AN EVALUATION OF GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN ENDURANCE RUNNERS AND LOW PHYSICAL ACTIVITY INDIVIDUALS

A DISSERTATION PREPARED BY KIM BUCHHOLTZ (BCHKIM001) IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER OF PHILOSOPHY DEGREE IN SPORTS PHYSIOTHERAPY (MPHIL SPORTS PHYSIOTHERAPY) FROM THE UNIVERSITY OF CAPE TOWN

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DECLARATION

I, Kim Buchholtz (BCHKIM001), hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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LIST OF ABBREVIATIONS

ACSA	Anatomical cross sectional area
ICC	Intra-class coefficient
MRI	Magnetic resonance imaging
MTU	Muscle tendon unit
PCSA	Physiological cross sectional area
ROM	Range of movement
RUSI	Realtime ultrasound imaging
US	Ultrasound

ABSTRACT

Background

Distance running has become increasingly popular in recreational runners. The gastrocnemius is the main muscle used for propulsion in running, and may be at risk for injury due to its morphology. In previous studies, changes in the morphology and architecture of the gastrocnemius muscle have been evident following training, but it is unclear whether these changes are related to training or youth. Previous studies of runners have shown a decrease in gastrocnemius and soleus flexibility, as well as changes in the fascicle length and pennation angle. Gastrocnemius volume has not been compared in low physical activity and active participants. Physiological cross sectional area, based on volume and fascicle length measurements may also provide valuable information about the muscle's ability to produce force. Ultrasound may be a useful tool in assessing potential training adaptations in the morphology and architecture of the gastrocnemius muscle.

Aim

The aim of this cross-sectional descriptive study was to assess the differences in architecture and function of the gastrocnemius in endurance runners compared to low physical activity participants.

Specific objectives

(a) To assess differences in calf function and flexibility between endurance runners and low physical activity individuals, and between male and female participants; (b) To determine differences in gastrocnemius muscle architecture and composition between endurance runners versus low physical activity individuals, and between males and females; and (c) To determine whether there are any relationships between training factors and the structure and function of the gastrocnemius muscle.

Methods

Thirty participants between 20 and 45 years old were recruited for this study and allocated to groups based on their level of physical activity. The low physical activity group (n = 14) were not participating in any regular physical activity, while the endurance running group (n = 16) were running a minimum of 40 $km.wk^{-1}$, and had participated in at least one full marathon (42.2 km) in the previous six months. All participants completed informed consent, a physical activity and training questionnaire, and a Physical Activity Readiness Questionnaire (PAR-Q) at the first session.

The first session also included body composition measurements; ultrasound imaging to measure gastrocnemius length, thickness, fascicle length, pennation angle and volume; and familiarisation with all physical tests. Physical tests were conducted in the second session, including gastrocnemius and soleus flexibility, calf raise endurance and vertical jump height to assess the function of the components of the triceps surae.

Results

There were no significant differences between low physical activity and running groups for gastrocnemius thickness, fascicle length, pennation angle and gastrocnemius length. Gastrocnemius volume ($p = 0.02$) and physiological cross sectional area ($p = 0.01$) were significantly greater in the running group compared to the low physical activity group. There were no significant differences between low physical activity and running groups in flexibility or vertical jump height, although male participants had significantly decreased gastrocnemius muscle flexibility ($p = 0.046$) and significantly greater vertical jump heights ($p = 0.01$) than females. Calf raise endurance was significantly greater in the running group than in the low physical activity group ($p = 0.03$).

Conclusion

Endurance running leads to specific adaptations in participants in both structure and function. While ultrasound appears to be a reliable measure for assessing architectural components of the gastrocnemius muscle in both active and inactive populations, further cadaver studies may provide valuable information on muscle architecture.

CHAPTER 1: INTRODUCTION AND SCOPE OF THE THESIS

1.1 INTRODUCTION

Running is a popular form of exercise worldwide for athletes of all ages and capabilities [1–4]. Due to the repetitive nature of running, injury is a common problem, leading to time off training. The incidence of injury in runners has been reported to be as high as 90% in some studies [5,6]. Propulsion in running gait is primarily performed by the calf muscle complex [7]. Due to the high forces created in the gastrocnemius during the push off phase of running, the gastrocnemius appears to be at risk for injury [7]. Injury to the calf muscle region has been reported to be up to 30% of the running injuries reported each year [8]. These figures are difficult to assess due to few standard methods of describing and reporting injury. In addition, calf injuries have been described as calf pain, calf spasm, lower leg pain, gastrocnemius pain or strain and in combination with Achilles tendon injuries [7,9].

The architecture of the muscle is the structural make-up of the tissue [10]. Fibre type, muscle thickness, fascicle (fibre) length, pennation angle and volume affect the functional ability of the muscle [10]. Changes to the architecture may change the characteristics, such as the force producing capacity or the speed at which a muscle contracts [11]. The triceps surae is made up of three parts, the soleus, gastrocnemius and plantaris muscles [12,13]. The gastrocnemius is made up of two separate heads, the medial and lateral heads [14]. These two portions of the muscle have some functional and structural differences. Architectural differences in the medial head of the muscle appear to place it at higher risk than either the lateral head or the soleus for injury [12,13]. Structural changes in the gastrocnemius muscle in response to resistance or power training have been noted in other studies [75]. Although much research has been conducted into the changes in distance runners, these studies fail to adequately compare the results to a non-running population.

Ultrasound has been used in the past to assess the architecture of various muscles around the body [15]. It has rarely been used to measure changes in endurance runners, and has not been used in previous studies to assess gastrocnemius volume in this group of athletes. Ultrasound can assess thickness, fascicle length, pennation angle and physiological cross sectional area [15]. These measurements may improve our understanding of training-related adaptations to muscle architecture [15].

Research is required to compare a healthy, low physical activity† group with an endurance running group to assess the differences in structure and function between the groups. This will allow a better understanding of the architectural and functional changes following endurance running training.

1.2 AIMS AND OBJECTIVES

1.2.1 Aim

The aim of this cross-sectional descriptive study was to assess the differences in architecture and function of the gastrocnemius in endurance runners compared to low physical activity participants.

1.2.2 Specific objectives:

The specific objectives were:

- To assess differences in calf function and flexibility between endurance runners and low physical activity individuals, and between male and female participants.
- To determine differences in gastrocnemius muscle architecture and composition between endurance runners versus low physical activity individuals, and between male and female participants.
- To determine whether there were any relationships between training factors and the structure and function of the gastrocnemius muscle.

1.2.3 Significance of this dissertation

While there is a vast amount of research on running and running injuries, few studies have investigated the changes at a structural level on the effect of running on the gastrocnemius. Imaging techniques have been used in the past to investigate the gastrocnemius, but rarely in endurance runners, or in comparison to a control group of participants. As there is little data available on the ultrasound results in a healthy, low physical active population, this research may assist in developing normal values for both the populations investigated.

† Low physical activity is defined as physical activity below the recommended amount of 5×30 min sessions of moderate intensity activity, or 3×20 min sessions of vigorous intensity activity each week (128).

1.3 PLAN OF DEVELOPMENT

In preparation for the experimental phase of this dissertation, a comprehensive review of the literature on running, gastrocnemius structure and function, and instrumentation of measurement techniques will be presented (Chapter 2). This will be followed by a descriptive cross-sectional study that was designed to investigate the structural and functional differences in the gastrocnemius muscle in endurance runners compared to low physical activity participants (Chapter 3). A summary and conclusion section, including recommendations for future research (Chapter 4) will complete this dissertation.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Running has become an increasingly popular form of exercise over the last 30 years, particularly among recreational runners, due to its cardiovascular, relaxation, socialisation and fitness benefits [1–3]. As the number of athletes participating in running multiplies, the number of injuries is also increasing. In addition, as running distance per week increases, so too does the possibility of injury [1,16]. Calf injuries are common injuries in runners [8,17]. Although there is a significant change in length of the calf muscles following running training, the effect of this change is unclear [18,19]. The decreased length may predispose to injury, or conversely, lead to an increase in performance [18,19]. This literature review will study the function of calf muscles in running and the structural changes to those muscles as a result of this training. The review will discuss running participation, the epidemiology of injury in runners, specific calf anatomy and injury, and the structural assessment of gastrocnemius including ultrasound imaging and functional testing.

Data was sourced from sports medicine and science literature incorporating medical literature sourced through online databases including PubMed, CINAHL, PEDro and Google Scholar. Keywords included in the search were: '*calf injuries*', '*gastrocnemius*', '*ultrasound imaging'*, '*running injuries'*, '*biomechanics of running'*, '*leg stiffness', 'volume', 'MRI volume', 'muscle architecture', 'pennation angle', 'fascicle length', 'gastrocnemius flexibility', 'vertical jump height' and 'calf raise', .*

2.2 ENDURANCE RUNNING AND THE EPIDEMIOLOGY OF CALF INJURIES

2.2.1 Participation in running as a sport

Running is a sustainable long term method of cardiovascular training [20]. The health benefits of running include a reduction in obesity, cardiovascular disease and type II diabetes [2,6]. Running is considered an easily accessible sport and high number of runners continue to train over many years [6,20]. Over a ten year follow up period, Koplan et al [20] found that 56% of runners were still running and 81% were still participating in some type of sporting activity. As running has increased in the non-elite population, so have the number of injuries [1,3].

Running is generally described as either sprinting or endurance (distance) running [21]. Endurance running is described as any distance above 3000 m [22] or as the ability to run many kilometres over extended time periods [21]. Ultra distance running is accepted as any distance above the standard marathon (42.2 km).

While humans are relatively slow and poorly developed for sprinting in comparison to their animal counterparts, they are far more efficient endurance runners than the majority of primates and quadrupedal mammals due, in part, to the Achilles tendon and calf muscle unit [5].

According to the Association of Road Running Statisticians [4], there were 1.5 million runners who completed marathons (42.2 km) worldwide in 2011. These statistics include only road running events and only those events that have submitted results to the Association, so it is possible that the numbers are far higher than this. The largest number of marathon runners in a single event is 46 759 in the 2011 New York Marathon. In South Africa alone, there are 62 registered road marathons and 14 ultramarathons held each year. Another website [23] states that there are a further 11 ultramarathons in South Africa, which includes some trail and offroad events. The numbers competing in these events range from 10 or 20 runners to 18 000 runners in the Comrades Marathon. In the two most well known ultradistance events in South Africa, the Comrades Marathon and the Old Mutual Two Oceans Marathon, there have been 337 100 and 200 307 finishers over the history of each race respectively.

2.2.2 Epidemiology of running injuries

The yearly incidence of injuries is around 60% in runners, although when training for a marathon (42.2 km) this incidence can increase to as much as 90% as a result of the increase in training load [1,16]. In a review of running injury studies, van Gent et al [6] reported a 26% to 92% incidence of injury in runners. Around 80% of all injuries were reported to occur at or below the knee [6,24]. Other commonly reported injuries included stress fractures, shin splints, low back pain, patellofemoral pain syndrome and tendinopathies [25–27]. The exact incidence and prevalence of injuries is difficult to determine as many studies rely on retrospective self-reporting questionnaires, which may lead to a poor recall of the details relating to the injuries. In cases where biomechanical alignment, muscle weakness, overload and poor flexibility have a combined impact on the injury sustained, it is also difficult to describe the injured region as a single structure [28].

Ultramarathoners tend to be older and more experienced than marathoners [29]. As a result, the injuries differ to marathon runners. Most commonly, ultramarathon runners suffer more from overuse injuries such as patellofemoral pain syndrome (7-16%), iliotibial band syndrome (2-12%), medial tibial stress syndrome (5%), stress fractures (10%), chronic exertional compartment syndrome and Achilles tendinopathies (12%) [29].

There is a large variation in the incidence and prevalence of running injuries between studies. Injury history was not collected in all studies, which led to a lack of information on re-injury and the risk of recurrent injuries in certain structures. In a systematic review [30] of 2924 studies describing injuries in running, only eight were included in the final analysis. The remaining studies were excluded due to a lack of clarity regarding areas of injury, possible injury from other sporting activities, incomplete data, and lack of information regarding rate and frequency of injury. There is also a lack of consensus among researchers regarding the presentation of injuries in running. As many of the injuries are due to overuse, Lopes et al [30] suggest that injuries be reported per 1000 hours of running. In addition, it appears that weekly running distance may influence the type and severity of injuries [17,29], and therefore studies need to be more specific about the type of running discipline and weekly distance trained.

2.2.3 Calf muscle injury in runners

2.2.3.1 Epidemiology of calf injuries in endurance runners

In a study of novice runners, muscle strains and ruptures accounted for 15.5% of injuries over one year [31]. The anatomical description of the area involved was lower leg and 12.7% of injuries were in this area. The area could include gastrocnemius, soleus, Achilles tendon and tibialis anterior for example, it is therefore difficult to assess the specific impact of calf injuries on these runners [31].

Van Middelkoop et al [8] reported that calf injuries were the highest reported injury in the month before and during the Rotterdam Marathon. Calf injuries accounted for 30% of injuries, while knee injuries were the next most common site of injury (29%). Of these calf injuries, most were self-reported as strain, cramp or overload of the calf; only seven out of 49 of these injuries persisted at follow up after three months. This suggests that the prognosis of calf injuries is relatively good, but there was no evidence to show whether or not a previous calf injury predisposed to a recurrent injury in the same area [8]. Calf and hamstring injuries were more common in males, while females were more at risk for hip injuries [17]. Participants who had been medically unwell in the two weeks prior to the marathon event were at higher risk for calf injuries [17]. The calf was the most commonly injured area (20% of injuries) during a 16 week study at a Cape Town running club [32]. The limited period of the study may not be an accurate representation of the annual prevalence of injuries in runners, and 62% of the participants were running fewer than 50 $km.wk^{-1}$ as recreational runners [32]. This appears to be the only epidemiological study available in South Africa. Other studies report greater mileage during training [33,34], which may affect injury patterns.

Achilles tendinopathy was one of the most common general running related injury, as well as the most common injury in ultramarathon runners [30]. Prevalence was up to 10% and 19% in runners and ultramarathon runners respectively. Achilles tendinopathies are reported to be linked to gastrocnemius injury [35]. Exact numbers of gastrocnemius injuries are difficult to define, as they are described as calf pain, gastrocnemius pain, Achilles tendinopathy and calf muscle strain [30].

2.2.4 Summary of the literature: Endurance running and the epidemiology of calf injuries

Large numbers of people have started running recreationally, and completing events up to marathon and ultramarathon distances [36]. This increase in numbers has led to a greater number of injuries which interfere with the runners' training and competition [1]. While the incidence of injury is difficult to accurately assess due to problems with retrospective self-reporting and poor definitions of sites of injury, calf injuries appear to be a significant concern. The anatomical and structural arrangement of the calf muscles may predispose these muscles to injury, in combination with their function in running.

2.3. CALF ANATOMY AND ARCHITECTURE

The following section describes the calf muscle complex in terms of anatomy, architecture or macroscopic structure and function. These factors will be considered in relation to predisposition to injury in runners.

2.3.1 Gross anatomy and function of the triceps surae

The calf muscle complex, (or triceps surae) is made up of three separate muscles which become a conjoined tendon (Achilles) and attach to the calcaneus. The three muscles, the gastrocnemius, soleus and plantaris form the primary plantarflexors of the ankle and gastrocnemius has a small role as a knee flexor when the knee is extended due to its attachment above the knee [12,13].

The gastrocnemius is a two joint muscle running from the femoral condyles to the conjoined tendon and is considered high risk for injury due to this biarthrodial nature [12,13]. It arises as two separate heads, medial and lateral, from the posterior femoral condyles and connects in a flat aponeurotic musculotendinous junction before joining the soleus aponeurosis in forming the Achilles tendon eight to ten centimetres above the calcaneus [14]. The soleus muscle is a flat muscle deep to the gastrocnemius, arising from the posterior fibula and upper part of the medial tibia [37].

The plantaris muscle also attaches to the femoral condyles, medially and superiorly to the lateral head of gastrocnemius. It crosses the knee joint and runs between the medial head of the gastrocnemius and soleus before joining the Achilles tendon and is considered to have a small plantarflexion role (14). Plantaris is absent in 7-20% of lower limbs (38).

The Achilles tendon is the combined tendon of the gastrocnemius, soleus and plantaris muscles and attaches distally into the calcaneus. It is the strongest and thickest tendon in the human body and is surrounded by a paratenon (or paratendon), which is continuous with the fascia of the muscle and the periosteum of the calcaneus rather than a synovial sheath (12). The fibres of the tendon spiral through 90° as they move distally, and this structure may explain some of the elastic qualities of the tendon and its ability to withstand exceptionally high loads (39). Function of the calf muscle-tendon unit (MTU) depends on the structural integrity of the Achilles tendon as well as the aponeurosis to function optimally, so injury to either of these could negatively affect the function of the calf muscles (40).

Normal range of movement (ROM) of the ankle is considered to be from approximately -20° to 60° plantarflexion (41). A minimum of 10° of dorsiflexion is required for normal locomotion and this range may be limited by a decrease in gastrocnemius or soleus flexibility, tight ankle joint capsule or abnormal bony formation of the ankle (41).

2.3.2 Architecture of gastrocnemius

The macroscopic arrangement of the muscle fibres is described as the architecture. This muscle architecture is one of the primary determinants of function and can determine the direction of force production and movement (10). Properties of the muscle are determined by the muscle fibre type and distribution, fibre length, pennation angle, physiological cross sectional area and volume (10).

2.3.2.1 Muscle fibre types

Muscle fibre types are described as either type I, slow twitch, oxidative fibres or type II, fast twitch, glycolytic fibres. These fibres have significant differences in contraction, metabolism, and susceptibility to fatigue as shown in Table 2.1 (42). Type II fibres can be further divided into type IIa and type IIb. Type IIa are intermediate fibres with a faster contraction time than type I, but better fatigue resistance than type IIb (43). Gastrocnemius has a higher proportion of fast twitch type II fibres in comparison to soleus. Fibre types and distribution are shown on Table 2.3.

Table 2.1: Properties of skeletal muscle fibre types (adapted from Nordin & Frankel, 2012 [43]).

	Type I **Slow Twitch Oxidative**	**Type IIa** **Fast Twitch Oxidative-Glycolytic**	**Type IIb** **Fast Twitch Glycolytic**
Speed of contraction	Slow	Fast	Fast
Metabolic pathway	Oxidative phosphorylation	Oxidative phosphorylation	Anaerobic glycolysis
Fibre diameter	Small	Intermediate	Large
Rate of fatigue	Slow	Intermediate	Fast

2.3.2.2 Muscle thickness

Muscle thickness is the width of the muscle between the superficial and deep aponeuroses [44]. Together with pennation angle, thickness is reported to be an important factor in overall force production [44]. Differences in thickness may also be indicative of atrophy in the muscle [45]. Thickness of the medial gastrocnemius is measured ⅓ down the length of the muscle, as measured between the proximal and distal musculotendinous junctions [34,44,46]. The average medial gastrocnemius muscle thickness reported in previous studies is 2.05 cm. These values are shown in Table 2.5 [34,47,48]. Thickness in distance runners has been reported to be 2.10 cm [47].

2.3.2.3 Fascicle length

The muscle fibres or fascicles lie between the superficial and deep aponeuroses attaching at an angle to the deep aponeurosis [49]. Fascicle length determines the muscle's ability to contract rapidly, and those muscles with longer fascicles have potentially faster shortening velocities [47]. The average fascicle length of the studies shown in Table 2.5 is 6.02 cm [34,47,48,50–53]. Distance runners were reported to have a fascicle length of 5.36 cm in a single previous study [47].

2.3.2.4 Pennation angle

Pennation angle is the angle at which the muscle fascicles attach into the deep aponeurosis. The medial and lateral heads of gastrocnemius are each described individually as a unipennate muscle, with pennation being the angle at which the muscle fibres attach to the connective tissue [54]. The pennation angle can be calculated on an ultrasound image by measuring the angle between the fascicles (fibres) and the deep aponeurosis [55].

Muscle fibres arranged in parallel with short fascicles and a high pennation angle, such as the gastrocnemius, have a significant advantage in producing high forces (56). In a study investigating distance runners, the mean value of pennation angle was 23.3° (47). Mean pennation angle across the studies shown in Table 2.4 and Table 2.5 averages 21° (34,47,48,51–53). These values are also much greater than the cadaver study (57), possible related to the method of preservation, or the condition of the specimen in terms of age, sex‡ and physical activity (57). These factors are not reported in the study.

2.3.2.5 Anatomical cross sectional area

Anatomical cross sectional area (ACSA) is described as the area of the muscle at right angles to the muscle belly (53). While ACSA is necessary for volume calculations when using ultrasound imaging (58), it is not a good indicator of the functional or force producing capacity of the muscle (53). Physiological cross sectional area is preferred as a measure of force producing capacity as it takes the pennation angle of the muscle into account (53). The role of physiological cross sectional area is discussed further in Section 2.3.2.7 (page 11).

2.3.2.6 Muscle volume

Calf volume is described in a number of studies using a variety of methods (50–53,57,59–62). A cadaver dissection study was performed in 1983 (57), and has been used as a standard in all further studies. In this study, the muscles were dissected out and weighed to provide the mass (57). In addition, the study assessed muscle length, fibre length, pennation angle and ACSA. Muscle volume may be extrapolated from muscle mass using the following equation:

$$D = m/V$$

with D, m and V representing muscle density (assumed to be $1.056 g.cm^{-3}$), muscle mass and total volume respectively (57). The average values of the measurements performed on three cadaver specimens are shown in Table 2.2. Some measurements were performed on the entire gastrocnemius muscle, and others on the medial or lateral components individually.

‡ The term 'sex' is used in this study according to the following definition: '***Sex** refers to the biological and physiological characteristics that define men and women. **Gender** refers to the socially constructed roles, behaviours, activities, and attributes that a given society considers appropriate for men and women.'* (129)

While the cadaver study has regularly been used as the standard against which other results have been compared to [46,52,54,61], the values may be lower than those participants to be investigated in this study. This may be explained by the absence of age, sex and physical activity information on the cadaver specimens, and it is possible that the cadavers were older and potentially inactive prior to death. The process of preservation with formalin may also affect the results [57]. In addition, only three specimens were studied.

A method using leg length and muscle thickness has also been used to calculate volume [63]. This method was effective in measuring total triceps surae volume, based on a single ultrasound scan to measure thickness, when compared to MRI volume measurements [63]. However the method was not practical in assessing gastrocnemius volume, due to unacceptable levels of errors in regression calculations.

Table 2.2: Average of architectural components of the gastrocnemius muscle (n = 3) (adapted from Wickiewicz et al [57]).

	Muscle length (cm)	Fibre/fascicle length (cm)	Pennation angle (°)	Muscle mass (g)	Muscle volume = m/D (cm^3)
Total gastrocnemius	-	-	-	149.9	142
Medial gastrocnemius	24.8	3.5	17	-	-
Lateral gastrocnemius	21.6	5.1	8	-	-

Key: '-' not assessed.

2.3.2.7 Physiological cross sectional area

Physiological cross sectional area is an indication of the amount of maximal force generating capacity of a muscle [50]. In pennate muscle, such as the gastrocnemius, the fibres lie at an angle to the direction of its movement, and therefore physiological cross sectional area (PCSA) is calculated to take this into account [53]. The maximum force produced by a muscle is therefore dependant on its PCSA rather than ACSA [53]. The medial gastrocnemius has a high PCSA, and comprises about 24% of the total cross sectional area of the triceps surae (Table 2.3). Soleus contributes 60% and lateral gastrocnemius contributes a further 13% [55].

This high PCSA found in medial gastrocnemius, together with the relatively short fibre length, therefore allows the muscle to generate high forces, with a small amount of excursion. This is a common arrangement in anti-gravity muscles [10].

Table 2.3: Summary of differences between soleus, medial and lateral gastrocnemius muscle (Adapted from Hebert Losier et al [40]).

	PCSA	Volume	Fibre type	Fascicle length
Soleus	SOL ≈ 3 x GM SOL≈ 8 x GL	SOL ≈ 2 x GM SOL ≈ 2 x GL	70-90% Type I 10-30% Type IIa	20-39 mm
Medial and lateral gastrocnemius	GM≈ 2.5 x GL	GM ≈ 2 x GL	50% Type I 50% Type IIa+b	GM: 35-57 mm GL: 44-77 mm
Total	200-440 cm^2	640 – 870 cm^3	-	-

Key: SOL: soleus; GM: Medial gastrocnemius; GL: Lateral gastrocnemius; ≈: approximately, '-': not assessed.

The gastrocnemius is described in most of the available research as the main force producers during the propulsion in the take-off phase of gait [11]. It is well established that changes in muscle morphology (such as architecture, tendon stiffness and muscle strength) may affect its functional performance ability [34]. Specific factors affecting calf injuries are further discussed in Section 2.4.3 (page 15).

2.3.3 Summary of the literature: Calf anatomy and architecture

The calf muscle complex is made up of three separate muscles; the gastrocnemius, soleus and plantaris muscles, and the combined tendon of these three (Achilles tendon) [12,13]. The calf muscles in general, and the gastrocnemius in particular are strong plantarflexors of the foot, and due to the physiological structure can produce powerful contractions during running [10,12,13]. Muscle thickness, fascicle length and pennation angle all contribute to the function of the gastrocnemius [34,47,48,50–53,57,59–62]. The gastrocnemius has relatively short fibres and a high PCSA, meaning that it is a powerful producer of force [40]. The anatomical attachments and structural architecture of these muscles determine the function, endurance and power of each. These factors may contribute to the risk of injury during running, but should be considered in relation to other extrinsic risk factors [10,43,55].

