regarding improvements in insulin sensitivity following endurance training. Although many studies have reported improvements in insulin sensitivity after endurance training, subjects were often tested between 24 and 48 hours after a training session, thereby confounding the interpretation due to the profound effect of acute exercise on insulin sensitivity.

Dela et al[181] observed improvements in insulin sensitivity and oxidative capacity following prolonged endurance training. However, it was established that insulin sensitivity returned to untrained levels within a few days after the cessation of training, despite a persistent increase in oxidative capacity. In contrast, Kirwan et al[341] determined that regular exercise training was associated with improved insulin activation of insulin receptor substrate 1. This was related to increased activation of the phosphatidylinositol 3-kinase pathway, thereby indicating that the cumulative effects of regular exercise may be associated with a sustained improvement in insulin sensitivity.

Exercise-induced muscle damage may be associated with a reduction in insulin sensitivity. Kirwan et al[342] observed an ongoing insulin resistance for up to 48 hours after an eccentric exercise bout, with a 37% reduction in insulin-mediated whole body glucose disposal. It was suggested that the decreased glucose uptake following exercise-induced muscle damage may be related to decreased insulin binding to skeletal muscle, and altered glucose transporter translocation in the plasma membrane.

The muscle glucose transporter GLUT-4 and cytokine responses have been examined as potential mechanisms for the reduction in insulin sensitivity following exercise-induced muscle damage. Asp et al[23] established that GLUT-4 content remained unchanged during the recovery period after the marathon, compared to pre-race values. This finding was contrary to a previous study that showed a 17% reduction in muscle GLUT-4 content after an eccentric exercise protocol[21]. The contrasting methods used to induce muscle damage, mainly lengthening muscle actions in untrained males[21] compared to marathon running in well-trained males[23], may contribute to the equivocal evidence relating to GLUT-4 content following exercise-induced muscle damage.

Cytokines appear to provide an important link between the immune and neuroendocrine systems[402;548;597]. It is theorised that a small group of cytokines, including interleukin (IL)-1, IL-2, IL-6, interferon, and tumour necrosis factor-α (TNF-α) may be the principle mediators of the inflammatory response[307;520;614;635]. del Aguila et al[179] demonstrated that TNF-α impairs insulin activation of insulin receptor substrate 1, and the phosphatidylinositol 3-kinase pathway.

Furthermore, del Aguila et al[180] observed impaired insulin activation of insulin receptor substrate 1, the phosphatidylinositol 3-kinase pathway, and protein kinase B following a 30-minute downhill run. There was also a significant relationship between TNF-α production and phosphatidylinositol 3-kinase activity.

It was therefore proposed that the reduction in insulin sensitivity following exercise-induced muscle damage may be related to an acute-phase response mediated by TNF-α, in response to disruption in cellular integrity after damaging exercise[340]. Alternatively, Steinacker et al[614] theorised that the reduction in insulin sensitivity during exhaustive exercise may be a protective mechanism to facilitate the maintenance of euglycaemia during exercise in glycogen-depleted conditions.

However, this theory does not provide a mechanism to explain the occurrence of insulin resistance after exercise-induced muscle damage where exercise is not exhaustive. It may also be suggested that glucose uptake into damaged muscle fibres may be limited by central or peripheral control mechanisms, to spare glucose for the intact, functional muscle fibres[626]. These theories remain speculative, and require further investigation.

7.5.2 GLYCOGEN METABOLISM

Intramuscular glycogen is an important energy source, particularly during endurance exercise[82]. Previous studies have demonstrated that increased muscle glycogen content may improve endurance capacity[282], and that the maintenance of muscle glycogen stores may enhance fatigue-resistance during endurance exercise[62]. There is also a large degree of inter-subject variability in muscle glycogen content at exhaustion[158;266]. In addition, pre-exercise muscle glycogen content is a local regulator of glycogenolysis[62;282;585;588]. The metabolic response to exercise may therefore be largely influenced by the starting muscle glycogen concentration[551].

During exercise, it is hypothesised that a direct metabolic signal from the active muscle may increase circulating norepinephrine and free fatty acid concentrations, and decrease circulating insulin concentrations, thereby stimulating lipid oxidation when muscle glycogen concentrations fall during exercise. Furthermore, neural or hormonal factors also determine the rate of lipid oxidation in response to changing muscle glycogen concentrations during exercise[665].

Numerous studies have established impairments in muscle glycogen concentration associated with exercise-induced muscle damage[20;21;23;156;284;342;498;587;656]. Muscle glycogen stores have been shown to be depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after a marathon[587]. The time taken to normalise muscle glycogen concentration after a race is thought to be 10 days or longer[498].

The mechanism of impaired muscle glycogen concentrations following exercise-induced muscle damage may be attributed to either a decreased uptake of glucose through the disrupted sarcolemma in the damaged cells, or to an increased insulin resistance[342]. Sherman et al[587] observed reductions in muscle glycogen concentrations for up to five days after a marathon. Glycogen synthase activity was reduced immediately after the marathon. Hexokinase activity was significantly elevated for up to five days after the marathon, and hexose monophosphate pathway enzyme activity was significantly reduced for up to seven days after the marathon.

It was proposed that the decrease in hexose monophosphate pathway enzyme activity may be associated with the alterations in glycogen synthase and hexokinase activity in an attempt to normalise muscle glycogen stores[587]. However, further studies are required to determine peripheral and central control mechanisms for muscle glycogen concentration following exercise-induced muscle damage.

7.5.3 MUSCLE FIBRE TYPE AND MUSCLE ENERGETICS

Several studies have reported selective damage to type II muscle fibres after lengthening muscle actions[80;95;211;227;229;231;324;384;388;427;651;652]. Fridén and Lieber[227;229;389] suggested that during the initial stages of lengthening, type II glycolytic fibres are instantaneously fatigued. These fibres are subsequently unable to regenerate ATP, enter a state of rigor, and undergo systematic mechanical disruption. In addition, structural differences between type I and type II muscle fibres may also predispose type II muscle fibres to selective damage. Type II muscle fibres are characterised by narrower Z-lines, reflecting a lower actin-myosin attachment, and thus a weaker sarcomere connection[227;229].

However, numerous studies have observed alterations in the metabolic profile of the damaged muscle after eccentric exercise protocols, which tend to indicate that there may be an increased reliance on type II muscle fibres compared to type I muscle fibres during the recovery period following exercise-induced muscle damage[20;22;242;587].

Sherman et al[587] established that muscle glycogen stores were depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after a marathon. However, the muscle glycogen stores that remained after the marathon were predominantly located in type II muscle fibres. Further, Asp et al[22] observed selective glycogen depletion in type I and type IIa muscle fibres, compared to type IIb muscle fibres.

In addition, Gleeson et al[242] reported an increased respiratory exchange ratio, higher blood lactate concentrations, and a tendency for submaximal oxygen consumption to be reduced following exercise-induced muscle damage. Tuominen et al[642] also demonstrated reductions in the basal glucose oxidation rate, glucose disposal, and the rate of glucose oxidation following a marathon. These findings may reflect an alteration in muscle fibre recruitment patterns, with an increased reliance on type II muscle fibres after eccentric exercise[242;642]. In contrast, O'Reilly et al[498] was unable to determine selective glycogen repletion in type I and type II muscle fibres following an eccentric cycling exercise bout.

It may be proposed that eccentric exercise may be associated with an increased reliance on non-oxidative metabolism, potentially as a result of compromised muscle oxidative function that may include mitochondrial dysfunction and impaired oxygen transport[654]. The disruption of the oxidative pathway for glucose metabolism may therefore be related to subsequent alterations in the metabolic profile of the damaged muscle. Possible mechanisms associated with alterations in the metabolic profile may include preferential recruitment of type II muscle fibres, or an increased relative contribution of type II muscle fibres to the metabolic cost[626].

Furthermore, damage to the oxidative pathway for glucose metabolism and a simultaneous increased reliance on non-oxidative metabolism may provide an alternative explanation for the prolonged depletion of glycogen following exercise-induced muscle damage[626].

It may be hypothesised that, if glycogen was being used as a preferential fuel source after damaging exercise, the reduction in glycogen concentration may reflect increased utilisation, rather than impaired repletion. Consequently, the reduction in insulin sensitivity following exercise-induced muscle damage may be due to impaired glucose oxidation[626].

Further studies are required to determine the underlying mechanisms and contributing factors to the alterations in the metabolic profile of damaged muscle.

7.5.4 MUSCLE OXIDATIVE METABOLISM

Current literature provides evidence to suggest that exercise-induced muscle damage may have long-term effects on muscle metabolism. Numerous studies have used magnetic resonance spectroscopy to establish the ratio between inorganic phosphate (Pi) and phosphocreatine (PCr) in resting muscle. An increase in the PCr: Pi ratio may indicate either an increase in the organic phosphate concentration possibly due to sarcolemmal disruptions, or an increase in the resting metabolic rate[425].

The PCr: Pi ratio in resting muscle may be elevated for up to 10 days following eccentric exercise protocols that induced muscle damage[395;396;425;557]. The PCr: Pi ratio may also be increased for between two to six hours during exercise at any intensity following exercise-induced muscle damage. The PCr: Pi ratio usually returns to baseline levels within one to two days after eccentric exercise[425].

In addition, previous research has demonstrated that lactate production is increased following exercise-induced muscle damage. Lactate release from the muscle of the lower limb increases at rest after eccentric exercise[20]. Increased blood lactate concentrations have also been observed following submaximal and maximal exercise bouts that caused muscle damage[241;242].

Potential mechanisms associated with higher blood lactate concentrations after eccentric exercise protocols may include impaired oxygen extraction from the blood by the active muscle due to muscle damage, increased intracellular calcium concentrations, increased intracellular pH, or increased activation of glycogen phosphorylase by catecholamines[149;150;241;242]. Alternatively, the rate of efflux of lactate from the active muscles may be increased due to increased membrane permeability during the inflammatory phase of exercise-induced muscle damage[466].

Conversely, Walsh et al[654] failed to determine any alterations in maximal respiration or respiratory control by ADP following a 30-minute eccentric cycling exercise protocol. However, no significant increases in plasma CK activity were observed after the eccentric cycling exercise protocol. It was therefore proposed that the exercise protocol was insufficient to induce muscle damage.

Collectively, these findings indicate that exercise-induced muscle damage may modify muscle energetics towards an increased reliance on non-oxidative metabolism, and therefore an increased relative contribution of the oxygen-independent glycolytic power system to ATP production. Potential mechanisms that may explain the shift towards non-oxidative metabolism following exercise-induced muscle damage include increased resting muscle oxygen utilisation due to muscle damage and the subsequent increased energy requirements of the repair process. There may also be decreased oxygen availability due to restricted diffusion and/or local blood flow, decreased maximal mitochondrial respiration, and decreased ADP sensitivity to mitochondrial respiration[654].

7.6 SUMMARY OF THE LITERATURE

Although this review has focused on the metabolic changes associated with exercise-induced muscle damage, it is known that the mechanical components also contribute to the development of symptoms. The relative contribution of mechanical and metabolic stress to the development of exercise-induced muscle damage should be considered in relation to the type of exercise, as there may be consequences related to the repair and adaptation process[626].

As discussed in Chapter 2, the physiological and neuromuscular responses to exercise-induced muscle damage are relatively well understood. This review provides equivocal evidence for the metabolic consequences of exercise-induced muscle damage. The underlying mechanisms responsible for these metabolic adaptations also require further elucidation.

Although the previous studies (Chapter 3 and Chapter 4) have established disturbances in the respiratory exchange ratio following the ultramarathon race, it is acknowledged that the respiratory exchange ratio only provides an indirect understanding of the metabolic adaptations that may occur in response to exercise-induced muscle damage.

In addition, little is known about the relationship between metabolic adaptations, running economy, and exercise-induced muscle damage, particularly in the recovery period following endurance running.

Therefore, the aim of the next study was to determine the effects of exercise-induced muscle damage and fatigue, induced by an ultramarathon, on the glucose oxidation rate and submaximal oxygen consumption in experienced ultramarathon runners.

CHAPTER EIGHT

STUDY FOUR: CHANGES IN SUBMAXIMAL OXYGEN CONSUMPTION AND GLUCOSE METABOLISM AFTER A 90 KM ULTRAMARATHON

8.1 INTRODUCTION

The focus of previous studies (Chapter 4 and Chapter 6) has been to identify possible underlying kinematic and neuromuscular mechanisms that could contribute to the reduction in submaximal oxygen consumption following an ultramarathon race. Although discrete kinematic and neuromuscular changes were observed in the presence of exercise-induced muscle damage and fatigue, it may be suggested that a mechanical model provides an incomplete explanation for the reduction in submaximal oxygen consumption which occurred within the four weeks after the race.

An increase in respiratory exchange ratio has been observed following the ultramarathon race, in both Chapter 3 and Chapter 4. Prior to these findings, Gleeson et al[242] reported an increase in respiratory exchange ratio, as well as a tendency for a reduction in submaximal oxygen consumption during submaximal cycling, in the presence of exercise-induced muscle damage.

However, the increase in respiratory exchange ratio was unexpected, particularly when considering the known adaptive changes that occur in response to endurance events, and exercise-induced muscle damage. Indeed, muscle glycogen stores have been shown to be depleted to 40% of pre-race levels in both type I and type II muscle fibres immediately after a marathon[587], and it is estimated that a period of approximately 10 days or longer is required for muscle glycogen concentrations to normalise after a race[498].

Furthermore, an ongoing insulin resistance has been demonstrated for 48 hours after exercise-induced muscle damage[342]. A reduction in glucose transporter proteins 4 (GLUT-4) has also been identified following exercise-induced muscle damage[242]. The prediction from these findings would be that the respiratory exchange ratio would be reduced during recovery from prolonged exercise, due to the development of a relative carbohydrate resistance.

There is conflicting evidence regarding the metabolic consequences of exercise-induced muscle damage[626]. Respiratory exchange ratio only provides an indirect understanding of the metabolic adaptations that may occur in response to exercise-induced muscle damage. It may therefore be theorised that the higher respiratory exchange ratio values may be associated with increased carbohydrate metabolism during the recovery period following the ultramarathon race and consequently, a reduction in submaximal oxygen consumption. However, the underlying mechanisms responsible for this proposed metabolic adaptation are unclear.

Therefore, the aim of this study was to investigate the effects of exercise-induced muscle damage and fatigue on submaximal oxygen consumption and glucose metabolism during the recovery period after a 90 km ultramarathon race in experienced ultramarathon runners.

Based on the results of Chapter 3 and Chapter 4, all tests after the ultramarathon race were conducted nine to 11 days later, to coincide with the time when the runners had expected reduced submaximal oxygen consumption, and in the absence of muscle pain and elevated plasma CK activity.

8.2 METHODS

8.2.1 SUBJECTS AND STUDY DESIGN

Twenty-three experienced endurance runners, similar to those recruited for the first study (Chapter 3, Section 3.2.1, page 114), were selected to participate in this study, which had a quasi-experimental design. A schematic diagram of the research design is shown in Figure 8.1. Due to the duration of the testing procedures for the familiarisation, maximal test, and submaximal tests, it was not possible to test all subjects on a single day. These tests were therefore conducted over a three-day period.

The time stamps (days) for the familiarisation, maximal test, and submaximal tests shown in Figure 8.1 reflect the midpoint of each testing period respectively. In addition, based on the data from the previous studies (Chapter 3 and Chapter 4), the submaximal test was conducted between days 9 to 11 following the ultramarathon race. This testing period was referred to as day 10 in the following sections.

Eleven runners, who participated in the Comrades marathon, were assigned to the experimental group. Twelve runners, who did not participate in the Comrades marathon, formed the control group. The study was granted ethical clearance by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town. The subjects were requested to avoid any medication, and strenuous training and racing, other than the 90 km race, for the duration of the study. Subjects were instructed to maintain the same diet and training regimen for 24 hours prior to testing. To facilitate adherence with instructions, subjects completed a training logbook for the duration of the study, and were questioned about compliance with instructions prior to testing. Testing occurred at a similar time (to within one hour) for each subject for the duration of the study.

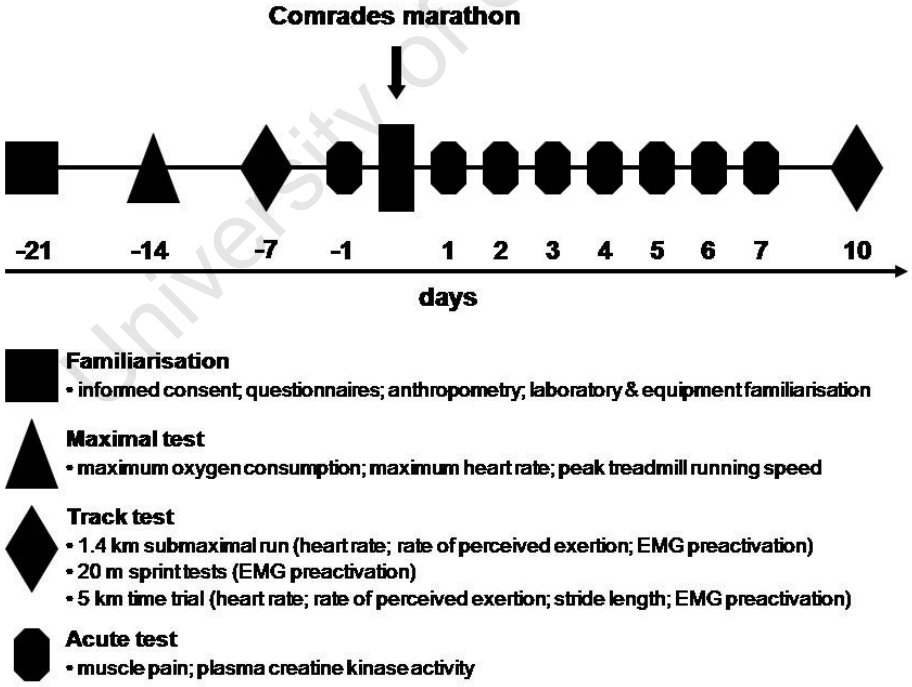

Figure 8.1: *Study design.*

8.2.2 FAMILIARISATION

During the first visit to the laboratory, three weeks before the ultramarathon race, subjects gave written consent after being informed about the demands of the study. The subjects completed questionnaires, and underwent an anthropometrical assessment, as described in Chapter 3 (Section 3.2.2, page 116).

The subjects were also familiarised with the laboratory equipment and testing protocols that would be used during the trial. This familiarisation process was conducted to reduce error associated with subjects performing unaccustomed exercise.

8.2.3 MAXIMAL TEST

Preliminary testing was conducted on all subjects two weeks before the ultramarathon race. A maximal treadmill test, as described in Chapter 3 (Section 3.2.2, page 116) was performed to determine maximum oxygen consumption (VO_{2max}), peak treadmill running speed (PTRS), and maximum heart rate (HR_{max}).

8.2.4 SUBMAXIMAL TEST

The submaximal test was conducted seven days before the ultramarathon race, and was repeated 10 days after the ultramarathon race (Figure 8.1). Testing occurred at a similar time (to within two hours) for each subject for the duration of the study. Laboratory conditions were standardised at a temperature of approximately 20 °C, and a relative humidity of approximately 60%.