2.4 CALF MUSCLE INJURY IN RUNNERS

2.4.1 Muscle strains

Muscle injuries are among the most common injuries in sport with an incidence of 10-55% of all reported injuries. Strains are a common injury in running type exercise, especially in the superficial, two-joint muscles such as gastrocnemius [64]. The most frequently reported injury in the calf is a muscle strain called 'Tennis Leg'. This injury was initially described in tennis in the 1800's following rapid knee extension with the ankle in dorsiflexion, but has been accepted as a common injury in running and sprinting sports [12,14]. It is often seen in the middle aged sports person who describe the injury as being a snapping sensation or as if a ball had hit the person in the back of the leg [9]. This injury was initially suspected to be a plantaris muscle rupture by Powell [65]. This has since been confirmed using MRI and cadaveric dissection to be a medial gastrocnemius tear in 67% of the cases studied [9]. Tennis leg is most often seen as an injury of the distal musculotendinous junction, and the pain is experienced in the mid-calf area. While it is rarely seen at the proximal musculotendinous junction, this may occur, with the pain presenting behind the knee [14].

Gastrocnemius injuries appear to be *'pacing injuries'*, related to increases in running speeds [35]. The rate of the lengthening and shortening cycle of the calf MTU must respond appropriately as the speed of running increases [35]. This is important due to the role of the gastrocnemius in propulsion [35]. As a result, runners who run at a higher velocity are more at risk for muscular strains of the gastrocnemius. In addition, an increase in running velocity results in a shift of the body mass forwards, placing an increased load on the posterior musculature of the leg [2]. Sudden eccentric overstretch (such as running up onto a curb) or rapid acceleration from a stationary position are common mechanisms of injury to the gastrocnemius, particularly in running [12].

2.4.2 Overuse Injuries

Overuse injuries occur due to repetitive loading of the same structures, and cumulative micro-trauma. Training is acknowledged to cause neuromuscular adaptations in the muscles as a result of strain caused during training sessions [19]. Muscle tissue adapts according to the level of strain applied to it during training. Repeated strain is tolerated by the body if the strain applied is below the threshold limit of the structure, and if there is sufficient time to recover between the repeated stresses [28,66]. Participating in a sport which is characterised by repetitive loading of the same muscles for long periods creates a greater risk of overuse injury due to continuous loading of the same muscle and bony structures [66].

Each foot of the average runner strikes the ground approximately 300 times per kilometer, and due to this repetitive loading, there is a high risk of injury [16,67]. Injury occurs in runners once they have exceeded a threshold in running distance or intensity. There is no specific data to prescribe exactly what the general limits for running are, as these vary between individuals [28]. For each runner, training, anatomical and biomechanical factors need to be assessed to identify the injury risk to that particular athlete [28]. Anatomical factors predisposing to calf injury are further discussed in Section 2.4.3 (page 15).

The training factors that should be considered when minimising the risk of injury associated with running are excessive running distance, high training intensity and rapid increases in either distance or intensity, as well as extrinsic factors such as shoes and surfaces [68]. The number of injuries appears to be related to the weekly kilometres covered in training. This training variable may be particularly important to injury risk. Van Gent et al [6] found the training threshold to be 64 km of running per week, and above this limit the risk of injury appears to increase sharply. When training for marathons or ultradistance events, runners are regularly training in excess of this threshold and therefore at higher risk of injury. While frequency of training (the number of training sessions per week) is important when considering the risk of injury, total distance covered per week appears to be more definitive in terms of predisposition to injury [6,69]. Marti et al [69] found Achilles tendon pain and calf muscle injury to be the two most common overuse injuries in endurance runners, and they occurred more often in older runners with a high weekly mileage.

Biomechanical factors that may be involved in overuse injuries are arch height and decreases in ROM of either dorsiflexion or plantarflexion [68]. There is no conclusive evidence to confirm or reject these theories. Hreljac et al [68] found that injured endurance runners had significantly decreased hamstring flexibility compared to non-injured runners, but they failed to specify which overuse injuries were related to this anatomical change. They speculated that poor flexibility could indicate a muscle imbalance which would result in an earlier onset of muscular fatigue [68].

While many runners report calf pain and injury, there is very little published data on the overuse mechanisms of injury in the calf muscles, and gastrocnemius specifically.

2.4.3 Anatomical and physiological predisposing factors to gastrocnemius injury

Rapid knee extension in ankle dorsiflexion caused injury in 67% of cases in the medial gastrocnemius (13,14). This is due to the high proportion of fast twitch fibres in the medial head of the gastrocnemius and the fact that the gastrocnemius crosses two joints. During exercise the fast twitch fibres appear to be preferentially recruited (70), which could explain the higher number of injuries in comparison to the soleus muscle.

Superficial muscles crossing two joints such as the gastrocnemius are more predisposed to muscle strains (64). The short muscle fibres and high pennation angle produce greater force which may lead to more injuries (56). There are multiple muscles involved in plantarflexion of the ankle, but it appears that there is some preferential activation of medial gastrocnemius in comparison to the lateral gastrocnemius and soleus (71). This increased activity could explain the higher number of injuries found in the medial head of gastrocnemius (9,14). Medial gastrocnemius was also found to have a higher cross sectional area (CSA), and it is possible that it produces more of the plantarflexion force than the lateral head (71). In addition the medial head has shorter fibres and a greater pennation angle than the lateral head. This results in a larger number of fibres within a given volume in the medial gastrocnemius than in either the soleus or lateral head of the gastrocnemius and consequently a greater force producing capacity (72).

Soleus muscle strains are also common injuries in sport (12). Soleus injuries are considered lower risk since the muscle crosses only one joint. Injuries of the soleus present in a far less dramatic manner than gastrocnemius, worsening over time rather than as a sudden onset (12,13).

2.4.4 Summary of the literature: Calf muscle injury in running

The calf muscle may be injured in acute episodes involving a strain or as an overuse injury from repetitive loading (14,69). Gastrocnemius injuries seem to be related to higher velocity running due to the shift of body mass forward and the increased pressure on the posterior muscle structures (2,35). The medial gastrocnemius is particularly at risk for injury as it has a high proportion of fast twitch fibres and crosses two joints. The medial head is preferentially activated compared to the lateral and possibly produces more plantarflexion force (13,14,56). Repetitive training leads to adaptation in the muscle structure and function that may lead to positive or negative changes in the runner's ability or injury risk.

2.5 LOWER LIMB ADAPTATIONS IN ENDURANCE RUNNERS

Exercise training leads to changes in the body as a result of repeated conditioning of the structures involved [73]. For example, there are changes in the architecture of the muscle after a period of training [34,61]. Endurance running training causes hypertrophy of the lower limb muscles, which results in concomitant inflexibility, particularly in the gastrocnemius and hamstring muscles [18]. There is controversy over whether this inflexibility predisposes to injury or whether it may in fact protect the muscle from injury while contributing to improved performance [18,34].

2.5.1 Architectural adaptations to training

Several studies have reported that high volume, low load training, as in the case of endurance running, alters the mitochondrial content and therefore the oxidative capacity of muscle, but the stimulus is insufficient to cause structural changes to the muscles [34]. As endurance training is usually performed at low intensities, mostly Type I and IIa fibres are recruited. There are small or no changes in cell diameter in these fibers with only small gains in strength [74].

Karamanidis & Arampatzis [34] found that in a group of runners who had been regularly training 30 to 100 $km.wk^{-1}$, the medial gastrocnemius pennation angle was significantly increased compared to non-runners. In addition, Tate et al [61] found significant differences in volume, CSA and muscle length between young, elite athletes and the previously reported cadaver specimens [57]. The athletes in this study were participating in a variety of jumping and change of direction sports, ranging from 50 $hr.yr^{-1}$ to 500 $hr.yr^{-1}$. They acknowledge that the differences may be due to age-related changes, rather than physical activity, as there is very little descriptive information available about the cadaver subjects [61], in addition to the large variation in participants in their own study. More studies investigating these components in healthy, active participants are needed. Significant changes in thickness, fascicle length and pennation angle were found following a five week training programme incorporating sprint, jumping and resistance training [75]. Sprinters also had significantly thicker triceps surae, and greater fascicle length than distance runners. A longer fascicle length leads to a faster contraction velocity [47]. It is unclear whether this increased fascicle length is an adaptation to the sprint training, or whether people with genetically longer fascicles tend towards sprinting as a sport due to an apparent ability in this discipline [47].

Pennation angle was the only significantly greater architectural feature in the gastrocnemius of distance runners compared to either sprinters or inactive controls [47]. However, participants in the previous study were 10 km runners (n=24) and marathon runners (n=10). It is possible that due to the greater number of 10 km runners, the changes in pennation angle may be more significant compared to the runners in the current study [47]. This supports the previous evidence that endurance running potentially does not provide enough stimulus for structural adaptation, other than changes in pennation angle [34]. Changes in gastrocnemius volume in runners compared to a low physical activity population have not been measured in previous studies.

There are multiple studies investigating the effect of aging on muscle volume [34,44,53]. However, no studies have investigated changes in volume in active participants compared to an inactive control group. Further research in the changes in volume as an adaptation to training needs to be conducted.

2.5.2 Neuromuscular adaptations to training

Following exercise training there are changes in both the neural and motor systems which lead to improvements in muscle function. In repetitive motor tasks such as walking or running, humans use feedback mechanisms from both internal sources (musculoskeletal system) and external sources (environment) to make adjustments to the tasks they are performing [34]. Muscle recruitment patterns improve with repeated training, and in running specifically, more highly trained runners display more refined patterns of recruitment in the utilised muscles [19]. These changes are as a result of task learning and can lead to improvements in both performance and running economy [19].

In running, performance is limited by both aerobic capacity of the athlete, as well as their neuromuscular system [76]. Adaptations in the neuromuscular system following running training allow the body to utilise the muscular systems more efficiently to improve performance with less effort [76]. Improvements in neuromuscular control can lead to a better running economy by allowing the body to more efficiently use the stored elastic energy in the lower limbs [76]. Following training, changes such as pre-activation of the lower limb muscles may be evident which leads to a shorter transition phase from braking to push-off in running gait, ultimately resulting in an improvement in running economy [19]. These adaptations may be protective against injury as more experienced runners, with a long history of training appear to report fewer injuries [17,77].

2.5.3 Decreased length of gastrocnemius muscle

The most commonly reported change in the muscles of long distance runners is a decrease in flexibility (18). The posterior muscles including hamstrings, gastrocnemius and soleus were all shortened in males and females when compared to non-runners. In addition, runners with a high weekly mileage were shortened in the posterior lower limb muscles by a greater amount than those running an average of 69 km per week or less (18). Another study showed that in runners there was greater muscle shortening on the dominant side than on the non-dominant side (78). A lack of flexibility in the gastrocnemius may lead to decreased range in both the knee and ankle joints (79). Shortening of the gastrocnemius is only noticeable when the knee is in full extension with dorsiflexion of the ankle.

Since the knee is never fully extended in running, Neely (41) reported that gastrocnemius shortening in isolation is unlikely to be the cause of lower limb injuries in running. Other studies found that a shortening in the calf muscles and the resulting ankle equinus has been found to predispose to muscle strains, plantar fasciitis, iliotibial band syndrome, Achilles tendinopathy and hamstring muscle strains (78,79). In contrast, Craib et al (80) found that runners with decreased gastrocnemius flexibility had a better running economy. This study was a correlational study and made no comment about whether the changes were adaptations due to training or whether the runners were more efficient due to the intrinsic inflexibility (80).

Dorsiflexion range of movement (ROM) may also be affected by the compliance of the Achilles tendon as the movement requires stretching of both the gastrocnemius muscle belly as well as the conjoined Achilles tendon to gain the largest range (81). The authors found during passive dorsiflexion to 30°, that the muscle belly contributed about 25 mm of stretch, while the Achilles tendon contributed about 17 mm. The tendon made a significant contribution to the overall ROM (81) and needs to be considered in studies evaluating ankle ROM.

2.5.4 Leg stiffness and passive elastic energy in runners

As the speed of the athlete increases while running, the body needs to repeatedly produce force in the lower limbs at a rapid rate. The ability of the athlete to do this may improve their performance, and faster athletes generally have shorter stance phase ground contact periods, and greater muscle pre-activation than slower runners (19). Dalleau et al (82) demonstrated that greater leg stiffness in the propulsive leg was related to quicker running performance.

‘Leg stiffness’ is described as the overall stiffness of muscle, ligaments and tendons in the lower limb structures, and considers the joint structure range as well [(82)]. Leg stiffness cannot be used interchangeably with the term musculoskeletal stiffness, but they are related as leg stiffness incorporates the MTU stiffness [(83)]. Leg stiffness may be increased by activating the muscles prior to landing during running, and as a result there is maximum use of the stored elastic energy [(19)]. The neuromuscular adaptations of the lower limb as a result of running training lead to increased pre-activation of muscles, shorter stance phase and use of passive elastic energy to improve running economy [(19,83)].

In addition, during running, humans use a passive ‘spring-like’ mechanism to create propulsion, thus decreasing the energy cost of exercise [(5,21)]. Tendons and ligaments store this passive energy during the braking part of the stance phase, and it is then released through elastic recoil during propulsion. The longitudinal arch and plantar fascia in particular store this passive elastic energy, to assist the spring-like plantarflexion [(25)]. Runners with the best economy while running have a higher energy storage capacity in the triceps surae musculotendinous unit than those with poor economy [(33)]. Tendon stretch and recoil reduce the amount of active muscle contraction required and stretch-shortening cycles can occur at much higher velocities than those controlled by active contraction alone [(34)]. This may be linked to the decreased range of gastrocnemius reported by Craib et al [(80)]. There is also evidence that increased leg stiffness is associated with an increase in velocity and smaller stride lengths [(84)].

2.5.5 Summary of the literature: Lower limb adaptations in endurance runners

Architectural adaptations are evident in the muscle structure following training. The changes depend on whether the training is primarily endurance or strength and power training [(34,47,61,75)]. There are adaptations in both the neuromuscular control of the lower limb [(34)] and the flexibility of the individual muscles as a result of endurance running training [(18)]. Leg stiffness relates to the sum of the structures in the lower limb, of which the ankle joint ROM is an important component [(82)]. As a result, gastrocnemius length has an effect on the total leg stiffness. These may be considered intrinsic factors contributing to injury. When assessing injury in the runner, both intrinsic and extrinsic factors need to be considered, and addressed as appropriate [(36)]. Assessment of these changes may be useful in understanding the adaptations to endurance running.

2.6. INSTRUMENTATION

The following testing methods are used to assess the flexibility, power and endurance of the participants. Each measurement will be discussed in the context of this study, including their reliability and validity.

2.6.1 Ultrasound

Ultrasound imaging is being used in this study to assess the architecture of the gastrocnemius muscle. Ultrasound has been used effectively since the 1950's for imaging of muscle structure, since the 1960's for the measurement of muscle size, and more recently by physiotherapists for the assessment of the architecture and function even in clinical settings [15].

The use of conventional grayscale brightness mode (B-mode) imaging has allowed for visualisation of the macroscopic components of the muscle and allows biofeedback during the rehabilitative process [15]. This use of ultrasound has been termed rehabilitative ultrasound imaging (RUSI) [15]. Most conventional ultrasound imaging units update 20-40 times per second allowing an accurate image of movement and changes in real time. Generally, tissue structures with high collagen content tend to appear whiter on the image, and are referred to as hyperechoic; while those tissue structures with low collagen content such as fluids appear black, and are termed hypoechoic. Muscle tissue tends to appear mostly black due to the perfusion of blood throughout its structure in contrast to fascia with its highly organised collagen structure which appears white [15].

Ultrasound imaging is useful to provide two types of information about the tissue that is being scanned. The echogenicity of the tissue can be evaluated to assess the composition of the muscle, including fluid and collagen content, while the architecture of the muscle (size, structure and shape) can also be ascertained from the images [15].

2.6.1.1 The use of ultrasound for injury diagnosis

Ultrasound can be effectively used to diagnose soft tissue injury, based on changes in the composition of the muscle following injury [15]. The cost of ultrasound is relatively low and it is highly portable as well as producing high resolution images [85]. The disadvantages of ultrasound is that it is most useful in superficial structures, as it is unable to image through bulky tissue or muscle, and the quality of the images and interpretation relies heavily on the operator's skill and training [14]. Due to the superficial nature of the gastrocnemius, ultrasound has been found to be reliable in diagnosing muscle injuries as well as excluding deep vein thrombosis as a differential diagnosis [14].

When assessing muscle strains, ultrasound can be used to grade the injury which assists in management. Grade I strains will often appear normal on ultrasound, or may show areas of increased echogenicity, while Grade II strains can show discontinuity of the muscle fibres together with increased vascularity in the area of the injury. Grade III injuries may show complete disruption of the muscle fibres and haematoma [85]. Participants were excluded from the current study if they were currently suffering from any lower limb injuries, and gastrocnemius injury was therefore not assessed on ultrasound.

2.6.1.2 Ultrasound assessment of muscle architecture

Ultrasound may also be used to assess the architecture and determine the volume and physiological cross sectional area (PCSA) of the gastrocnemius. The following architectural components (thickness, fascicle length, pennation angle) were all found to have correlations greater than 0.8, on condition of standardised testing position, in healthy young participants [15].

2.6.1.2.1 Muscle Thickness

Thickness of the muscle is calculated by the distance between the two aponeuroses. Ultrasound has been found to be highly reliable (r = 0.88-0.94) in measuring thickness in repeated measurements on a single day [15]. This reliability is reported to be very dependent on the investigator, methodology and instruments used and if just one of these components is changed, they recommend that the reliability be rechecked [15].

2.6.1.2.2 Fascicle length

Fascicle length may be visualized on ultrasound as the line between the superficial and deep aponeuroses [33]. While a curvature of the fascicle is visible on the ultrasound images, it is considered negligible and therefore measurement in a straight line is considered adequate [86].

2.6.1.2.3 Pennation angle

The pennation angle is calculated as the angle of attachment of the fascicle on to the deep aponeurosis [33]. Pennation angle measurement on ultrasound was found to be reliable (r > 0.8) on condition that all scans were performed under the same conditions by the same investigator [15].

2.6.1.2.4 Muscle volume

Volume is calculated on ultrasound using the technique described by Esformes et al [58]. The muscle between the proximal and distal musculotendinous junctions is scanned in evenly spaced axial plane sections. The volume between each of those sections is then calculated based on the formula below where *a* and *b* are the Anatomical Cross Sectional Areas (ACSA) in the two consecutive scans (calculated on the scans) and *t* is the length between the adjacent scans. Total volume of the muscle is calculated by adding all the volumes together, using the following equation [58,87]:

$$V = \tfrac{1}{3} \times [a+\sqrt{(ab+b)}] \times t$$

Esformes, Narici and Maganaris [58] compared the use of ultrasound and magnetic resonance imaging (MRI) to measure the volume of tibialis anterior muscle. The authors found ultrasound to be an accurate and reproducible technique of measuring volume in human muscle. The intra-class correlation was r = 0.99 when comparing repeated measurements of volume by ultrasound, indicating that this method is highly reproducible [58]. They found a 7% error in calculation in comparison to MRI, which the authors considered acceptable [58]. The limitation of ultrasound when compared to MRI is the extended length of time required to perform the measurements, and in addition ultrasound can only be used to measure superficial muscles [58]. MRI studies on the gastrocnemius are shown in Table 2.4. The average volume reported across the studies is 339 cm^3 [50,52,53,59–62]. There appears to be only a single study using ultrasound specifically for gastrocnemius calculations. This study is shown in Table 2.5. The total volume (medial and lateral) is reported as 363 cm^3 [51]. These results are much higher than the figure reported by Wickiewicz et al of 142 cm^3 [57]. The differences may be related to the process of preservation by formalin, in addition to the effects of aging or lack of physical activity that is likely in cadaver subjects. No descriptive data were available for these participants [57].

2.6.1.2.5 Physiological cross sectional area

Physiological cross sectional area can not be measured on ultrasound scans but is based on a formula which takes volume and fascicle length as described above into account [53]. PCSA is calculated based on the following formula:

$$PCSA\ (mm^2) = (V/\ l_f)$$

where V is the total volume and l_f is the mean fibre/fascicle length [51].

2.6.1.4 Ultrasound assessment of Achilles tendon compliance

Ultrasound may be used to assess Achilles tendon compliance during an isometric contraction of the gastrocnemius muscle. This gives valuable information on how much flexibility is provided by the tendon compared to the muscle belly. Normal tendon compliance is described as about 18 mm of movement proximally during an isometric plantarflexion contraction in neutral (81). Muramatsu et al (86) also found that both the Achilles tendon and deep aponeurosis possess the ability to stretch, and therefore fascicles at any point along the length of the aponeurosis may be assessed to determine displacement. This ability to stretch appears to be relatively uniform along the structure, which is functionally important as weaker areas may be more prone to injury (86).

A decrease in the tendon compliance may increase the stored elastic energy, which appears to improve the running economy in distance runners(88). In participants with similar range of ankle motion, maximal forces were higher in participants with stiffer tendons (88).

Table 2.4: Summary of studies investigating gastrocnemius volume using magnetic resonance imaging.

	Study design	Sample size (n)	Participants	Measurements performed	Volume (cm^3)
Albracht, Arampatzis, & Baltzopoulos [50]	Descriptive cross-sectional LOE: III	13 males	29 ± 6 years Recreationally active	MRI volume, US fascicle length and ACSA	GM: 285 ± 45 GL: 146 ± 23 Total: 431
Commean, Tuttle, Hastings, Strube, & Mueller [59]	Cross-sectional comparative LOE: III	21 participants (11 male, 10 female)	61 ± 12 years Not specified but most had existing medical conditions	MRI volume of bone, muscle and intramuscular adipose tissue	Average gastrocnemius vol + IMAT gastrocs =168
Elliott et al [60]	Cross-sectional comparative LOE: III	7 participants (3 male, 4 female)	19-50 (mean = 32.14) years Physical activity not specified	MRI volume of GM, GL and SOL	GM: 281 ± 36 GL: 154 ±23 Total = 435
Hasson, Kent-braun, & Caldwell [62]	Cross-sectional comparative LOE: II	24 participants: 12 younger (6 males, 6 females) 12 elderly (6 males, 6 females)	Young males: 27 ± 3 years Young females: 26 ± 3 years Older males: 73 ± 3 years Older females: 70 ± 5 years All regularly physically activity	MRI volume of lower leg, CSA and distribution of contractile and non contractile structures	Young males: GM: 264±59 GL: 147±30 Total: 411 Young females: GM: 220±69 GL: 117±12 Total: 337 Older males: GM: 233 ± 32 GL: 135 ± 33 Total: 368 Older females: GM: 181 ± 29 GL: 85 ± 13 Total: 266

Key: GM=gastrocnemius medialis, GL=gastrocnemius lateralis, SOL=soleus, IMAT=intramuscular adipose tissue.

Table 2.4 cont: Summary of studies investigating gastrocnemius volume using magnetic resonance imaging.

	Study design	**Sample size (n)**	**Participants**	**Measurements performed**	**Volume (cm^3)**
Morse, Thom, Reeves, Birch, & Narici [52]	Cross-sectional comparative LOE: III	27 males (19 elderly, 12 young)	Younger males: 25 ± 4 years Older males: 74 ± 4 years All recreationally active	MRI volume of GL, US fascicle length and pennation angle	GL: Younger: 185.6 ± 38.8 Older: 133.3 ± 23.6
Narici, Maganaris, Reeves, & Capodaglio [53]	Cross-sectional comparative LOE: II	30 participants (16 elderly, 14 young men)	Younger: 27-42 years Older: 70-81 years Recreationally active, no competitive sportsmen	MRI volume and ACSA, US of pennation angle, fascicle length	Younger: GM: 279 ± 59 Older: GM: 209 ± 49
Tate, Williams, Barrance, & Buchanan [61]	Descriptive cross-sectional LOE: III	10 participants (6 males, 4 females)	16-29 years Active in change of direction sports (>50hr/yr)	MRI volume of lower limb muscles, CSA and muscle length. Differentiated between dominant and non-dominant	Dominant: GM: 217 ± 50 GL: 118 ± 33 Total: 335 Non-dominant: GM: 180 ± 41 GL: 122 ± 31 Total: 302

Key: GM=gastrocnemius medialis, GL=gastrocnemius lateralis, SOL=soleus, IMAT=intramuscular adipose tissue.

Table 2.5: Summary of studies investigating the architectural components of the gastrocnemius muscle using ultrasound imaging.

	Study design	Sample size (n)	Participants	Gastrocnemius length (cm)	Fascicle length (cm)	Thickness (cm)	Pennation angle (°)	Volume (cm^3) and PCSA (cm^2)
Abe, Kumagai, & Brechue [47]	Cross-sectional comparative LOE: III	71 total: Sprinters= 23 Distance runners=24 Controls=24	Sprinters: 21 ± 2 years Distance runners: 22 ± 2 years Inactive controls: 21 ± 2 years	-	Sprinters: 7 ± 1 Distance runners: 5 ± 1 Controls: 6 ± 1	Sprinters: 2.4 ± 0.3 Distance runners: 2.1 ± 0.2 Controls: 2 ± 0.3	Sprinters: 22 ± 3 Distance runners: 23 ± 2 Controls: 20 ± 3	-
Albracht et al [50]	Descriptive cross-sectional LOE: III	13 males	29 ± 6 years Recreational sport	GM: 27.8 GM: 23.9	GM: 6 ± 1 GL: 7 ± 1	-	-	-
de Oliveira & Menegaldo [51]	Descriptive cross-sectional LOE: III	8 males	19 ± 1 years Regular physical activity	-	GM: 4.5 ± 0.4 GL: 4.9± 0.5	-	GM: 25 ± 3 GL: 18 ± 3	Volume: GM: 233 ± 31 GL: 131 ± 18 Total: 363 PCSA: GM: 47 ± 7 GL: 25 ± 4

Key: GM: gastrocnemius medialis, GL: gastrocnemius lateralis, '-': not assessed.

Table 2.5 cont: Summary of studies investigating the architectural components of the gastrocnemius muscle using ultrasound imaging.

	Study design	Sample size (n)	Participants	Gastrocnemius length (cm)	Fascicle length (cm)	Thickness (cm)	Pennation Angle (°)	Volume (cm^3) PCSA (cm^2)
Karamanidis & Arampatzis [34]	Cross-sectional comparative LOE: III	49: 30 older males, 19 young males	Young runners: 27 ± 4 years, 30-100 km.wk^{-1} running Young inactive: 29 ± 3 years, no activity	Young runners: 31.7 ± 9.9 Young inactive: 29.3 ± 3.0	Young runners: 6.9 ± 2.8 Young inactive: 6.3 ± 0.8	Young runners: 2 ± 0.5 Young inactive: 1.9 ± 0.1	Young runners: 22 ± 3 Young inactive: 19 ± 2	-
Morse et al [52]	Cross-sectional comparative LOE: III	27 males: 19 elderly, 12 young	Young: 25 ± 4 years Elderly: 74 ± 4 years All recreationally active	-	GL: Young: 5.5 ± 1.1 Elderly: 5 ± 0.8	-	Young: 18 ± 4 Elderly: 16 ±4	-
Narici et al [53]	Cross-sectional comparative LOE: II	30: 16 elderly males, 14 young males	Elderly: 70 - 81 years Young: 27 - 42 years All recreationally active	-	E: 4.3 ± 0.7 Y: 4.8 ± 0.6	-	Young: 27 ± 4 Elderly: 24 ± 3	-
Stafilidis & Arampatzis [48]	Cross-sectional comparative LOE: III	28 males (slow/fast sprinters: speed not specified)	Mean = 21 years Regular sprint training ≥ 5x week	-	GM: slow: 8.6 ± 3.2 fast: 7.5 ± 1.5	Slow: 2 ± 0.1 Fast: 2 ± 0.2	Slow: 17 ± 3 Fast: 18 ± 2	-

Key: GM: gastrocnemius medialis, GL: gastrocnemius lateralis, '-': not assessed.

2.6.2 Flexibility

There has been some debate about whether muscle shortening is beneficial or detrimental to the performance of endurance runners, or whether it possibly even predisposes to injury [18,41,78,89]. While there is research to support both possibilities, the most important fact to be considered is that there is significant shortening in the gastrocnemius muscles as a result of endurance running training [18,79]. Flexibility of the calf muscles may be assessed by calculating the ankle dorsiflexion range. Gastrocnemius is tested with the participant in a standing position with the leg to be tested behind (in hip extension) and the knee in full extension. Maximal dorsiflexion is assessed by the participant leaning forwards while keeping the heel in place on the floor [13]. Reliability of this test was reported by Wang et al [18] as r = 0.98 in both dominant and non-dominant legs. The soleus is assessed in the same standing position with the knee of the tested leg, which is in hip extension, flexed and leaning forwards with the ankle into maximal dorsiflexion. The knee flexion removes the influence of the gastrocnemius on the range [13]. Reliability of soleus flexibility was r = 0.93 and 0.94 in dominant and non-dominant legs respectively. Inclinometers have been found to be effective and reliable methods of calculating lower limb ROM when compared to three dimensional orientation sensors applied to the body [90]. Reliability ranged from r = 0.82 to 0.96 [90].

2.6.3 Vertical jump test

Muscle power has been measured in various studies using an eight camera, high speed video system, but this method is extremely expensive and not portable [91,92]. Other studies used explosive leg extensions and ergonometers to assess power in watts, but these also required expensive equipment [93,94]. A force plate measuring ground reaction forces during a vertical jump have also been used in the past, but this was found to have similar results to the '*jump and reach'* protocol used in this study [95].

Vertical jump height using the jump and reach protocol has been used as an alternate measure to indicate power. Vertical jump height is calculated as the difference between the standing and jump heights on a vertical jump tester (Vertec, South Africa) [96]. Participants are measured in a standing position with an arm extended above the head, and the maximum standing height is measured. Maximum jump height is then measured as the highest value of a jump from a squatting position with no forwards propulsion. The vertical jump test is a reliable indicator of power produced by the lower limbs (ICC = 0.87) [96].

2.6.4 Calf raise test

The calf raise test has been used to assess plantarflexor strength, endurance, fatigue, power and performance [97]. It may also assist with the diagnosis and grading of injuries, and give an indication of the functional level of impairment in the plantarflexors. Although this test is regularly used in clinical practice, there is poor consensus of the exact procedure to be followed when using the test [98–100]. Testing is normally performed in unilateral standing, with the tested leg straight [97]. One complete calf raise is considered raising the heel off the ground until the participant is in full plantarflexion on that side, and then the heel is lowered to the ground. Calf raise testing has been studied with the knee in both flexion and extension in an attempt to isolate either the gastrocnemius or soleus components of the triceps surae [101]. No significant difference was found between the testing positions, suggesting that calf raises give an adequate indication of calf MTU function, but not specific detail on either gastrocnemius or soleus function [101]. The test can be biased towards the gastrocnemius by instructing that all raises should be higher than 5 cm [40]. Using these results as determinants for injury or fatigue in specific sports does need to be done with care, as the test assesses the full calf MTU and it is difficult to analyse the results as specifically gastrocnemius, soleus or Achilles tendon function [40].

Hébert-Losier et al [97] reported 28 ± 11 repetitions to be a reasonable number of calf raises for a healthy individual, and 19 ± 11 in the case of pathology. In a later study, the authors report that a healthy individual should be able to achieve 36-45 repetitions of the calf raise in either knee flexion or extension before fatiguing [101]. In a test-retest study, using a strict protocol of 5 cm calf raise at 40 raises per minute, intra-class coefficients of 0.78 and 0.84 were reported for left and right side respectively [99]. The average of the calf raises reported in that study was 29 [99].

2.6.5 Summary of the literature: Instrumentation

Ultrasound has many uses in musculoskeletal diagnosis and assessment and is particularly useful in the superficial muscles such as gastrocnemius. It is safe, inexpensive and portable [14,15,85]. Ultrasound may be used to assess the architecture (macroscopic composition) of healthy muscle, diagnosis of injury, volume and PCSA calculations and Achilles tendon compliance [45,58,81]. Fascicle length, thickness, pennation angle and volume may be reliably assessed using ultrasound [34,47,48]. The flexibility measurements and vertical jump test have been found to be reliable methods of testing gastrocnemius and soleus dorsiflexion range [13] and lower limb power [96] respectively. Reliability of the calf raise test as a measure of endurance still needs to be confirmed, as no standard method of testing has been devised [97].

2.7 SUMMARY OF THE LITERATURE

Injuries in running are a significant concern as the numbers participating in this sport increase [1,16]. Runners who steadily increase their distances to participate in marathon and ultramarathon distance events are at increased risk of injury due to the repetitive loading through the lower limbs [16,67]. While results are conflicting, there is some evidence that calf injuries are a substantial concern in runners. These may include muscle strains, overuse injuries, cramp and spasm [8,17]. The anatomy and structure of the calf appears to contribute to the number of injuries and location of the injuries in the gastrocnemius muscle [43,101]. The muscles of the lower limb, particularly the posterior muscles are shortened by repetitive running training. Shortening in the gastrocnemius has been reported to predispose to injury, but may also increase performance as it increases the amount of passive stored energy that is available for propulsion. This shortening may be a training-induced adaptation to improve running speed [18]. In addition there are adaptations to training evident in the architecture of the gastrocnemius including pennation angle and volume [34,61]. Very little research into these aspects of endurance runners has been performed to date.

The use of ultrasound has value in assessing both healthy and dysfunctional muscle especially the gastrocnemius [14,15,58]. Architectural structures in the gastrocnemius can be reliably imaged by ultrasound, and provide an inexpensive, portable method of measurement [15,58]. Other measures such as vertical jump height, calf raise test and flexibility testing can give further valuable information on the function of this muscle group [13,40,96,102].

There is a lack of knowledge regarding the effect of running training on the calf muscle in general and gastrocnemius muscle in particular. While shortening has been described, this needs to be assessed in combination with the other measures of power, endurance and information on performance and running speed. The muscle structure needs to be considered in runners in comparison to low physical activity adults as this information could be useful in planning appropriate training of runners by better understanding the adaptations to training that occur. This study aims to assess and report the effects of endurance training on the structure and function of these muscles.

CHAPTER 3: AN EVALUATION OF GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN ENDURANCE RUNNERS AND LOW PHYSICAL ACTIVITY INDIVIDUALS

3.1 INTRODUCTION

Endurance running has become increasingly popular, with a large number of runners completing marathons and ultramarathons each year [(1–4)]. With an increase in mileage, runners are at greater risk for injury [(5,6)]. The plantarflexors are the main muscles used for propulsion of the body during running [(11)]. These plantarflexors are made up of gastrocnemius, soleus and plantaris muscles [(12,13)]. While the soleus has the greatest volume of the three, the gastrocnemius is the muscle that generates the most power. These differences in function are related to the architecture of the muscle [(74)]. The medial gastrocnemius has a higher proportion of fast twitch fibres, shorter fascicles and higher pennation angle than soleus or lateral gastrocnemius [(14)]. This, in addition to the fact that the muscle spans two joints, makes it more vulnerable to injury [(12,13)].

Research has been performed to investigate the architecture of the gastrocnemius using both ultrasound and magnetic resonance imaging [(50,52,53,59–62)]. Ultrasound has been found to be a reliable method of measuring architectural components of muscle [(15)]. The majority of research into the measurement of the gastrocnemius muscle has been conducted to assess changes related to aging [(52)]. Changes related to resistance training have also been assessed [(76)]. It has been reported that due to the low load, high volume nature of endurance running training, the stimulus for architectural adaptations is not sufficient [(10)]. No research has been performed to assess architecture of the gastrocnemius in healthy, low physical activity participants, compared to endurance runners.

The aim of this study was to assess these differences in architecture and function of the gastrocnemius in endurance runners compared to low physical activity participants. The specific objectives of this dissertation have been described in Section 1.2.2 (page 2).

3.2 METHODS

3.2.1 Research design and recruitment

This study had a descriptive cross-sectional design. Healthy male and female volunteers were recruited for this study. The endurance group was recruited from local running clubs in the greater Cape Town area.

The low physical activity group was recruited from office complexes in the area around the Sport Science Institute of South Africa (SSISA). Running club secretaries were emailed the advertisement and requested to forward it on to the club members (Appendix I). The Human Resources departments at Old Mutual, Rand Merchant Bank, Environmental Resources Management, Rustenburg Girls' Junior and High Schools and Coronation Fund Managers were contacted and permission requested for the study information to be forwarded to the staff members (Appendix II).

3.2.2 Participants

3.2.2.1 Inclusion criteria

Endurance group

Male and female runners aged between 20 and 45 years of age who were regularly running more than 40 km per week were recruited for the endurance group. The decision to include runners up to 45 years was chosen to ensure that no changes as a resut of aging were seen in the sample group [(103)]. As ultradistance runners are more likely to be older and more experienced, the age range needed to be large enough to ensure that these runners were included [(104)]. Participants needed to be training between four to six times per week for at least six months prior to the study, and must have completed at least one marathon in the previous 12 months.

Low physical activity group

Healthy male and female participants between 20 and 45 years of age who were not taking part in any regular form of physical activity were recruited for the low physical activity group. Regular physical activity was defined as any exercise that was performed on a weekly basis, at least once a week, for the last six months.

3.2.2.2 Exclusion criteria

Any participant currently undergoing treatment for a calf injury was excluded from the study. Participants with other lower limb injuries were also excluded. If any medical concerns were detected during the health and physical activity screening, for example high blood pressure or heart abnormalities, these participants were excluded due to the physical nature of the testing. Anyone currently using analgesics and non-steroidal anti-inflammatory drugs were also excluded from the study.

3.2.2.3 Sample size determination

Data from a previous study that used ultrasonography to measure Achilles tendon length change [81] were used to ensure that the sample size would provide sufficient statistical power. Tendon length change was selected to determine the required sample size, as this was one of the main outcome measures for this study, and may also have the greatest variance of all the parameters measured in this study. Required sample size for tendon length change was calculated using a smallest meaningful difference of 20 mm, and a standard deviation of 10 mm. With statistical significance accepted as $p < 0.05$, groups of 11, 14, and 17 participants provided 80%, 90% and 95% statistical power for tendon length change respectively. The sample size for this study was 30 participants, with 14 and 16 participants in each of the low physical activity and endurance groups respectively.

3.2.3 Measurement instruments

3.2.3.1 Informed consent form

All participants were required to complete the informed consent form (Appendix III) prior to their involvement in the research study. All relevant information relating to the study and the physical testing that occurred was included on the informed consent form. The risks and benefits to the participants were described and the participants' right to withdraw from the study at any time was discussed.

3.2.3.2 Physical Activity Readiness Questionnaire (PAR-Q)

Participants completed the revised Physical Activity Readiness Questionnaire (PAR-Q) (Appendix IV) to screen their general health and to assess for any underlying medical conditions that may have excluded the participants from the study before performing the physical tests [105]. If any medical conditions were identified, participants were referred for the appropriate medical follow up.

3.2.3.3 Physical activity and training questionnaire

The questionnaire (Appendix V) was a self-designed questionnaire that was completed at the first testing session following the completion of the informed consent form. The questionnaire was used to assess personal details, training history, competition history, general physical activity and injury history in each of the participants. Previous physical activity and reasons for stopping activity were assessed for the low physical activity group, while the endurance group reported current training information.

The questionnaire was developed and then reviewed by a panel of three experts in both the running and exercise science fields to ensure content and construct validity. The panel assessed whether the questions were clear and easily understood. In addition they advised on rewording of questions that may not give the required answers. These recommendations were included and the questionnaire was adapted before being completed by participants in the feasibility study.

3.2.3.4 Anthropometry measurements

Body mass (kg) was recorded using a calibrated scale (Seca model, 708 Germany). Stature (cm) was recorded using a stadiometer (Seca model, 708 Germany). Body fat was expressed as the sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, calf, thigh and abdomen) [106]. Body fat was also expressed as a percentage of body mass [107]. This information was used to describe body composition of the participants in both groups. The validity of these tests has previously been established [106,107]. Intra-rater reliability was assessed during a feasibility study (Appendix VI).

3.2.3.5 Ultrasound imaging

Ultrasound imaging was performed using a Siemens ACUSON X150 diagnostic ultrasound machine (Siemans Medical Solutions Inc, USA). Participants were positioned in prone with the calf muscle relaxed and ankle in plantarflexion for the first portion of the testing. Testing in this position included measurement of the length of the gastrocnemius muscle belly, thickness, fascicle length and pennation angle. Medial gastrocnemius was measured due to it being the most commonly injured portion of the triceps surae complex [13,14]. Ultrasound imaging was first performed on the right gastrocnemius, and was then completed on the left gastrocnemius. These architectural components (thickness, fascicle length, pennation angle) were all found previously to have correlations greater than 0.8, on condition of standardised testing position, in healthy young participants [15].

3.2.3.5.1 Gastrocnemius muscle belly length

Length of the gastrocnemius muscle belly was accepted as the distance between the proximal to distal musculotendinous junction in a straight line over the skin. The musculotendinous junctions were identified on ultrasound in the mid-sagittal plane and marked with non-permanent marker [58].

3.2.3.5.2 Muscle thickness

Three scans were taken of the medial gastrocnemius and measurements were calculated electronically after the testing session. The mid-belly scans were performed over the medial gastrocnemius, measured halfway between the proximal and distal musculotendinous junctions, as measured for gastrocnemius length. Thickness of the muscle was calculated as the perpendicular distance in mm between the two aponeuroses [45]. An example of a thickness measurement is shown in Figure 3.1.

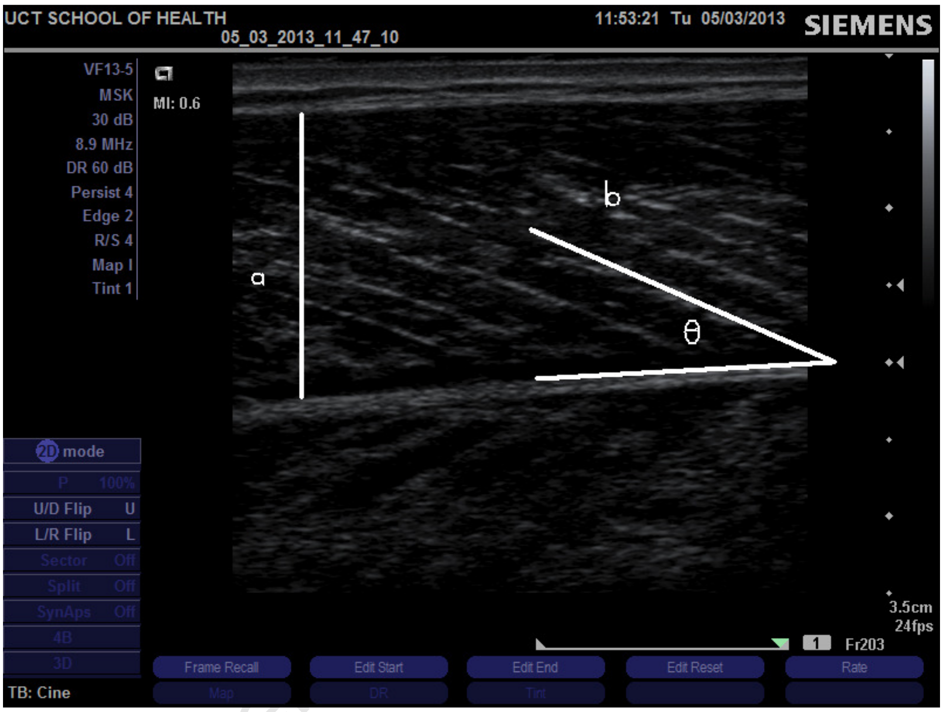

Figure 3.1: Mid belly medial gastrocnemius ultrasound scan demonstrating (a) thickness and (b) pennation angle (θ) measurements.

3.2.3.5.3 Fascicle length

The fascicle length (mm) was then measured on the same mid-belly scans as a straight line along the fascicle between the superficial and deep aponeuroses. Fascicle curvature has been shown to be negligible and therefore measuring along a straight line is considered satisfactory [86]. When the fascicle length extended beyond the line of the scanned image, the length of fascicle missing was estimated by linearly extending the line of the fascicle and the deep or superficial aponeurosis involved [48]. Three separate fascicles were measured on the mid-belly scans, and the average was recorded.

3.2.3.5.4 Pennation angle

Pennation angle (degrees) was calculated as the angle between a single chosen fascicle and its insertion onto the deep aponeurosis [51]. Three separate angles were measured from each of the three mid-belly scans, as seen in Figure 3.1, and the degrees were averaged for data analysis.

3.2.3.5.5 Muscle volume

Ultrasound was also used to calculate the volume (cm^3) of the muscle tissue. The muscle between the proximal and distal musculotendinous junctions was scanned in four to six evenly spaced axial plane sections, 30 mm apart, using a grid as a position marker on the surface.

Anatomical cross sectional area (ACSA) (cm^2) was calculated by stitching the adjacent scans together and measuring the area on an imaging programme (ImageJ 1.46r; National Institutes of Health, USA) as shown in Figure 3.2. The volume between each of those sections was then calculated based on the following formula:

$$V = \tfrac{1}{3} \times [a+\sqrt{(ab+b)}] \times t$$

where *a* and *b* are the ACSA in the two consecutive scans and *t* the length between the adjacent scans, which in this study was 30 mm. The volume of each 30 mm slice needs to be calculated and added together to give the total volume of the gastrocnemius [58,87].

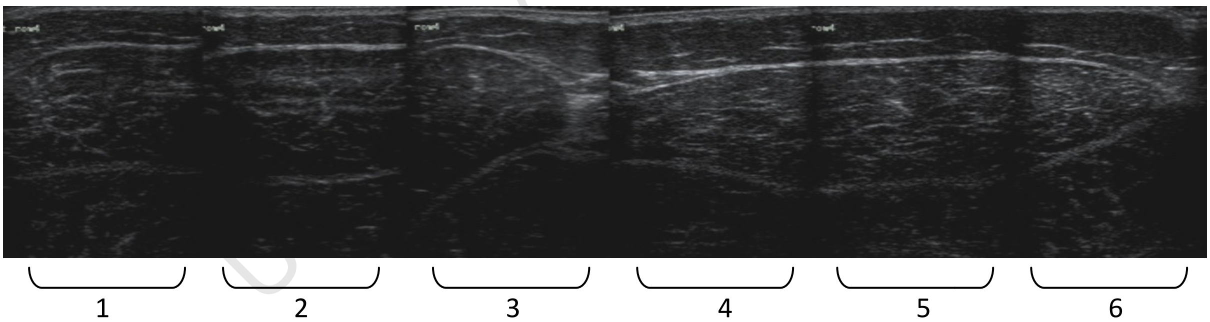

Figure 3.2: A horizontal cross sectional view of the medial and lateral gastrocnemius created by stitching together six individual images (1-6) to calculate ACSA.

3.2.3.5.6 Physiological cross sectional area

Physiological cross sectional area was then calculated using a formula based on fascicle length (l_f) and total muscle volume, both measured as above. Physiological cross sectional area was calculated based on the following formula:

$$PCSA\ (cm^2) = (V/\ l_f)$$

where l_f is the mean fibre/fascicle length and V is the total volume of the muscle belly [51].

3.2.3.5.7 Achilles tendon compliance

Ultrasound was also used to measure the compliance of the Achilles tendon with participant in prone lying. The right tendon was assessed first, followed by the left tendon. The foot was positioned at 90° (neutral) with the foot resting against the wall and the ultrasound head was placed over the muscle and scanned from above until the musculotendinous junction was visualised on the screen [81]. Image (a) in Figure 3.3 shows the musculotendinous junction at rest prior to the isometric contraction.

The participant was then instructed to press the forefoot as hard as possible into the wall, without lifting the heel, to perform a maximal isometric contraction of plantarflexion and the movement of the musculotendinous junction (b) was measured as shown in Figure 3.3. This movement was representative of the elongation of the tendon [81] as shown in Figure 3.3. Each scan was repeated three times and an average was recorded. Intra-tester reliability was established during a feasibility study.

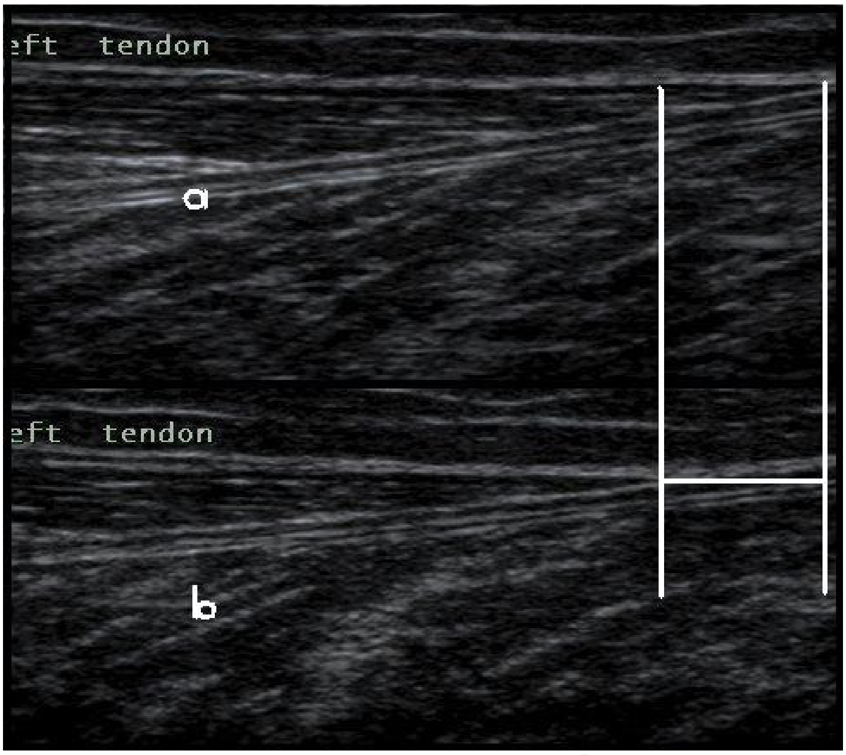

Figure 3.3: The distal musculotendinous junction (a) at rest, and (b) at full isometric contraction. The distance between the two positions of the musculotendinous junction is considered the elongation.