8.2.4.1 U-^{14}C glucose infusion

20G Teflon cannulas with stopcocks were inserted into the antecubital vein of each arm. One cannula was used for the infusion of a sterile, pyrogen-free [U-^{14}C] glucose tracer dissolved in saline. The other cannula was cleared and kept patent with saline solution, to be used for later blood sampling during the 20-minute submaximal treadmill test.

At this time, an initial resting blood sample was taken for the determination of resting plasma glucose and lactate concentrations, and plasma CK activity. A 1.5 µCi of [U-^{14}C] bicarbonate bolus was immediately infused to avoid loss of $^{14}CO_2$ into the body bicarbonate pool[63;217]. Thereafter, a priming dose of 6 µCi [U-^{14}C] glucose was infused. This was followed by a constant infusion of [U-^{14}C] glucose at a rate of 0.17 µCi.min^{-1} for the duration of the submaximal test.

A 20-minute rest period followed the administration of the priming dose, for the equilibration of the glucose tracer prior to the start of the treadmill test. The total [U-^{14}C] glucose infusion for each submaximal test was 14.5 µCi. Therefore, each subject received a total of 29 µCi [U-^{14}C] glucose.

8.2.4.2 Muscle pain

Muscle pain was assessed during the 20-minute rest period following the administration of the priming dose of [U-^{14}C] glucose, prior to the treadmill test. Muscle pain was assessed subjectively using a multidimensional pain scale. Subjects were required to rate the pain in the quadriceps, hamstrings, and gastrocnemius muscles according to "*general pain at rest*", "*pain during activities of daily living*", "*pain during a passive stretch*", and "*pain when pressure was applied to the mid-belly of the muscle*". The methods of muscle pain assessment using a multidimensional pain scale have been previously described in Chapter 6 (Section 6.2.4.4, page 220).

8.2.4.3 Plasma creatine kinase activity

An initial resting 15 ml blood sample was taken from the subject's antecubital vein during the 20-minute rest period following the administration of the priming dose of [U-^{14}C] glucose, prior to the treadmill test. A 5 ml sample, for later analysis of plasma CK activity, was collected into a pre-chilled tube containing lithium heparin. The methods of blood sampling and storage, and the analysis of plasma CK activity have been previously described in Chapter 3 (Section 3.2.3, page 117).

8.2.4.4 Plasma glucose and lactate concentrations

An initial resting 15 ml blood sample was taken from the subject's antecubital vein during the 20-minute rest period, following the administration of the priming dose of [U-^{14}C] glucose, prior to the treadmill test. Two 5 ml samples, for later analysis of resting plasma glucose and lactate concentrations, were collected into pre-chilled tubes containing potassium oxalate and sodium fluoride. Further blood samples were collected every five minutes during the 20-minute treadmill test, for the determination of plasma glucose and lactate concentrations.

The samples were kept on ice until centrifugation. Samples were centrifuged at 3000 x *g* for 10 minutes at 4 °C upon completion of the submaximal test. Samples were stored at -20 °C until the analysis of plasma glucose and lactate concentrations. Blood glucose and lactate concentrations were determined using an automated glucose and lactate analyser (2300 STAT PLUS, YSI Incorporated, Ohio, USA).

8.2.4.5 Expired carbon dioxide

Expired carbon dioxide (CO_2) samples were collected every five minutes during the 20-minute treadmill test. The subjects were required to breathe into a 3L rubber bag through a one-way valve, and carbon dioxide samples were thus collected. The breath sample was then passed through a CO_2 trapping mixture. The CO_2 trapping mixture consisted of 1 ml of hyamine hydroxide in methanol, 1 ml of ethanol, and 2 drops of 1% phenolphthalein indicator. The expired air was bubbled through the trapping mixture until the solution became clear, at which point exactly 1 ml of CO_2 would have been absorbed. Following collection, 10 ml of scintillation cocktail (Aquasafe 500, Zinsser Analytic, Frankfurt, Germany) was added to the sample, which was stored for subsequent analysis.

8.2.4.6 20-minute treadmill test

Subjects warmed up in a similar way for each 20-minute treadmill test. The test started with the treadmill speed set at 10 km.h^{-1} and a 1% elevation. This speed was maintained for two minutes, and was then increased to the speed that coincided with 75% of the peak treadmill running speed (PTRS) for each subject. Each subject maintained this speed for 20 minutes.

During the 20-minute treadmill test, oxygen consumption (VO_2), respiratory exchange ratio (RER), heart rate (HR), and the rate of perceived exertion (RPE) were recorded, as previously described in Chapter 3 (Section 3.2.3, page 117), at 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 19.5 minutes. Blood samples, for the determination of plasma glucose and lactate concentrations, as well as plasma glucose specific activity, were taken at 5, 10, 15, and 19.5 minutes during the test. Expired CO_2 samples were also taken at 5, 10, 15, and 19.5 minutes during the test.

Unfortunately, due to an unforeseen delay in the delivery of [U-^{14}C] glucose to the laboratory, it was not possible to perform glucose oxidation measurements on all subjects during the designated post-ultramarathon race test period. Therefore, six control subjects were tested on a third occasion.

These subjects completed the submaximal test with all measurements, aside from those related to the measurement of plasma glucose oxidation rate, during the designated post-ultramarathon race test period. The six subjects then completed a third submaximal test with all measurements, including the measurement of plasma glucose oxidation rate, two weeks after the ultramarathon race.

8.2.4.7 Glucose oxidation rate

The assessment of glucose oxidation rate was performed according to the methods described by Clark et al[131]. Briefly, plasma glucose specific activity was determined after first deproteinising and driving off any ^{14}C-bicarbonate present in the plasma samples as $^{14}CO_2$. This was achieved by adding 1.5 ml of distilled H_2O to 0.5 ml of plasma, heating at 100 °C for five minutes, cooling in ice for 10 minutes, and then centrifuging at 4000 x *g* for 10 minutes. Thereafter, 10 ml of scintillation cocktail was added to each sample.

The activity of all CO_2 and plasma glucose samples was determined using a liquid scintillation counter (1500 Tri-Carb, Packard Instruments, Meriden, USA). The measured recovery was approximately 95% (range 93% to 97%). All measured activity readings were corrected to 100%. In the first 47 plasma samples analysed, both the glucose and lactate specific activities were determined after separation using an anion exchange resin (AG 1-X8, 100-200 mesh, chloride form, Bio-Rad, California, USA). However, subsequent analysis showed the lactate specific activity of the samples to be negligible and thus the separation process was discontinued.

Plasma glucose oxidation rates (R_{ox}) were calculated in grams per minute according to the following equation[131]:

$$R_{ox} = ([SA\ CO_2 \times 6]/SA\ glu) \times VCO_2 \times 1.35$$

SA CO_2 is the specific activity of CO_2 (dpm.mmol^{-1}) multiplied by six, as there are six carbon atoms per millimole ^{14}C-glucose. SA glu is the plasma glucose specific activity (dpm.mmol^{-1}). VCO_2 is the volume of CO_2 (L.min^{-1}), and 1.35 is the grams of glucose oxidized to produce 1 L CO_2.min^{-1}.

The glucose oxidation rates measured during the pre- and post-race 20-minute treadmill tests were then normalised to the baseline glucose oxidation rate obtained at five minutes during the pre-race 20-minute treadmill test. These data were normalised to reduce the effects of inter-subject variability.

8.2.5 ULTRAMARATHON RACE

Subjects in the experimental group completed a 90 km ultramarathon race. In this study, subjects completed the "*down*" run[145]. A race profile of the "*down*" run is included in Appendix I. Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at one-minute intervals for the duration of the ultramarathon race. Race heart rate data were averaged, and expressed as a percentage of maximum heart rate to provide an indication of exercise intensity during the ultramarathon race.

8.2.6 ACUTE TESTS

Daily muscle pain measurements, as described for the 20-minute submaximal treadmill test, and blood samples, for the analysis of plasma CK activity, were collected for one day before, and for seven days after the ultramarathon race as an estimate of muscle damage. The methods for the determination of plasma CK activity and muscle pain have been described in Chapter 3 (Section 3.2.5, page 118) and Chapter 6 (Section 6.2.4.4, page 220) respectively.

8.2.7 STATISTICAL ANALYSES

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in descriptive variables between the experimental and control groups were assessed using an independent t-test. Statistical significance for the two main effects of group and time, and the interaction (group x time) of all other variables were assessed using a two-way analysis of variance (ANOVA) with repeated measures. Tukey's *post hoc* comparisons were performed where necessary.

A Mann-Whitney U test was used to assess differences in the pain scores between groups. A Friedman's ANOVA and Kendall's concordance was used to assess differences in the pain scores within groups over time. All data are presented as the mean ± standard deviation. Statistical significance was accepted as $p < 0.05$.

In addition, effect sizes were assessed for the experimental and control groups glucose oxidation rate before and after the ultramarathon race. The effect size (d) was calculated using a spreadsheet downloaded from www.work-learning.com/effect_sizes.htm. The following criteria were used: < 0.15 = negligible effect, 0.15 – 0.40 = small effect, 0.40 – 0.75 = medium effect, 0.75 – 1.10 = large effect, 1.10 – 1.45 = very large effect, and > 1.45 = huge effect.

8.3 RESULTS

8.3.1 SUBJECTS

The descriptive characteristics of subjects are shown in Table 8.1, and the training and racing history of subjects are shown in Table 8.2. These subjects were also used in Chapter 6 (Study 3). There were no significant differences between groups for any of these variables. The subjects in this study were similar to those in the previous studies (Chapter 3, page 120 and Chapter 4, page 147), based on their general characteristics, and training and racing history.

The subjects in the experimental group completed the 90 km race in 602.5 ± 90.9 minutes. The average intensity (% HR_{max}) during the race was 80 ± 2%. Although this group displayed a relatively wide range of finishing times for the ultramarathon race, compared to the previous studies, the average race times and the intensity (% HR_{max}) during the race were similar to those reported in the previous studies (Chapter 3, page 121 and Chapter 4, page 148).

Table 8.1: *Descriptive characteristics of subjects in the experimental (n = 11) and control (n = 12) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Age (years)	42.2 ± 6.1	37.5 ± 5.9
Weight (kg)	77.4 ± 4.6	74.2 ± 14.9
Height (cm)	176.8 ± 7.0	177.9 ± 8.4
Sum of skinfolds (mm)	70.6 ± 13.6	68.8 ± 27.0
Body fat (%)	20.6 ± 3.2	18.5 ± 3.7
Maximum heart rate ($b.min^{-1}$)	180 ± 10	181 ± 10
VO_2max ($ml.kg^{-1}.min^{-1}$)	60.6 ± 5.2	63.0 ± 6.9
Peak treadmill running speed (PTRS) ($km.h^{-1}$)	18.0 ± 1.1	18.9 ± 1.4

Table 8.2: *Training and racing history of subjects in the experimental (n = 11) and control (n = 12) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	EXPERIMENTAL	CONTROL
Total years running	13.9 ± 7.3	12.5 ± 6.8
Pre-competition training distance ($km.wk^{-1}$)[$]	75.9 ± 7.4	66.7 ± 17.5
Average training distance ($km.wk^{-1}$)	51.4 ± 14.7	43.4 ± 14.7
Number of standard marathons (42 km)	21 ± 10	12 ± 17
Personal best 10 km time (min)	40.8 ± 3.5	39.5 ± 5.5
Personal best 42 km time (min)	201.4 ± 18.9	197.8 ± 25.5

[$] *Average training distance in the 3 months preceding the race*

8.3.2 MUSCLE PAIN

Subjective pain scores of "*general pain at rest*" and "*pain during activities of daily living*" are shown in Figure 8.2. Pain scores "*during a static stretch*", and "*pressure pain*" are shown in Figure 8.3. "*General pain*" was significantly higher in the experimental group compared to the control group in the quadriceps ($p < 0.002$) and hamstrings ($p < 0.04$) on day 1, and in gastrocnemius ($p < 0.04$) on days 2 and 3 after the ultramarathon. "*Daily living pain*" was significantly higher in the experimental group compared to the control group in the quadriceps on days 1,2 ($p < 0.004$), and 3 ($p < 0.03$), and gastrocnemius on days 2 and 3 ($p < 0.05$) after the ultramarathon (Figure 8.2).

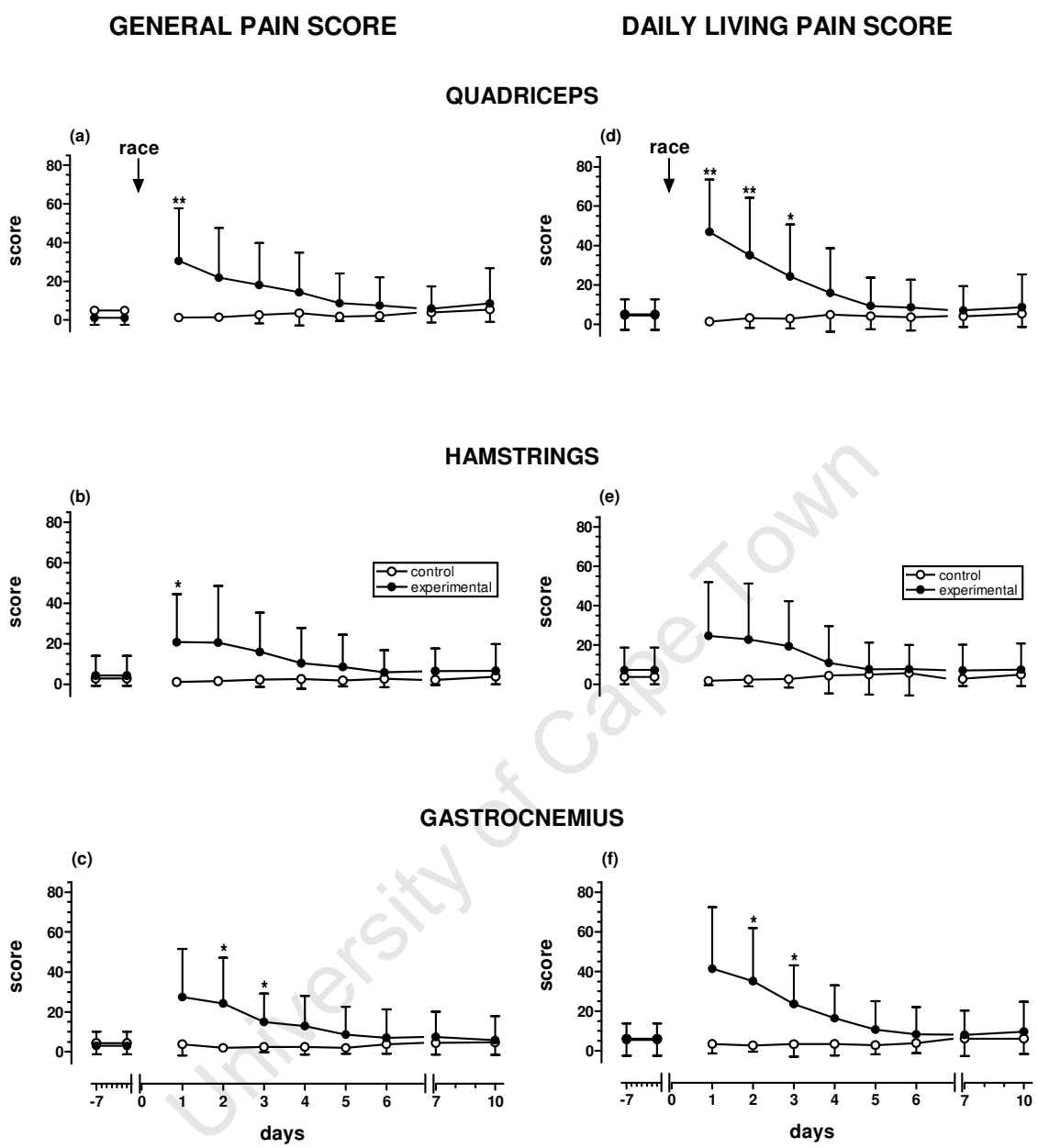

Figure 8.2: *Pain scores of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 12) groups. General pain scores in the (a) quadriceps, (b) hamstrings, and (c) gastrocnemius muscles, and daily living pain scores in the (d) quadriceps, (e) hamstrings, and (f) gastrocnemius muscles. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences (continued on next page).

Significant differences:

General pain:

(a) Quadriceps: ** experimental day 1 vs. control day 1 ($p < 0.002$)
(b) Hamstrings: * experimental day 1 vs. control day 1 ($p < 0.04$)
(c) Gastrocnemius: * experimental days 2 and 3 vs. control days 2 and 3 respectively ($p < 0.04$)

Daily living pain:

(d) Quadriceps: ** experimental days 1 and 2 vs. control days 1 and 2 respectively ($p < 0.004$)
* experimental day 3 vs. control day 3 ($p < 0.03$)
(f) Gastrocnemius: * experimental days 2 and 3 vs. control days 2 and 3 respectively ($p < 0.05$)

"*Stretch pain*" was significantly higher in the experimental group compared to the control group in the quadriceps on days 1 ($p < 0.004$) and 2 ($p < 0.04$) after the ultramarathon. "*Pressure pain*" was also significantly higher in the experimental group compared to the control group in the quadriceps on days 1 and 2 ($p < 0.01$), and gastrocnemius ($p < 0.04$) on day 1 after the ultramarathon (Figure 8.3). From day 4 onwards, for the duration of the experiment, there were no differences between groups (Figures 8.2 and 8.3).