3.2.3.6 Flexibility:

Muscle length testing was performed on both the gastrocnemius and soleus muscles using an inclinometer. Muscle length was tested initially on the right leg and repeated on the left. The inclinometer was attached to the distal fibula with the leg in neutral, and the forward angulation of the tibia and fibula on the talus was measured. The movement to be tested was ankle dorsiflexion as shown in Figure 3.4 (108). Gastrocnemius was tested first with the participant in a standing position with the leg to be tested in hip extension. The knee was held in full extension and the participant was instructed to lean forward to move the ankle into maximal dorsiflexion. Each test was repeated three times on the right side followed by three times on the left and the average ROM was recorded on each side.

Soleus was tested with the hip extended, knee flexed and ankle fully dorsiflexed on the leg being tested. Each test was repeated three times on each side and an average was recorded (90). Reliability of these tests were reported as r = 0.98 in both dominant and non-dominant legs for gastrocnemius , and r = 0.93 and 0.94 in dominant and non-dominant legs respectively for soleus flexibility (18).

Figure 3.4: Testing position of the gastrocnemius flexibility (left) and soleus flexibility (right).

3.2.3.7 Vertical jump testing

Vertical jump testing was assessed to measure muscle power in the lower limbs and to compare whether there was a significant difference between low physical activity participants and endurance runners. Standing reach height (cm) was measured with participants standing with one arm extended over their head and their feet flat on the ground. Participants were instructed to squat down with the fingertips touching the floor in a standardised starting position below the vertical jump tester (Vertec, South Africa). They were instructed to jump as high as possible from the squat position with their dominant arm reaching above their head and reaching for the highest marker possible on the tester. Vertical jump height was recorded as the highest point reached on the Vertec.

The participants received standard verbal encouragement during the test to ensure maximal performance. The test was repeated three times with a two minute break between each attempt and the maximum jump height was recorded. Vertical jump height is calculated as the difference between the standing height and the maximum jump height achieved. Vertical jump test is a valid measure of lower limb muscle power [96].

3.2.3.8 Calf raise test

The endurance of the calf MTU was assessed using single leg calf raises. The starting position was in unilateral standing with the knee extended, on the right leg as shown in Figure 3.5. The calf raise was performed unilaterally to maximal plantarflexion range, until fatigue. A rate of 60 raises per minute was maintained, using a metronome to guide the speed. Participants were instructed to 'raise as high as possible onto the toes'. The test was terminated if participants were unable to achieve full plantarflexion ROM for three consecutive attempts; if participants rated their perception of effort on the modified Borg scale between 17 ('very very hard') and 20 ('maximal effort') [(109)] (Appendix VII); or if participants were not able to maintain the required frequency of 60 calf raises per minute [(97)]. Participants received standard verbal encouragement to ensure maximal performance. After testing the participant had three minutes of rest before repeating the test on the left side.

The calf raises were video recorded to ensure that the number completed was accurately assessed as well as full plantarflexion ROM is achieved on each repetition. Participants were recorded from a lateral view to ensure that the ROM was visible. A normal range was considered to be 36-45 reps, and any significant difference between the two sides was noted [(101)]. The number of repetitions were counted from the recording following the test. Repetitions were counted three times to reduce error, and an average was recorded. As the test required the participants to terminate the test at maximal effort, it was only tested once. Repeated attempts may be affected by fatigue in the muscle. Intra-class coefficients of 0.78 and 0.84 have previously been reported for left and right side respectively, using the same protocol [(99)].

Figure 3.5: Calf raise test position into full plantarflexion unilaterally.

3.2.4 Ultrasound training

Training on the ultrasound machine was performed by an anatomist who had extensive experience in imaging of the gastrocnemius muscle. All measurements as described in Section 3.2.3 (page 33) were then performed on three participants who closely matched the inclusion criteria and repeated three times. These data were not included in the final analysis. A total of 23 hours (five hours under supervision) were completed. In previous studies, 4 hours of faculty guided training in ultrasound imaging was found to be superior to self-guided training in ultrasound use, although both improved competence in ultrasound imaging [110]. It does need to be considered that this training included a variety of techniques, including visualisation of the jugular vein, ascites, and pleural effusions rather than the structural components of a single muscle. In addition, a study on minimally training medical residents compared to an experienced ultrasonographer found high levels of inter-rater reliability when examining the structural components of the patella tendon (ICC: 0.9 – 0.99) [111].

3.2.5 Feasibility study

Five participants were recruited for a feasibility study. These participants matched the inclusion and exclusion criteria for either the low physical activity or endurance running groups. The intra-tester reliability of the anthropometrical measurements, ultrasound imaging and physical tests was assessed during the feasibility study. Each of the seven skin-fold measurements was taken three times on each participant to assess reliability of the test. The assessment of the ultrasound imaging was piloted on this same group of participants and was also repeated three times on each participant to ensure that the same results were achieved each for each of the thickness, fascicle length, pennation angle, cross-sectional area, volume and PCSA measurements of the gastrocnemius muscle. Physical tests were performed three times each, in the following order: gastrocnemius and soleus flexibility, vertical jump test and calf raises. The intra-tester reliability of the investigator was assessed (Appendix VI). The data were included in the final data analysis due to acceptable ($r = 0.7$) to high ($r = 0.99$) levels of reliability.

3.2.6 Testing procedure

Endurance runners were recruited from running clubs in the greater Cape Town area, and low physical activity participants were recruited from the general population, by approaching local office complexes in the Claremont/Newlands region. Both groups were required to attend testing at the Sports Science Institute of South Africa, Newlands. Participants completed the informed consent form, and the physical activity and training questionnaire with the guidance of the investigator, as well as the PAR-Q form to ensure safety when performing the physical testing. These were completed during at a familiarisation session three to five days before the physical testing was performed. Anthropometric measurements were completed by an assistant trained in skinfold testing. All other testing at the two sessions was performed by the principal investigator. No blinding of investigators was performed as there was no intervention performed that may be affected by investigator bias. Mass, stature and skinfold measurements were recorded at the first session. The participants were instructed on the testing procedure and had an opportunity to practice the required tests. Ultrasound imaging of the calf complex was performed during this session. Testing in the first session took approximately one hour.

The vertical jump test was explained as described above and the participant had two attempts at this test. The calf raise test was described and the participant will be made fully aware of the conditions for termination of the test, and had opportunity to practice using the metronome for the rate of raises. At the second session, participants underwent the physical testing. The functional tests included gastrocnemius and soleus flexibility, vertical jump testing and calf raise testing. Testing took approximately 30 minutes at the second session

3.2.7 Statistical analyses

Statistical analyses were performed using Statistica software (StatSoft, Inc. 2004) STATISTICA (Data analysis software system, version 11, www.statsoft.com). During the feasibility study, the typical error of measurement and intra-class coefficient were used to assess intra-tester reliability. Normality was assessed using the Shapiro-Wilkes test. Differences in descriptive variables (training distance, flexibility of calf MTU, cross sectional area of gastrocnemius, vertical jump height, calf raises) between the endurance and low physical activity groups were assessed using a Chi-squared test. A factorial ANOVA was performed to assess main effects of sex, group (low physical activity vs. running) and interaction between sex and group, in anthropometric measurements, architectural measurements and physical tests. An unequal HSD post-hoc test was performed where necessary. Pearson's product-moment correlations were also performed to assess the relationships between changes in the gastrocnemius muscle and the amount of running.

The relationships between individual architectural measurements such as thickness, pennation angle, fascicle length, volume and PCSA with the physical tests performed were assessed using a Pearson's product moment correlation. In addition, correlations between physical tests and training factors such as speed and distance were assessed. Statistical significance was accepted as $p < 0.05$.

3.2.8 Ethical considerations

This study adhered to the ethical principles outlined in the Declaration of Helsinki (Seoul version, 2008). The proposal was submitted for ethics approval to the Human Research Ethics Committee of the Faculty of Health Sciences, University of Cape Town (HREC REF: 259/2012) (Appendix VIII). Once ethical approval was obtained, the participants were recruited according to the inclusion and exclusion criteria. The participants were informed about the purpose of the project, the testing procedures and all the possible risks that were involved with taking part in the study. The participants were also informed of their right to withdraw from the study at any stage. Written informed consent was obtained from all participants (Appendix III). All data were kept confidential and anonymous.

3.2.8.1 Risks to participants

The risks were explained to the participants prior to signing the informed consent. The PAR-Q (Appendix IV) was completed by all participants to screen for exclusion criteria and factors that may increase their risk in the physical testing. All information obtained from the questionnaires remained confidential and anonymous. There were no physical risks associated with the ultrasound imaging assessment or anthropometrical measurements. There was a risk of musculoskeletal injury in this study due to the physical testing nature of the investigations. Prior to testing the participants had the opportunity to practice the tests during the familiarisation session in an attempt to reduce the risk of injury. All tests were carefully explained, and participants were also instructed to discontinue physical tests if they experienced any discomfort. The majority of testing did not require maximal effort. The exception was the vertical jump test, which was carefully explained during the familiarisation session to minimise the risk of injury.

3.2.8.2 Benefits to participants

The participants were given feedback on the structure and function of their gastrocnemius based on their testing. Flexibility of the gastrocnemius and soleus, and feedback on their vertical jump height was also given to them following their tests. This information may be useful to medical personnel and physiotherapists in planning running programmes or other physical activities. Anthropometrical measurements including sum of seven skinfolds and body fat percentage was made available to each of the participants which may be useful in planning lifestyle changes or adapting current training programmes. Each participant was given a booklet with information on training (Appendix IX). The information for low physical activity participants included a running programme for beginners with information about starting an exercise programme safely after they had been tested. Both groups also received a booklet describing flexibility, stability and strength training exercises (Appendix IX).

3.3 RESULTS

3.3.1 Participants

Thirty participants were recruited for this study. The low physical activity group consisted of 14 participants and the endurance running group consisted of 16 participants. No participants were excluded following the screening tests. The study sample is summarised in Figure 3.6.

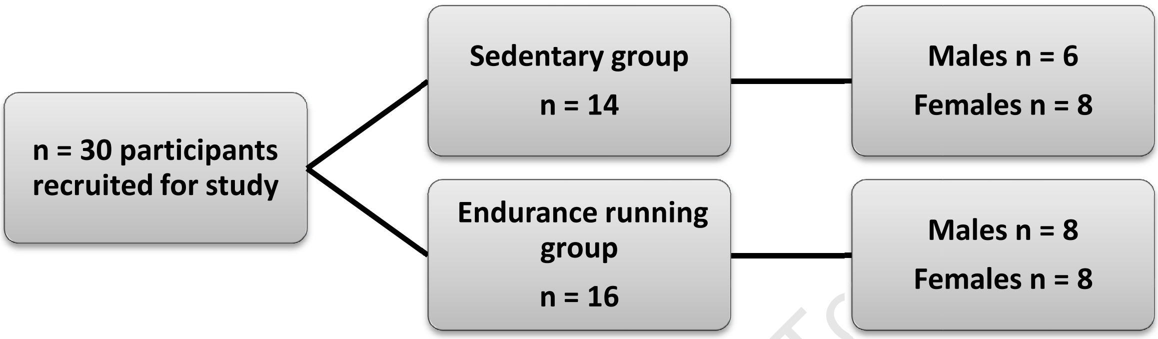

Figure 3.6: Summary of study sample.

The descriptive characteristics of the low physical activity and running groups are shown in Table 3.1. There were no significant differences in age, BMI or sum of 7 skinfolds between male and female participants, or between low physical activity and running participants. However, there was a significant main effect of sex for body mass ($F_{(1, 26)}$ = 12.69; p = 0.01). Body mass was significantly increased in males compared to females (p = 0.01). There was also a significant main effect of sex for stature ($F_{(1, 26)}$ = 13.59; p=0.01). Stature was significantly higher in males compared to females (p = 0.01). In addition, there was a significant main effect of sex for lean body mass ($F_{(1, 26)}$ = 40.51; p = 0.01). Lean body mass was significantly higher in males compared to females (p = 0.01).

Table 3.1: Descriptive characteristics of participants in the low physical activity and endurance groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		Endurance runners (n = 16)	
Sex	**Male (n = 6)**	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Age	34 ± 8	36 ± 5	35 ± 5	33 ± 5
Mass (kg)	83.5 ± 30.5	63.5 ± 13.0	83.0 ± 8.5	60.5 ± 7.0
Stature (cm)	174.5 ± 11.5	164.0 ± 12.0	182 ± 6.5	167.0 ± 6.5
Body mass index	27.0 ± 7.2	24.2 ± 6.0	25.1 ± 3.0	21.6 ± 1.1
Sum of 7 skinfolds	105.55 ± 50.72	131.33 ± 42.65	83.84 ± 42.17	93.35 ± 20.93
Fat percentage	20.8 ± 7.2	30.8 ± 5.3	18.4 ± 4.7	25.7 ± 4.0
Lean body mass (kg)	64.5 ± 16.5	44.0 ± 5.5	67.5 ± 7.5	45.0 ± 4.5

3.3.2 Training and competition history

3.3.2.1 Low physical activity group

In the low physical activity group (n = 14), four of the male, and six of the female participants were previously active, but had stopped training for at least a year. There was no significant difference in previous physical activity between males and females. In addition there were no significant differences in the reason for stopping physical activity between males and females. The most commonly stated reasons for ceasing physical activity were lack of time, work and family commitments.

3.3.2.2 Endurance running group

Competition data of the endurance group are shown in Table 3.2. There were no significant differences between the male and female runners in the number of 10 km, 21.1 km and 42.2 km races completed; or in the best times in the previous 12 months for these races.

Table 3.2: Competition history of male and female runners. Data are expressed as mean ± standard deviation (SD).

	Male (n = 8)	**Female (n = 8)**
Number of 10 km races in previous year (n)	4 ± 7	1 ± 1
Fastest time for 10 km race in previous year (min)	42 ± 5	50 ± 4
Number of 21.1 km races in previous year (n)	4 ± 4	2 ± 2
Fastest time for 21.1 km in previous year (min)	102 ± 21	111 ± 12
Number of 42.2 km races in previous year (n)	2 ± 1	2 ± 1
Fastest time for 42.2 km in previous year (min)	227 ± 28	249 ± 24

Weekly training data are shown in Table 3.3. There were no significant differences between male and female runners in average, maximum and minimum weekly mileage; or in the number of running sessions per week.

Table 3.3: Average, minimum and maximum weekly mileage (km) of male and female runners. Data are expressed as mean ± standard deviation (SD).

	Male (n = 8)	**Female (n = 8)**
Average weekly training (km)	52 ± 10	51 ± 11
Maximum weekly training (km)	76 ± 8	78 ± 18
Minimum weekly training (km)	24 ± 21	19 ± 18
Running sessions per week (days)	4 ± 1	4 ± 1

Training speeds are shown in Table 3.4. There were no significant differences between males and females in minimum and maximum running speeds during training. Average training speed was significantly faster in males compared to females ($p = 0.04$) (Figure 3.7).

Table 3.4: Maximum and minimum training speeds ($m.s^{-1}$) of male and female runners. Data are expressed as mean ± standard deviation (SD).

	Male (n = 8)	**Female (n = 8)**
Maximum training speed ($m.s^{-1}$)	4.1 ± 0.8	3.7 ± 0.6
Minimum training speed ($m.s^{-1}$)	2.8 ± 0.3	2.5 ± 0.2

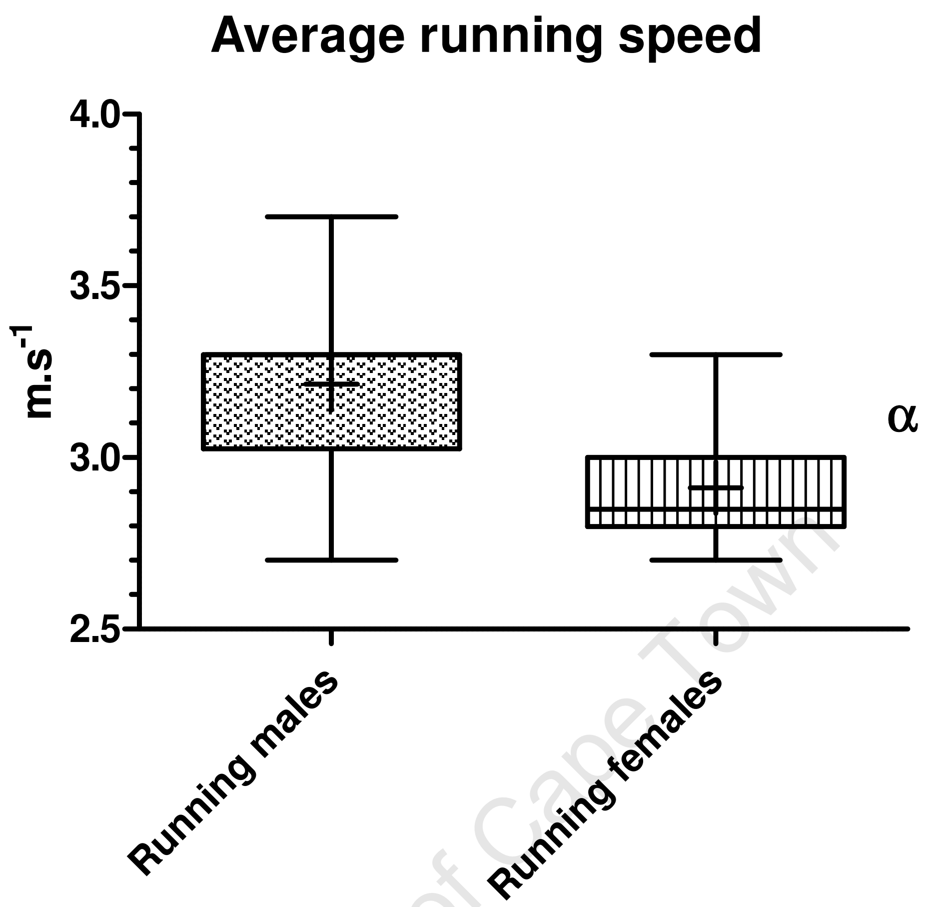

Figure 3.7: Average running speed (m.s^{-1}) of participants in the running male (n = 8) and running female (n = 8) groups. Data are expressed as median ± 5th and 95th percentile. The mean is expressed as "+".

Significant differences:

α main effect of sex (p = 0.04)

The numbers of injuries in the running group sustained in the last 12 months are shown in Table 3.5.

Table 3.5: Description of injuries of participants in the endurance running group in the previous 12 months.

	Male (n = 8)	**Female (n = 8)**
Running calf injury	2	1
Total other injuries	2	6
Non-running calf injury	1	0

Please refer to Appendix X for other non-significant training and competition data that were analysed as part of this study.

3.3.3 Ultrasound measurements

3.3.3.1 Architecture of the gastrocnemius

Ultrasound measurements of the gastrocnemius muscle are shown in Table 3.6. There was a significant main effect of sex for right gastrocnemius muscle belly length ($F_{(1,26)}$ = 4.84, p = 0.04), left gastrocnemius muscle belly length ($F_{(1,26)}$ = 6.44, p = 0.02) and average gastrocnemius muscle belly length ($F_{(1,26)}$ = 5.97, p = 0.02). There were significant increases in right (p = 0.03), left (p = 0.02) and average (p = 0.02) gastrocnemius length in males compared to females.

Table 3.6: Ultrasound architectural measurements of participants in the low physical activity and running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Gastrocnemius muscle belly length (right) (mm) $^{\alpha\,\theta}$	203 ± 35	193 ± 15	222 ± 21	196 ± 18
Gastrocnemius muscle belly length (left) (mm) $^{\alpha\,\theta}$	215 ± 41	191 ± 20	231 ± 29	203 ± 22
Gastrocnemius muscle belly length (average) (mm) $^{\alpha\,\theta}$	209 ± 38	192 ± 7	227 ± 24	200 ± 19
Pennation angle (right) (°)	30 ± 6	30 ± 5	33 ± 7	32 ± 3
Pennation angle (left) (°)	26 ± 6	28 ± 5	30 ± 7	28 ± 4
Pennation angle (average) (°)	28 ± 6	29 ± 4	31 ± 6	30 ± 3
Fascicle length (right) (mm)	40 ± 9	42 ± 7	43 ± 8	41 ± 5
Fascicle length (left) (mm)	41 ± 12	41 ± 5	42 ± 10	39 ± 5
Fascicle length (average) (mm)	41 ± 10	41 ± 6	42 ± 9	40 ± 4
Thickness (right) (mm)	17 ± 5	17 ± 2	18 ± 3	17 ± 1
Thickness (left) (mm)	17 ± 5	17 ± 2	19 ± 4	18 ± 1
Thickness (average) (mm)	17 ± 5	17 ± 2	18 ± 3	17 ± 1

Significant differences:

α main effect of sex ($p < 0.05$)
θ significant difference between males and females (on post-hoc test) ($p < 0.05$)

The typical error of the length of the gastrocnemius muscle belly was 2.6 mm (95% CI: 1.9 – 4.9) right and 1.6 mm (95% CI: 1.2 – 2.9) left. The typical error of gastrocnemius thickness was 0.6 mm (95% CI: 0.4 – 1.1) right and 0.7 mm (95% CI: 0.5 – 1.2) left. The typical error of pennation angle was 1.8° (95% CI: 1.3 – 3.3) right and 1.4° (95% CI: 1.0 – 2.6) left, and of fascicle length was 3.2 mm (95% CI: 2.5 – 4.5) right and 3.5 mm (95% CI: 2.8 – 5.0) left (Appendix VI).

There were no significant differences in fascicle length between low physical activity and endurance participants as shown in Figure 3.8.

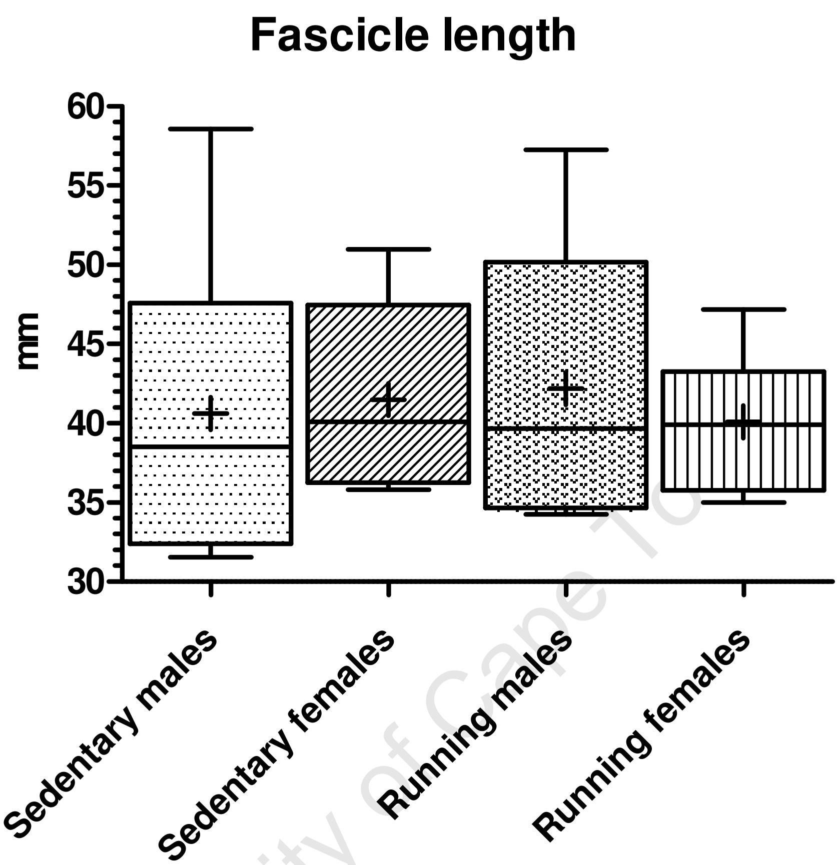

Figure 3.8: Fascicle length (mm^3) of participants in the low physical activity male (n = 6), low physical activity female (n = 8), running male (n = 8) and running female (n = 8) groups. Data are expressed as median ± 5th and 95th percentile. The mean is expressed as "+".

There were no significant differences between sex or groups in pennation angle, fascicle length or thickness of the gastrocnemius muscle.

3.3.3.2 Volume of gastrocnemius

Volume of the gastrocnemius muscle is shown in Table 3.7. There was a significant main effect of sex for right gastrocnemius volume ($F_{(1,26)}$ = 11.69, p = 0.01), left gastrocnemius volume ($F_{(1,26)}$ = 13.51, p = 0.01) and average gastrocnemius volume ($F_{(1,26)}$ = 12.92, p = 0.01). There were significant increases in right (p = 0.01), left (p = 0.01) and average gastrocnemius volume (p = 0.01). There was also a significant main effect of running for right gastrocnemius volume ($F_{(1,26)}$ = 7.99, p = 0.01) and average gastrocnemius volume ($F_{(1,26)}$ = 6.06, p = 0.02). There were significant increases in right (p = 0.01) and average gastrocnemius volume (p = 0.02) in runners compared to low physical activity participants (Figure 3.9).

Table 3.7: Gastrocnemius volume measurements of participants in the low physical activity and endurance running groups. Data are expressed at mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Volume (right) (cm^3) α θ Φ **	193.7 ± 68.2	149.89 ± 33.4	257.3 ± 57.1	183.5 ± 20.3
Volume (left) (cm^3) α θ	202.5 ± 68.1	145.8 ± 30.6	242.8 ± 56.8	174.4 ± 21.7

Significant differences:

α main effect of sex (p = 0.01)
θ significant difference between males and females (on post-hoc test) (p = 0.01)
ϕ main effect of running (p < 0.05)
** significant difference between running and low physical activity (on post-hoc test) (p < 0.01)

The typical error of gastrocnemius volume was 4.2 cm^3 (95% CI: 3.0-7.8) right and 3.4 cm^3 (95% CI: 2.5- 6.4) left (Appendix VI).

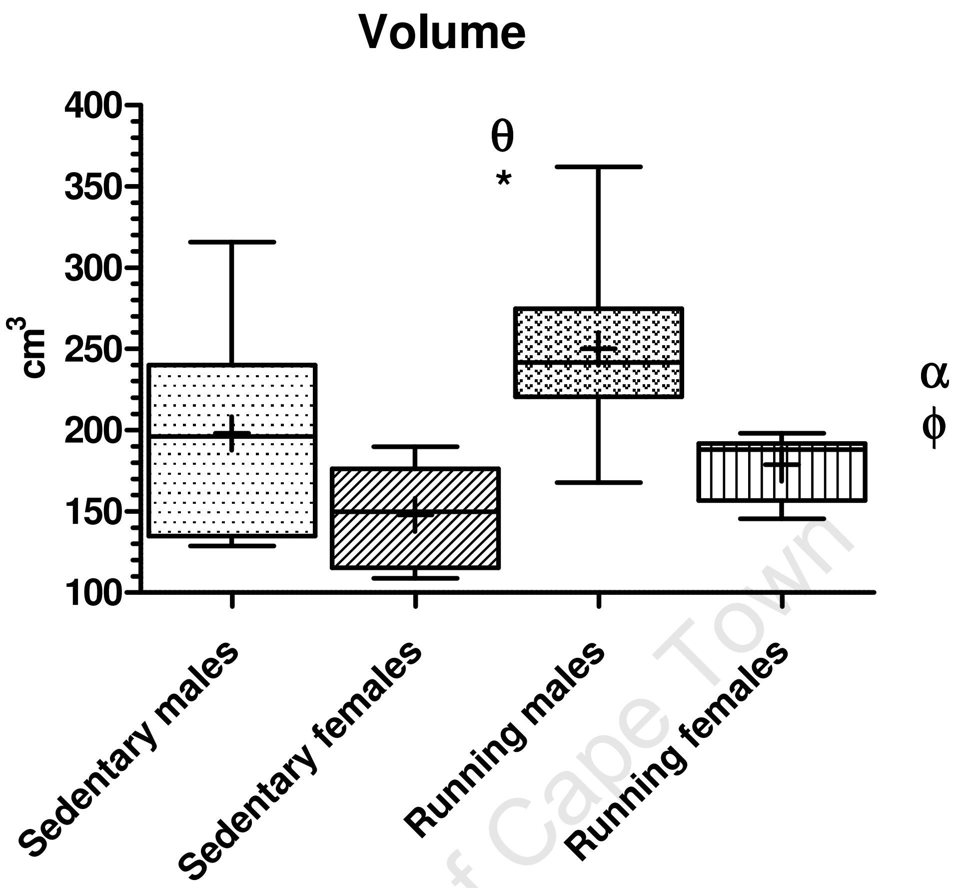

Figure 3.9: Volume (cm^3) of participants in the low physical activity male (n = 6), low physical activity female (n = 8), running male (n = 8) and running female (n = 8) groups. Data are expressed as median ± 5th and 95th percentile. The mean is expressed as "+".

Significant differences:

α main effect of sex (p = 0.01)
ϕ main effect of running (p = 0.02)
θ significant difference between males and females (on post-hoc test) (p = 0.01)
* significant difference between running and low physical activity (on post-hoc test) (p = 0.02)

3.3.3.3 Physiological cross sectional area

Physiological cross sectional area (PCSA) of the gastrocnemius muscle is shown in Table 3.8. There was a significant main effect of sex for right gastrocnemius PCSA ($F_{(1,26)} = 11.86$, $p = 0.01$), left gastrocnemius PCSA ($F_{(1,26)} = 14.34$, $p = 0.01$), and average gastrocnemius PCSA ($F_{(1,26)} = 14.19$, $p = 0.01$). There were significant increases in right ($p = 0.01$), left ($p = 0.01$) and average gastrocnemius PCSA ($p = 0.01$). There was also a significant main effect of running for right gastrocnemius PCSA ($F_{(1,26)} = 7.06$, $p = 0.01$), left PCSA ($F_{(1,26)} = 7.45$, $p = 0.01$), and average PCSA ($F_{(1,26)} = 7.91$, $p = 0.01$). There were significant increases in right ($p = 0.01$), left ($p = 0.01$) and average PCSA ($p = 0.01$) (Figure 3.10).

Table 3.8: Physiological cross sectional area measurements of participants in the low physical activity and endurance running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Physiological cross sectional area (right) (cm^2) $^{\alpha\,\theta\,\Phi\,**}$	48.2 ± 11.8	36.3 ± 7.9	62.4 ± 17.6	44.8 ± 5.3
Physiological cross sectional area (left) (cm^2) $^{\alpha\,\theta\,\Phi\,**}$	49.4 ± 9.7	35.5 ± 7.2	60.2 ± 14.9	45.4 ± 7.2

Significant differences

α main effect of sex ($p = 0.01$)
θ significant difference between males and females (on post-hoc test) ($p = 0.01$)
ϕ main effect of running ($p = 0.01$)
** significant difference between running and low physical activity (on post-hoc test) ($p < 0.01$)

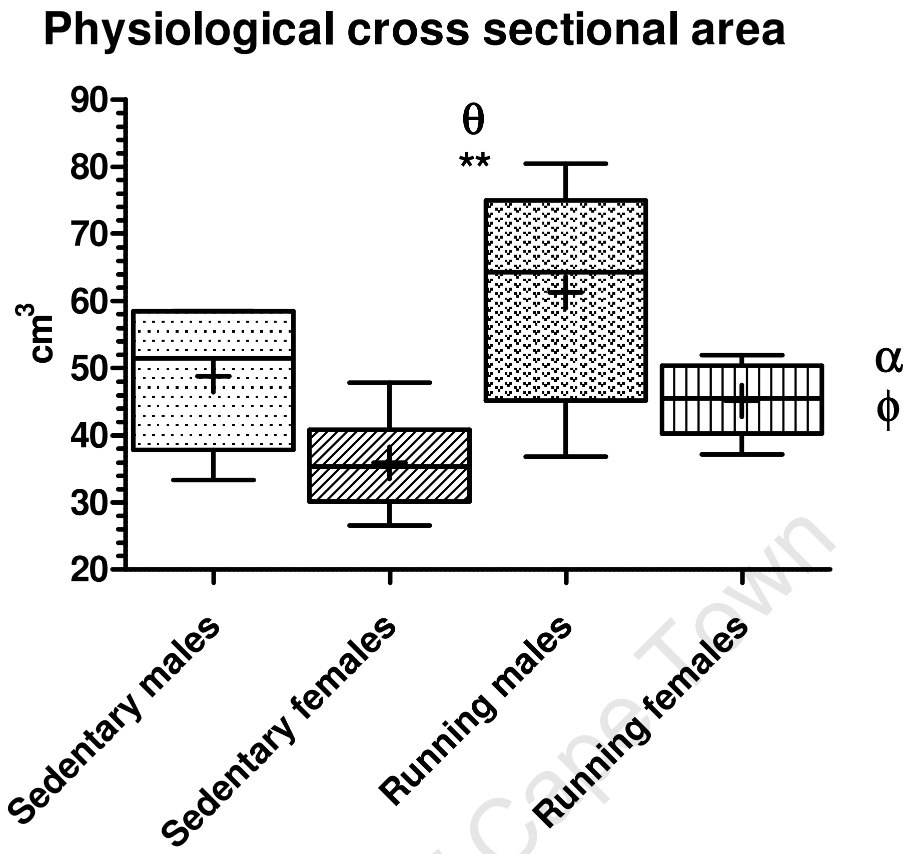

Figure 3.10: Average physiological cross sectional area (cm^3) of participants in the low physical activity male (n = 6), low physical activity female (n = 8), running male (n = 8) and running female (n = 8) groups. Data are expressed as median ± 5th and 95th percentile. The mean is expressed as "+".

Significant differences:

α main effect of sex (p = 0.01)
ϕ main effect of running (p = 0.01)
θ significant difference between males and females (on post-hoc test) (p = 0.01)
** significant difference between running and low physical activity (on post-hoc test) (p = 0.01)

3.3.3.4 Achilles tendon compliance

The compliance of the Achilles tendon is shown in Table 3.9. There were no significant differences in the Achilles tendon compliance between sex or groups.

Table 3.9: Achilles tendon compliance range of participants in the low physical activity and endurance running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Achilles tendon compliance (right) (mm)	10 ± 5	10 ± 2	15 ± 10	12 ± 6
Achilles tendon compliance (left) (mm)	12 ± 5	12 ± 3	14 ± 10	13 ± 5
Achilles tendon compliance (average) (mm)	11 ± 6	11 ± 2	14 ± 10	13 ± 5

The typical error of Achilles tendon elongation was 2.3 mm (95% CI: 1.7 – 4.2) right and 4.6 mm (95% CI: 3.4 – 8.6) left (Appendix VI).

3.3.4 Physical tests

3.3.4.1 Gastrocnemius and soleus flexibility

The gastrocnemius and soleus flexibility ranges are shown in Table 3.10. There was a significant main effect of sex for right gastrocnemius flexibility ($F_{(1, 26)}$ = 4.26, p = 0.04). Right gastrocnemius flexibility was increased in females compared to males (p = 0.04), but there was no significant difference in left gastrocnemius flexibility between males and females. In addition there was a significant main effect of sex for average gastrocnemius flexibility ($F_{(1,26)}$ = 4.34, p = 0.04). Average gastrocnemius flexibility was increased in females compared to males (p = 0.04). There were no significant differences in soleus flexibility for either sex or running.

Table 3.10: Gastrocnemius and soleus flexibility of participants in the low physical activity and endurance running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Gastrocnemius flexibility (right) (°) $^{\alpha\,\theta}$	29 ± 5	29 ± 4	25 ± 5	33 ± 7
Gastrocnemius flexibility (left) (°)	26 ± 4	28 ± 4	26 ± 6	32 ± 7
Gastrocnemius flexibility (average) (°) $^{\alpha\,\theta}$	28 ± 4	29 ± 4	26 ± 5	33 ± 7
Soleus flexibility (right) (°)	35 ± 5	37 ± 6	32 ± 8	38 ± 8
Soleus flexibility (left) (°)	32 ± 3	35 ± 7	32 ± 6	35 ± 8
Soleus flexibility (average) (°)	34 ± 3	36 ± 6	32 ± 7	37 ± 7

Significant differences:

α main effect of sex ($p < 0.05$)
θ significant difference between males and females (on post-hoc test) ($p < 0.05$)

3.3.4.2 Vertical jump testing

Lower limb power data calculated from the vertical jump test are shown in Table 3.11. There was a significant main effect of sex for maximum vertical jump height ($F_{(1,26)} = 10.21$, $p = 0.01$). Maximum vertical jump height was significantly increased in males compared to females ($p = 0.01$).

Table 3.11: Vertical jump height of participants in the low physical activity and endurance running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Maximum vertical jump (cm) $^{\alpha\,\theta}$	40.7 ± 13.5	30.1 ± 8.7	42.4 ± 7.1	32.1 ± 6.3

Significant differences:

α main effect of sex (p = 0.01)
θ significant difference between males and females (on post-hoc test) (p = 0.01)

3.3.4.3 Calf raise testing

Calf raise measurements (repetitions) are shown in

Table 3.12. There was a significant main effect of running for left calf raises ($F_{(1,26)} = 5.13$, $p = 0.03$). Left calf raises were significantly increased in the running group compared to the low physical activity group ($p = 0.04$). There was also a significant main effect of running for average calf raises ($F_{(1,26)} = 5.50$, $p = 0.03$). Average calf raises were increased in the endurance group compared to the low physical activity group ($p = 0.03$) (Figure 3.11).

Table 3.12: Calf endurance of participants in the low physical activity and endurance running groups. Data are expressed as mean ± standard deviation (SD).

	Low physical activity (n = 14)		**Endurance runners (n = 16)**	
	Male (n = 6)	**Female (n = 8)**	**Male (n = 8)**	**Female (n = 8)**
Calf raise (right)	24 ± 6	24 ± 6	33 ± 9	26 ± 6
Calf raise (left) $^{\Phi\,*}$	23 ± 8	23 ± 8	33 ± 10	27 ± 6

Significant differences:

ϕ main effect of running ($p < 0.05$)
* significant difference between running and low physical activity (on post-hoc test) ($p < 0.05$)

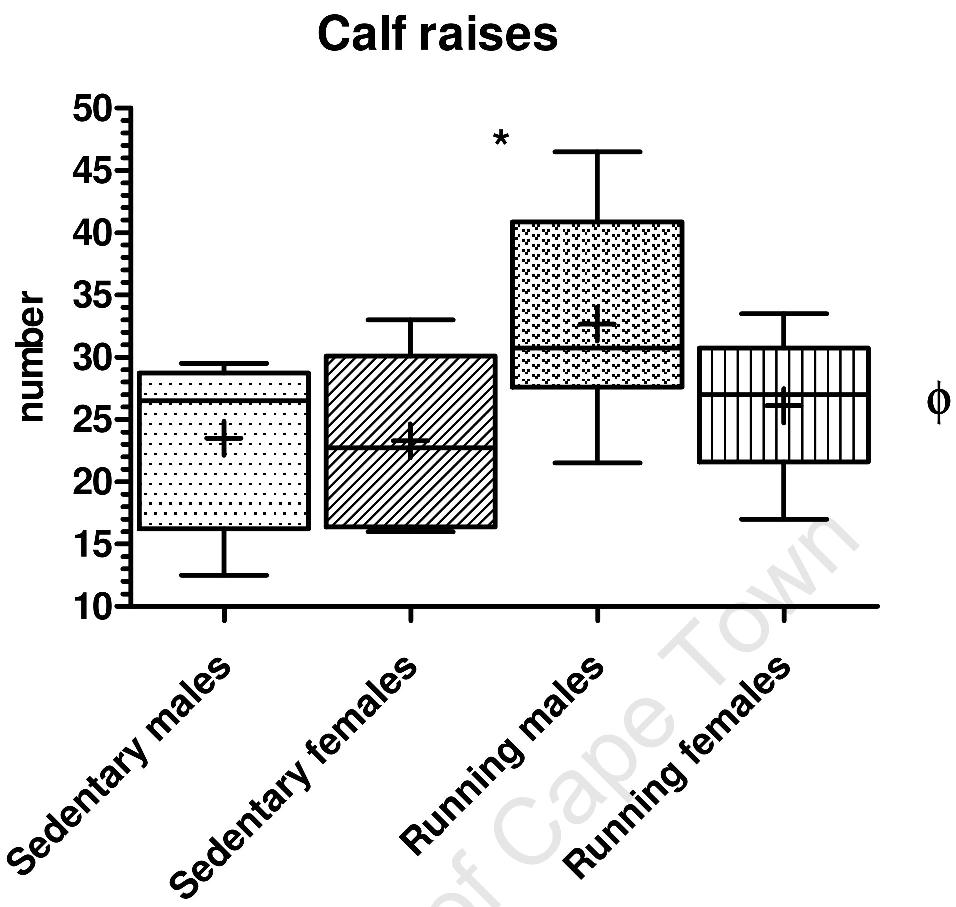

Figure 3.11: Calf raise average (n) of participants in the low physical activity male (n = 6), low physical activity female (n = 8), running male (n = 8) and running female (n = 8) groups. Data are expressed as median ± 5th and 95th percentile. The mean is expressed as "+".

Significant differences:

ϕ main effect of running ($p = 0.03$)
* significant difference between running and low physical activity (on post-hoc test) ($p = 0.03$)

3.3.5 Correlational analyses

3.3.5.1 Ultrasound measurements

3.3.5.1.1 Gastrocnemius volume and morphological measurements

There was a significant positive correlation between pennation angle and volume for all groups (r = 0.47, p = 0.01). No significant correlations were found for either the low physical activity or running groups (Table 3.13). A positive correlation indicates that as the pennation angle increases, the gastrocnemius volume increases.

There were significant positive correlations between volume and fascicle length for all groups (r = 0.41, p = 0.02) and the low physical activity group (r = 0.59, p = 0.03). No significant correlations were found for the endurance group (Table 3.13). A significant correlation indicates that as the fascicle length increases, the gastrocnemius volume increases.

3.3.5.1.2 Gastrocnemius thickness and architectural measurements

There was a significant positive correlation between pennation angle and thickness for all groups (r = 0.53, p = 0.01). There were also significant positive correlations between pennation angle and thickness for the low physical activity (r = 0.55, p = 0.04) and endurance (r = 0.52, p = 0.04) groups (Table 3.13). A positive correlation indicates that as thickness increases, the pennation angle increases.

There were significant positive correlations between fascicle length and thickness for all groups (r = 0.58, p = 0.01) and low physical activity (r = 0.69, p = 0.01) groups. There was no significant correlation between fascicle length and thickness in the endurance group (Table 3.13). A positive correlation indicates that as thickness increases, the fascicle length increases.

Table 3.13: Relationships between ultrasound measurements. Note '+' indicates a positive correlation, and '-' indicates a negative correlation. Significant relationships (p < 0.05) are highlighted in bold.

Correlation		**All groups**			**Low physical activity**			**Endurance running**		
		Relationship	**r (95% CI)**	**p**	**Relationship**	**r (95% CI)**	**p**	**Relationship**	**r (95% CI)**	**p**
Volume	**Pennation angle**	***+***	***0.47 (0.19-0.68)***	***0.01***	+	0.49 (0.05-0.61)	0.05	+	0.36 (0.22-0.70)	0.20
	Fascicle length	***+***	***0.41 (0.12-0.64)***	***0.02***	***+***	***0.59 (0.18-0.82)***	***0.03***	+	0.32 (-0.13-0.66)	0.23
Thickness	**Pennation angle**	***+***	***0.53 (0.11-0.77)***	***0.01***	***+***	***0.55 (0.12-0.80)***	***0.04***	***+***	***0.52 (0.11-0.77)***	***0.04***
	Fascicle length	***+***	***0.58 (0.21-0.81)***	***0.01***	***+***	***0.69 (0.35-0.87)***	***0.01***	+	0.45 (0.03-0.74)	0.08

3.3.5.2 Physical testing

3.3.5.2.1 Calf endurance and maximum vertical jump height

There was a significant positive correlation between maximum vertical jump height (r = 0.39, p = 0.03) and calf raise endurance for all groups. No significant correlations were found between maximum vertical jump height and calf raise endurance in either the low physical activity or endurance running groups (Table 3.14). A positive correlation indicates that as the maximum vertical jump height increases, the calf raise endurance also increases.

3.3.5.2 Calf endurance and gastrocnemius flexibility

There were no significant relationships between calf raise endurance and gastrocnemius flexibility (Table 3.14).

3.3.5.3 Calf endurance and soleus flexibility

There was a significant negative correlation between calf raise endurance and soleus flexibility in the endurance running group (r = -0.51, p = 0.04). There were no significant correlations in all groups and the low physical activity group (Table 3.14). A negative correlation indicates that as the calf raise endurance increases, the soleus muscle flexibility decreases.

3.3.5.4 Maximum vertical jump height and PCSA

There were significant positive correlations between lower limb power average and PCSA in all groups (r = 0.43, p = 0.02) and endurance group (r = 0.55, p = 0.03). There was no significant correlation for the low physical activity group (Table 3.14). A positive correlation indicates that as the PCSA increases, the lower limb power increases.

3.3.5.5 Calf raise endurance and PCSA

There was a significant positive correlation between calf raises and physiological cross sectional area for all groups (r = 0.42, p = 0.02). There was also a significant positive correlation between calf raise and PCSA in the endurance group (r = 0.53, p = 0.03) (Table 3.14). A positive correlation indicates that as PCSA increase, the number of calf raises increase.

Table 3.14: Relationships between calf endurance and PCSA and other physical tests. Note '+' indicates a positive correlation and '-' indicates a negative correlation. Significant relationships (p < 0.05) are highlighted in bold.

Correlation		**All groups**			**Low physical activity**			**Endurance running**		
		Relationship	**r (95% CI)**	**p**	**Relationship**	**r (95% CI)**	**p**	**Relationship**	**r (95% CI)**	**p**
Calf endurance	**Maximum vertical jump height**	***+***	***0.40 (-0.04-0.70)***	***0.03***	+	0.31 (-0.17-0.67)	0.28	+	0.47 (0.06-0.75)	0.06
	Gastrocnemius flexibility	-	0.22 (-0.59-0.23)	0.25	+	0.23 (-0.26-0.62)	0.44	-	0.46 (-0.76- -0.09)	0.05
	Soleus flexibility	-	0.33 (-0.66-0.12)	0.08	+	0.04 (-0.43-0.49)	0.90	***-***	***0.51 (-0.71- -0.11)***	***0.04***
PCSA	**Maximum vertical jump height**	***+***	***0.43 (-0.02-0.71)***	***0.02***	+	0.28 (-0.19-0.66)	0.34	***+***	***0.55 (0.13-0.78)***	***0.03***
	Calf endurance	***+***	***0.42 (-0.01-0.72)***	***0.02***	-	0.13 (-0.56-0.35)	0.66	***+***	***0.53 (0.14-0.78)***	***0.03***

3.3.5.3 Training history

3.3.5.3.1 Gastrocnemius flexibility and fastest race times in the last 12 months

The relationships between gastrocnemius flexibility and fastest race times in the last 12 months are shown in Table 3.15. There was a significant positive correlation for gastrocnemius flexibility and 10 km race time for all groups ($r = 0.62$, $p = 0.01$). There were no significant correlations in the male and female groups. There was also a significant positive correlation for gastrocnemius flexibility and 21.1 km race times for all groups ($r = 0.66$, $p = 0.01$). There were no significant correlations in the male and female groups. In addition, there were significant positive correlations for gastrocnemius flexibility and 42.2 km race time for all groups ($r = 0.71$, $p = 0.01$) and the female group ($r = 0.85$, $p = 0.01$). There was no significant correlation for the male group. A positive correlation indicates that as gastrocnemius flexibility increases, the race time increases for all three distances.

3.3.5.3.2 Soleus flexibility and fastest race times in the last 12 months

There was a significant positive correlation between soleus flexibility and 42.2 race time for all groups ($r = 0.53$, $p = 0.04$). There was no significant correlation for male and female groups. There were no other significant correlations for soleus flexibility and 10 km or 21.1 km race times in any groups (Table 3.15). A positive correlation indicates that as soleus flexibility increases, the race times increase.

Table 3.15: Relationships between gastrocnemius flexibility and 10 km, 21.1 km and 42.2 km race times in the past 12 months. Note '+'indicates a positive correlation and '-'indicates a negative correlation. Significant relationships ($p < 0.05$) are highlighted in bold.

Correlation		All Groups			Male			Female		
		Relationship	r (95% CI)	p	Relationship	r (95% CI)	p	Relationship	r (95% CI)	p
Gastrocnemius Flexibility	10 km time	***+***	***0.62 (0.37-0.94)***	***0.01***	+	0.56 (-0.39-0.96)	0.15	+	0.63 (-0.81-0.97)	0.10
	21.1 km time	***+***	***0.66 (-0.04-0.78)***	***0.01***	+	0.39 (-0.45-0.89)	0.34	+	0.68 (-0.87-0.96)	0.07
	42.2 km time	***+***	***0.71 (0.19-0.80)***	***0.01***	+	0.39 (-0.18-0.86)	0.34	***+***	***0.85 (-0.23-0.85)***	***0.01***
Soleus flexibility	10 km time	+	0.46 (0.01-0.88)	0.08	+	0.35 (-0.63-0.92)	0.40	+	0.42 (-0.87-0.96)	0.29
	21.1 km time	+	0.46 (-0.21-0.71)	0.07	+	0.33 (-0.61-0.83)	0.43	+	0.42 (-0.58-0.85)	0.30
	42.2 km time	***+***	***0.53 (-0.04-0.70)***	***0.04***	+	0.22 (-0.35-0.80)	0.60	+	0.68 (0.48-0.74)	0.06

3.3.6 Summary of results

With statistical significance accepted as $p < 0.05$, the following architectural changes were detected in endurance runners compared to low physical activity participants:

- Volume showed significant main effects for running compared to low physical activity participants in right ($p = 0.01$) and average ($p = 0.02$) volume.
- Physiological cross sectional area showed significant main effects for running compared to low physical activity participants in right ($p = 0.01$), left ($p = 0.01$) and average ($p = 0.01$) PCSA.
- Calf raises showed significant main effects for running compared to low physical activity participants in left ($p = 0.04$) and average ($p = 0.03$) calf raises.

Significant correlations were reported between a number of measurements:

- Volume was positively correlated in all groups to both pennation angle ($p = 0.01$) and fascicle length ($p = 0.01$). As volume increased, so too did pennation angle and fascicle length.
- Thickness was positively correlated in all groups to both pennation angle ($p = 0.01$) and fascicle length ($p = 0.01$). As thickness increased, so too did pennation angle and fascicle length.
- Calf raise was positively correlated in all groups to maximum vertical jump height ($p = 0.03$). As the number of calf raises increased, so too did the maximum vertical jump.
- Physiological cross sectional area was positively correlated in all groups to both maximum vertical jump height ($p = 0.02$) and calf raises ($p = 0.02$). As the PCSA increased, so too did the maximum vertical jump height and the number of calf raises.
- Gastrocnemius flexibility was positively correlated in all groups to best 10 km ($p = 0.01$), 21.1 km ($p = 0.01$) and 42.2 km ($p = 0.01$) races times. As the gastrocnemius flexibility increased, so too did the amount of time taken to complete 10 km, 21.1 and 42.2 km races.
- Soleus was positively correlated in all groups to best 42.2 km time ($p = 0.04$). As soleus flexibility increased, so too did the best time for a 42.2 km race.