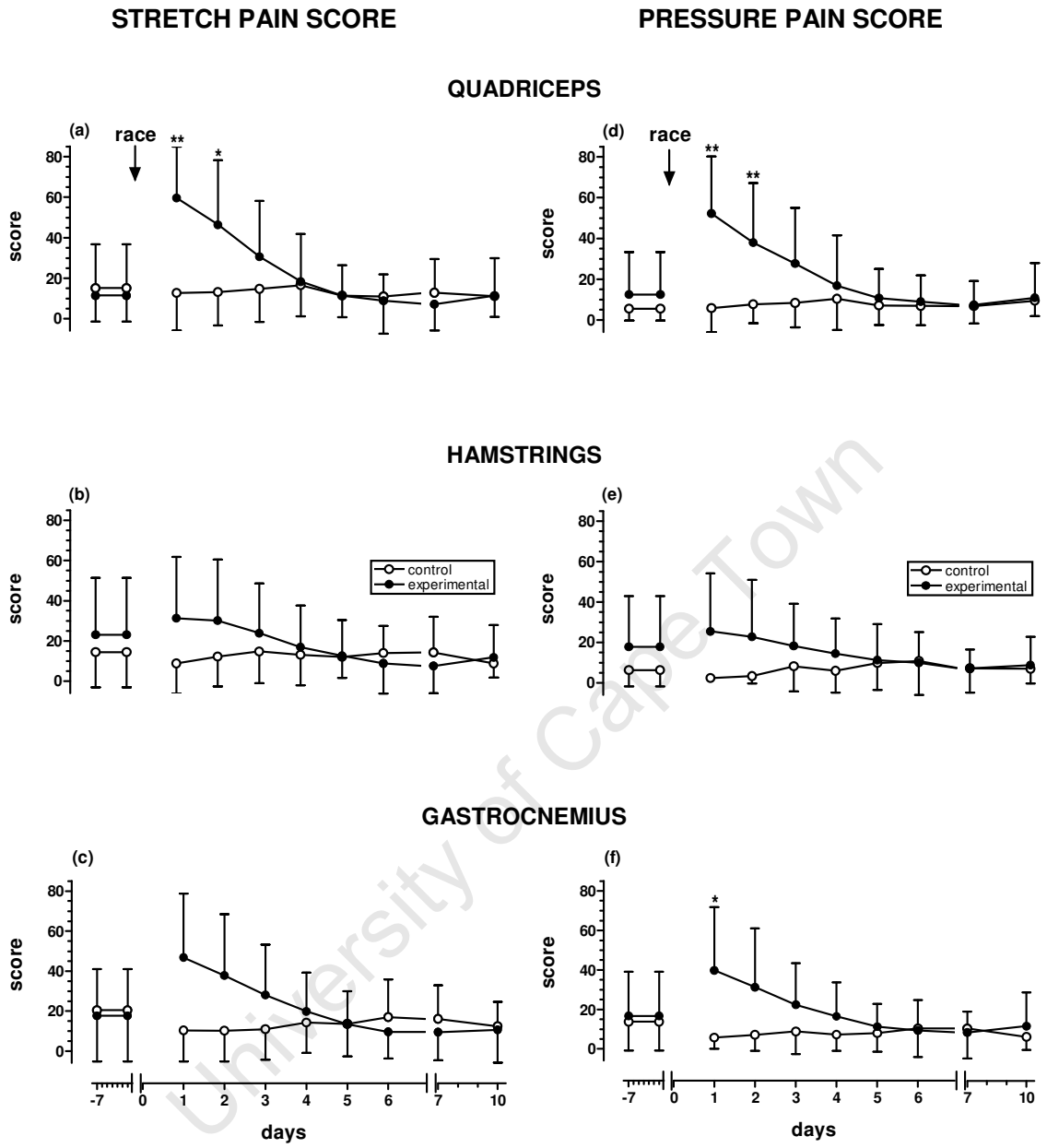

Figure 8.3: *Pain scores of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 12) groups. Stretch pain scores in the (a) quadriceps, (b) hamstrings, and (c) gastrocnemius muscles, and pressure pain scores in the (d) quadriceps, (e) hamstrings, and (f) gastrocnemius muscles. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences (continued on next page).

Significant differences:

Stretch pain:

(a) Quadriceps: ** experimental day 1 vs. control day 1 ($p < 0.004$)
* experimental day 2 vs. control day 2 ($p < 0.04$)

Pressure pain:

(d) Quadriceps: ** experimental days 1 and 2 vs. control days 1 and 2 respectively ($p < 0.01$)

(f) Gastrocnemius: * experimental day 1 vs. control day 1 ($p < 0.04$)

8.3.3 PLASMA CREATINE KINASE ACTIVITY

There was a significant interaction between groups over time for plasma CK activity ($F_{(8, 168)} = 16.25$; $p < 0.00009$) (Figure 8.4). The plasma CK activity was significantly higher in the experimental group on days 1, 2, 3, and 4 ($p < 0.007$) after the ultramarathon. From day 5 onwards, for the duration of the study thereafter, there were no differences between groups (Figure 8.4).

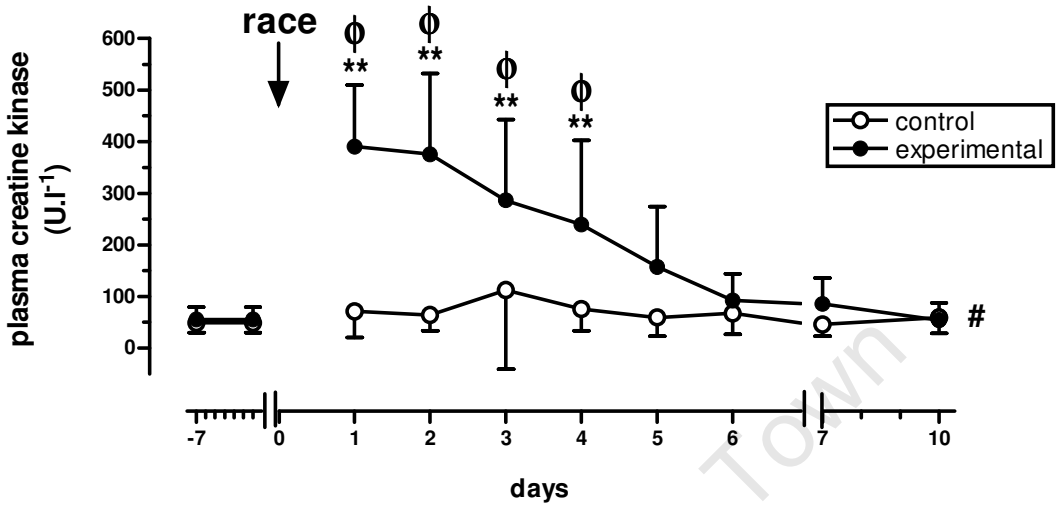

Figure 8.4: *Plasma creatine kinase (U.l^{-1}) of subjects in the experimental (-●-) (n = 11) and control (-o-) (n = 12) groups. Tests were conducted at 7 and 1 days before the race, daily for 7 days after the race, and at 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** experimental days 1, 2, and 3 vs. experimental days -7, -1, 4, 5, 6, 7, and 10 ($p < 0.007$)

** experimental day 4 vs. experimental days -7, -1, 6, 7, and 10 ($p < 0.003$)

ϕ experimental days 1, 2, and 3 vs. control days -7, -1, 1, 2, 3, 4, 5, 6, 7, and 10 ($p < 0.002$)

ϕ experimental day 4 vs. control days -7, -1, 1, 2, 4, 5, 6, 7, and 10 ($p < 0.003$)

interaction of group x time ($p < 0.00009$)

8.3.4 OXYGEN CONSUMPTION

The differences in oxygen consumption (VO_2) ($ml.kg^{-1}.min^{-1}$) during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.5. There were no significant differences in oxygen consumption between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(7, 133)} = 10.23$; $p < 0.00001$).

In the experimental group, there was a significant decrease in post-race oxygen consumption at 2.5 minutes during the 20-minute treadmill test, compared to pre-race values at 5, 7.5, 10, 15, 17.5, and 20 minutes ($p < 0.004$). There was also a significant decrease in post-race oxygen consumption at 12.5 and 15 minutes, compared to 15 minutes during the pre-race treadmill test ($p < 0.04$).

In the control group, during the pre-race 20-minute treadmill test, oxygen consumption was significantly decreased at 2.5 minutes, when compared to values at 7.5, 10, 12.5, 15, 17.5, and 20 minutes ($p < 0.04$). There was also a significant difference in post-race oxygen consumption at 2.5 minutes during the 20-minute treadmill test, compared to pre-race values at 17.5 and 20 minutes ($p < 0.006$). In addition, there was a significant decrease in pre-race oxygen consumption at 2.5 minutes, compared to 7.5, 10, 17.5, and 20 minutes during the post-race treadmill test ($p < 0.05$) (Figure 8.5).

There was a tendency for the average post-race oxygen consumption to be reduced in the experimental group, compared to pre-race values (50.2 ± 3.9 vs. 51.5 ± 4.2 $ml.kg^{-1}.min^{-1}$ respectively; $p < 0.09$). However, average post-race and pre-race oxygen consumption in the control group remained relatively unchanged (53.7 ± 5.0 vs. 53.9 ± 5.7 $ml.kg^{-1}.min^{-1}$ respectively).

Oxygen consumption

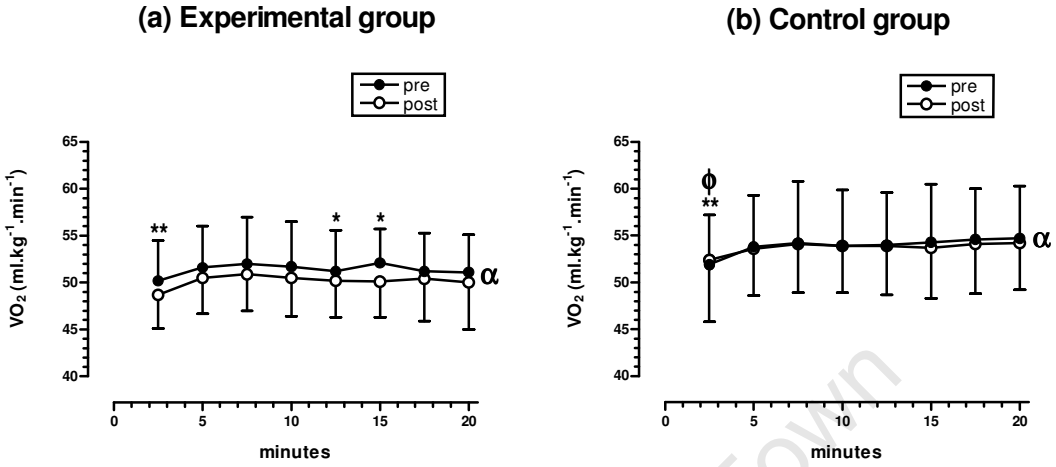

Figure 8.5: *Oxygen consumption (ml.kg^{-1}.min^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** post 2.5 minutes vs. pre 5, 7.5, 10, 15, 17.5, and 20 minutes ($p < 0.004$)
* post 12.5 and 15 minutes vs. pre 15 minutes ($p < 0.04$)
α main effect of time ($p < 0.00001$)

(b) Control group: ** post 2.5 minutes vs. pre 17.5 and 20 minutes ($p < 0.006$)
* pre 2.5 minutes vs. post 7.5, 10, 17.5, and 20 minutes ($p < 0.05$)
ϕ pre 2.5 minutes vs. pre 7.5, 10, 12.5, 15, 17.5, and 20 minutes ($p < 0.04$)
α main effect of time ($p < 0.00001$)

8.3.5 RESPIRATORY EXCHANGE RATIO

The differences in respiratory exchange ratio (RER) during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.6. There were no significant differences in respiratory exchange ratio pre-post the ultramarathon race. However, there was a significant interaction between groups over time for respiratory exchange ratio ($F_{(7, 133)} = 2.59$; $p < 0.02$).

In the experimental group, during the pre-race 20-minute treadmill test, respiratory exchange ratio was significantly increased at 5 minutes, when compared to values at 17.5 minutes ($p < 0.02$). There were also significant increases in post-race respiratory exchange ratio at 5, 7.5, 10, 12.5, 15, and 17.5 minutes, compared to pre-race values at 17.5 and 20 minutes ($p < 0.02$). In the control group, there were no significant differences in respiratory exchange ratio pre- or post- the ultramarathon race (Figure 8.6).

There was a tendency for the average post-race respiratory exchange ratio to be increased in the experimental group, compared to pre-race values (0.95 ± 0.05 vs. 0.93 ± 0.09 respectively; $p < 0.50$). However, in the control group the average post-race and pre-race respiratory exchange ratio remained unchanged (0.93 ± 0.03 vs. 0.93 ± 0.06 respectively).

Respiratory exchange ratio

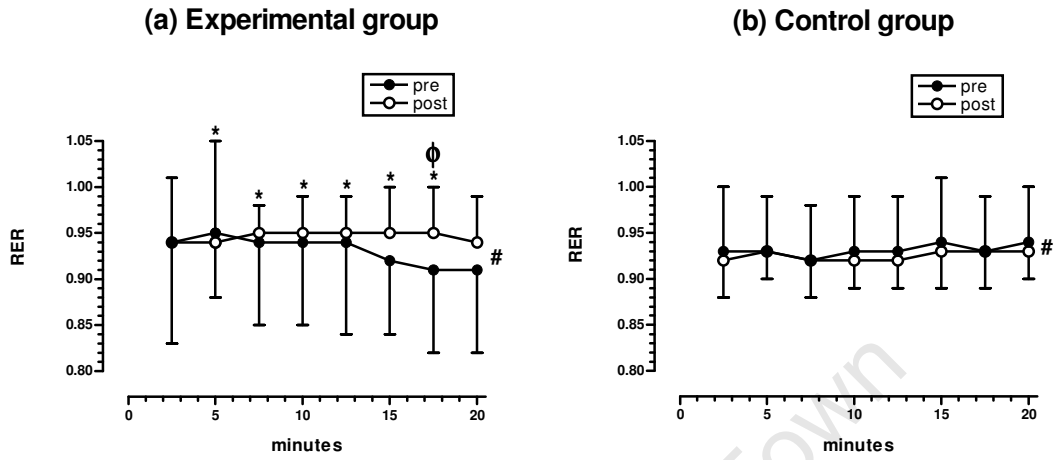

Figure 8.6: *Respiratory exchange ratio (RER) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: * pre 17.5 and 20 minutes vs. post 5, 7.5, 10, 12.5, 15, and 17.5 minutes ($p < 0.02$)
ϕ pre 5 minutes vs. pre 17.5 minutes ($p < 0.02$)
interaction of group x time ($p < 0.02$)

(b) Control group: # interaction of group x time ($p < 0.02$)

8.3.6 HEART RATE

The differences in heart rate ($b.min^{-1}$) during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.7. There were no significant differences in heart rate between groups. However, there were significant differences in heart rate pre-post the ultramarathon race ($F_{(1, 20)} = 4.51$; $p < 0.05$), and over time ($F_{(7, 140)} = 46.80$; $p < 0.00009$).

In the experimental group, post-race heart rate was significantly increased at 2.5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes, compared to pre-race values ($p < 0.05$). In the control group, post-race heart rate was significantly increased at 7.5, 10, 12.5, 15, 17.5, and 20 minutes, compared to pre-race values at 2.5, 5, 7.5, 10, and 12.5 minutes ($p < 0.05$) (Figure 8.7).

In addition, in both the experimental and control groups pre- and post- the ultramarathon race, heart rate increased over the duration of the 20-minute treadmill test, with significant increases in heart rate at 12.5, 15, 17.5, and 20 minutes, compared to values at 2.5 and 5 minutes ($p < 0.05$).

Furthermore, there was a significant interaction between groups over time for the average heart rate during the 20-minute treadmill test ($F_{(1, 21)} = 5.03$; $p < 0.04$). Average heart rate was significantly increased in the experimental group during the post-race 20-minute treadmill test, compared to pre-race values (165 ± 9 vs. 158 ± 13 $b.min^{-1}$ respectively; $p < 0.02$). Average heart rate tended to remain relatively unchanged in the control group, when comparing post-race to pre-race values (163 ± 9 vs. 160 ± 11 $b.min^{-1}$ respectively).

8.3.7 RATE OF PERCEIVED EXERTION

The differences in the rate of perceived exertion (RPE) during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.8. There were no significant differences in the rate of perceived exertion between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(7, 140)} = 18.61$; $p < 0.00009$).

In the experimental group, the post-race rate of perceived exertion was significantly increased at 7.5, 10, 12.5, 15, 17.5, and 20 minutes, compared to pre-race values at 2.5, 5, 7.5, 10, 12.5, 15, and 17.5 minutes ($p < 0.05$). In the control group, the post-race rate of perceived exertion was significantly increased at 15, 17.5, and 20 minutes, compared to pre-race values at 2.5 and 5 minutes ($p < 0.03$) (Figure 8.8).

In addition, in both the experimental and control groups pre- and post- the ultramarathon race, the rate of perceived exertion increased over the duration of the 20-minute treadmill test, with significant increases in the rate of perceived exertion at 15, 17.5, and 20 minutes, compared to values at 2.5 and 5 minutes ($p < 0.03$).

Heart rate

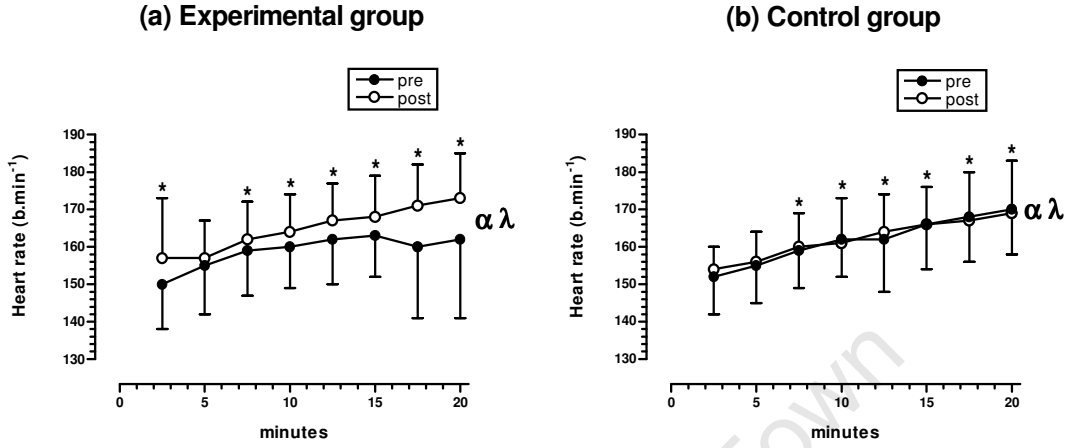

Figure 8.7: *Heart rate (b.min^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: * pre 2.5 – 20 minutes vs. post 2.5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes ($p < 0.05$)
α main effect of time ($p < 0.00009$)
λ main effect of pre-post ($p < 0.05$)

(b) Control group: * pre 2.5 – 12.5 minutes vs. post 7.5, 10, 12.5, 15, 17.5, and 20 minutes ($p < 0.05$)
α main effect of time ($p < 0.00009$)
λ main effect of pre-post ($p < 0.05$)

Figure 8.8: *Rate of perceived exertion (Borg scale) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(b) Experimental group: * pre 2.5 – 17.5 minutes vs. post 7.5, 10, 12.5, 15, 17.5 and 20 minutes ($p < 0.05$)
α main effect of time ($p < 0.00009$)

(c) Control group: * pre 2.5 and 5 minutes vs. post 15, 17.5, and 20 minutes ($p < 0.03$)
α main effect of time ($p < 0.00009$)

8.3.8 BLOOD LACTATE CONCENTRATION

Blood lactate concentrations during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.9. There were no significant differences in blood lactate concentrations between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(4, 64)} = 38.04$; $p < 0.00001$).

In both the experimental and control groups pre- and post- the ultramarathon race, the blood lactate concentrations increased over the duration of the 20-minute treadmill test, with significant increases at 15 and 20 minutes, compared to values at 0 and 5 minutes ($p < 0.05$) (Figure 8.9).

In addition, there was a tendency for the average post-race blood lactate concentration to be decreased in the experimental group, compared to pre-race values (3.10 ± 1.11 vs. 3.46 ± 1.62 respectively; $p < 0.06$). However, in the control group the average post-race and pre-race blood lactate concentrations remained relatively unchanged (2.85 ± 0.97 vs. 2.92 ± 1.03 respectively).