These results are discussed further in Section 3.4 (page 67).

3.4 DISCUSSION

Endurance running causes adaptations in skeletal muscle due to the increased demands on the body [34,56,61]. In this study, there were no significant changes in the architectural components of thickness, fascicle length and pennation angle of the gastrocnemius as a result of running. However, there were significant increases in total volume and physiological cross sectional area (PCSA). These results differ somewhat to previous studies, which may be related to imaging techniques and calculation methods [15,34,45,47,49,52–54,58,63,86,112–116]. In addition, calf raise endurance was increased in runners compared to low physical activity participants. Further, in runners there was a significant negative association between gastrocnemius muscle flexibility and running speed. The findings of this study will be discussed in more detail. The discussion follows the order of presentation of the results in Section 3.3 (page 44); however the discussion will be focused on the main findings of this study that have been described above.

3.4.1 Participants

3.4.1.1 Sample size

The total sample size of this study was 30 participants, 14 low physical activity and 16 endurance runners. Recent studies investigating ultrasound measurements had sample sizes of between six and 145 participants [34,47,52–54,58,63,86,112–114,116]. Most of the ultrasound studies investigated the architecture of various muscles including digastric [113], psoas major [114], tibialis anterior [58] and vastus lateralis [49], and included measurements of fascicle length, pennation angle, thickness and occasionally volume [51]. Many of the studies had small sample sizes of between six and 14 participants [49,54,58,86,113,114,116], and used only one limb for investigation, which may not account for error in participants who may have asymmetrical limbs. This could affect the means and correlations reported. Bilateral measurements were performed on all participants in this study and averaged for use in data analysis.

Only two studies investigated runners specifically [34,47], and neither of these studies utilized ultrasound to assess volume. It is thus difficult to ascertain whether the volume measurements are accurate in athletes, and make comparisons to other studies. Karamanidis & Arampatzis [34] allocated their participants into two groups based on their age, and then further divided them into sub-groups based on their physical activity. This made for much smaller groups in the overall analysis and possibly fewer significant results. The only existing cadaver dissection study used three cadavers and only measured a single limb from each cadaver [57].

3.4.1.2 Descriptive characteristics

There were no significance differences in the age, mass, stature, BMI, body fat percentage or lean body mass between the low physical activity and endurance groups. There were significant differences in mass, stature and lean body mass between males and females in the total group, with males having greater mass, stature and lean body mass across both groups, which were to be expected. There were no significant differences between groups in individual skinfold measurements, although previous studies have found changes in the lower limb skinfolds related to highly trained runners [117]. Most of the similar studies previously completed used exclusively male participants [34,48,51–53] who were either recreationally active [48,52,53] or elite sportsmen [34,51]. In a previous study comparing male marathoners and ultramarathoners, the body fat percentage and mass were slightly lower than the participants in this study, and the average age slightly greater [118]. Females were not assessed in that particular study. By including both male and female participants, the total changes across a running population may be observed, rather than sex specific changes.

3.4.2 Training and competition history

There was no significant difference between male and female runners in the number of races and times in these races in the past year. In addition, there was no significant difference between the male and female runners in minimum, maximum, and average weekly mileage. Weekly mileage ranged from 24 to 76 km per week for males, and 19 to 74 km per week for females, averaging 52 and 51 km per week respectively. In previous studies, the mileage of the runners ranged from 30 to 120 km per week [33,34] in all male runners.

Three out of 11 injuries (27%) reported in this study were running-related calf injuries. This is similar to the injuries reported before and during the 2005 Rotterdam Marathon [8]. It is significantly greater than the number reported by Lopes et al [30] and Nielsen et al [7]. It is possible that due to the nature of calf injuries, and the fact that in only 14% of cases they persisted after 3 months [8], that calf injuries are underreported in studies requiring long term retrospective recall. Prevalence of running injuries has a large range of reported values across studies [1,5,6,24,28,29,67]. This may be due to lack of consensus between researchers on the definition of injury and severity of injury in runners [2].

3.4.3 Ultrasound measurements

3.4.3.1 Architecture of the gastrocnemius

Architectural changes have previously been reported following both inactivity and training [11,56,74]. Magnetic resonance imaging has previously been used to a greater extent than ultrasound, as it as it appears to be a more reliable, and time efficient method than ultrasound [50,52,53,59–62]. There were no significant differences between groups or sex in thickness, fascicle length and pennation angle. Medial gastrocnemius muscle belly length, measured between the proximal and distal musculotendinous junctions, was found to be significantly greater in males than females as expected, due to significant difference in height in the males.

Thickness was not found to be significantly different in the endurance group compared to the low physical activity group. Thickness and pennation angle have previously found to be correlated, indicating that pennation angle is related to the size of the muscle [119]. Thickness should also affect the anatomical cross sectional area (ACSA) by the nature of ACSA being a cross section of the total muscle. As ACSA is used for the volume calculation, it could be expected that thickness should be greater in the running group in this study, as the volume was found to be significantly greater. Thickness measurements in this study may have been affected by the depth of the probe utilised for measurement. This particular probe had an imaging depth of 35 mm, and in participants with greater subcutaneous fat stores or thicker muscle, the entire muscle was not clearly visualised on the scan. This same error would have affected the ACSA calculation used for volume and may have led to an underestimation of muscle volume. As the same methodology was used for all the measurements, this error would have been consistent throughout the study, and would not have influenced the between group analyses.

Fascicle length was also not significantly different in low physical activity participants compared to the endurance group. Farris & Sawicki [116] found that malalignment of the probe to the plane of the fascicle may affect the fascicle length readings and that for best results the entire fascicle should be visible on the image [116]. In this study every attempt was made to keep the probe perpendicular to the muscle tissue, but due to shape and thickness variances in the participant's subcutaneous fat and muscle, it is possible that this was not always the case. Optimal fascicle length of the gastrocnemius is difficult to assess [50]. It appears that in a neutral position (ankle at 90°), the fascicles may be as near as possible to optimum length, but there is some variation with changes in muscle length in movement. Testing position was kept uniform in this study (prone lying with the ankle in plantarflexion, relaxed on the plinth) to avoid changes in muscle length and position affecting the imaging between participants.

Pennation angle was not significantly different either between groups or between males and females. Ultrasound measures pennation angle in two dimensions (2D) rather than the three dimensional (3D) orientation that it exists in vivo [120]. Rana et al found that in the gastrocnemius, ultrasound was a reliable measure, but in soleus there was a significant difference between the 2D and 3D values [120]. This study did not assess the architecture of the soleus.

Arampatzis et al [33] assessed fascicle length, pennation angle and thickness in endurance runners who had different running economies. There was no significant difference in any of these architectural characteristics between the three groups (high, moderate and low running economy based on oxygen consumption) in any of the three positions in which they were assessed. These results led the authors to believe that the architectural properties alone did not explain the difference between the endurance runners with differing running economies [33]. This supports the lack of difference in fascicle length, thickness and pennation angle between low physical activity and running participants in this study.

Esformes et al [58] immersed the limb in water as the coupling agent to avoid tissue compression due to the placement of the probe on the limb. It is possible that in this study the use of ultrasound gel and direct contact with leg may have led to an underestimation of thickness as well as ACSA. This could have led to a lower volume in the final calculation. Esformes et al [58] performed imaging on the tibialis anterior muscle, which could be visualized in a single scan and therefore did not require multiple scans to be stitched together. When measuring gastrocnemius in adults, the probe is only able to measure a width of 25 mm on a single scan. The process of stitching multiple scans together allows the potential for error to occur at this stage. The authors recommended that appropriate external markers be used to reduce error [58]. In this study the investigator used a grid to map the images, which may have assisted with accuracy.

3.4.3.2 Volume

Volume has been found to be a more reliable indicator of muscle atrophy following lower limb immobilisation than PCSA [121]. In this study, there was a significant difference between low physical activity and endurance runners in volume suggesting that volume may potentially be a reliable indicator of level of physical activity in healthy populations. Multiple methods of calculating volume have been employed in previous studies to estimate the volume of muscle tissue [50,51,53,57–61]. Volumes recorded in this study appeared to be smaller than reported volumes in most previous studies using MRI [50,53,60,61] and ultrasound [51], but greater than the cadaver study [57].

Previous studies measuring volume used 11 equal slices through the length of the muscle, with the distance between slices varying according to the total length of the muscle measured per participant [58]. In this study, slices were kept routinely 30 mm apart to use a uniform grid on the participants, and the number of slices varied between four and six depending on the length of gastrocnemius. This may have led to inaccuracies due to fewer cross-sectional areas being measured. As mentioned in Section 3.4.3.1 (page 69), inconsistencies in ultrasound technique may have affected the ACSA measurements that could have resulted in lower volume readings.

Macrae et al [113] found that magnetic resonance imaging calculated ACSA at 10% greater than ultrasound. The muscle measured in the study was the anterior digastric muscle of the mouth and the ACSA was extremely small (0.92cm^2) in comparison to the gastrocnemius. As multiple slices rely on the ACSA to calculate their volume, a 10% difference could become magnified as this error is repeated with each slice. Magnetic resonance imaging is considered the gold standard for measuring volume in muscle. However, it is possible that due to the small sample sizes of previous studies [50,60,61] and the use of only one limb, ignoring the effect of dominance, the results may not be as high a standard as reported. In addition, cadaver dissection volume measurements were noticeably smaller than those of all participants with the exception of low physical activity females [57]. It is not specified what the age, sex or previous levels of activity of the specimens were. It is also possible that the preservation of the specimens may have decreased the mass [57].

3.4.3.3 Physiological cross sectional area

Physiological cross sectional area measurements were significantly greater in both males compared to females and in runners compared to low physical activity participants. Physiological cross sectional area is proportional to the force generating capacity of a muscle [50]. There was a correlation between PCSA and vertical jump height difference, which is an indication of power, and therefore supports this fact. As PCSA is calculated using fascicle length and volume, it is assumed that fascicle length is uniform throughout range, but this is not necessarily the case [50]. Until other methods for measuring PCSA are developed, this appears to be the only viable method. However, it is important to be aware of the limitations when the data are interpreted.

Previous studies have used a formula that incorporates pennation angle to account for the fact that the fibres are not parallel to the aponeuroses [61]. In muscles that are cylindrical in shape with fascicles of a constant length, such as the gastrocnemius, the above equation is adequate [122]. In MRI studies it is not possible to measure fascicle length, therefore ultrasound is needed to calculate PCSA without using ultrasound to assess fascicle length. This makes the MRI technique of measuring PCSA more labour intensive than ultrasound alone [50].

3.4.3.4 Achilles tendon compliance

There were no significant differences in the Achilles tendon compliance between groups or sex. The contribution of the Achilles tendon to the passive elastic component of the triceps surae muscle-tendon unit is acknowledged through the literature [81,116]. Muramatsu et al [86] recorded displacement of the Achilles tendon during maximal isometric contraction of plantarflexion. They used a myometer to measure the contraction and corrected for any changes in ankle angle during the contraction. Arampatzis et al [33] reported that it was almost impossible to prevent ankle movement during isometric contraction, even when using fixation. For this reason the recorded tendon compliance may not be accurate. In this study the ankle was not fixed in neutral, and maximal voluntary contraction of the muscle was not measured. Therefore, it is possible that some participants may not have been contracting maximally, which would have affected the slide of the Achilles tendon. The tendon displacement recorded in this study was less than those reported by Kawakami et al [81], potentially for this reason.

3.4.4 Physical tests

3.4.4.1 Gastrocnemius and soleus flexibility

There was a significant increase in gastrocnemius flexibility in females compared to males, but there were no differences between low physical activity and running groups. Flexibility of the calf muscles has been reported to be decreased in runners, with decreased flexibility of the calf muscles being related to higher running speeds [80]. This shortening leads to an increase in stored elastic power, which may be associated with improved running economy [80].

In this study, there was a positive correlation between gastrocnemius flexibility and race times, supporting the evidence from previous studies. Increased gastrocnemius flexibility was associated with increased race times for 10 km, 21.1 km and 42.2 km events. Soleus was found to be correlated to the 42.2 km race time only, which may be an indication of its endurance or stability function rather than the power function of gastrocnemius [101].

Gastrocnemius was injured more often during higher speed sessions [35]. This may be related to the decrease in gastrocnemius flexibility seen in runners with a greater running speed. The structure and architecture of soleus and gastrocnemius are discussed in greater detail in Section 2.3.2 (page 8). As the functional demands on these muscles are different, their architectural structure differs [101]. Soleus is reported to have a more complex fascicle structure than gastrocnemius, which in addition to the fibre type differences, and shorter fascicle length may contribute to the difference in function [101,120]. Long-term prospective research into runners with accurate injury information would be useful to improve understanding of gastrocnemius structure and function in relation to running-related injuries.

3.4.4.2 Vertical jump testing

Vertical jump testing has been used in research to give an indication of lower limb power [96]. While there was a significant increase in maximum vertical jump height in males compared to females, there was no difference between the low physical activity and endurance groups. In previous studies vertical jump height was found to increase with specific jump training such as plyometrics [96], rather than improving with resistance training alone. It is possible that running training is not specific enough to affect these changes, which may explain the absence of differences between the low physical activity and endurance groups. Morrissey et al [123] found no change in vertical jump height following either specific concentric or eccentric training of the calf muscles. Power has been tested in other studies using a variety of methods. An isokinetic dynamometer has been used to provide information on peak torque produced by the muscle [123], as well as an 'all-out cycle test' in which peak power output and total work were measured [124]. These tests may provide more specific information than the vertical jump, but require expensive equipment.

Earp et al [125] assessed architectural components of muscle and vertical jump height. Lateral gastrocnemius was assessed rather than medial, making it difficult to compare directly to this study. They found that lateral gastrocnemius pennation angle was a weak predictor of jump height [125]. Pennation angle appears to be more important in drop jumps and counter-movement jumps that add negative momentum to the jump movement [125]. The participants were resistance trained rather than endurance trained. Earp et al [125] recommended that specific training may be required to cause architectural adaptations and lead to improvements in jump height, rather than training in general, supporting the research by Brown et al [96,125].

3.4.4.3 Calf raises

There was a significant increase in the number of calf raises in the endurance group compared to the low physical activity group. Calf raises have been used to assess endurance or performance in the past [101]. This suggests that endurance runners had better calf endurance than the low physical activity group as a result of their training. Hebert-Losier et al [101] found the average calf raise amount to be 36-45 repetitions compared to 33 ± 8 in male runners and 26 ± 5 in female runners in this study. The sample of the study included 17 healthy participants, including nine males and eight females, aged between 18 and 65 years [101]. As the sample was a much broader age range and consisted of a smaller number of participants in comparison to the current study, it is difficult to critically compare the results. There are very few validated studies on the norms for calf raise testing, and none on runners in particular, which also makes it difficult to evaluate these results [97].

3.4.5 Limitations of study

The main limitation of this study appears to be the repeatability of the volume calculations of the gastrocnemius using ultrasound. While intra-rater reliability was high in this study, the results are quite different to previous studies using both ultrasound and MRI [50,51,53,57–61]. This method of calculating volume has some value when used by the same clinician or investigator but it may not be accurate to compare to other studies using different methods or different testing positions. More cadaver dissection studies may be of value. As the cadaver specimens were poorly described with no age, sex, or previous physical activity information available, it was difficult to compare to the results in this study [57]. High levels of inter-rater and intra-rater reliability have previously been reported for the assessment of structural components of the patella tendon in minimally trained students compared to experienced ultrasonographers [126]. As the hours of supervised training were limited in this study, inter-rater reliability data between the trainer and researcher may have strengthened the results.

While sample size was adequate, and in many cases greater than previous studies [49,54,58,86,113,114,116], once sub-group analyses were performed for sex or physical activity, the numbers may not have been large enough to provide adequate statistical power.

3.5 SUMMARY

The results of this study show that there are structural and functional changes in endurance runners compared to low physical activity participants. Increases in volume and PCSA were evident in the endurance group. Functionally, the endurance group had a greater vertical jump height and increased number of calf raises indicating greater power and endurance in the lower limb and gastrocnemius respectively. There were no significant differences in gastrocnemius or soleus flexibility between the two groups. There was a positive correlation between running time for races, and gastrocnemius flexibility in the endurance group. Changes in gastrocnemius flexibility may be associated with alterations in running speed [(80)] . Decreased gastrocnemius flexibility may be related to an increased risk of running-related injuries [(35)].

CHAPTER 4: SUMMARY AND CONCLUSION

Running is an increasingly popular sport in the non-elite population [1,2]. As a result the number of injuries are increasing [6,24,28]. Calf muscle injuries are a significant concern in runners, with an incidence of up to 30%, affecting both training and competition [8]. The gastrocnemius muscle is an important muscle for propulsion in both walking and running [78]. Changes in the architecture and function of gastrocnemius have been reported following training and it is unknown whether these changes are related to the injuries observed [34,70]. This study appears to be the first to compare low physical activity participants to endurance runners, incorporating architectural assessment in addition to functional testing, which may contribute to a greater understanding of adaptation in ultradistance runners.

An understanding of changes in the gastrocnemius muscle may be important to understanding the training-induced adaptation in muscles. The overall aim of this study was to assess whether endurance running leads to changes in gastrocnemius structure and function. For this purpose, endurance runners were compared to low physical activity participants. Based on the evidence provided in this thesis, the study objectives as described in Section 1.2.2 (page 2) may be answered as follows:

> *To assess differences in calf function and flexibility between endurance runners and low physical activity individuals.*

Gastrocnemius and soleus flexibility, vertical jump height and calf raises were assessed in both low physical activity and endurance runners. No significant differences were found between the endurance and low physical activity groups in either gastrocnemius or soleus flexibility. In addition there were no significant differences between the endurance and low physical activity groups in maximum vertical jump height. The number of calf raises were significantly greater in the endurance group than in the low physical activity group. Calf raises are an indication of endurance capacity of the triceps surae group of muscles.

To determine differences in gastrocnemius muscle architecture and composition between endurance runners versus low physical activity individuals.

There were no significant differences between the low physical activity and endurance groups in any of the following three architectural components: thickness, fascicle length or pennation angle. The absence of differences between groups may potentially be due to the low-load, high volume nature of endurance running, which may not lead to alterations in these architectural components, compared to resistance or power training. Volume was significantly greater in the endurance group compared to the low physical activity group. This change in volume is thought to be a training-induced adaptation in the muscle, as a result of many hours of training. Physiological cross sectional area was also significantly greater in endurance runners in comparison to the low physical activity group. Physiological cross sectional area indicates the force generating capacity of the muscle, but changes in PCSA are smaller in comparison to changes in volume following training. As PCSA is based on the volume of the muscle, increases in volume, while fascicle length remains the same, as was seen in the endurance runners in this study, will result in a greater PCSA. Physiological cross sectional area in this study was shown to be greater in the endurance runners, therefore it appears that PCSA increases as an adaptation to training.

To determine whether there are any relationships between training factors and the structure and function of the gastrocnemius muscle.

Gastrocnemius flexibility was positively correlated to the current fastest times for 10 km, 21.1 km and 42.2 km races of the runners in the endurance group. This indicates that the runners who are faster over these distances appear to have tighter gastrocnemius muscle. There were no significant differences between the endurance and low physical activity groups in gastrocnemius and soleus flexibility, but it is possible that a study with a greater number of participants may find a difference between groups. Soleus flexibility was only found to be correlated to the fastest times in 42.2 km races, possible due to its function as an endurance muscle rather than a power muscle. This shortening in the muscle may be advantageous to endurance runners as it allows them to utilise the passive elastic energy stored in the calf MTU more effectively, reducing the active muscular contraction required (19,83).

Based on the findings in this study, there are significant changes in the gastrocnemius muscle following endurance training. Further research is necessary to assess whether these changes exist in elite runners to a greater or lesser extent. A better understanding of muscle architecture may assist in the application of evidence based treatment and physiotherapy management. There was a high incidence of calf injuries in this group of endurance runners indicating that gastrocnemius injury is a significant concern for runners. Clinically the information regarding gastrocnemius tightness and faster running speeds may be important to consider when prescribing generic stretching programmes for runners. Further research is required to determine the relationships between the architecture and the incidence of calf injury.

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APPENDICES

APPENDIX I: RECRUITMENT LETTER FOR ENDURANCE RUNNERS

Department of Health and Rehabilitation Sciences

Faculty of Health Sciences

Divisions of Communications Sciences and Disorders,
Nursing and Midwifery, Occupational Therapy, Physiotherapy

F45 Old Main Building, Groote Schuur Hospital

16 March 2012

Club Secretary

To Whom It May Concern:

Re: Participants required for University of Cape Town Sports Physiotherapy study

I am a Masters student at the University of Cape Town. I am conducting a study to investigate differences in the gastrocnemius (calf) muscle structure and function between endurance runners and low physical activity individuals.

I am currently looking for endurance runners who are between 20 and 45 years of age, run more than 40 hours per week for the last six months, and have completed a marathon in the previous 12 months. The study requires an hour of testing at the University of Cape Town, Division of Physiotherapy at Groote Schuur Hospital on two separate occasions.

I have attached the study advertisement for interested participants and would appreciate your assistance in distributing it to the club members.

Please contact me if you have any questions or concerns, or would like any more information regarding this study.

Yours sincerely

Kim Buchholtz

BSc Physiotherapy (UCT)

Tel: 083 411 4214

Email: kimbphysio@gmail.com

MALE AND FEMALE ENDURANCE RUNNERS WANTED FOR UCT RESEARCH

For a study evaluating the calf muscle structure and function in endurance runners and low physical activity individuals

Study outline

I am a Masters student at the University of Cape Town, investigating the difference between the gastrocnemius (calf) muscle structure and function in endurance runners compared to low physical activity individuals. The study aims to provide information regarding the changes in the calf muscle following long distance running training and whether this predisposes to calf injury.

You will be required to attend two testing sessions of one hour each at the University of Cape Town, Division of Physiotherapy at Groote Schuur Hospital. During the two visits you will be required to complete a questionnaire on your training and competition history, injury history and general physical activity. You will also have mass, height and skinfold measurements taken. An ultrasound scan will be taken of the calf muscle complex and physical tests to measure the strength, endurance and power of the calf muscle will be completed.

Those interested in participating should:

- be between the ages of 20 and 45 years
- be running at least 40 km per week over four to six training sessions each week for at least six months
- have run a marathon in the previous 12 months

Benefits of participating in the study include

- Individual anthropometric measurements (Height, weight, body fat %)
- Advice on risk of calf injury and preventative strategies
- Information booklet including exercises to improve strength, flexibility and mobility

DEADLINE FOR APPLICATIONS: (to be specified)

If you are interested in taking part in the study and would like additional information, please contact:

Kim Buchholtz
Cell: 083 411 4214
Email: kimbphysio@gmail.com

APPENDIX II: RECRUITMENT LETTER FOR LOW PHYSICAL ACTIVITY PARTICIPANTS

Department of Health and Rehabilitation Sciences

Faculty of Health Sciences

Divisions of Communications Sciences and Disorders, Nursing and Midwifery, Occupational Therapy, Physiotherapy

F45 Old Main Building, Groote Schuur Hospital

16 March 2012

Human Resources Manager

To Whom It May Concern:

Re: Participants required for UCT/ESSM MPhil Sports Physiotherapy study

I am a Masters student at the University of Cape Town). I am conducting a study investigating the difference in the gastrocnemius (calf) muscle structure and function between endurance runners and low physical activity individuals.

I am currently looking for low physical activity individuals who are between 20 and 45 years of age who are not currently taking part in any regular training. The study requires an hour the University of Cape Town, Division of Physiotherapy at Groote Schuur Hospital on two separate occasions.

I have attached the study advertisement for interested participants and would appreciate your assistance in distributing it to your employees.

Please contact me if you have any questions or concerns, or would like any more information regarding this study.

Yours sincerely

Kim Buchholtz

BSc Physiotherapy (UCT)

Tel: 083 411 4214

Email: kimbphysio@gmail.com

MALE AND FEMALE LOW PHYSICAL ACTIVITY INDIVIDUALS WANTED FOR UCT RESEARCH

For a study evaluating the calf muscle structure and function in endurance runners and low physical activity individuals

Study outline

I am a Masters student at the University of Cape Town, investigating the difference between the gastrocnemius (calf) muscle structure and function in endurance runners compared to low physical activity individuals. The study aims to provide information regarding the changes in the calf muscle following long distance running training and whether this predisposes to calf injury.

You will be required to attend two testing sessions of one hour each at the University of Cape Town, Division of Physiotherapy at Groote Schuur Hospital. During the two visits you will be required to complete a questionnaire on your health and general physical activity. You will also have mass, height and skinfold measurements taken. An ultrasound scan will be taken of the calf muscle complex and physical tests to measure the strength, endurance and power of the calf muscle will be completed.