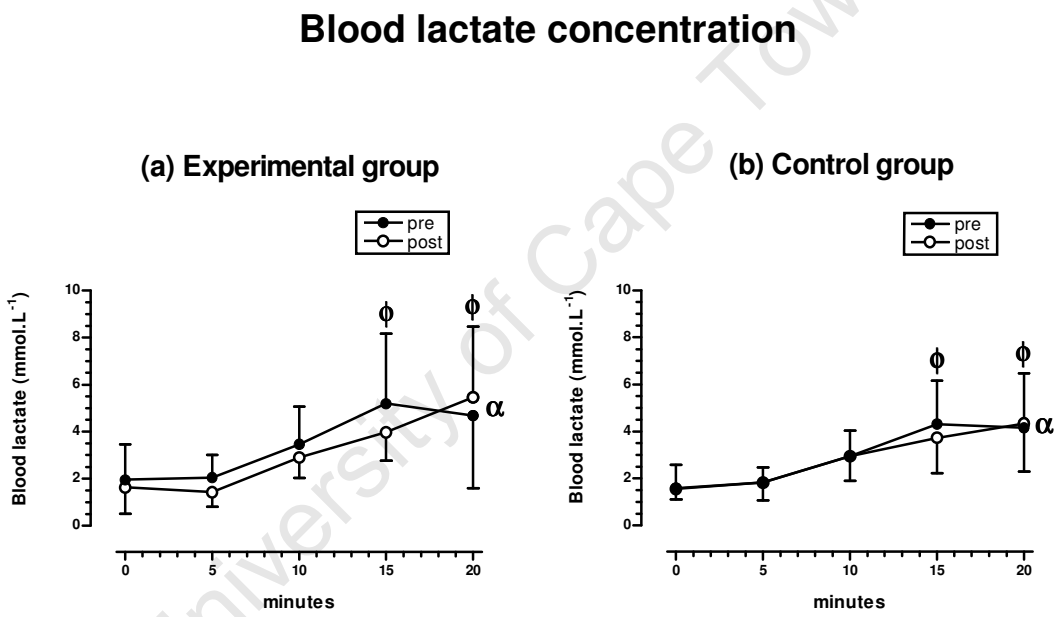

Figure 8.9: *Blood lactate concentration (mmol.L^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 0, 5, 10, 15, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group, and (b) Control group:

ϕ pre 0 and 5 minutes vs. pre 15 and 20 minutes ($p < 0.05$)

ϕ post 0 and 5 minutes vs. post 15 and 20 minutes ($p < 0.05$)

α main effect of time ($p < 0.00001$)

8.3.9 BLOOD GLUCOSE CONCENTRATION

Blood glucose concentrations during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Table 8.3. There were no significant differences in blood glucose concentrations between groups, pre-post the ultramarathon race, or over time.

Table 8.3: *Blood glucose concentration (mmol.L^{-1}) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 0, 5, 10, 15, and 20 minutes during the submaximal bout of exercise, (a) pre and (b) post the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

MINUTES	EXPERIMENTAL		CONTROL	
	(a) Pre	(b) Post	(a) Pre	(b) Post
0	4.80 ± 0.46	4.72 ± 0.48	4.99 ± 0.99	4.81 ± 0.28
5	4.50 ± 0.46	4.64 ± 0.54	4.82 ± 0.55	5.01 ± 0.57
10	4.56 ± 0.59	4.74 ± 0.54	4.38 ± 0.79	4.83 ± 0.65
15	4.98 ± 0.92	4.68 ± 0.67	4.80 ± 0.76	4.79 ± 1.30
20	5.44 ± 2.07	5.44 ± 1.92	5.24 ± 0.86	4.99 ± 1.38

8.3.10 GLUCOSE OXIDATION RATE

Glucose oxidation rates during the 20-minute treadmill test pre- and post- the ultramarathon race for subjects in the experimental and control groups are shown in Figure 8.10. There were no significant differences in the glucose oxidation rate between groups, or pre-post the ultramarathon race, however there was a significant difference in the measurement over time ($F_{(3, 45)} = 11.43$; $p < 0.00002$).

In the experimental group, the pre-race glucose oxidation rate was significantly increased at 20 minutes, compared to post-race values at 5, 10, and 15 minutes ($p < 0.002$), and at 15 minutes, compared to post-race values at 5 minutes ($p < 0.03$) (Figure 8.10).

There was a strong tendency for average post-race glucose oxidation rate to be decreased in the experimental group, compared to pre-race values (0.19 ± 0.08 vs. 0.29 ± 0.11 respectively; $p < 0.06$), representing a large difference ($d = 0.94$). However, in the control group the average post-race and pre-race glucose oxidation rates remained unchanged (0.32 ± 0.19 vs. 0.32 ± 0.13 respectively), representing a negligible difference ($d = 0$).

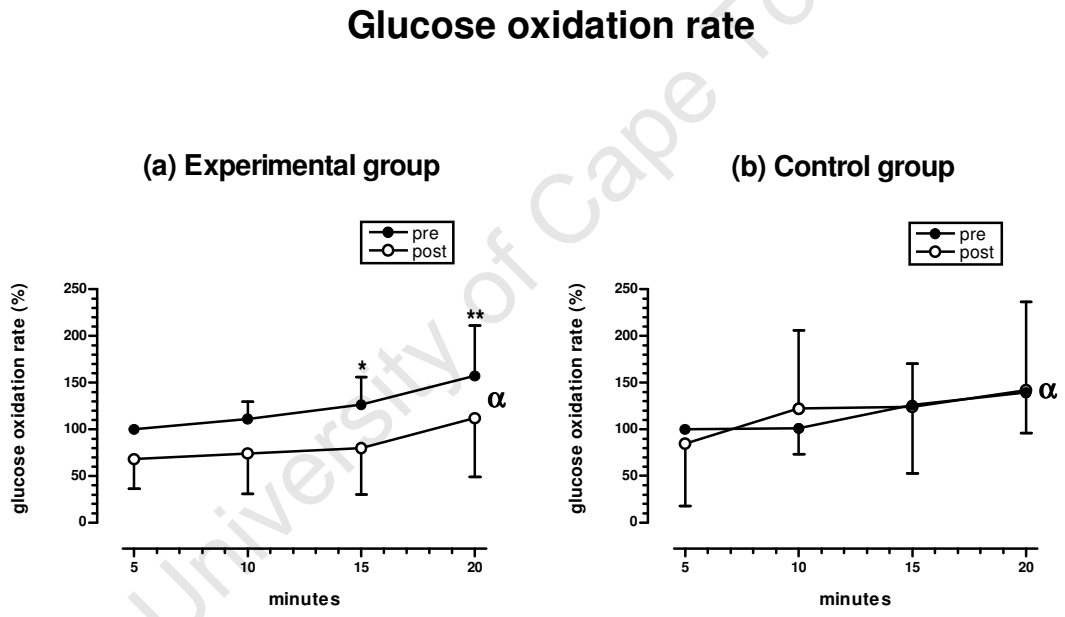

Figure 8.10: *Glucose oxidation rate (%) of subjects in the (a) experimental (n = 11) and (b) control (n = 12) groups at 5, 10, 15, and 20 minutes during the submaximal bout of exercise, pre (-●-) and post (-o-) the ultramarathon race. Tests were conducted 7 days before, and 10 days after the race. Data are expressed as mean ± SD.*

Significant differences:

(a) Experimental group: ** pre 20 minutes vs. post 5, 10, and 15 minutes ($p < 0.002$)
* pre 15 minutes vs. post 5 minutes ($p < 0.03$)
α main effect of time ($p < 0.00002$)

(b) Control group: α main effect of time ($p < 0.00002$)

8.4 DISCUSSION

As previously demonstrated in Chapter 3 and Chapter 4, the 90 km ultramarathon race induced muscle pain in the experimental group consistent with delayed onset muscle soreness. In this study, muscle pain remained significantly elevated in the experimental group for three days after the ultramarathon race (Figures 8.2 and 8.3), compared to the results presented in Chapter 4, where muscle pain remained significantly elevated for seven days after the ultramarathon race. The average exercise intensity during the race was similar in both studies. In addition, the race profile was almost identical in the two studies. It is acknowledged that the use of different assessment tools in the previous and current studies to determine the extent of muscle pain following the ultramarathon race does limit the comparison of muscle pain scores between the two studies. However, the difference in the duration of the pain response following the ultramarathon race between the two studies is somewhat unexpected.

It is recognised that the expression of average exercise intensity during the ultramarathon race as a percentage of maximum heart rate may mask differences in the rate of stretch shortening cycle exercise during the ultramarathon race. Although the average race times are similar between studies, there was a wide range of finishing times for the ultramarathon race in this study (602.5 ± 90.9 minutes), compared to the previous studies (Chapter 3 and Chapter 4). It may be proposed that differences in absolute running speed may be associated with differences in loading forces, and therefore the extent of exercise-induced muscle damage and delayed onset muscle soreness.

Plasma CK activity was significantly higher in the experimental group for four days after the ultramarathon race (Figure 8.4). Differences in plasma CK activity may also be observed in this study, compared to Chapter 4. In this study, plasma CK activity remained significantly elevated for four days after the ultramarathon race, with peak plasma CK activity of 390.4 ± 118.8 $U.l^{-1}$ on day one after the race. In Chapter 4, plasma CK activity was significantly elevated for two days after the ultramarathon race, with peak plasma CK activity of 2863 ± 2729 $U.l^{-1}$ on day 1 after the race. However, control group data were relatively similar between the two studies. In this study, the average plasma CK activity was 71 ± 54 $U.l^{-1}$, whereas in the previous study the average plasma CK activity was 86 ± 32 $U.l^{-1}$. These control group findings eliminate the concern of assay variability between the two studies.

The differences in plasma CK activity following downhill running and high-force eccentric exercise protocols is well-documented[133], however the underlying mechanism for the different responses is unclear. This is the first study to demonstrate a difference in the magnitude of plasma CK activity following similar ultra-endurance exercise.

Previous studies have identified a dissociation between CK activity and the extent of exercise-induced muscle damage[483;583], therefore the observed differences in the magnitude of plasma CK activity, particularly in relation to the extent of exercise-induced muscle damage, should be interpreted with caution. It is also recognised that the aforementioned issues relating to exercise intensity, duration, and loading forces during prolonged endurance exercise may contribute towards the differences in plasma CK activity between the two studies.

Interestingly, the total years of running and training distances were similar between the two studies. However, a greater number of standard marathons and faster personal best times for 10 km and 42 km were observed in the experimental group of the previous study, compared to the experimental group in this study. It may be theorised that an increased exposure to high mileage racing may modulate the duration of elevated plasma CK activity following an ultramarathon race. It may also be suggested that subjects in the previous study were exercising at a lower relative percentage of maximum, based on personal best performances over 10 km and 42 km distances. It may therefore be hypothesised that a combination of these factors may provide a protective effect for the increase in plasma CK activity following exercise-induced muscle damage associated with endurance running. However, these theories are speculative, and require further investigation.

One of the main findings of this study was that there was a strong tendency for submaximal oxygen consumption to be reduced in the experimental group following the 90 km ultramarathon race, compared to pre-race values (Figure 8.5). Similar reductions in submaximal oxygen consumption were observed in Chapter 3 and Chapter 4. This unusual finding has therefore been verified in three separate experiments conducted over the course of a few years, with control group measurements.

As previously discussed in Chapter 3 and Chapter 4, the mechanisms underlying the paradoxical reduction in submaximal oxygen consumption following the ultramarathon race may only be speculated. A possible theoretical explanation may include a change in muscle recruitment patterns, with an increase in type II muscle fibre recruitment following exercise-induced muscle damage[20;23;241]. A preferential use of type II muscle fibres may be associated with increased utilisation of oxygen-independent glycolytic pathways, and a reduction in the total number of motor units recruited to perform exercise at a fixed submaximal workload, thereby resulting in a reduction in submaximal oxygen consumption.

In addition, the optimum angle for torque generation shifts to the right following lengthening muscle actions, indicating a shift in the length-tension relationship towards longer muscle lengths for maximal force generation[322;669]. The shift in optimum length may be related to a reduction in active stiffness at shorter muscle lengths, potentially due to sarcomereogenesis[449;450;543]. In addition, the shift in optimum length may also be associated with an increase in passive stiffness at longer muscle lengths[553]. In terms of neuromuscular function, a more compliant musculotendinous unit has an increased ability to store elastic energy, whereas a stiffer musculotendinous unit is capable of producing a faster rate of force output.

During stretch shortening cycle exercise, increased compliance at the beginning of the stretch may be associated with improved storage of elastic energy. In addition, increased stiffness towards the end of the stretch shortening cycle may be related to improvements in the amount and rate of energy released. These adaptations may therefore enhance the action of the stretch shortening cycle[87]. It may be further postulated that improved efficiency of the stretch shortening cycle associated with the shift in optimum length following exercise-induced muscle damage may be associated with improvements in running economy. However, this theory is speculative, and requires further investigation.

It is also apparent that the reduction in submaximal oxygen consumption observed in this study was of a lesser magnitude than those changes demonstrated in Chapter 3 and Chapter 4. It is recognised that the wide range of finishing times for the ultramarathon race in this study may be associated differences in absolute running speed and loading forces, thereby potentially influencing the extent of exercise-induced muscle damage and associated neuromuscular and metabolic adaptations.

It may also be proposed that training state or endurance experience may possibly influence the submaximal oxygen consumption response to exercise-induced muscle damage[442]. The experimental group in this study had less endurance running experience, based on the number of standard marathons completed, compared to the experimental group in Chapter 4. It may be theorised that an increased exposure to high mileage racing may provide a protective effect for the exercise-induced muscle damage associated with endurance running, thereby modulating the submaximal oxygen consumption response to muscle damage. However, this theory is speculative, and requires further investigation.

In addition, the ultramarathon race may have provided an advantageous training stimulus. The reduction in submaximal oxygen consumption following the race may reflect improvements in running style and biomechanics, the optimisation of motor unit recruitment patterns, and the development of an efficient oxidative energy supply that may occur in association with endurance training[76;454;518]. Improvements in running economy have also been associated with high levels of running experience and training volume[319;454;515], which lends support to the hypothesis that an increased exposure to high mileage racing may provide a protective effect for the exercise-induced muscle damage. However, although this explanation is plausible, it does not consider the simultaneous effects of exercise-induced muscle damage following the race. Further studies are required to investigate these theories.

Significant changes in heart rate values were observed in both the experimental and control groups (Figure 8.7). As previously described, Lamberts et al[381] determined that a difference in heart rate of greater than 5 to 8 $b.min^{-1}$ reflects a meaningful difference in heart rate during controlled submaximal exercise. Therefore, in this study a meaningful difference in heart rate was detected in the experimental group at 17.5 and 20 minutes during the post-race 20-minute treadmill test, compared to pre-race values, as a difference of 11 $b.min^{-1}$ was observed in the experimental group at these two time points.

Previous studies have demonstrated increases in heart rate during submaximal cycling exercise 48 hours after performing stepping exercise which caused delayed onset muscle soreness[242], and for up to 25 days after an prolonged endurance running[120]. The lack of a consistent increase in post-race heart rate may be related to a potential increase in plasma volume due to the physiological stress of an ultramarathon race[310].

An increase in plasma volume would lead to an increase in stroke volume, and a subsequent reduction in heart rate at submaximal exercise intensities, thereby diminishing the measurable effects of any post-race elevation in heart rate[120]. Additional studies are required to determine the duration of a meaningful change in heart rate following prolonged endurance exercise.

Furthermore, significant differences in the rate of perceived exertion were observed in both the experimental and control groups, with the rate of perceived exertion increasing over the duration of the submaximal treadmill test in both groups (Figure 8.8). There were also no differences in the rate of perceived exertion between the experimental and control groups.

However, the rate of perceived exertion in the experimental group tended to increase during the post-race 20-minute treadmill test compared to pre-race values, whereas the rate of perceived exertion in the control group remained relatively unchanged in the post-race and pre-race tests. The post-race increase in the rate of perceived exertion in the experimental group occurred in the absence of muscle pain and elevated plasma CK activity.

It is well documented that exercise-induced muscle damage is associated with an increased rate of perceived exertion during stretch shortening cycle exercise[107;544;663]. Proposed mechanisms to explain an increased perception of effort following exercise-induced muscle damage include a higher central motor command in order to produce the same exercise intensity due to the force loss associated with exercise-induced muscle damage[544], the contribution of muscle pain to the rate of perceived exertion[61;544], and alterations in glycogen metabolism and availability[20;37].

It is recognised that, as muscle strength was not measured in this study, the potential involvement of force loss after the ultramarathon race in relation to an increase in the rate of perceived exertion is unknown. In addition, muscle pain had returned to pre-race levels when the post-race rate of perceived exertion was determined, thereby limiting the contribution of muscle pain to the development of increased perception of effort. These testing conditions may therefore partly explain the lack of differences in the rate of perceived exertion between the experimental and control groups. However, the role of central mechanisms in the perception of effort[412], and the relationship between exercise-induced muscle damage, fatigue, and the rate of perceived exertion require further investigation.

This is the first study that has examined the glucose oxidation rate during submaximal running, before and after exercise-induced muscle damage, using radiolabelled tracer techniques. Although there were no significant differences in the glucose oxidation rate between groups, or pre-post the ultramarathon race, there was a strong tendency for the glucose oxidation rate to be decreased in the experimental group after the ultramarathon race, compared to pre-race values (Figure 8.10). In addition, there were no significant differences in blood glucose concentrations between groups, before or after the ultramarathon race, or over time.

Tuominen et al[642] reported a similar reduction in the basal glucose oxidation rate following participation in a marathon run. It was determined, through the use of indirect calorimetry, that there was a 12% reduction in glucose disposal, and a 43% reduction in the rate of glucose oxidation after the marathon run.

Further, there was a compensatory increase in free fatty acid oxidation. It was also established that the reduction in the glucose oxidation rate after the marathon was associated with a reduction in oxidative glucose metabolism, compared to non-oxidative glucose metabolism[642].

In addition, although there was no difference in respiratory exchange ratio pre-post the ultramarathon race, there was a significant interaction between groups over time (Figure 8.6). Control group values remained relatively constant, while significant increases in respiratory exchange ratio were observed in the experimental group after the ultramarathon race, compared to pre-race values. Similar increases in respiratory exchange ratio have been observed following the ultramarathon race, as described in Chapter 3 and Chapter 4. Gleeson et al[242] also demonstrated an increased respiratory exchange ratio during submaximal cycling following exercise-induced muscle damage. In contrast, Tuominen et al[642] observed an increase in free fatty acid oxidation following a marathon run, which would be associated with a decrease in respiratory exchange ratio.

It is recognised that the findings of this study are paradoxical, as an increase in respiratory exchange ratio is associated with an increase in total carbohydrate metabolism. However, this increase in total carbohydrate oxidation occurred in the presence of a reduction in plasma glucose oxidation.

A potential explanation for these findings may be that although plasma glucose oxidation is decreased following exercise-induce muscle damage, there may be an associated increase in intramuscular glycogen oxidation. Numerous studies have reported impairments in muscle glycogen synthesis following exercise-induced muscle damage[20;21;23;156;284;498;587;656]. It is thought that the impaired muscle glycogen synthesis may be related to a reduction in plasma glucose uptake, and increased insulin resistance. However, it may be theorised that an increased utilisation of intramuscular glycogen may also contribute to the delayed muscle glycogen repletion following exercise-induced muscle damage[626].

Furthermore, a reduction in oxidative glucose metabolism, together with a shift from extramuscular to intramuscular glycogen oxidation, may indicate an alteration in muscle fibre recruitment patterns with an increased reliance on type II muscle fibres[626;642]. Lengthening muscle actions result in a similar extent of glycogen depletion in type I oxidative muscle fibres, and type II glycolytic muscle fibres, suggesting that there is no preferential use of a particular fibre type during eccentric exercise[21;23;82;156].