Those interested in participating should:

- be between the ages of 20 and 45 years
- not be currently doing any regular form of exercise
- be healthy with no existing medical conditions that could cause the physical testing to put them at risk

Benefits of participating in the study include

- Individual anthropometric measurements (Height, weight, body fat %)
- Advice on risk of calf injury and preventative strategies
- Information booklet including exercises to improve strength, flexibility and mobility and advice on beginning an exercise programme

DEADLINE FOR APPLICATIONS: (to be specified)

If you are interested in taking part in the study and would like additional information, please contact:

Kim Buchholtz
Cell: 083 411 4214
Email: kimbphysio@gmail.com

APPENDIX III: INFORMED CONSENT FORM

Department of Health and Rehabilitation Sciences

Faculty of Health Sciences

Divisions of Communications Sciences and Disorders,
Nursing and Midwifery, Occupational Therapy, Physiotherapy

F45 Old Main Building, Groote Schuur Hospital

MPhil Sports Physiotherapy Study: An evaluation of gastrocnemius muscle structure and function in endurance runners and low physical activity individuals

INFORMED CONSENT FORM

Dear Participant

I am Masters student in the Division of Physiotherapy at the University of Cape Town. I will be conducting a study to determine the changes in the structure and function of the gastrocnemius (calf) muscle in endurance runners compared to low physical activity individuals. Information such as training and competition information will be obtained as well as flexibility, muscle power and endurance, which will be tested. Information obtained within the study will be used to complete my mini-dissertation in part fulfillment of the MPhil Sports Physiotherapy programme. This study has been given ethical approval by the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (HREC REF 259/2012).

Calf injuries are common injuries in endurance runners leading to time off running while recovering. There is a lack of evidence regarding the cause of these injuries and whether there are intrinsic factors within the runner such as tight calf muscles or poor mobility in the nerves. The possible causes of calf injuries need to be investigated further.

You will be asked to attend a total of two appointments, lasting approximately an hour each, three to five days apart at the University of Cape Town, Division of Physiotherapy at Groote Schuur Hospital. For each session, you will be required to travel to the laboratory at the Division of Physiotherapy at your own cost as there is no funding for the study.

This study will be supervised by Dr Theresa Burgess and Professor Mike Lambert from the University of Cape Town. Please take time to read this form thoroughly before signing.

On the first appointment:

The first appointment will last approximately an hour. You will be asked to complete a questionnaire regarding your training, competition history, injury history and physical activity levels. There will be questions included to assess your readiness to complete the necessary physical tests which will screen for any medical conditions that may exclude you from the study. Should any medical conditions be detected, you will be referred to the appropriate medical facility. Anthropometry measurements including weight, height, and body fat percentage will be taken. You will be familiarised with all testing procedures that will be used during the study and have the opportunity to practice any of the tests that will be completed in the second session. The testing procedure will be explained and any questions will be addressed.

On the second appointment:

The second appointment will also take approximately an hour to complete the tests. At the second meeting (three to five days after the first meeting), ultrasound imaging will be done on the calf. During the initial portion of the ultrasound scan you will required to stay still while the investigator uses an ultrasound machine to assess the muscle, while in the second part you will be required to contract the calf muscle against a board during the scan. You will feel a cold sensation during this portion of testing due to the ultrasound gel used on the ultrasound machine.

After the ultrasound scans are complete you will have the mobility of your neural system assessed during a straight leg raise test while lying on your back on a plinth. Each of your legs will be passively lifted off the bed and any stiffness or discomfort will be recorded as well as how high the leg can go. The flexibility of both of the muscles in the calf will be assessed in standing with one leg out behind you. In the first part of the test the knee will be straight with the foot flat on the floor, and a small device on the ankle will measure the range of movement. The back knee will then be bent with the foot remaining flat on the floor and the range recorded in this position. Muscle power will be assessed using a vertical jump test which involves jumping as high as possible from a squatting position. Each of these tests will be performed on the right leg first followed by the left leg, and each test will be repeated three times to ensure accurate recordings. A calf raise test will then be performed to assess how many calf raises can be completed before the muscle becomes too tired to continue. This test will be video recorded and the number of repetitions will be counted. All recordings will be stored in a locked cabinet for the duration of the data analysis and once the number of repetitions have been confirmed, these recordings will be permanently deleted.

Potential Risks:

There are no risks associated with the anthropometrical measurements and ultrasound scanning. You may feel slight discomfort during measurement of skinfold thicknesses, as the calipers used for testing may pinch your skin slightly. The ultrasound gel will feel cold, but there are no other risks with scanning your calf muscles. There is a small risk of injury to your muscles during the neural, flexibility, muscle strength and endurance tests. You will have the opportunity to practice all of the tests at the first session which will decrease the risk of injury. I will also ask you to tell me if you feel any discomfort during testing, so that we can stop testing immediately. You may also experience some soreness after the testing, which is similar to the soreness after any unaccustomed exercise. This soreness should go away within two to five days after the testing. In addition, all of the tests, excluding the vertical jump test, are performed below maximal performance and therefore the changes of injury are small. Although every effort will be taken to minimise injury, should you sustain an injury during testing, you will be referred for the appropriate medical care.

Benefits:

You will be given feedback on all the anthropometrical measurements taken so that the information can be used to create a training programme or adjust your current training programme to reach your goals. You will also be given information regarding the calf specifically to help protect you from injury. You will be given an information booklet with information on training, including running specific information as well as advice for that will allow you to start training from scratch. Flexibility, stability and strength training exercises will be described in this booklet. Unfortunately no financial compensation is available for participation in this study.

Questions or Concerns:

Please note that UCT does offer a no-fault insurance that will cover all participants in the event that something may go wrong. This insurance will provide prompt payment of compensation for any trial-related injury according to the Association of the British Pharmaceutical Industry (ABPI) guidelines (1991). These guidelines recommend that UCT, without any legal commitment, should compensate you without you having to prove that UCT is at fault. An injury is considered trial-related if, and to the extent that, it is caused by study activities. You must notify the study investigators immediately of any injuries during the trial, whether they are research-related or other related complications. UCT reserves the right not to provide compensation if, and to the extent that, your injury came about because you chose not to follow the instructions that you were given while taking part in the study. Your right in law to claim compensation for injury where you prove negligence is not affected.

If at any time you have any questions about the study, please feel free to contact any of the individuals listed below. You are assured that all inquiries will remain confidential.

Kim Buchholtz

Physical Address:	21 Constantia Road
	Plumstead
	7806
Tel number:	083 411 4214
Email:	kimbphysio@gmail.com

Dr. T. Burgess

Physical Address:	Division of Physiotherapy
	School of Health and Rehabilitation
	University of Cape Town
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Professor Marc Blockman

Chairperson, Faculty of Health Sciences Human Research Ethics Committee

Tel number:	021 406 6492
E-mail:	marc.blockman@uct.ac.za

By placing your signature below, it serves as confirmation that you have had adequate time to read through the study information, that you have understood the consent form and that you are willing to participate in this study. You have the right to withdraw at any time and you may ask questions at any time during the study. All information recorded during this study will remain confidential, and no participants will be identified in the event of future publication. Your signature is further confirmation that you are aware of the possible risks involved in this study.

______________________	______________________	______________
Signature of Participant	Name (Please Print)	Date
______________________	______________________	______________
Signature of Investigator	Name (Please Print)	Date

APPENDIX IV: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Name:

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor? Yes ☐ No ☐

2. Do you feel pain in your chest when you do physical activity? Yes ☐ No ☐

3. In the past month, have you had chest pain when you were not doing physical activity?

Yes ☐ No ☐

4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes ☐ No ☐

5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity? Yes ☐ No ☐

6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition? Yes ☐ No ☐

7. Do you know of any other reason why you should not do physical activity?

Yes ☐ No ☐

APPENDIX V: QUESTIONNAIRE

MPhil Sports Physiotherapy

Calf structure and function study

Physical Activity and Training Questionnaire

The information collected in this questionnaire will only be used for research purposes within the scope of this study. All information will be kept strictly confidential and anonymous.

Instructions

The questionnaire must be completed during the first session of the testing procedure. Please answer each question by filling in the details in the allocated space or checking one or more of the option boxes.

Informed consent must be signed prior to completing the questionnaire online, and handed in to the investigator.

Investigator: Kim Buchholtz

Tel number: 083 411 4214

Email: kimbphysio@gmail.com

Supervisors: Dr Theresa Burgess

Tel number: 021 406 6171

Fax number: 021 406 6323

E-mail: theresa.burgess@uct.ac.za

Prof Mike Lambert

Tel number: 021 650 4558

E-mail: mike.lambert@uct.ac.za

A/Prof Andrew Bosch

Tel number: 021 650 4578

Email: andrew.bosch@uct.ac.za

Please complete the following sections:

Section A	Personal Details
Section B	General Physical Activity
Section C	Running information
Section D	Competition History
Section E	Running Training
Section F	General Training History
Section G	Injury History

Section A: Personal details

Name:

Email address:

Date of birth:

Cell number:

Home number:

Gender: Male ☐ Female ☐

Height:

Weight:

Age:

Occupation:

Do you currently do any regular physical activity? Yes ☐ No ☐

If YES, please complete the entire questionnaire

If NO, please attach completed Physical Activity Screening, complete section B and leave out the rest of the questionnaire

Section B: General Physical Activity

1a. If you are not currently doing any regular physical activity, have you previously engaged in any regular exercise programmes? Yes ☐ No ☐

If NO, you may continue to the next Section.

1b. If YES, when did you last do any regular physical activity? ______________________________

1c. When did you stop doing regular physical activity? ___________________________________

1d. Why did you stop doing physical activity?

- Lost interest ☐
- Lack of time ☐
- Injury/illness ☐
- Family commitments ☐
- Work commitments ☐
- Other ☐ Please specify: __________________________

Section C: Running information

1a. Running Club:

1b. Running Shoes:

- Neutral ☐
- Stability ☐
- Barefoot/Minimal ☐

Average mileage covered in a pair of shoes? ________________km

1c. In which running disciplines do you currently take part?

- Road ☐
- Trail ☐
- Track ☐
- Cross country ☐

Section D: Competition history

1. Have you completed any of the following races in the last 12 months? How many did you complete in each category, and please state your best time in the last 12 months.

10 km	Yes	☐	No	☐	Number: _____	Best time: ______
21.1 km	Yes	☐	No	☐	Number: _____	Best time: ______
42.2 km	Yes	☐	No	☐	Number: _____	Best time: ______
Ultra-distance (>50 km)	Yes	☐	No	☐	Number: _____	Best time: ______

Which Ultra events? ____

2. At what speed would you currently complete the following during races? Place an **X** in the appropriate box:

	5km (including time trials)	10km	21.1km	42.2km	>50km
2:30 min/km – 3 min/km					
3:01 min/km – 3:30 min/km					
3:31min/km - 4 min/km					
4:01 min/km – 4:30min/km					
4:31 min/km – 5 min/km					
5:01 min/km – 5:30 min/km					
5:31 min/km – 6 min/km					
6:01 min/km – 6:30 min/km					
6:31 min/km – 7min/km					

Section E: Running Training history

1a. What is your average training distance per week in the last 3 months? ______________km

1b.What is your maximum training distance per week in the last 3 months? ____________km

1c. What is your minimum training distance per week in the last 3 months? ____________km

2a. How many running training sessions do you complete each week? ☐

2b. How many days do you rest from running training each week? ☐

3a. What is your average running speed during training sessions (in min/km)? _________min/km

3b. What is your maximum running speed during training sessions? _________________min/km

3c. What is your minimum running speed during training sessions? _________________min/km

4a. Have you stopped running for a particular period of time in the last 12 months (rest period)?

Yes ☐ No ☐

4b. If YES, how long was this rest period? ______________

4c. If YES, what was the reason for this rest period?

- Injury ☐
- Illness ☐
- Work commitments ☐
- Family commitments ☐
- Pregnancy ☐
- Other ☐ Please specify: ______________________________

4d. Did you have a second period of rest during the year? Yes ☐ No ☐

4e. If YES, please state how long the second rest period was: ____________________

4f. What was the reason for the second rest period?

- Injury ☐
- Illness ☐
- Work commitments ☐
- Family commitments ☐
- Pregnancy ☐
- Other ☐ Please specify: _______________________________

4g. Did you have a third period of rest during the year? Yes ☐ No ☐

4h. If YES, please state how long the third rest period was: ____________________

4i. What was the reason for the third rest period?

- Injury ☐
- Illness ☐
- Work commitments ☐
- Family commitments ☐
- Pregnancy ☐
- Other ☐ Please specify: _______________________________

5. Do you include the following in your running training? On average, how often per week do you include them?

Low slow runs	Yes	☐	No	☐	How often/wk?
Speed/Interval sessions	Yes	☐	No	☐	How often/wk?
Hill training	Yes	☐	No	☐	How often/wk?

Section F: General Training

1. Do you do any other forms of training on a regular basis? Yes ☐ No ☐

2. Which type of training, how often per week and for how many months of the year do you participate in this training?

Cycling	☐	____________hrs/wk	_____________months/year
Swimming	☐	____________hrs/wk	_____________months/year
Rugby	☐	____________hrs/wk	_____________months/year
Touch Rugby	☐	____________hrs/wk	_____________months/year
Cricket	☐	____________hrs/wk	_____________months/year
Dancing	☐	____________hrs/wk	_____________months/year
Martial arts	☐	____________hrs/wk	_____________months/year
Pilates	☐	____________hrs/wk	_____________months/year
Yoga	☐	____________hrs/wk	_____________months/year
Resistance training	☐	____________hrs/wk	_____________months/year
Hockey	☐	____________hrs/wk	_____________months/year
Canoeing	☐	____________hrs/wk	_____________months/year
Horse riding	☐	____________hrs/wk	_____________months/year
Aerobics/ Step	☐	____________hrs/wk	_____________months/year
Skating	☐	____________hrs/wk	_____________months/year
Volleyball	☐	____________hrs/wk	_____________months/year
Walking	☐	____________hrs/wk	_____________months/year
Squash	☐	____________hrs/wk	_____________months/year
Basketball	☐	____________hrs/wk	_____________months/year
Hiking	☐	____________hrs/wk	_____________months/year
Tennis	☐	____________hrs/wk	_____________months/year

Soccer	☐	___________hrs/wk	____________months/year
Golf	☐	___________hrs/wk	____________months/year
Badminton	☐	___________hrs/wk	____________months/year
Other	☐	Please specify:____	

3a. Do you do any flexibility/stretch exercises regularly? Yes ☐ No ☐

3b. If YES, on average, how many days a week do you perform a stretching session? ☐

3c. Do you stretch: Before exercise

During exercise

After exercise

3d. Which muscle groups do you include in your stretches? Hamstrings ☐

Quadriceps ☐

Calves

Groin

Other: Please specify

3e. When you stretch the above muscle groups, how long, on average, do you hold each stretch for?

☐ Seconds

3f. On each occasion, when you stretch the above muscle groups, how often, on average do you repeat each stretch?

Once ☐

Twice ☐

3 times ☐

4 times ☐

5+ times ☐

Section G: Injury History

1a. Have you sustained any calf muscle injuries while running in the last year, that have interrupted your running training? Yes ☐ No ☐

1b. If NO, please continue to Question 2

If YES: On the right side? ☐

On the left side? ☐

Both sides? ☐

1c. Were you diagnosed by a medical professional? Yes ☐ No ☐

1d. If yes, what was your diagnosis? ________________________________

1e. Did you receive any treatment for this injury? Yes ☐ No ☐

1f. If YES, what type of treatment did you receive (Tick all appropriate answers)?

Tablets ☐

Stretches ☐

Cortisone injection ☐

Physiotherapy ☐

Orthotics ☐

Strengthening exercises ☐

Equipment change ☐

Surgery ☐

Other: ☐ Please specify:___________

1g. Does this injury still interfere with your running training? Yes ☐ No ☐

1h. How long did it take to recover? _______________________________________

2a. Have you sustained any other injuries while running in the last year that have resulted in time off training? Yes ☐ No ☐

2b. If NO, please skip to Question 3

If yes, please complete the questions for each injury.

Injury 1: What did you injure? ____________________________________

On the right side? ☐

On the left side? ☐

Both sides? ☐

2c. Were you diagnosed by a medical professional? Yes ☐ No ☐

2d. If yes, what was your diagnosis? _______________________________

2e. Did you receive any treatment for this injury? Yes ☐ No ☐

2f. If YES, what type of treatment did you receive (Tick all appropriate answers)?

Tablets ☐

Stretches ☐

Cortisone injection ☐

Physiotherapy ☐

Orthotics ☐

Strengthening exercises ☐

Equipment change ☐

Surgery ☐

Other: ☐ Please specify:___________

2g. Does this injury still interfere with your running training? Yes ☐ No ☐

2h. How long did it take to recover? ______________________________________

Injury 2: What did you injure? ___________________________________

On the right side? ☐

On the left side? ☐

Both sides? ☐

2j. Were you diagnosed by a medical professional? Yes ☐ No ☐

2k. If yes, what was your diagnosis? ______________________________

2l. Did you receive any treatment for this injury? Yes ☐ No ☐

2m. If YES, what type of treatment did you receive (Tick all appropriate answers)?

Tablets ☐

Stretches ☐

Cortisone injection ☐

Physiotherapy ☐

Orthotics ☐

Strengthening exercises ☐

Equipment change ☐

Surgery ☐

Other: ☐ Please specify:___________

2n. Does this injury still interfere with your running training? Yes ☐ No ☐

2o. How long did it take to recover? _____________________________________

Injury 3: What did you injure? ___________________________________

On the right side? ☐

On the left side? ☐

Both sides? ☐

2p. Were you diagnosed by a medical professional? Yes ☐ No ☐

2q. If yes, what was your diagnosis? ________________________________

2r. Did you receive any treatment for this injury? Yes ☐ No ☐

2s. If YES, what type of treatment did you receive (Tick all appropriate answers)?

- Tablets ☐
- Stretches ☐
- Cortisone injection ☐
- Physiotherapy ☐
- Orthotics ☐
- Strengthening exercises ☐
- Equipment change ☐
- Surgery ☐
- Other: ☐ Please specify:___________

2t. Does this injury still interfere with your running training? Yes ☐ No ☐

2u. How long did it take to recover? _______________________________________

3a. Have you sustained any calf injuries during other sporting activities? Yes ☐ No ☐

3b. If NO, your questionnaire is now complete

If YES,
- On the right side? ☐
- On the left side? ☐
- Both sides? ☐

3c. Were you diagnosed by a medical professional? Yes ☐ No ☐

3d. If yes, what was your diagnosis? ________________________________

3e. Did you receive any treatment for this injury? Yes ☐ No ☐

3f. If YES, what type of treatment did you receive (Tick all appropriate answers)?

- Tablets ☐
- Stretches ☐
- Cortisone injection ☐
- Physiotherapy ☐
- Orthotics ☐
- Strengthening exercises ☐
- Equipment change ☐
- Surgery ☐
- Other: ☐ Please specify:___________

3g. Does this injury still interfere with your running training? Yes ☐ No ☐

3h. How long did it take to recover? ___________________________________

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

APPENDIX VI: FEASIBILITY STUDY

INTRA-RATER RELIABILITY OF MEASUREMENTS REQUIRED FOR DETERMINING THE DIFFERENCES BETWEEN LOW PHYSICAL ACTIVITY AND ENDURANCE RUNNING PARTICIPANTS

VI.I BACKGROUND:

Intra-rater reliability is the ability of an examiner to accurately perform a specific testing method repeatedly, over a period of time. It is essential in clinical practice as independent practitioners commonly utilise tests to re-evaluate and determine a specific patient's progress in injury healing and response to treatment protocols (127).

VI.II AIM:

The aim of this feasibility study was to establish reliability of the tests utilised in the main research study.

VI.III SPECIFIC OBJECTIVES:

The specific objectives of this study were to determine:

- Intra-rater reliability of anthropometrical measurements including skinfolds and body fat percentage
- Intra-rater reliability of the range of movement measurements using a universal inclinometer
- Intra-rater reliability of the measurement of the length of the gastrocnemius using ultrasound imaging to determine the position of the proximal and distal musculotendinous junctions
- Intra-rater reliability of the ultrasound measurements including thickness, fascicle length and pennation angle
- Intra-rater reliability of the ultrasound imaging and calculation of the volume of gastrocnemius
- Intra-rater reliability of the ultrasound imaging of the Achilles tendon compliance

VI.IV PARTICIPANTS:

Five participants were included in this study (n = 5). Three participants fulfilled the criteria for the endurance running group, and two participants for the low physical activity group.

VI.V TESTING PROCEDURE:

The five participants were each tested three times at a single session. Anthropometrical measurements were performed by the research assistant, while range of movement and ultrasound imaging were performed by the principal investigator. Each participant completed the self developed questionnaire.

a) Anthropometrical measurements

Body mass (kg) was recorded using a calibrated scale (Seca model, 708 Germany). Stature (cm) was recorded using a stadiometer (Seca model, 708 Germany). Body fat was expressed as the sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, calf, thigh and abdomen), as described by (106). Body fat was also expressed as a percentage of body mass (107). This descriptive information was used to describe body composition of the participants.

b) Ultrasound measurements: length of gastrocnemius, pennation angle, thickness and fascicle length

Ultrasound imaging was performed using a Siemens ACUSON X150 diagnostic ultrasound machine (Siemans Medical Solutions Inc, USA). The participant was positioned in prone with the calf muscle relaxed and ankle in plantarflexion for the first portion of the testing. Testing in this position included measurement of the length of the gastrocnemius muscle belly, thickness, fascicle length and pennation angle. Medial gastrocnemius was measured due to it being the most commonly injured portion of the triceps surae complex [13,14]. Ultrasound imaging was first performed on the right gastrocnemius, and was then completed on the left gastrocnemius.

Gastrocnemius muscle belly length

Length of the gastrocnemius muscle belly was accepted as the distance between the proximal to distal musculotendinous junction in a straight line over the skin. The musculotendinous junctions were identified on ultrasound in the mid-sagittal plane and marked with non-permanent marker.

Muscle thickness

Three scans were taken of the medial gastrocnemius and measurements were calculated electronically after the testing session. The mid-belly scans were performed over the medial gastrocnemius, measured halfway between the proximal and distal musculotendinous junctions, as measured for gastrocnemius length. Thickness of the muscle was calculated as the perpendicular distance in mm between the two aponeuroses (45).

Fascicle length

The fascicle length was then measured on the same mid-belly scans as a straight line along the fascicle between the superficial and deep aponeuroses. Fascicle curvature has been shown to be negligible and therefore measuring along a straight line is considered satisfactory [86]. When the fascicle length extended beyond the line of the scanned image, the length of fascicle missing was estimated by linearly extending the line of the fascicle and the deep or superficial aponeurosis involved (48). Three separate fascicles were measured in mm on the mid-belly scans, and the average was reported.

Pennation angle

Pennation angle was calculated as the angle between a single chosen fascicle and its insertion onto the deep aponeurosis (51). Three separate angles were measured from each of the three mid-belly scans, and the degrees were averaged for data analysis.

c) Ultrasound measurement: volume calculation

Ultrasound was also used to calculate the volume of the muscle tissue. The muscle between the proximal and distal musculotendinous junctions was scanned in four to six evenly spaced axial plane sections, 30 mm apart, using a grid as a position marker on the surface.

Anatomical cross sectional area (ACSA) was calculated by stitching the adjacent scans together and measuring the area on an imaging programme (ImageJ 1.46r; National Institutes of Health, USA). The volume between each of those sections was then calculated based on the following formula:

$$V = \frac{1}{3} \times [a+\sqrt{(ab+b)}] \times t$$

where *a* and *b* are the ACSA in the two consecutive scans and *t* the length between the adjacent scans, which in this study was 30 mm. The volume of each 30 mm slice needs to be calculated and added together to give the total volume of the gastrocnemius [58,87].

d) Ultrasound measurement: Achilles tendon compliance

Ultrasound was also used to measure the compliance of the Achilles tendon with participant in prone lying. The right tendon was assessed first, followed by the left tendon. The foot was positioned at 90° (neutral) with the foot resting against the wall and the ultrasound head was placed over the muscle and scanned from above until the musculotendinous junction was visualised on the screen [(81)].

The participant was then instructed to press the forefoot as hard as possible into the wall, without lifting the heel, to perform a maximal isometric contraction of plantarflexion and the movement of the musculotendinous junction was measured. This movement was representative of the elongation of the tendon [(81)]. Each scan was repeated three times and an average was recorded.

e) Flexibility: gastrocnemius and soleus

Muscle length testing was performed on both the gastrocnemius and soleus muscles using an inclinometer. Muscle length was tested initially on the right leg and repeated on the left. The inclinometer was attached to the distal fibula with the leg in neutral, and the forward angulation of the tibia and fibula on the talus was measured. The movement to be tested was ankle dorsiflexion (108).

Gastrocnemius was tested first with the participant in a standing position with the leg to be tested in hip extension. The knee was held in full extension and the participant was instructed to lean forward to move the ankle into maximal dorsiflexion. Each test was repeated three times on the right side followed by three times on the left and the average ROM was recorded on each side. Soleus was tested with the hip extended, knee flexed and ankle fully dorsiflexed on the leg being tested. Each test was repeated three times on each side and an average was recorded to ensure accuracy [(90)].

VI.VI DATA ANALYSIS

Measurements were recorded on independent data collection sheets for principal investigator and research assistant. These data were then collated into an Excel spreadsheet (Microsoft Corporation, Redmond, USA).

VI.VII STATISTICAL ANALYSES

Data were analysed using a spreadsheet specifically designed for this purpose downloaded from www.sportsci.org. Typical error of measurement and intra-class coefficients were assessed, and reported with their respective 95% confidence intervals. Intra-rater reliability was accepted as $r \geq 0.7$. All data are presented as the mean ± standard deviation.