However, Asp et al[20] observed an increased use of glycogen in leg muscles, and a greater amount of glycogen depletion from type II muscle fibres following a bout of eccentric exercise which caused muscle damage[20], as well as increased muscle glycogen repletion in type II muscle fibres compared to type I muscle fibres after a marathon run[23]. These findings support a preferential use of type II muscle fibres following exercise-induced muscle damage.

It may be proposed that exercise-induced muscle damage may disrupt oxidative glucose metabolism, potentially in association with changes in mitochondrial structure[284;656], resulting in a compensatory increased reliance on non-oxidative glucose metabolism. Subsequent alterations in the metabolic profile of muscle may include preferential recruitment of type II muscle fibres in an attempt to spare damaged muscle fibres, or a reduction in functional type II muscle fibres with an associated increase in the relative contribution of type II muscle fibres[626].

In this study, blood lactate concentrations increased over the duration of the submaximal run in both the experimental and control groups (Figure 8.9). The increase in blood lactate concentrations over the duration of the submaximal run may possibly reflect a higher intra-muscular lactate concentration, and an increased relative contribution of the oxygen-independent glycolytic power system to ATP production[242]. In addition, there was a tendency for blood lactate concentrations to be decreased in the experimental group after the ultramarathon race, compared to pre-race values.

Although previous research has demonstrated an increase in blood lactate concentrations following exercise-induced muscle damage[242], the findings of this study are similar to those observed in Chapter 3, where there were no significant differences in blood lactate concentrations between groups over the time course of the study. It may therefore be suggested that no significant changes in lactate metabolism occur in response to the muscle damage associated with the ultramarathon race.

In conclusion, a 90 km ultramarathon race consistently induces muscle damage, which causes muscle pain and elevated plasma CK activity for up to four days. The race caused a paradoxical tendency for an increase in respiratory exchange ratio, whereas there was a strong tendency for a decrease in glucose oxidation rate. These findings, together with the tendency for submaximal oxygen consumption to be reduced after the race, may indicate the preferential use of type II muscle fibres following exercise-induced muscle damage. It is recommended that further studies should investigate the potential relationship between neuromuscular and metabolic adaptations after an ultramarathon race. In addition, it should be established whether these adaptations are favourable or detrimental to long-term endurance running performance.

CHAPTER NINE
SUMMARY AND CONCLUSIONS

9.1 INTRODUCTION

This thesis examined the cardiorespiratory, kinematic, neuromuscular, and metabolic recovery patterns following an ultramarathon race. There is evidence to suggest that the recovery period after an ultramarathon is characterised by a complex interaction between the positive adaptations associated with endurance training in preparation for the race, and exercise-induced muscle damage and fatigue as a result of the race.

A significant novel finding of this thesis was the reduction in submaximal oxygen consumption following the ultramarathon race. This result conflicts with that of previous research[78;102;125;240;268;369;474;605;628;687]. However, a number of important differences between the previous investigations and the current study may provide an explanation for the conflicting results.

It is recognised that the comparison with previous results is complicated by differences in experimental design, subject characteristics, and the exercise protocol used to induce muscle damage. However, specific differences were observed between this study, and previous studies[78;102;125;240;268;369;369;474;605;628;687] in terms of the age of subjects, training specificity of subjects, and the training volume and running experience of subjects. In this study, both the experimental and control groups subjects were generally older, were all endurance runners, reported greater training volumes, and had greater levels of endurance running experience, when compared to subjects in the previous studies[78;102;125;240;268;369;474;605;628;687].

Although there is much evidence to suggest that marathon and ultramarathon races impose a severe physiological stress on runners[120;284;592;656], the studies in this thesis have identified a unique response to distance competition in a group of moderately trained, experienced distance runners.

The series of studies in this thesis have led to the theory that, in this group of runners, the ultramarathon race may be associated with adaptive or compensatory mechanisms, resulting in adaptation to the stress of an ultramarathon race, leading to a "positive" physiological response. In accordance with this theory, inexperienced or overtrained runners may lack the capacity to adapt or compensate in response to the stress of an ultramarathon race, and as a result have a "negative" physiological response. This theory is illustrated in Figure 9.1.

An initial acute response follows the ultramarathon race, and may be characterised by increases in muscle pain and plasma CK activity, and reductions in force production and passive tension associated with exercise-induced muscle damage and fatigue[137;175;198;225;394;422;468;658].

It may be proposed that, in moderately trained, experienced endurance runners, the recovery period following an ultramarathon race may reflect "positive" adaptations to the stress induced by distance training and competition, and that these adaptations may be facilitated through prior training and experience, muscle wisdom, and the repeated bout effect. It may further be suggested that the adaptations occur in an attempt to maintain homeostasis or endurance running performance, and may therefore be associated with a reduction in the energy cost of exercise, and neural protective mechanisms that may limit the extent of stretch shortening cycle fatigue. In contrast, the "negative" stress reaction may be associated with an inability to maintain homeostasis, and may therefore be related to an increase in the energy cost of exercise, stretch shortening cycle fatigue, and a reduction in endurance running performance (Figure 9.1).

Although these are theoretical models of recovery that require rigorous testing, the proposed "positive" stress adaptation recovery model provides a basis for discussion regarding the cardiorespiratory, kinematic, neuromuscular, and metabolic adaptations following the ultramarathon race.

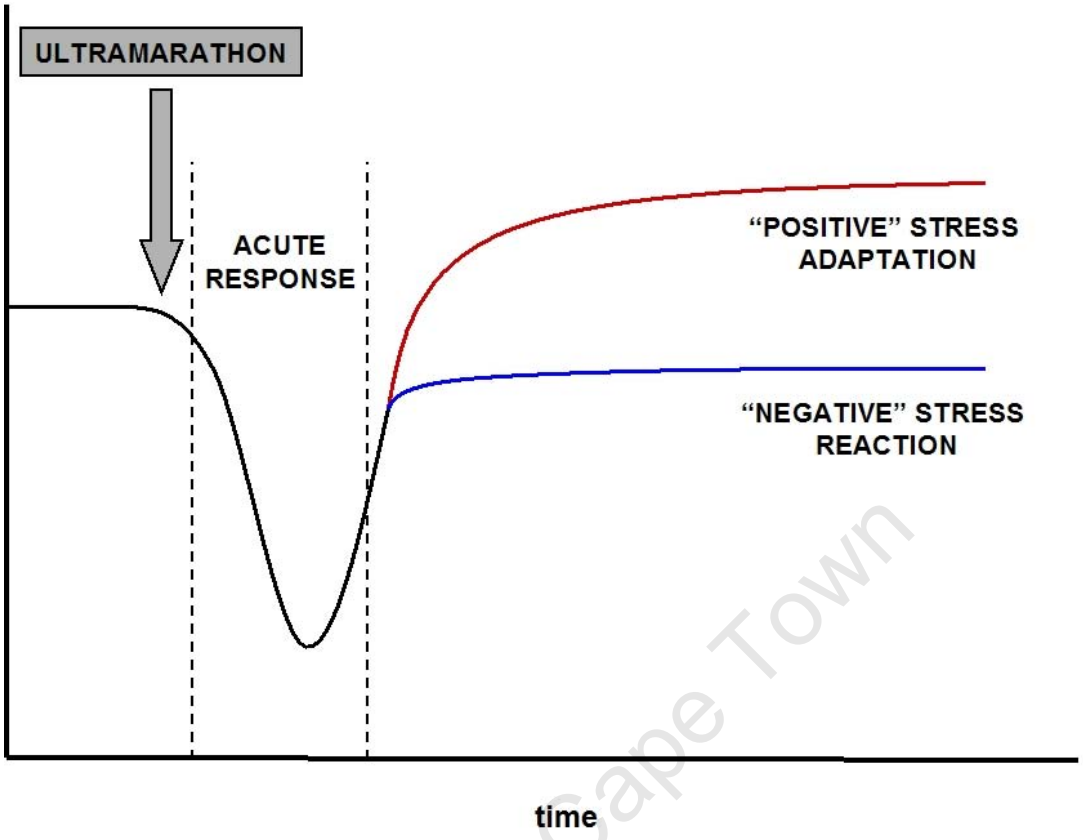

Figure 9.1: *Proposed "positive" stress adaptation and "negative" stress reaction recovery patterns following an ultramarathon race.*

9.2 PROPOSED RECOVERY MODEL

Based on the findings of this thesis, a proposed model of recovery has been developed, and is illustrated in Figure 9.2. This model characterises the "positive" stress adaptation recovery model, and considers the "negative" stress reaction recovery model.

9.2.1 "POSITIVE" STRESS ADAPTATION RECOVERY MODEL

9.2.1.1 Perception of effort

The series of studies in this thesis consistently demonstrated an increase in the rate of perceived exertion following the ultramarathon race, in response to prescribed submaximal exercise intensities, and self-paced exercise during performance testing.

It is likely that effort perception involves the integration of multiple afferent signals that may include the force loss associated with exercise-induced muscle damage[544], the contribution of muscle pain to the rate of perceived exertion[61;544], and alterations in glycogen metabolism and availability[20;37]. It is theorised that the increase in the perception of effort after the ultramarathon race may provide afferent input for a system of central teleoanticipation. A system of simultaneous efferent feed forward and afferent feedback signals may facilitate the regulation of exercise performance, and may be associated with continuous compensatory adaptations to counterbalance the effects of exercise-induced muscle damage and fatigue.

9.2.1.2 Teleoanticipation and the maintenance of homeostasis and performance

Ulmer[647] proposed an integrative model of a control system for the optimisation of performance. It was hypothesised that factors such as training, muscle reserve, muscle metabolic rate, and prior or antecedent experiences may alter the interpretation of afferent input from muscle or peripheral organs. This teleoanticipatory model is thought to be specific for exercise, and associates programming of power output and pacing strategies with the end point of the exercise bout.

Teleoanticipation includes feed forward planning and feedback control from afferent changes associated with peripheral metabolic structures and the external environment, and also incorporates the knowledge obtained from prior exercise bouts. Prior experience may alter the interpretation of the perception of effort, and there is evidence to support teleoanticipatory pacing strategies in the optimisation of performance. In addition, the teleoanticipatory model provides an integrative control system to ensure that homeostasis of the peripheral physiological system is maintained[378;647].

Therefore, based on this integrative, teleoanticipatory control system, it may be postulated that, in moderately trained, experienced endurance runners, prior training and experience, muscle wisdom, and the repeated bout effect may facilitate compensatory adaptations to maintain homeostasis or endurance running performance, and may therefore be associated with a reduction in the energy cost of exercise, and neural protective mechanisms that may limit the extent of stretch shortening cycle fatigue.

Indeed, the results of the studies in this thesis have demonstrated a positive relationship between time trial performance and prior endurance training and racing experience. In addition, chronic endurance training, muscle wisdom, and the repeated bout effect may be associated with protective adaptations against repetitive loading and muscle damage.

9.2.1.3 Endurance training and racing

Endurance training may be associated with neuromuscular adaptations that include an increased recruitment of muscle fibres and therefore a large, active muscle mass[272]. Noakes[479] proposed that improved performance following endurance training may be related to an increased ability of the brain to recruit a larger muscle mass for extended periods of time[260;262]. There may be training-related improvements in mechanical efficiency, and the rate of EMG development during the preactivation phase of the stretch shortening cycle[366;368]. The endurance training-induced increase in muscle mitochondrial content and oxidative capacity may also be associated with a decreased reliance on anaerobic energy supply, which therefore extends the time to fatigue the muscle fibres. Subsequently, less additional muscle fibres will be recruited to replace the fatigued fibres, therefore decreasing the end-exercise active muscle and oxygen consumption[569].

9.2.1.4 Muscle wisdom

It has been proposed that muscle wisdom may be related to either the available percentage of type II muscle fibres, and exists to protect these fibres from damage associated with metabolite accumulation, or to selectively recruit type I muscle fibres that are more fatigue resistant, thereby maintaining levels of force production[584].

9.2.1.5 The repeated bout effect

Neural adaptations associated with the repeated bout effect may include a more efficient recruitment of motor units, increased recruitment of type I muscle fibres, activation of a larger motor unit pool, a more even distribution of workload over the active fibres, increased motor unit synchronisation, and improved use of synergist muscles[244;428;429;431;657].

Mechanical adaptations may occur at the level of the cytoskeleton and myofibril, the muscle fibre, and the whole muscle[398;402;428;429;612], and include increases in passive and dynamic stiffness[539;553]. The alterations in stiffness have been attributed to increased tendon or cross-bridge stiffness[539], or cytoskeletal adaptations in order to maintain sarcomere alignment and structure[553].

In addition, it is theorised that cellular adaptations associated with the repeated bout effect may include strengthening of the cell membrane[137], removal of select populations of weak fibres or sarcomeres following the initial muscle damage[16;99;407], and the longitudinal addition of sarcomeres[397]. The repeated bout effect may therefore be associated with neural, mechanical, and cellular adaptations that limit the mechanical stress of exercise-induced muscle damage.

9.2.1.6 Integration of teleoanticipation and protective adaptations

In summary, current literature provides evidence to suggest that endurance training, muscle wisdom, and the repeated bout effect lead to neuromuscular, mechanical, and cellular adaptations that act as protective mechanisms against repetitive loading and muscle damage.

However, the positive relationship between running performance and prior endurance training and racing experience established in this thesis may support the role of teleoanticipation and the central regulation of performance following exercise-induced muscle damage and fatigue. The studies in this thesis were not designed to provide mechanisms to investigate the relative contribution of teleoanticipation or protective adaptations to the regulation of performance.

It may therefore be hypothesised that there is an interaction between these two proposed mechanisms resulting in "positive" adaptations, and the maintenance of homeostasis and running performance during the recovery period after an ultramarathon race in this group of athletes.

9.2.1.7 Compensatory physiological adaptations during recovery

This thesis examined the cardiorespiratory, kinematic, neuromuscular, and metabolic characteristics during the recovery period following an ultramarathon race. The main findings of the series of studies in this thesis indicate that the recovery period after an ultramarathon race is characterised by a reduction in submaximal oxygen consumption, an increase in the respiratory exchange ratio with a paradoxical decrease in glucose oxidation rate, a reduction in EMG preactivation of the biceps femoris and gastrocnemius muscles. In addition, numerous discrete alterations in lower limb kinematics included increases in hip, knee, and ankle angles at heelstrike and toe-off, and alterations in ankle range of movement during the stance and swing phases of the running gait cycle. Endurance running performance was also relatively unchanged in the recovery period after the race.

Based on the proposed "positive" stress adaptation model, these cardiorespiratory, kinematic, neuromuscular, and metabolic alterations may reflect compensatory adaptations that contribute to the maintenance of homeostasis after the ultramarathon. Alternatively, these alterations may be the measurable consequences of protective adaptations that limit the extent of exercise-induced muscle damage and fatigue.

The reduction in submaximal oxygen consumption, and the increase in respiratory exchange ratio may occur as direct consequences of a change in muscle recruitment patterns, with an increase in type II muscle fibre recruitment following exercise-induced muscle damage[20;23;241].

A preferential use of type II muscle fibres may be associated with increased utilisation of oxygen-independent glycolytic pathways, and a reduction in the total number of motor units recruited to perform exercise at a fixed submaximal workload, thereby resulting in a reduction in submaximal oxygen consumption. The preferential recruitment of type II muscle fibres may also reflect a protective mechanism to spare damaged muscle fibres following the ultramarathon race[626].

The kinematic and neuromuscular alterations during the recovery period after the race may reflect a further protective mechanism to increase shock attenuation during the stance phase of running[263;435], or may be compensatory adaptations to alterations in motor unit activation associated with exercise-induced muscle damage[78;125;127;263]. Furthermore, it may be proposed that a reduction in preactivation may reflect a neural protective mechanism that prevents further damage to the muscle[29;292].

It may further be postulated that the accumulation of many years of endurance training and racing may be associated with central adaptations that may enhance these compensatory and protective mechanisms. However, this theory remains speculative, and requires further investigation.

9.2.2 "NEGATIVE" STRESS REACTION RECOVERY MODEL

As previously discussed, a number of differences were observed between previous investigations and the current study. This thesis has led to the theory that, in a group of experienced, moderately trained runners, the recovery period after the ultramarathon race may be associated with adaptive or compensatory mechanisms, resulting in a "positive" stress adaptation. Therefore, it may be further hypothesised that inexperienced or overtrained runners may lack the capacity to adapt favourably to the stress of an ultramarathon race, resulting in a "negative" stress reaction.

The "negative" stress reaction may be associated with an inability to maintain homeostasis, and may therefore be related to an increase in the energy cost of exercise, stretch shortening cycle fatigue, and a reduction in endurance running performance. However, this recovery model was not studied in this thesis, and needs further investigation.

The "positive" stress adaptation and "negative" stress reaction recovery models are summarised in Figure 9.2. These are theoretical models based on the findings of the studies in this thesis, and therefore require further systematic research.

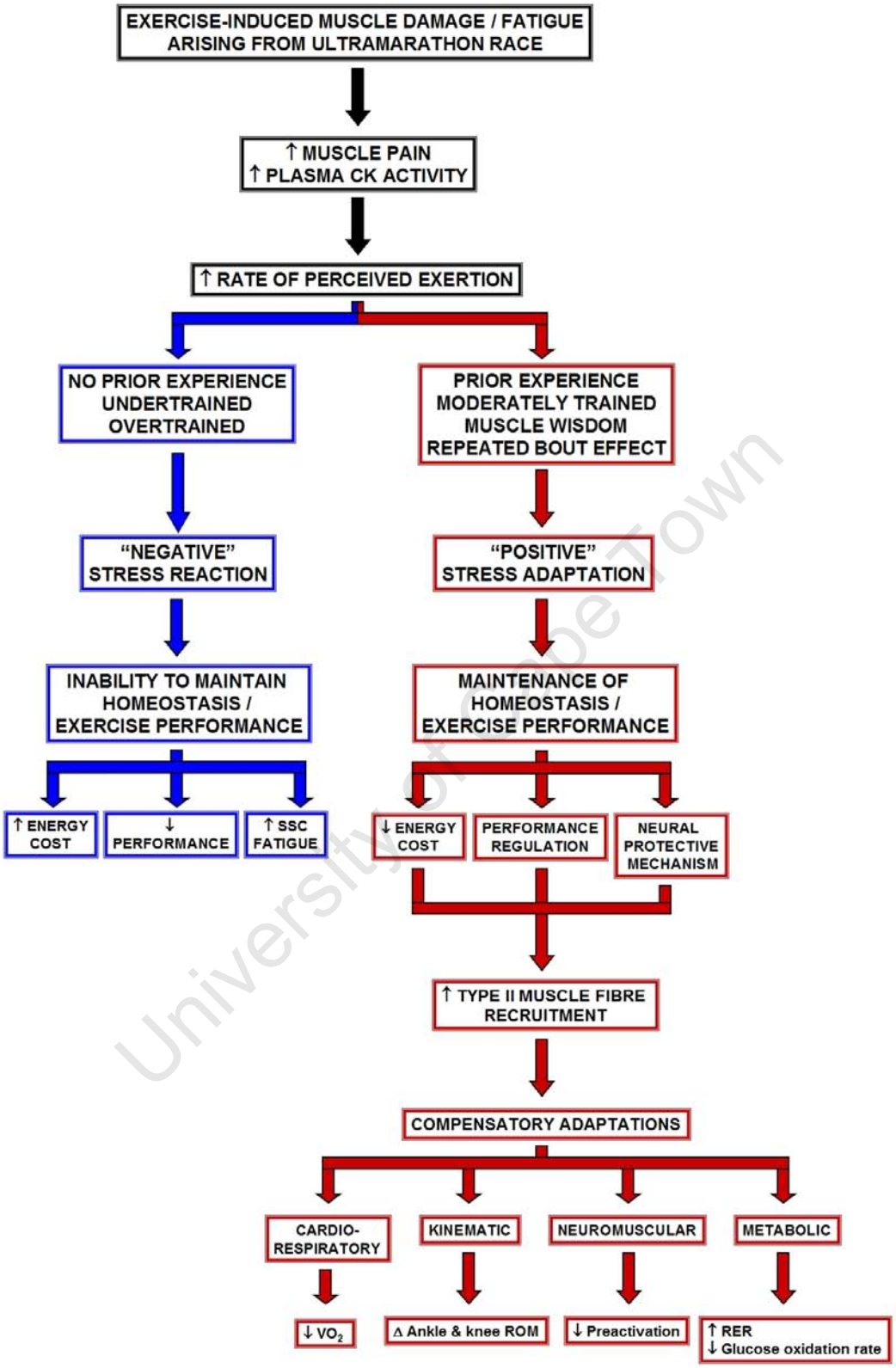

Figure 9.2: *Proposed "positive" stress adaptation and "negative" stress reaction recovery models.*

9.3 CONCLUSIONS

The overall aim of this thesis was to determine the effects of exercise-induced muscle damage on cardiorespiratory, kinematic, neuromuscular, and metabolic characteristics during the recovery period following an ultramarathon race. Based on the evidence provided in this thesis, the research questions, as described on pages 2 and 3, may be answered as follows:

1. *Are alterations in running economy evident during the recovery period following exercise-induced muscle damage induced by an ultramarathon race?*

The series of studies in this thesis, conducted on three different races, consistently demonstrated a reduction in submaximal oxygen consumption, and thus by definition an improvement in running economy during the recovery period after the ultramarathon race. The mechanisms underlying the reduction in submaximal oxygen consumption during the recovery period following the race may only be speculated. Potential mechanisms may include the preferential recruitment of type II muscle fibres, alterations in muscle stiffness, and improved efficiency of the stretch shortening cycle associated with the shift in optimum length following exercise-induced muscle damage.