VI.VIII RESULTS

The results of each measurement tested are shown in the Tables below.

Table 1: Intra-rater reliability of anthropometrical tests on participants in the feasibility study (n=5). Data are expressed as typical error and intra-class coefficients (ICC) with their 95% confidence intervals (CI) and mean ± standard deviation (SD).

Variable		Typical error (95% CI)	ICC (95% CI)	Mean ± standard deviation
Anthropometric measurements	Triceps skinfold (mm)	0.92 (0.68-1.72)	0.94 (0.80-0.98)	15.76 ± 3.46
	Biceps skinfold (mm)	0.85 (0.62-1.59)	0.98 (0.92-0.99)	12.36 ± 5.04
	Subscapular skinfold (mm)	0.39 (0.28-0.72)	0.98 (0.93-0.99)	11.56 ± 2.56
	Suprailiac skinfold (mm)	0.99 (0.72-1.84)	0.93 (0.76-0.99)	10.70 ± 3.39
	Thigh skinfold (mm)	1.27 (0.93-2.38)	0.96 (0.85-0.98)	24.76 ± 5.57
	Calf skinfold (mm)	1.22 (0.90-2.29)	0.95 (0.85-0.98)	13.58 ± 3.56
	Abdominal skinfold (mm)	0.61 (0.45-1.14)	0.99 (0.96-1.00)	16.16 ± 5.43
	Sum of 7 skinfolds (mm)	2.63 (1.93-4.91)	0.99 (0.97-1.00)	105.12 ± 26.46
	Body fat percentage	0.54 (0.39-1.00)	0.98 (0.94-0.98)	23.98 ± 3.73

Table 2: Intra-rater reliability of the ultrasound measurements in the feasibility study (n=5). Data are expressed as typical error and intra-class coefficients (ICC) with their 95% confidence intervals (CI) and mean ± standard deviation (SD).

Variable		Typical error (95% CI)	ICC (95% CI)	Mean ± standard deviation
Ultrasound measurements	Length of gastrocnemius muscle belly (right) (mm)	2.63 (1.93-4.91)	0.99 (0.95-0.99)	212.74 ± 20.23
	Length of gastrocnemius muscle belly (left) (mm)	1.57 (1.15-2.95)	1.00 (0.99-1.00)	229.82 ± 29.00
	Thickness (right) (mm)	0.59 (0.43-1.09)	0.93 (0.76-0.97)	16.30 ± 2.00
	Thickness (left) (mm)	0.65 (0.48-1.22)	0.89 (0.66-0.96)	17.16 ± 1.87
	Pennation angle (right) (°)	1.77 (1.30-3.30)	0.85 (0.53-0.94)	24.26 ± 4.13
	Pennation angle (left) (°)	1.37 (1.00-2.56)	0.96 (0.86-0.98)	26.60 ± 6.22
	Fascicle length (right) (mm)	3.17 (2.48-4.50)	0.78 (0.55-0.89)	45 ± 2
	Fascicle length (left) (mm)	3.53 (2.76-5.01)	0.75 (0.49-0.88)	42 ± 5
	Volume (right) (cm^3)	4.15 (3.04-7.75)	0.96 (0.88-0.99)	193 ± 20
	Volume (left) (cm^3)	3.42 (2.51-6.39)	0.97 (0.91-0.99)	186 ± 19
	Achilles tendon elongation (right) (mm)	2.26 (1.66-4.23)	0.95 (0.84-0.98)	16.66 ± 9.47
	Achilles tendon elongation (left) (mm)	4.61 (3.38-8.60)	0.70 (0.14-0.87)	18.38 ± 7.42

Table 3: Intra-rater reliability of the range of movement tests in the feasibility study (n=5). Data are expressed as typical error and intra-class coefficients (ICC) with their 95% confidence intervals (CI) and mean ± standard deviation (SD).

Variable		**Typical error (95% CI)**	**ICC (95% CI)**	**Mean ± standard deviation**
Flexibility (°)	Gastrocnemius (right)	1.44 (1.06-2.69)	0.97 (0.91-0.99)	32.14 ± 8.24
	Gastrocnemius (left)	0.92 (0.68-1.72)	0.97 (0.89-0.99)	32.06 ± 4.69
	Soleus (right)	2.55 (1.87-4.76)	0.87 (0.59-0.95)	37.74 ± 6.51
	Soleus (left)	1.94 (1.42-3.62)	0.70 (0.13-0.87)	35.26 ± 4.96

VI.IX SUMMARY AND CONCLUSION

Intra-rater reliability is expressed as typical error and its 95% confidence interval, as well as intra-class coefficient and its 95% confidence interval. Acceptable intra-rater reliability is regarded as $r \geq 0.7$. Therefore the results reported above indicate satisfactory reliability for each measurement.

APPENDIX VII: BORG SCALE

Borg Scale: Rate of Perceived Exertion (109)

6	
7	Very, very light (rest)
8	
9	Very light (gentle walking)
10	
11	Fairly light
12	
13	Somewhat hard (steady pace)
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	Exhaustion

APPENDIX VIII: ETHICS APPROVAL

UNIVERSITY OF CAPE TOWN

Faculty of Health Sciences
Faculty of Health Sciences Research Ethics Committee
Room E52-24 Groote Schuur Hospital Old Main Building
Observatory 7925
Telephone [021] 406 6338 • **Facsimile** [021] 406 6411
e-mail: sumayah.ariefdien@uct.ac.za

06 July 2012

HREC REF: 259/2012

Miss K Buchholtz
c/o Dr T Burgess
Physiotherapy
F-Floor
OMB

Dear Miss Buchholtz

PROJECT TITLE: AN EVALUATION OF GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN ENDURANCE RUNNERS AND SEDENTARY INDIVIDUALS

Thank you for addressing the issues raised by the committee.

It is a pleasure to inform you that the HREC has formally approved the above mentioned study.

Approval is granted for one year till the 28 July 2013.

Please submit a progress form, using the standardised Annual Report Form (FHS016), if the study continues beyond the approval period. Please submit a Standard Closure form (FHS010)if the study is completed within the approval period.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the REC. REF in all your correspondence.

Yours sincerely

PROFESSOR M BLOCKMAN
CHAIRPERSON, HSF HUMAN ETHICS

Federal Wide Assurance Number: FWA00001637.
Institutional Review Board (IRB) number: IRB00001938

sAriefdien

UNIVERSITY OF CAPE TOWN

FACULTY OF HEALTH SCIENCES
Human Research Ethics Committee

FHS016: Annual Progress Report / Renewal

HREC office use only (FWA00001637; IRB00001938)			
This serves as notification of annual approval, including any documentation described below.			
☑ Approved	Annual progress report	Approved until/next renewal date	28/07/2014
☐ Not approved	See attached comments		
Signature Chairperson of the HREC	[signature]	Date Signed	15/7/2013

Comments to PI from the HREC

Principal Investigator to complete the following:

1. Protocol information

Date form submitted	25/6/2013		
HREC REF Number	259/2012	Current Ethics Approval was granted until	28/7/2013
Protocol title	An evaluation of gastrocnemius muscle structure and function in endurance runners and sedentary individuals		
Protocol number (if applicable)			
Are there any sub-studies linked to this study?	☐ Yes ☒ No		
If yes, could you please provide the HREC Ref's for all sub-studies? Note: A separate FHS016 must be submitted for each sub-study.			
Principal Investigator	Kim Buchholtz		
Department / Office Internal Mail Address	Health and Rehabilitation Sciences		

RESEARCH ETHICS COMMITTEE
2013 -07- 15
HEALTH SCIENCES FACULTY
UNIVERSITY OF CAPE TOWN

1.1 Does this protocol receive US Federal funding?	☐ Yes	☒ No
1.2 Does this study require full committee approval?	☐ Yes	☒ No

(Note: Please complete the Closure form (FHS010) if the study is completed within the approval period)

APPENDIX IX: INFORMATION BOOKLET FOR PARTICIPANTS

Weight: __________

Height: __________

Sum of seven skinfolds: _________

BMI: _________

Fat percentage: __________

Thank you for participating in our study. I hope you find the exercises below and training programme useful in your future training.

Mobility/stability exercises:

1. Pelvic clocks:

Lie flat on your back with your knees bent and the legs parallel and hip width apart. Your arms are resting next to your sides.

Picture a clock on your stomach with the 12 on your belly button, and the 6 on your pubic bone. The 3 and 9 sit on each of your hip bones.

Tilt the pelvis forwards and backwards towards the 12 and 6 positions on your pelvic clock as shown below with using your gluteus muscles and just using abdominals:

12 'o clock position

6 'o clock position

Reps: _____ Sets: _____

2. Abdominal drawing in manoeuvre (Transverse abdominus)

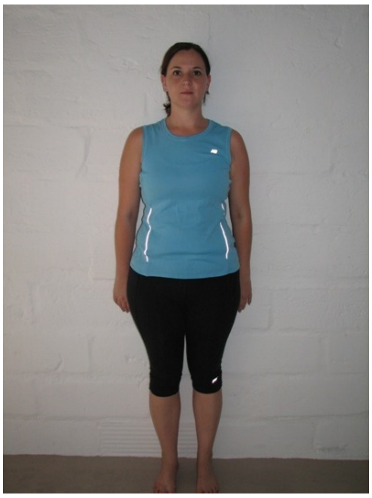
Breathe in and out to relax all the muscles, then gently draw in the lower part of your stomach as if trying to move the skin away from the elastic of your pants. Once you have a gently activated the lower belly (without any gluts working and with no movement in the back) then breathe in and out while maintaining the contraction.

Reps: _____ Sets: _____

3. Spinal twists

Start with the legs in the middle, with the knees and ankle squeezed together. Drop the knees to one side while keeping the feet on top of one another. The shoulders stay on the ground and the hip can lift up to allow the spine to rotate. Draw the knees back to the middle using the abdominal muscles and then lower to the opposite side.

Reps: _____ Sets: _____

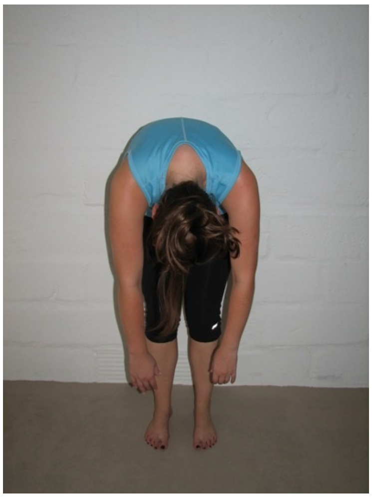


4. Roll downs

Start standing against the wall with the feet about 20 cm away from the wall. Knees remain slightly soft (not locked) throughout the exercise.

Peel yourself away from the wall, starting at the head, and moving one vertebra away from the wall at a time. The pelvis stays against the wall at all times.

Relax the arms and let me them hand at your sides throughout the moment. Reach as far down to the floor as possible and then roll yourself back up one vertebra at a time with the head coming up last.



Reps: _____ Sets: _____

5. Cat stretch

Start on the hands and knees with the hands directly below the shoulders and the knees below the hips. There is a slight curve in the lower back and the head is in line with the spine. Roll up from the pelvis into an arched position, drawing in the abdominals towards the spine, and drop the head to get a stretch throughout the spine. Return to the starting position, rolling slowly through the spine.

Reps: _____ Sets: _____

Stretches:

1. Dynamic hamstring stretch

Stand holding on to a wall to support yourself, and keep your spine still while swinging the leg forwards as high as you can (you should feel a hamstring stretch). Then swing the leg backwards as high as possible while keeping the spine still. This exercise can be used as a warm up before training.

Reps: _____ Sets: _____

2. Dynamic calf stretch

Start leaning against a wall as if you are going to stretch out your calf, with both feet in line with each other and a stretch on the calf muscles. Bend one knee and release the stretch on that side and then straighten that leg and bend the opposite side. You will make a stepping type movement with the feet.

Reps: _____ Sets: _____

3. Gluts stretch

Cross one ankle over the opposite knee and draw the leg up towards the body, holding behind the knee. Try to press the shoulders towards the floor and keep the chin tucked.

Repeat on the other side.

Hold: _____ Sets: _____

4. Lumbar rotation stretches

Draw one leg up towards the chest, while keeping the other leg straight along the ground and then take it across the body with the opposite hand. Keep the shoulder on the ground, but let the hip lift up to allow the spine to twist.

Repeat on the other side.

Hold: _____ Sets: _____

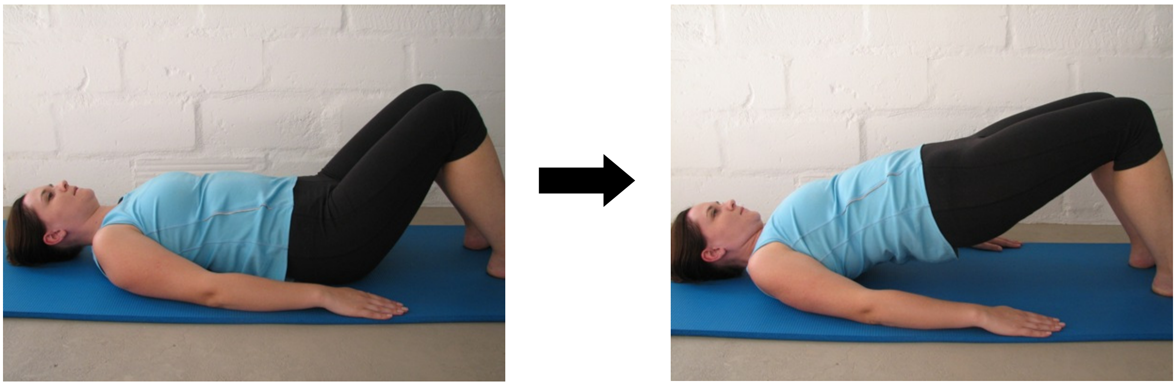
5. Shell stretch

Start on the hands and knees with the knees together and then press the buttocks backwards onto the heels, to stretch the lower part of the back. Focus on pressing the weight backwards towards the feet rather than trying to rest the head on the ground. This stretch must be performed with care when experiencing knee pain.

Hold: _____ Sets: _____

Strength exercises:

1. Bridging



Start lying flat on the back with the feet slightly closer to the buttocks than usual, hands are resting next to your sides. Squeeze the gluts and abdominal muscles as you lift up into a bridge position, pushing the hips towards the ceiling and not arching the lower back. The hands should be relaxed and not pushing into the ground.

Reps: _____ Sets: _____

2. Step ups

Start with one foot resting on a step, and lift up slowly on to the step using the quads and gluts on that side, not pushing off the foot on the floor. The knee should stay in line with the ankle and second toe at all times. Lower back slowly towards the ground in the same sequence without swapping feet. Do all your repetitions on one side first before repeating them on the other side.

Reps: _____ Sets: _____

3. Step downs



Start at the top of the step and lower one foot slowly to the ground, while keeping the alignment of the knee over the ankle and second toe. Step back up in the same order, making sure to keep the hips level. Complete all the repetitions on one side first before swapping to the other side.

Reps: _____ Sets: _____

4. Wall squats


Start with a large ball behind the lower back, and the feet far forward. Lower slowly into a squat, making sure that the knees do not go over the toes so that you are in a sitting position with the knees and hips at 90°. Press through the heels and squeeze the quads and gluts to return to standing.

Reps: _____ Sets: _____

5. Clam

Lie on your side with you head supported on your arm or a pillow, with the knees bent to 90° and the feet in line with the buttocks. Press the heels together and open the top knee up towards the ceiling whilst keeping the hips and spine still. Lower slowly back to the starting position.

Reps: _____ Sets: _____

Running programme for beginners: 12 weeks to 10 km

The following programme was designed by Kathy McQuaide at Sports Science Institute of South Africa. It will assist you to safely increase your running gradually to protect your body from injury when starting to run for the first time, or after a long break from running.

Week	Monday	Thursday	Saturday
Week 1	**Field** 10 min walk (warm-up) 1 min jog/3min walk x5	**Field** 10 min walk (warm-up) 1 min jog/3min walk x6	**Field** 10 min walk (warm-up) 2 min jog/3min walk x4
Week 2	**Field** 10 min walk (warm-up) 2 min jog/3min walk x5	**Field** 10 min walk (warm-up) 3 min jog/2min walk x4	**Field** 10 min walk (warm-up) 4 min jog/2min walk x2 3 min jog/2min walk x2
Week 3	**Field** 10 min walk (warm-up) 4 min jog/3min walk x4	**Field** 10 min walk (warm-up) 4 min jog/2min walk x4	**Field** 10 min walk (warm-up) 6 min jog/2min walk x2 3 min jog/2min walk x2
Week 4	**4-5 km route** 10 min walk (warm-up) 6 min jog/2min walk x2 4 min jog/2min walk x2	**4-5 km route** 10 min walk (warm-up) 7 min jog/2min walk x2 4 min jog/2min walk x2	**4-5 km route** 10 min walk (warm-up) 8 min jog/2min walk x2 4 min jog/2min walk x2
Week 5	**5km route** 5 min walk (warm-up) 10 min jog/2min walk x2 5 min jog/2min walk	**5km route** 5 min walk (warm-up) 10 min jog/2min walk x2 5 min jog/2min walk	**5km route** 5 min walk (warm-up) 14 min jog/2min walk 6 min jog/2min walk x2
Week 6	**5-6 km route** 5 min walk (warm-up) 16 min jog/2min walk 6 min jog/2min walk x2	**5km route** 5 min walk (warm-up) 10 min jog/2min walk x2 5 min jog/2min walk	**6km route** 5 min walk (warm-up) 16 min jog/2min walk 8 min jog/2min walk x2
Week 7	**6km route** 5 min walk (warm-up) 18 min jog/2min walk 8 min jog/2min walk x2	**5km route** 5 min walk (warm-up) 10 min jog/2min walk x3	**6-7km route** 5 min walk (warm-up) 20 min jog/2min walk 8 min jog/2min walk x2
Week 8	**7km route** 5 min walk (warm-up) 22 min jog/2min walk 8 min jog/2min walk x2	**5km route** 5 min walk (warm-up) 10 min jog/2min walk x3	**7km route** 5 min walk (warm-up) 25 min jog/2min walk 15 min jog/2min walk
Week 9	**7-8km route** 5 min walk (warm-up) 25 min jog/2min walk 20 min jog/2min walk	**5km route** 5 min walk (warm-up) Jog 5km continuously	**7km route** 5 min walk (warm-up) 25 min jog/2min walk 15 min jog/2min walk
Week 10	**8-9km route** 5 min walk (warm-up) 30 min jog/2min walk 20 min jog/2min walk	**5km route** 5 min walk (warm-up) Jog 5km continuously	**7km route** 5 min walk (warm-up) 25 min jog/2min walk 15 min jog/2min walk
Week 11	**9-10 km route** 5 min walk (warm-up) 30 min jog/2min walk 15 min jog/2min walk x2	**5km route** 5 min walk (warm-up) Jog 5km continuously	**5km route** 5 min walk (warm-up) Jog 8km continuously
Week 12	**6km route** 5 min walk (warm-up) Jog 6km continuously	**5km route** 5 min walk (warm-up) Jog 5km continuously	**10km route** 5 min walk (warm-up) 10km RACE – Good luck!!

APPENDIX X: ADDITIONAL RESULTS

Running speeds in competition

Table X.I: Running speed during 5 km race

	Males (n = 8)	Females (n = 8)	Chi-squared	P value
3:01 – 3:30 min/km	1		4.57	p = 0.33
3:31 - 4:00 min/km	2			
4:01 – 4:30 min/km	1	1		
4:31 – 5:00 min/km	2	5		
5:01 – 5:30 min/km	1	2		

Table X.II: Running speed during 10 km race

	Males (n = 8)	Females (n = 8)	Chi-squared	P value
3:31 - 4:00 min/km	2		4.67	p = 0.32
4:01 – 4:30 min/km	1			
4:31 – 5:00 min/km	2	4		
5:01 – 5:30 min/km	3	3		
5:31 – 6:00 min/km		1		

Table X.III: Running speed during 21.1 km race

	Males (n = 8)	Females (n = 8)	Chi-squared	P value
3:31 - 4:00 min/km	1		6.00	p = 0.31
4:01 – 4:30 min/km	1			
4:31 – 5:00 min/km	2			
5:01 – 5:30 min/km	3	6		
5:31 – 6:00 min/km	1	1		
6:01 – 6:30 min/km		1		

Table X.IV: Running speed during 42.2 km race

	Males (n = 8)	Females (n = 8)	Chi-squared	P value
4:01 – 4:30 min/km	1		7.13	p = 0.21
4:31 – 5:00 min/km	2			
5:01 – 5:30 min/km	3	1		
5:31 – 6:00 min/km	1	4		
6:01 – 6:30 min/km	1	2		
6:31 – 7:00 min/km		1		

Table X.V: Running speed during ultradistance races

	Males (n = 8)	Females (n = 5)	Chi-squared	P value
4:01 – 4:30 min/km			2.04	p = 0.57
4:31 – 5:00 min/km	1			
5:01 – 5:30 min/km				
5:31 – 6:00 min/km	5	2		
6:01 – 6:30 min/km	1	2		
6:31 – 7:00 min/km	1	1		

Table X.VI: Running shoe type in runners

	Males (n = 8)	Females (n = 8)	Chi-squared	P value
Neutral	6	5	0.42	p = 0.81
Stability	1	1		
Barefoot/Minimal	1	2		

Table X.VII: Other weekly training in endurance group

	Male (n = 8)	Female (n = 8)	Chi squared	P value
Cycling	6	5	1.33	p = 0.25
Swimming	4	3	0.25	p = 0.61
Dancing		1	1.07	p = 0.30
Pilates	2	1	0.41	p = 0.52
Yoga		2	2.29	p = 0.13
Hiking	1		1.07	p = 0.30
Resistance	3	5	1.00	p = 0.32
Hockey		1	1.07	p = 0.30
Tennis		1	1.07	p = 0.30

Table X.VIII: Relationships between fascicle length and weekly training distances. Note '+' indicates a positive correlation and '-' indicates a negative correlation.

Correlation	All groups			Male			Female		
	Relationship	**r**	**p**	**Relationship**	**r**	**p**	**Relationship**	**r**	**p**
Fascicle length and average weekly distance	+	0.11	0.72	+	0.54	0.27	-	0.36	0.38
Fascicle length and maximum weekly distance	+	0.31	0.28	+	0.79	0.06	+	0.12	0.78
Fascicle length and minimum weekly distance	+	0.19	0.51	+	0.22	0.67	+	0.13	0.76

Table X.IX: Relationships between gastrocnemius thickness and average, minimum and maximum weekly training distances ($km.wk^{-1}$). Note '+' indicates a positive correlation and '-' indicates a negative correlation.

Correlation		All groups			Male			Female		
		Relationship	**r**	**p**	**Relationship**	**r**	**p**	**Relationship**	**r**	**p**
Thickness	**Average weekly distance**	+	0.30	0.29	+	0.65	0.16	-	0.15	0.72
	Maximum weekly distance	+	0.19	0.51	+	0.41	0.42	+	0.14	0.74
	Minimum weekly distance	***+***	***0.63***	***0.02***	***+***	***0.86***	***0.03***	+	0.22	0.59

Table X.X: Relationships between volume and best 10 km, 21.1 km and 42.2 km times; and average, minimum and maximum weekly mileage (km.wk^{-1}). Note '+' indicates a positive correlation and '-' indicates a negative correlation.

Correlation		All groups			Male			Female		
		Relationship	**r**	**p**	**Relationship**	**r**	**p**	**Relationship**	**r**	**p**
Volume	**Best 10 km time**	-	0.71	0.08	-	0.40	0.60	+	0.89	0.30
	Best 21.1 km time	-	0.30	0.51	-	0.33	0.67	+	0.92	0.26
	Best 42.2 km time	-	0.68	0.12	+	0.53	0.48	+	0.87	0.33
	Average weekly mileage	+	0.01	0.99	+	0.23	0.77	+	0.79	0.42
	Maximum weekly mileage	-	0.38	0.40	-	0.52	0.48	-	0.21	0.87
	Minimum weekly mileage	***+***	***0.79***	***0.03***	+	0.42	0.58	+	0.96	0.18

Table X.XI: Relationships between gastrocnemius thickness, fascicle length and pennation angle and average, maximum and minimum training speeds (m.$^{s-1}$). Note '+' indicates a positive correlation and '-' indicates a negative correlation.

Correlation		All groups			Male			Female		
		Relationship	r	p	Relationship	r	p	Relationship	r	p
Thickness	**Average speed**	+	0.15	0.59	+	0.50	0.22	-	0.32	0.44
	Maximum speed	+	0.14	0.62	+	0.21	0.62	+	0.38	0.36
	Minimum speed	+	0.01	0.98	+	0.31	0.45	-	0.32	0.44
Fascicle length	**Average speed**	+	0.13	0.64	+	0.34	0.41	-	0.46	0.25
	Maximum speed	-	0.50	0.86	+	0.13	0.77	-	0.51	0.20
	Minimum speed	+	0.63	0.82	+	0.07	0.88	+	0.06	0.88
Pennation angle	**Average speed**	+	0.10	0.71	+	0.23	0.58	+	0.24	0.56
	Maximum speed	+	0.30	0.25	+	0.34	0.41	+	0.53	0.18
	Minimum speed	+	0.01	0.98	+	0.37	0.37	-	0.36	0.38