2. *Is running economy influenced by changes in stride parameters and running kinematics during the recovery period after an ultramarathon race?*

This thesis identified variable changes in stride length following the ultramarathon race. It is acknowledged that the differences in stride length observations between the studies may partially be explained by the different methods used to determine stride length. However, the variability in stride length during the recovery period after the race may reflect the selection of self-optimal stride parameters during exercise and fatigue. The optimisation of stride parameters may also indicate a balance between the elastic storage of energy and the energy cost of accelerating limbs.

In addition, numerous discrete alterations in lower limb kinematics after the ultramarathon race included increases in hip, knee, and ankle angles at heelstrike and toe-off, and alterations in ankle range of movement during the stance and swing phases of the running gait cycle.

The kinematic adaptations may either reflect a further protective mechanism to increase shock attenuation during the stance phase of running, or may be compensatory adaptations to alterations in motor unit activation associated with exercise-induced muscle damage.

Although there was a moderate association between submaximal oxygen consumption and the centre of mass before, and for up to 28 days after the ultramarathon race, the vertical displacement of the centre of mass remained relatively unchanged in the presence of delayed onset muscle soreness, and thereafter in the recovery period following the ultramarathon race. In addition, changes in the vertical displacement of the centre of mass occurred independently to changes in submaximal oxygen consumption in the presence of muscle pain.

Thus, changes in stride parameters, running kinematics, and the vertical displacement of the centre of mass probably did not account for the reductions in submaximal oxygen consumption during the recovery period after an ultramarathon race.

3. *What are the effects of an ultramarathon race, and subsequent muscle damage and fatigue, on muscle preactivation in experienced ultramarathon runners?*

This thesis identified reductions in centrally regulated lower limb muscle preactivation levels during the recovery period following an ultramarathon race. Specifically, reductions in EMG preactivation were observed in the experimental group biceps femoris and medial gastrocnemius muscles during a 5 km time trial. In addition, reductions in submaximal EMG preactivation were measured in both the experimental and control groups vastus lateralis and medial gastrocnemius muscles over the duration of a submaximal run. It is theorised that these alterations in muscle preactivation may protect the muscle from damage that occurs as a result of the high landing forces during running.

4. *What are the effects of exercise-induced muscle damage and fatigue on glucose metabolism during the recovery period after an ultramarathon race?*

The ultramarathon race caused a paradoxical increase in respiratory exchange ratio, whereas there was a strong tendency for a decrease in glucose oxidation rate. These differences appear to be associated with a potential shift from extramuscular to intramuscular glycogen oxidation, alterations in mitochondrial structure resulting in a compensatory increased reliance on non-oxidative glucose metabolism, and the preferential use of type II muscle fibres following exercise-induced muscle damage.

5. *Is running performance affected during the recovery period following an ultramarathon race?*

Endurance running performance, as measured by performance in a 5 km time trial, remained relatively unchanged in the recovery period after a 90 km ultramarathon. Importantly, there was a positive relationship between increased endurance training and racing experience, and improvements in endurance running performance. Similarly, there was a further positive association between personal best performances over 10 km and 42 km distances and the change in time trial performance (in other words, the time trial performance of the faster runners decreased less after the ultramarathon race).

Based on the result of these studies, it may be concluded that the cardiorespiratory, kinematic, neuromuscular, and metabolic alterations during the recovery period after an ultramarathon race may reflect compensatory adaptations that facilitate the maintenance of homeostasis after the race. Alternatively, the alterations may be the measurable consequences of protective adaptations that limit the extent of exercise-induced muscle damage and fatigue. Furthermore, the positive relationship between running performance and prior endurance training and racing experience established in this thesis may support the role of teleoanticipation and the central regulation of performance following exercise-induced muscle damage and fatigue. It is likely that there may be an interaction between central mechanisms and protective adaptations during the recovery period after an ultramarathon race.

The studies in this thesis were not designed to provide mechanisms to determine the relative contribution of teleoanticipation or protective adaptations to the regulation of performance. Accordingly, further research will be required to investigate these two proposed mechanisms that may contribute to the maintenance of homeostasis and running performance during the recovery period after an ultramarathon race.

CHAPTER TEN
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APPENDIX I

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STUDY FIVE: CHANGES IN MUSCLE PAIN AND PLASMA CREATINE KINASE ACTIVITY AFTER THE "UP" AND "DOWN" COMRADES MARATHON

ABSTRACT

The aim of this study was to compare the acute changes in muscle pain and plasma creatine kinase (CK) activity following the "up" and "down" Comrades marathon. Eleven male runners (39.7 ± 9.3 years) completed the "up" Comrades marathon, and eleven male runners (41.0 ± 8.4 years) completed the "down" Comrades marathon the following year. Maximum oxygen consumption and peak treadmill running speed were measured two weeks before the race. Daily measurements of muscle pain and plasma creatine kinase (CK) activity were recorded one day before, and for seven days after the race. Muscle pain remained significantly elevated for up to seven days after the Comrades marathon, compared to pre-race values ($p < 0.0009$). The pain scores following the "down" run were significantly higher than the pain scores following the "up" run for at least seven days after the race ($p < 0.004$). Plasma CK activity remained significantly elevated for up to five days after the Comrades marathon, compared to pre-race values ($p < 0.007$). Plasma CK activity following the "down" run was significantly higher than the plasma CK activity following the "up" run for five days after the race ($p < 0.04$). A high degree of intra-individual variability in plasma CK activity was observed. In conclusion, the "down" Comrades marathon causes significantly more muscle pain and plasma CK activity compared to the "up" Comrades marathon. Further studies are required to accurately define the regeneration of muscle following the Comrades marathon.

Keywords

Ultramarathon, exercise-induced muscle damage, pain, creatine kinase.

INTRODUCTION

The Comrades marathon is a 90 km ultramarathon race, run annually between Durban and Pietermaritzburg, South Africa. However, the start and finish of the race alternate each year, and the race is therefore run in different directions. In the "up" run, the race starts at sea level in Durban, and runners ascend to the finish in Pietermaritzburg, at 650 m above sea level. The highest point in the race is 870 m above sea level. In the "down" run, the race starts in Pietermaritzburg, and runners descend to the finish in Durban[11].

Marathon and ultramarathon races impose severe physiological stresses on runners[6;17]. Previous studies on runners of the 90 km Comrades marathon have provided information regarding changes in electrocardiographic (ECG) activity[13], serum enzyme activities, fluid balance[12], renal function[19], factors explaining the development of hyponatremic encephalopathy[18], and the decrement in muscle power associated with muscle damage[6].

It is well documented that muscle damage is a common occurrence associated with distance running[6;17]. Exercise-induced muscle damage is characterised by a disruption of the sarcolemma[2], sarcotubular system[2;4], contractile components of the myofibril, the extracellular matrix and the cytoskeleton[15]. Distance running is also associated with impaired muscle function[6;23;24] and delayed onset muscle soreness[22]. Previous studies have shown that muscle pain associated with delayed onset muscle soreness usually dissipates within 96 hours after exercise[3;5], but may persist for up to 10 days after exercise[8].

Plasma creatine kinase (CK) activity is one of the most commonly used indicators of muscle damage[22]. Creatine kinase is released into the blood when the cell membrane is damaged, or when there is an alteration in cell membrane permeability[1]. The extent and duration of the plasma CK response to exercise varies according to the type of exercise[7]. Plasma CK activity peaks within 24 to 48 hours after a marathon[22;27].

Anecdotally, runners report a greater degree of muscle pain and a prolonged recovery period following the “down” run, compared to the “up” run. This is not unexpected, as during the “down” run there will be more eccentric strain on the muscles which is known to be a risk factor for causing muscle damage[9]. However, the anecdotal observations have not been confirmed experimentally and the physiological responses associated with delayed onset muscle soreness following the Comrades marathon have not been established.

Accordingly, the aim of this study was to compare acute changes in muscle pain and plasma creatine kinase activity following the “up” and “down” Comrades marathon.

METHODS

SUBJECTS AND STUDY DESIGN

Twenty-two healthy male runners who participated in the Comrades marathon were selected for the study, which had a quasi-experimental design. The study was granted ethical clearance by the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town. Subjects gave written consent after being informed about the demands of the study. The subjects completed a questionnaire to determine their age, training history, medical and surgical history, and any past or present injuries to the lower limbs.

The study was conducted over a two-year period. Eleven subjects participated in the “up” Comrades marathon, and 11 subjects participated in the “down” Comrades marathon. One subject participated in both the “up” and “down” races. The subjects were requested to avoid any medication, and strenuous training and racing, other than the Comrades marathon, for the duration of the study (± 20 days). Testing occurred at a similar time (to within one hour) for each subject for the duration of the study.

PRELIMINARY TESTING

Preliminary testing was conducted on all subjects two weeks before the Comrades marathon. All subjects had their body composition assessed. Body fat was represented as the sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, calf, thigh and abdomen), as described by Ross and Marfell-Jones[29], and also as a percentage of body mass[14].

A maximal treadmill test was performed to determine maximum oxygen consumption (VO_{2max}), peak treadmill running speed (PTRS), and maximum heart rate (HR_{max}). The maximal test was performed on a treadmill (Quinton Instruments, Seattle, WA, USA), with the elevation set at 1%, in order to reproduce the energetic cost of running outdoors on a flat surface[20].

The subjects warmed up before the maximal test. The timing and intensity of the warm-up was specific for each subject, and was maintained for the duration the study. The test began with the treadmill speed set to 10 $km.h^{-1}$. This speed was maintained for two minutes, after which it was increased by 0.5 $km.h^{-1}$ until the subjects were unable to maintain the speed of the treadmill. During the maximal test, subjects wore a mouthpiece and a nose clip.

The expired air passed through an on-line computer system attached to an Oxycon Alpha automated gas analyser (Jaeger/Mijnhardt, Groningen, The Netherlands) for the determination of oxygen consumption (VO_2) and respiratory exchange ratio (RER). Before each test, the gas analyser was calibrated with a Hans Rudolph 5530 L syringe and an on-line CO_2:N_2 gas mixture of known composition. Heart rate was recorded (Polar Vantage XL, Polar Electro, Kempele, Finland) at five-second intervals. Maximum oxygen consumption was defined as the oxygen consumption value that coincided with volitional fatigue. Peak treadmill running speed was defined as the highest speed that the runner could maintain for a complete 30-second increment prior to fatigue. Maximum heart rate was recorded as the highest heart rate during the last 30 seconds of the treadmill test.

MUSCLE PAIN

Muscle pain was measured daily for one day before, and for seven days after the Comrades marathon. Muscle pain was measured subjectively, where subjects rated lower limb pain according to a "rating of perceived pain" on a scale of 0 to 10, where 0 represents "*no pain*", and 10 represents "*maximal pain*". This method of measurement of muscle pain has previously been shown to be highly correlated with objective pain measures[30].

PLASMA CREATINE KINASE ACTIVITY

Daily blood samples, for the analysis of plasma creatine kinase (CK) activity, were collected for one day before, and for seven days after the Comrades marathon. A 5 ml blood sample was taken from the subject's antecubital vein for the analysis of plasma CK activity. The blood samples were collected into pre-chilled tubes containing lithium heparin. The samples were kept on ice for a maximum of three hours until centrifugation.

Blood samples were centrifuged at 2000 x *g* for 10 minutes at 4 °C. Samples were stored at -20 °C until the analysis of plasma CK activity. Plasma CK activity was measured by spectrophotometric (Beckman DU-62, Beckman Instruments, Fullerton, CA) enzymatic assays (CK-NAC activated, Boehringer Mannheim Automated Analysis for BM/Hitachi Systems 704, Meylan, France).

COMRADES MARATHON

The "up" run for this study was 86.55 km, and the "down" run was 89.9 km. The race profiles for the "up" and "down" Comrades marathons are shown in Figure 1(a) and 1(b) respectively[11]. Comrades race speed was expressed as a percentage of each subject's personal best 10 km speed.

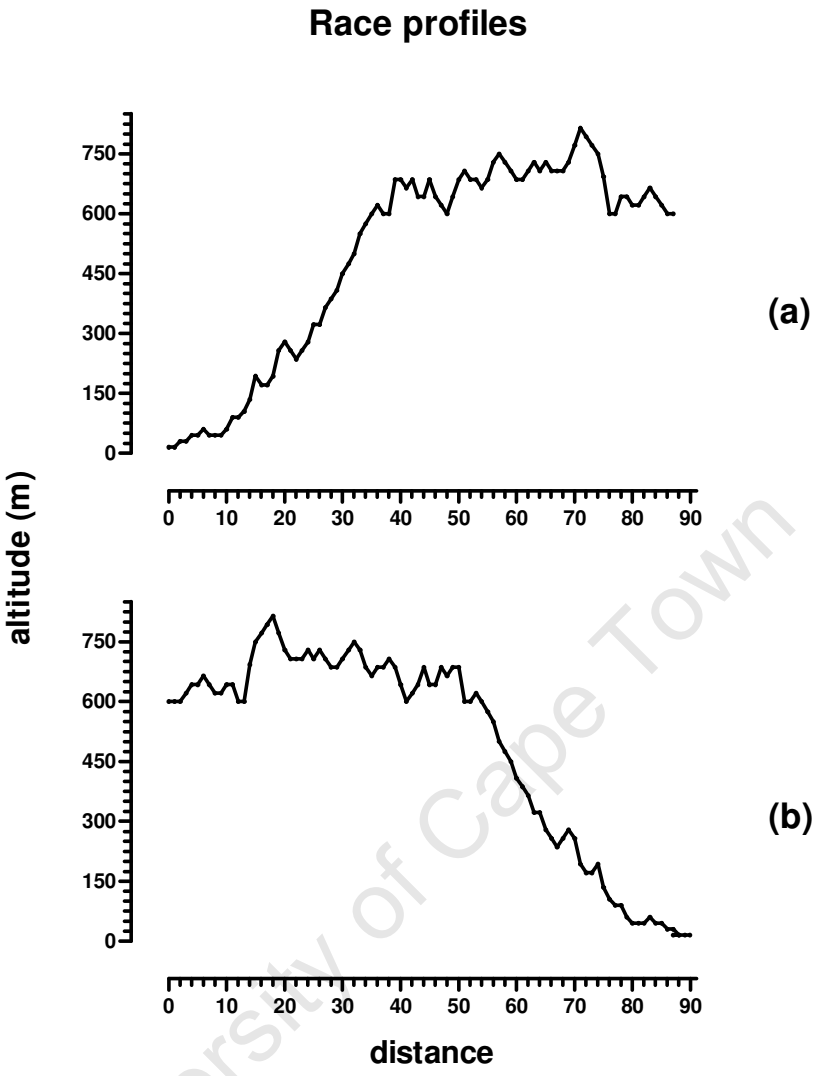

Figure 1: *Race profiles of the (a)"up" and (b) "down" Comrades marathon.*

STATISTICAL ANALYSES

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in descriptive variables between groups were assessed using an independent t-test. A Mann-Whitney U test was used to assess differences in the pain scores on each day between groups. A Friedman's ANOVA and Kendall's concordance was used to assess differences in the pain scores within groups over time.

As the plasma CK activity data had unequal variance, the logarithm of each value was determined, and these values were then used in an analysis of variance (ANOVA) with repeated measures to determine the significance for the two main effects of group and time, and the interaction (group x time). A Tukey's *post hoc* test was used to identify specific differences. All data are presented as the mean ± standard deviation. Statistical significance was accepted as $p < 0.05$.

RESULTS

The descriptive characteristics of subjects are shown in Table 1, and the training and racing history of subjects are shown in Table 2. There were no significant differences between groups for any of the descriptive variables. There were significant differences in the 10 km personal best times ($p < 0.006$) and the 42 km personal best times ($p < 0.04$) between groups, with the "down" group being significantly faster over both distances. However, when the Comrades race speeds were expressed as a percentage of the subjects' 10 km personal best speed there were no differences between groups. There were no significant differences between groups for any of the training history variables.

Table 1: *Descriptive characteristics of subjects in the "up" (n = 11) and "down" (n = 11) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	UP	DOWN
Age (years)	39.7 ± 9.3	41.0 ± 8.4
Body mass (kg)	74.9 ± 14.6	71.8 ± 11.6
Height (cm)	177.5 ± 7.6	177.2 ± 6.2
Sum of skinfolds (mm)	95.9 ± 36.0	74.9 ± 20.9
Body fat (%)	21.6 ± 5.1	19.6 ± 4.4
Maximum heart rate ($b.min^{-1}$)	177 ± 11	180 ± 15
VO_2max ($mlO_2.kg^{-1}.min^{-1}$)	54.7 ± 7.2	57.8 ± 5.5
Peak treadmill running speed (PTRS) ($km.h^{-1}$)	16.7 ± 1.5	17.6 ± 1.7

Table 2: *Training and racing history of subjects in the up (n = 11) and down (n = 11) groups. Data are expressed as mean ± standard deviation.*

VARIABLE	UP	DOWN
Total years running	7.6 ± 7.6	10.5 ± 7.2
Pre-competition training distance ($km.wk^{-1}$)	70.5 ± 10.6	72.7 ± 15.6
Average training distance ($km.wk^{-1}$)[$]	56.6 ± 6.5	55.5 ± 11.7
Number of standard marathons (42 km)	30 ± 30	37 ± 26
Personal best 10 km time (min) **	43.1 ± 3.0	37.9 ± 3.3
Personal best 42 km time (min) *	209.2 ± 15.8	189.7 ± 23.1
Race speed (%)[#]	60.1 ± 3.5	60.7 ± 5.8

[$] *Average training distance in the 6 months preceding the race.*
[#] *Comrades speed expressed as a percentage of 10 km personal best speed*

Significant differences:
Personal best 10 km time: up vs. down ($p < 0.006$)
Personal best 42 km time: up vs. down ($p < 0.04$)

MUSCLE PAIN

The muscle pain of subjects in the "down" and "up" groups is shown in Figure 2. The subjective pain scores (arbitrary units) were significantly higher in the "down" group on days 1 (6.6 ± 2.0 vs. 4.2 ± 0.8; $p < 0.004$), 2 (6.2 ± 1.9 vs. 2.8 ± 1.1; $p < 0.0003$), 3 (5.3 ± 1.4 vs. 2.1 ± 1.4; $p < 0.0004$), 4 (4.3 ± 1.2 vs. 1.3 ± 1.3; $p < 0.0005$), 5 (3.6 ± 1.3 vs. 0.7 ± 0.9; $p < 0.0003$), 6 (3.0 ± 1.3 vs. 0.6 ± 0.9; $p < 0.0008$), and 7 (2.6 ± 1.1 vs. 0.4 ± 0.7; $p < 0.0004$) after the Comrades marathon, compared to "up" group values on the same days. Although muscle pain in the "up" group had returned to pre-race values by day 7 after the Comrades marathon, muscle pain in the "down" group remained elevated compared to pre-race values (2.6 ± 1.1 vs. 0.0; $p < 0.0009$).

PLASMA CREATINE KINASE ACTIVITY

There was a significant interaction between groups over time for plasma CK activity ($F_{(7, 140)} = 3.13$; $p < 0.004$) (Figure 3). Plasma CK activity was significantly higher in the "down" group on days 1, 2, 3, 4, and 5, compared to pre-race values ($p < 0.007$). Plasma CK activity was also significantly higher in the "up" group on days 1, 2, and 3, compared to pre-race values ($p < 0.006$). Plasma CK activity had therefore returned to pre-race values by day 4 in the "up" group, and day 6 in the "down" group. The other differences between days and groups are shown in the legend in Figure 3.

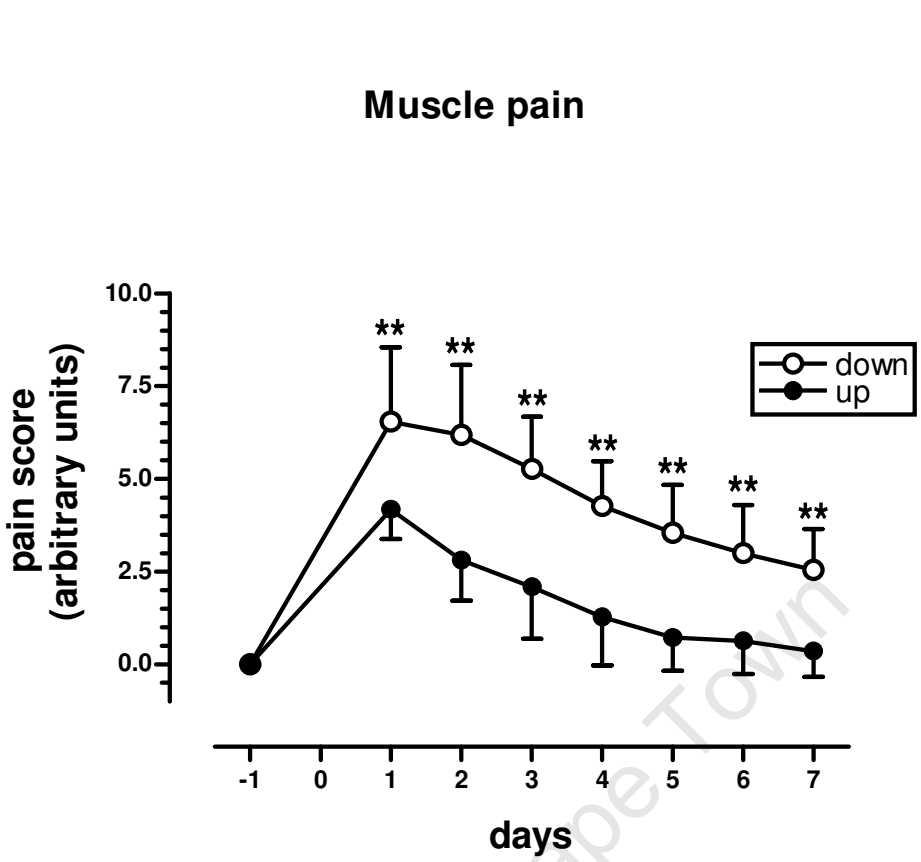

Figure 2: *Muscle pain (arbitrary units) of subjects in the "up" (-●-) (n = 11) and "down" (-o-) (n = 11) groups. Tests were conducted 1 day before the race, and daily for 7 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** "down" days 1,2, 3, 4, 5, 6, and 7 vs. "up" days 1, 2, 3, 4, 5, 6, and 7 respectively ($p < 0.004$)

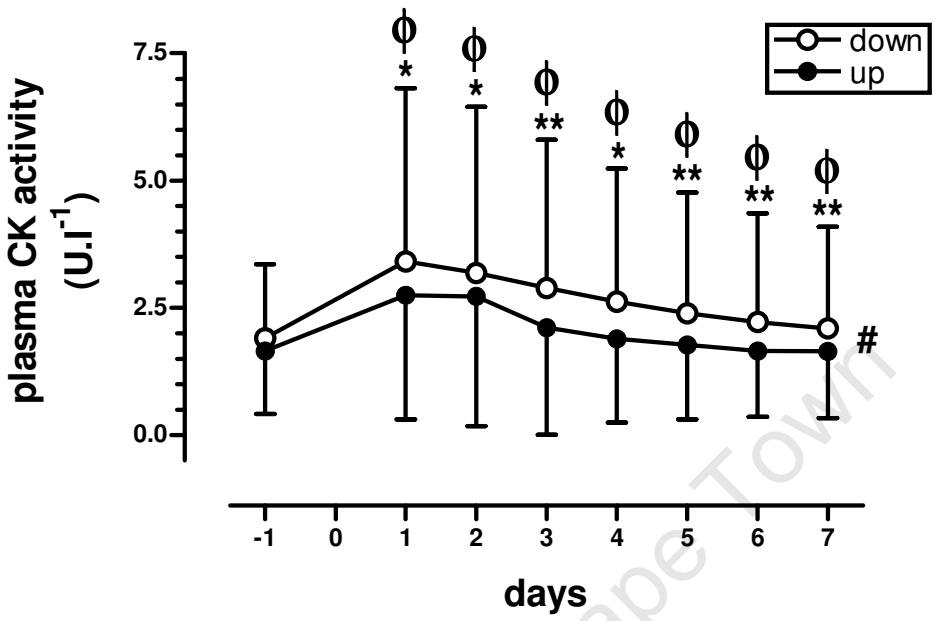

Figure 3: *Plasma creatine kinase activity (U.l^{1}) of subjects in the "down" (-●-) (n = 11) and "up" (-o-) (n = 11) groups. Tests were conducted 1 day before the race, and daily for 7 days after the race. Data are expressed as mean ± SD.*

Significant differences:

** "down" day 1 vs. "down" days -1, 1, 3, 4, 5, 6, 7 ($p < 0.00003$), and 2 ($p < 0.03$)
** "down" day 2 vs. "down" days -1, 4, 5, 6, and 7 ($p < 0.00003$)
** "down" day 3 vs. "down" days -1, 5, 6, and 7 ($p < 0.00004$)
** "down" day 4 vs. "down" days -1, 7 ($p < 0.00006$), and 6 ($p < 0.04$)
** "down" day 5 vs. "down" day -1 ($p < 0.007$)
** "up" days 1 and 2 vs. "up" days -1, 3, 4, 5, 6, and 7 ($p < 0.00003$)
** "up" day 3 vs. "up" days -1, 6, and 7 ($p < 0.006$)
ϕ "down" day 1 vs. "up" days -1, 1, 2, 3, 4, 5, 6, and 7 ($p < 0.02$)
ϕ "down" days 2 and 3 vs. "up" days -1, 3, 4, 5, 6, and 7 ($p < 0.003$)
ϕ "down" day 4 vs. "up" days -1, 4, 5, 6, and 7 ($p < 0.04$)
ϕ "down" day 5 vs. "up" days -1, 6, and 7 ($p < 0.02$)
ϕ "down" day 6 vs. "up" day 1 ($p < 0.02$)
ϕ "down" day 7 vs. "up" days 1 and 2 ($p < 0.007$)
interaction of group x time ($p < 0.004$)

DISCUSSION

The Comrades marathon induced muscle pain in both groups consistent with delayed onset muscle soreness[7]. The onset of muscle pain in both groups occurred within the first 24 hours following the race, which is consistent with other studies investigating the onset of delayed onset muscle soreness resulting from exercise-induced muscle damage[8;25]. In the "up" group, subjective pain had returned to pre-race values by day five after the race. However, in the "down" group, muscle pain remained elevated at seven days after the race. Studies have shown that muscle pain associated with delayed onset muscle soreness usually dissipates within 96 hours after exercise[3;5;10], but in some cases may persist for up to 10 days, particularly following high-force eccentric exercise protocols involving maximal contraction of the elbow flexors[8]. Unfortunately data were not collected beyond seven days, therefore the exact time course of recovery of muscle pain following the "down" run is unclear.

Further, although the time course of recovery of muscle pain is similar following different types of exercise-induced muscle damage, the extent of soreness may vary. For example, high-force eccentric exercise protocols involving maximal contraction of the elbow flexors are associated with higher subjective pain scores compared to protocols involving downhill running[7].

This is the first study to demonstrate a difference in subjective pain scores following the "up" compared to the "down" Comrades marathons. It is logical to assume that the difference in pain scores between the "down" and "up" groups is related to the increased amount of downhill running during the "down" Comrades marathon. Downhill running is associated with a greater magnitude of eccentric (muscle lengthening) action compared to level running, and therefore a greater degree of muscle damage[3].

The underlying mechanisms for the pain associated with delayed onset muscle soreness are not well understood. It has been suggested that soreness may result from swelling and pressure in the muscle[31].

Although biopsy studies have demonstrated increases in muscle fibre area and intramuscular pressure[16], discrepancies between the timing of peak muscle soreness and oedema have been identified[26].

It has also been suggested that chemicals such as histamines, prostaglandins, and bradykinins may be associated with the development of muscle soreness following exercise-induced muscle damage. It is theorised that these substances are released when the muscle is damaged, resulting in activation of type III and IV nerve afferents, leading to the sensation of pain[28]. However, there is no direct evidence to support this theory[7].

In addition, although subjective pain remained significantly elevated for up to seven days after the Comrades marathon, this does not necessarily reflect the magnitude of muscle damage[5] or the long-term changes in neuromuscular function which occur. For example, it is known that neuromuscular function is disturbed for at least 11 days after the Comrades marathon[6]. Furthermore, signs of regeneration are still present in the muscle of runners, twelve weeks after a standard marathon, despite the absence of pain[32].

There is a complex interaction between exercise-induced muscle damage and fatigue due to prolonged exercise. This is characterised by alterations in neuromuscular function including an increase in contact time, decreases in stretch reflex sensitivity, preactivation, and elastic energy potential, and changes in stiffness regulation[21]. These factors are all affected by absolute running speed. It is acknowledged that a potential limitation of this study is the difference in 10 km personal best time between the "up" and "down" groups. Due to the inherent differences in distance and profile between the "up" and "down" runs, race speed was expressed as a percentage of the individual 10 km personal best time. Although no significant differences were observed in race time (minutes), intensity (% HR_{max}), and speed (% 10 km time), it is recognised that expression of race speed as a percentage of the 10 km personal best time may mask differences in the rate of stretch-shortening cycle exercise during the ultramarathon race. Although it may be argued that differences in absolute running speed are associated with differences in loading forces, the differences in this study were subtle and arguably not a major factor associated with the development of the muscle damage.

Plasma creatine kinase (CK) activity is a commonly used indicator of muscle damage[22]. Plasma CK activity was significantly higher after the "down" run, compared to the "up" run, and remained significantly elevated for five days compared to pre-race values in the "down" group, whereas in the "up" group, values had returned to pre-race values by day four after the Comrades marathon. These findings are consistent with other studies that also reflect a rapid increase in CK activity from 24 hours after a marathon[22;27]. Kryöläinen et al[22] reported peak plasma CK activity of 1147 ± 520 $U.l^{-1}$ two days after a marathon. Conversely, after high-force eccentric exercise protocols, for example, maximal contraction of the elbow flexors, the increase in CK activity does not begin until approximately 48 hours after the exercise, with peak CK activity occurring only between four to six days following the exercise[7]. The differences in plasma CK activity following downhill running and high-force eccentric exercise protocols is well-documented[7], however the underlying mechanism for the different responses is unclear.

This is the first study to demonstrate a difference in the CK response to ultra-endurance exercise. It may be hypothesised that the difference in CK activity between the "down" and "up" groups is related to the increased amount of downhill running during the "down" Comrades marathon compared to the "up" Comrades marathon, and therefore the greater magnitude of eccentric (muscle lengthening) action during the "down" run. Studies have shown a dissociation between CK activity and the extent of exercise-induced muscle damage[26;30], therefore one should interpret the magnitude of CK activity as a direct marker of muscle damage with caution. However in this study, as pain was also elevated it is logical to conclude that the "down" group did indeed have more muscle damage[7].

There was also a large degree of intra-subject variability in plasma CK activity, particularly in the "down" group at days one and two after the Comrades marathon. This individual variation in CK activity may be associated with differences in the rate of CK clearance by muscle and the reticuloendothelial system[8], and not related to physical activity, gender, or muscle mass[7]. Unfortunately the design of this study cannot provide an explanation for the large degree of intra-individual variation in CK activity. Further studies are needed to investigate this finding.

In conclusion, the “down” Comrades marathon causes more muscle pain and plasma CK activity compared to the “up” Comrades marathon. Subjective pain scores remained elevated for at least seven days after the “down” race, but only for four days after the “up” race. Further studies are required to accurately define the regeneration of muscle following the Comrades marathon after the symptoms of damage have disappeared.

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APPENDIX II

PILOT STUDY: THE VALIDITY OF A DUAL AXIS ACCELEROMETER FOR THE DETERMINATION OF THE PERIOD OF PREACTIVATION

BACKGROUND

Muscle preactivation is essentially a centrally regulated, feed-forward, anticipatory mechanism[2;5;7-11;14;17], initiated by the brain[15]. Muscle preactivation functions to prepare the lower limb muscles for landing by increasing the neural activity in the appropriate muscle before the foot makes contact with the ground[1;2;4-6;16]. Muscle preactivation regulates muscle stiffness, and the transition time between the prestretch and shortening components of the stretch shortening cycle[9-11], as a high pre-landing stiffness is directly responsible for a high post-landing stiffness[13;21].

Preactivation during running is calculated from electromyographic (EMG) activity recorded 100 milliseconds (ms) before heelstrike[19]. Muscle preactivation is thought to contribute significantly to the effective utilisation of elastic energy[2;3;12;18;20].

The purpose of the third study (Chapter 6) was to investigate the effects of exercise-induced muscle damage and fatigue, induced by an ultramarathon, on muscle preactivation and running performance. A 5 km time trial was used to simultaneously measure EMG activity and running performance. Therefore, a valid method of collecting and analysing stride parameters was required, for the determination of muscle preactivation.

AIM

The aim of the pilot study was to determine the validity of a dual axis accelerometer for the determination of the period of preactivation (100 ms before heelstrike)[19] during running.

METHODS

SUBJECTS

Three healthy male (n = 2) and female (n = 1) subjects participated in the study. The subjects were recreational runners between 20 and 45 years of age.

ACCELEROMETER PLACEMENT

A dual axis accelerometer (MMA6233Q, Freescale Semiconductor Incorporated, Chandler, Arizona, USA) was positioned on the dorsal surface of the right shoe over the 3rd metatarsophalangeal joint. The accelerometer was mounted on a rigid platform, and was positioned at 45º to the direction of the earth's gravity field. In this position, 1 *g* was equivalent to 1.77 V. The accelerometer was secured to the right shoe using 50 mm Elastoplast adhesive tape. Data from the accelerometer were recorded simultaneously with the force plate data (Advanced Mechanical Technology Incorporated (AMTI®), Newton, MA, USA).

TESTING PROCEDURE

The trials were conducted with the subjects in running shoes, as subjects would perform the 5 km time trial in running shoes. The subjects warmed up before the validation trial. The timing and intensity of the warm-up was specific for each subject. The subjects were also given an opportunity to become familiar with the laboratory equipment and testing procedure, to reduce error usually associated with subjects performing unaccustomed exercise.

Subjects were required to run at a self-selected pace on a 10 m pathway in the gait laboratory. A 1000 Hz force plate (Advanced Mechanical Technology Incorporated (AMTI®), Newton, MA, USA) was positioned within and at the same level as the pathway, and at approximately the midpoint of the 10 m pathway.

Subjects were instructed to perform 10 running trials at a self-selected pace. Ground reaction force data were recorded simultaneously using the force plate and the accelerometer. A trial was considered valid when the subject's right foot made contact with the force plate, and when there was no alteration in the running style as assessed subjectively by the investigator.

DATA ANALYSIS

The kinetic data were visualised and processed into C3D files in Workstation (Oxford Metrics Ltd, Oxford, United Kingdom). The data were then exported as text files to Excel (Microsoft Corporation, Redmond, USA).

STATISTICAL ANALYSES

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Differences in heelstrike, toe-off, and ground contact time measurements between the force plate and accelerometer were assessed using an independent t-test. All data are presented as the mean ± standard deviation. Statistical significance was accepted as $p < 0.05$.

RESULTS

The average heelstrike, toe-off, and ground contact time measurements for the force plate and accelerometer are shown in Table 1. There were no significant differences between groups for any of these variables.

Table 1: *Average heelstrike, toe off, and ground contact time measurements for the force plate and accelerometer. Data are expressed as mean ± standard deviation.*

VARIABLE	FORCE PLATE	ACCELEROMETER
Heelstrike (ms)	2550.9 ± 2593.5	2561.7 ± 2599.6
Toe-off (ms)	3059.0 ± 2865.4	3029.6 ± 2885.0
Ground contact time (ms)	254.6 ± 223.9	237.9 ± 234.1

The differences in heelstrike, toe-off, and ground contact time measurements between the force plate and accelerometer are shown in Table 2.

Table 2: *Average heelstrike, toe off, and ground contact time measurements for the force plate and accelerometer. Data are expressed as mean ± standard deviation.*

VARIABLE	DIFFERENCE (FORCE PLATE - ACCELEROMETER)
Heelstrike (ms)	-5.4 ± 4.5
Toe-off (ms)	14.7 ± 21.9
Ground contact time (ms)	20.1 ± 22.2

SUMMARY AND CONCLUSIONS

Although there were no significant differences in the average heelstrike, toe-off, and ground contact times measured with the force plate and accelerometer, it is evident that there was a greater degree of variance in the accelerometer measurement of toe-off and ground contact time, compared to heelstrike. There was little difference between the force plate and accelerometer measurement of heelstrike. In addition, in relation to the period of preactivation, the difference between the force plate and accelerometer measurement of heelstrike represents a difference of 5%.

Therefore, the dual axis accelerometer is a valid instrument for the determination of heelstrike, and the period of preactivation. However, the degree of variance associated with the force plate and accelerometer measurements of toe-off and ground contact time indicate that the dual axis accelerometer cannot be considered as a valid measurement tool for these variables.

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APPENDIX III

ETHICS APPROVAL LETTERS

UNIVERSITY OF CAPE TOWN

Research Ethics Committee
Faculty of Medicine
Anzio Road, Observatory, 7925
Queries : Martha Jacobs
Tel : (021) 406-6492 Fax: (021) 406-6390
E-mail : Martha@medicine.uct.ac.za

8 June, 1998

REC REF NO: **069/98**

Ms T L Burgess
Sports Science Institute

Dear Ms Burgess

RE: CHANGE IN STRETCH SHORTENING CYCLE AND RUNNING ECONOMY AFTER A FOOTRACE

I have pleasure in informing you that the above study has been **formally approved** by the Research Ethics Committee on 29 May 1998.

Included is a list of Research Ethics Committee Members who have formally approved your protocol.

Please quote the above Reference number in all correspondence.

Yours sincerely,

Signed by candidate

Queries: Martha Jacobs
Research Ethics Committee
Room 212 Werner and Beit
UCT Medical School
Anzio Road, Observatory, 7925
Tel: (021) 406-6492 Fax: (021) 406-6390
E-Mail: martha@medicine.uct.ac.za

UNIVERSITY OF CAPE TOWN

Research Ethics Committee
Faculty of Medicine
Anzio Road, Observatory, 7925
Queries : Martha Jacobs
Tel : (021) 406-6492 Fax: (021) 406-6390
E-mail : Martha@medicine.uct.ac.za

05 May 1999

REC REF : # 134//99

Miss T Burgess
BERU

Dear Ms Burgess

BIOMECHANICS AND RUNNING ECONOMY AFTER A 90 KM FOOT RACE

I have pleasure in informing you that the above study has been **formally approved** by the Research Ethics Committee on 05 May 1999.

Included is a list of Research Ethics Committee Members who have formally approved your protocol.

Please quote the above Reference number in all correspondence.

Yours sincerely,

Signed by candidate

PROFESSOR FOLB
CHAIR: RESEARCH ETHICS COMMITTEE

Queries: Martha Jacobs
Research Ethics Committee
Room 212 Werner and Beit
UCT Medical School
Anzio Road, Observatory, 7925
Tel: (021) 406-6492 Fax: (021) 406-6390
E-Mail: martha@medicine.uct.ac.za

INFORMED CONSENT FORM AND DATA SHEETS

INFORMED CONSENT (EXAMPLE: STUDY THREE AND STUDY FOUR)

The MRC/UCT Research Unit for Exercise Science and Sports Medicine will be conducting a study to investigate the relationship between running economy, running performance, glucose oxidative capacity, and neuromuscular function after a 90 km ultramarathon race. These factors may be related to the rate of recovery after the Comrades marathon. This study will improve our understanding of the underlying mechanisms of muscle damage associated with endurance exercise.

The research project will involve the following tests:

1. Body mass and stature measurements.
2. Anthropometric assessment of body composition involving the measurement of skinfold thicknesses using skinfold calipers, and limb diameter and length measurements to determine fat content and muscle mass.
3. A maximum effort treadmill test (to exhaustion) to determine maximum oxygen consumption (VO_{2max}), maximal heart rate (HR_{max}), and peak treadmill running speed. The anthropometric assessment and maximum effort treadmill test will take place three weeks before the Comrades marathon.
4. A 20-minute submaximal treadmill tests to determine submaximal oxygen consumption (a measure of running economy), heart rate (using a heart rate monitor), rate of perceived exertion, and blood glucose oxidation.
5. The measurement of blood glucose oxidation involves an intravenous injection of a low dose of radioactive glucose to measure blood glucose oxidation while running. All injections will be performed under sterile conditions and under the supervision of a qualified medical practitioner. The total radioactivity injected into the body will be 1.8 mrem, the unit in which radiation dose is measured.

To put this in perspective, this is 1.1% of the radiation dose from a diagnostic bone scan. The health risk involved is a 0.000018% chance of developing leukaemia (1.8% of that from a bone scan)

6. Blood samples will be taken via a cannula inserted into the antecubital vein before and during each 20-minute submaximal treadmill test to measure plasma creatine kinase (an indicator of muscle damage) and blood glucose oxidation. Good clinical practice and sterile procedures will be strictly adhered to.
7. Muscle pain will be measured subjectively using a “rating of pain” scale.
8. Muscle recruitment is measured using sticky electrodes placed on the surface of the skin, which measure the electrical activity [electromyographic (EMG) activity] of the muscle.
9. A 1.4 km submaximal run and three 40 m sprint tests will be performed before a 5 km time trial run. The tests will be performed on an indoor running track. During the tests electromyographic (EMG) activity, ground contact time, heart rate (using a heart rate monitor), and rate of perceived exertion will be recorded.
10. EMG activity measures the amount of electrical activity in muscles. In this study, the EMG activity of the quadriceps (front thigh), hamstrings (back thigh) and calf muscles will be recorded during the 1.4 km submaximal run, the 40 m sprint tests, and the 5 km time trial run. This involves the placement of electrode on to the muscles so that EMG activity may be recorded.
11. Ground contact time will be measured during the 5 km time trial using an accelerometer that will be attached to the running shoe.
12. The 20-minute submaximal treadmill test, the 1.4 km submaximal run, the 40 m sprint tests, the 5 km time trial run, and the MRI tests will all be performed two weeks before the Comrades marathon, and will be repeated between 10-15 days after the Comrades marathon.
13. Subjects running the Comrades marathon will be required to wear a heart rate monitor for the duration of the race.
14. In addition, daily measurements of muscle pain, and blood samples, for the analysis of plasma creatine kinase activity, will be taken for 7 days after the Comrades marathon. This is to quantify the muscle damage experience after the ultramarathon. Sterile procedures and good clinical practice will be strictly adhered to.
15. Lastly, it will be requested that each subject keep a detailed logbook, and that all training during the testing procedure be recorded.

Time commitments

The following table summarises the time commitments required to participate in this study. The total time commitment necessary for this study from 4 weeks before the Comrades marathon until 15 days after the ultramarathon race is approximately 14 hours.

Date	Testing procedures	Number of visits/week	Time commitment
3 weeks before Comrades (23/05/2005 – 28/05/2005)	***Familiarisation*** - informed consent, questionnaire, anthropometry, familiarisation with equipment and testing procedures ***Maximum effort treadmill test*** - VO_{2max}, HR_{max}, PTRS	1	1 hour
2 weeks before Comrades (30/05/2005 – 04/06/2005)	***20 minute submaximal treadmill test*** - oxygen consumption, heart rate (HR), respiratory exchange ratio, blood glucose oxidation, rate of perceived exertion (RPE)	1	1 hour
	1.4 km submaximal run, 20 m sprint tests - EMG activity, RPE	1	1.5 hours
	5 km time trial run - EMG activity, ground contact time, HR, RPE		
Comrades marathon (16/06/2005)	Experimental group only		
1 week after Comrades (17/06/2005 – 23/06/2005)	***Acute post-race testing*** – plasma creatine kinase and muscle pain	7	15 minutes
10-15 days after Comrades (26/06/2005 – 01/07/2005)	***20 minute submaximal treadmill test*** - oxygen consumption, heart rate (HR), respiratory exchange ratio, blood glucose oxidation, rate of perceived exertion (RPE)	1	1 hour
	1.4 km submaximal run, 20 m sprint tests - EMG activity, RPE	1	1.5 hours
	5 km time trial run - EMG activity, ground contact time, HR, RPE		

Possible risks to subjects

There are no potential risks that may be associated with mass, stature, skinfold measurements, and muscle pain measurements. Treadmill running is associated with a risk of falling, and therefore possible injury. In this study, a thorough familiarisation process will be performed to ensure familiarity and confidence with treadmill running. In addition, a medical practitioner will be present for all maximal effort treadmill tests. A warm up will be performed before each running test to reduce the risk of musculoskeletal injury. The use of an accelerometer for the measurement of ground contact times provides no additional potential risks to the subjects.

The only potential risk associated with EMG activity measurements is an allergic reaction to the EMG electrodes. The skin will be carefully examined following removal of the electrodes on completion of testing. Any allergic reaction will be treated with topical cortisone cream, and referral to a medical practitioner for further management. In addition, subjects will excluded from further testing.

Blood samples will be drawn for the analysis of plasma creatine kinase activity and blood glucose oxidation. As always when working with blood, potential risks include infection with blood borne diseases including hepatitis and HIV. In order to minimize these potential risks, a trained phlebotomist will performed the procedures, and a medical practitioner will be present during the testing procedures. Furthermore, sterile equipment will always be used for these procedures, and good clinical practice will be strictly adhered to.

The measurement of blood glucose oxidation involves an injection of a low dose of radioactive glucose into the blood stream. All injections will be performed under sterile conditions and under the supervision of a qualified medical practitioner. The total amount of radioactivity injected into the body will be 1.8 mrem, the unit in which radiation dose is measured. To put this in perspective, this is 1.1% of the radiation dose from a diagnostic bone scan. The health risk involved is a 0.000018% chance of developing leukaemia (1.8% of that from a bone scan). For additional safety, all radioactive materials will be sent for independent testing to confirm the absence of pyrogens (which cause an increase in body temperature).

Anticipated benefits to subjects

Subjects will receive financial compensation (R300) to cover any costs related to time, travelling expenses, and inconvenience, due to participation in this study. In addition, subjects will receive a full summary of their individual results, as well as the overall findings from this study. The individual results will include information regarding body composition measurements, peak treadmill running speed, maximum oxygen consumption, maximum heart rate and running economy, and training advice. Finally, the runners participating in the Comrades marathon will have the use of a heart rate monitor (Polar Vantage XL, Polar Electro, Kempele, Finland) for the duration of the race.

Privacy and confidentiality

All records and results generated within this study will be stored in a computer database in a secure facility, and in a manner that maintains subject confidentiality. All participants will remain anonymous in any ensuing publication.

Contact Information

Investigator Name	Telephone	Email
Theresa Burgess	(021) 406 6043	tburgess@uctgsh1.uct.ac.za
Mike Lambert (Supervisor)	(021) 650 4569	mlambert@sports.uct.ac.za
	(021) 650 4567	

I confirm that the exact procedures and possible complications of the above tests have been explained to me. I understand that I may ask questions at any time during the testing procedures. I realise that I am free to withdraw from the study without prejudice at any time, should I choose to do so. I have been informed that the personal information required by the researchers will be held in strict confidentiality. In addition, I know that the information derived from the testing procedures will remain confidential and will be revealed only as a number in statistical analyses.

I have carefully read this form. I understand the nature, purpose and procedure of this study. I agree to participate in this research project of the MRC/UCT Research Unit for Exercise Science and Sports Medicine.

Name (in full) of volunteer: _____

Signature of volunteer: _____

Name (in full) of witness: _____

Signature of witness: _____

Date: _____

QUESTIONNAIRE (MEDICAL AND TRAINING HISTORY)

Name: _____

Date of Birth: _____

Age: _____

Medical and Surgical History (last 2 years): _____

_____

_____

_____

_____

_____

Present/previous injuries to lower limbs, pelvis or spine:

_____

_____

_____

Medication: _____

_____

_____

Are you currently receiving any massage, soft tissue or physiotherapy treatment?

Y	N

If "yes", please state details of treatment: _____

_____

In what year did you start running? _____

In what year did you run your first marathon? _____

In what year did you run your first ultra-marathon? _____

How many of the following races have you run in the past:

i. Standard Marathons (42,2km) _____

ii. Ultra-Marathons: Two Oceans (56km) _____

iii. Ultra-Marathons: Other (< 80km) _____ Other (>80km) _____

iv. Comrades: Up _____ Down _____

How many months a year do you run? _____

What is your average weekly distance when training for competition? _____

What is your average weekly distance when not training for competition? _____

What has been your average weekly training distance for the last three months? _____

Please complete the following table:

	PB		Most Recent Performance	
Event	**Year**	**Time**	**Year**	**Time**
5km				
10km				
21,1km				
42,2km				
Two Oceans				
Comrades Up				
Comrades Down				

Have you ever run on a treadmill before?

Y	N

Are you able to visit the laboratory at the Sports Science Institute (Boundary Road, Newlands) for testing in the 3 weeks before the Comrades marathon, daily for 1 week after Comrades, and thereafter, for testing sessions between 10-15 days after the Comrades marathon?

Y	N

Are you planning to train at a reduced level after Comrades (at least for the duration of the study)?

Y	N

Signature: _____

Date: _____

Thank-you for your co-operation in completing this questionnaire.

PHYSICAL ACTIVITY QUESTIONNAIRE

We would like to find out about any physical activities that you participate in. Below the table is a list of different types of activity. Please list by number any type of sport that you regularly participate in. Please indicate the number of times per week and the duration of participation in these events:

Type of Sport	Months per Year (months/year)	Number of Sessions per Week	Duration of Each Session (hr:min)	Total Hours per Week (hrs/week)

Examples of sporting activities:

1. Jogging
2. Aerobics/ Step
3. Martial arts
4. Volleyball
5. Strength/ Resistance Training
6. Hiking
7. Golf
8. Canoeing
9. Dancing
10. Skating
11. Rugby
12. Swimming
13. Cycling
14. Walking
15. Squash
16. Tennis
17. Badminton
18. Netball
19. Basketball
20. Soccer

ANTHROPOMETRY

Subject Name: _____

Subject Code: _____

Body mass _____
Stature _____
BMI _____
Dominant leg _____

Skinfold measurements (mm)	
Triceps	
Biceps	
Sub-scapular	
Supra-iliac	
Thigh	
Calf	
Abdominal	
Girth measurements (cm)	
Relaxed arm	
Contracted arm	
Forearm	
Wrist	
Chest	
Abdominal	
Bi-trochanteric	
Sub-gluteal	
Mid-thigh	
Above-knee	
Calf	
Ankle	
Diameter measurements (mm)	
Humerus	
Bi-acromial	
Transverse chest	
AP chest	
Bi-iliac	
Femur	
Length measurement (cm)	
Sub-gluteal to above- knee	

Sum of 7 skinfolds _____
Predicted % body fat _____
Lean body mass _____

MAXIMAL TREADMILL TEST

Subject Name: _____

Subject Code: _____

Time (min)	Speed (km/hr)	HR (bpm)	VO_2 (ml/min)	RER

VO_{2max} (ml/kg/min) _____

PTRS (km/hr) _____

75% of PTRS _____

HR_{max} _____

UNI-DIMENSIONAL PAIN SCALE (STUDY ONE AND STUDY TWO)

Subject Name: _____

Subject Code: _____

0	NOTHING AT ALL
1	VERY VERY SLIGHT
2	VERY SLIGHT
3	SLIGHT
4	MILD
5	MODERATE
6	MODERATE-SEVERE
7	SEVERE
8	VERY SEVERE
9	VERY VERY SEVERE
10	MAXIMAL PAIN

MULTIDIMENSIONAL PAIN SCALE (STUDY THREE AND STUDY FOUR)

Subject Name: _____

Subject Code: _____

QUADRICEPS

No pain Unbearable pain

Pain at rest

No pain Unbearable pain

Pain during normal daily activities

No pain Unbearable pain

Pain during passive stretch

No pain Unbearable pain

Pressure pain

Subject Name: _____

Subject Code: _____

HAMSTRINGS

No pain Unbearable pain

Pain at rest

No pain Unbearable pain

Pain during normal daily activities

No pain Unbearable pain

Pain during passive stretch

No pain Unbearable pain

Pressure pain

Subject Name: _____

Subject Code: _____

GASTROCNEMIUS

No pain Unbearable pain

Pain at rest

No pain Unbearable pain

Pain during normal daily activities

No pain Unbearable pain

Pain during passive stretch

No pain Unbearable pain

Pressure pain

DATA COLLECTION SHEET: STUDY ONE

Subject Name: _____

Subject Code: _____

Time	HR	VO_2	RER	RPE	Stride frequency
0					
0.5					
1.0					
1.5					
2.0					
2.5					
3.0					
3.5					
4.0					
4.5					
5.0					
5.5					
6.0					
6.5					
7.0					
7.5					
8.0					
8.5					
9.0					
9.5					
10.0					
10.5					
11.0					
11.5					
12.0					
12.5					
13.0					
13.5					
14.0					
14.5					
15.0					

DATA COLLECTION SHEET: STUDY TWO

Subject Name: _____

Subject Code: _____

Time	HR	VO_2	RER	RPE
0				
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				
8.5				
9.0				
9.5				
10.0				
10.5				
11.0				
11.5				
12.0				
12.5				
13.0				
13.5				
14.0				
14.5				
15.0				

Test number	Vicon code
1	
2	
3	
4	
5	
6	

DATA COLLECTION SHEETS: STUDY THREE

Subject Name: _____

Subject Code: _____

75% PTRS: _____

130% PTRS: _____

Submaximal run

Lap	EMG file	RPE	20m time (sec)	HR (b/min)
6				
8				
10				

Lap	1	2	3	4	5	6	7	8	9	10

20 m sprints

Sprint 1	EMG file		Sprint time (sec)	
Sprint 2	EMG file		Sprint time (sec)	
Sprint 3	EMG file		Sprint time (sec)	

Subject Name: _____

Subject Code: _____

75% PTRS: _____

130% PTRS: _____

5km time trial

Distance (km)	**EMG file**	**RPE**	**20m time (sec)**	**km time (min / sec)**
1				
2				
3				
4				
5				
Sprint				

5km time (min / sec) | |

Laps:

1 km	1	2	3	4	5	6	7
2 km	1	2	3	4	5	6	7
3 km	1	2	3	4	5	6	7
4 km	1	2	3	4	5	6	7
5 km	1	2	3	4	5	6	7

DATA COLLECTION SHEETS: STUDY FOUR

Subject Name: _____

Subject Code: _____

Time	HR	VO_2	RER	RPE	Stride frequency
0					
0.5					
1.0					
1.5					
2.0					
2.5					
3.0					
3.5					
4.0					
4.5					
5.0					
5.5					
6.0					
6.5					
7.0					
7.5					
8.0					
8.5					
9.0					
9.5					
10.0					
10.5					
11.0					
11.5					
12.0					
12.5					
13.0					
13.5					
14.0					
14.5					
15.0					
15.5					
16.0					
16.5					
17.0					
17.5					
18.0					
18.5					
19.0					
19.5					
20.0					

Subject Name: _____

Subject Code: _____

Sample		Code
Plasma CK	submax	
	timetrial	
Blood glucose	0 mins	
	5 mins	
	10 mins	
	15 mins	
	20 mins	
CO_2 trapping	0 mins	
	5 mins	
	10 mins	
	15 mins	
	20 mins	