GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN HABITUALLY RESISTANCE-TRAINED MARATHON RUNNERS AND TRADITIONALLY RUNNING-TRAINED MARATHON RUNNERS: A COMPARATIVE ANALYSIS

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<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACSA</td>
<td>Anatomical Cross Sectional Area</td>
</tr>
<tr>
<td>ACSM</td>
<td>American College of Sports Medicine</td>
</tr>
<tr>
<td>AHA</td>
<td>American Heart Association</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine Triphosphate</td>
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<tr>
<td>CECS</td>
<td>Chronic Exertional Compartment Syndrome</td>
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<tr>
<td>CSA</td>
<td>Cross Sectional Area</td>
</tr>
<tr>
<td>GL</td>
<td>Gastrocnemius lateralis</td>
</tr>
<tr>
<td>GM</td>
<td>Gastrocnemius medius</td>
</tr>
<tr>
<td>HREC</td>
<td>Human Research and Ethics Committee</td>
</tr>
<tr>
<td>ITBS</td>
<td>Iliotibial Band Syndrome</td>
</tr>
<tr>
<td>MTSS</td>
<td>Medial Tibial Stress Syndrome</td>
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<tr>
<td>MTU</td>
<td>Muscle Tendon Unit</td>
</tr>
<tr>
<td>PAR-Q</td>
<td>Physical Activity Readiness Questionnaire</td>
</tr>
<tr>
<td>PCr</td>
<td>Phosphocreatine</td>
</tr>
<tr>
<td>PCSA</td>
<td>Physiological Cross Sectional Area</td>
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<tr>
<td>PRE</td>
<td>Progressive Resistance Training</td>
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<tr>
<td>ROM</td>
<td>Range of Movement</td>
</tr>
<tr>
<td>RRI</td>
<td>Running-related Injury</td>
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<tr>
<td>RPE</td>
<td>Rate of Perceived Exertion</td>
</tr>
<tr>
<td>SOL</td>
<td>Soleus</td>
</tr>
<tr>
<td>UCT</td>
<td>University of Cape Town</td>
</tr>
<tr>
<td>VO&lt;sub&gt;2max&lt;/sub&gt;</td>
<td>Maximal Oxygen Consumption</td>
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GLOSSARY OF TERMS

Triceps Surae
A composite muscle formed by gastrocnemius, soleus and plantaris. The gastrocnemius and soleus muscle plantar flex the ankle joint and provide the main propelling force for locomotion \(^1,^2\).

Overload principle
The regular application of a specific exercise, which enhances physiologic function to create a training response \(^3\).

Exercise training specificity
The adaptation in metabolic and physiologic function due to overload depends on the type and mode of exercise imposed \(^3\).

Neuromuscular fatigue
Fatigue represents the decline in muscle tension or force capacity with repeated stimulation during a given time period. Fatigue may occur due to an interruption between a muscle nerve and the central nervous system \(^3\).

Delayed onset muscle soreness
Pain and stiffness due to exercise-induced muscle damage. This occurs after performing unaccustomed exercise or exercise of increased intensity or duration resulting in inflammation, swelling and impaired muscle function \(^3\).

Running economy
The steady state oxygen consumption at a given running velocity. It reflects the metabolic cost of running \(^3\).

Maximal oxygen consumption
The highest value of oxygen consumption measured during a graded exercise test. Reflects an individual's maximal rate of aerobic expenditure\(^3\).

Lactate threshold
A blood lactate concentration representing an exercise level where tissue hypoxia triggers an imbalance between lactate formation and its clearance \(^3\).

1RM
The maximum weight that can be lifted and performed for one repetition. This measure is used to calculate training intensities lower than maximum output \(^4\).
ABSTRACT

Background

Marathon running involves running long distances and is associated with a high prevalence of running-related injuries. The calf has been identified as one of the most commonly injured structures during running. Running training causes an overload on muscle and stimulates a physiological adaptation to create a training response. Specific adaptations in metabolic and physiological function of a muscle may be further achieved through specificity of exercise training. Resistance training programmes are commonly implemented to enhance specific muscle strength and endurance; and are effective methods of performance and injury prevention. While evidence-based guidelines for resistance training exist, it is unclear whether runners are routinely incorporating evidence-based resistance training into marathon training programmes. If runners are performing habitual resistance training, it is also unknown if the resistance training is of sufficient magnitude or intensity to induce dose-related responses in calf muscle structure or function.

Aim

The aim of this study was to evaluate gastrocnemius muscle structure and function in marathon runners who performed habitual resistance training in addition to regular endurance training, compared to marathon runners who performed traditional endurance running training only.

Specific Objectives

- To describe the demographic and training characteristics of habitually resistance-trained marathon runners and traditionally running-trained marathon runners.
- To determine if there were differences in gastrocnemius endurance, power and flexibility between habitually resistance-trained marathon runners and traditionally running-trained marathon runners.
- To evaluate if there were differences in the gastrocnemius muscle structure and architecture in habitually resistance-trained marathon runners compared to traditionally running-trained marathon runners.
- To establish if there were any differences in the number of calf injuries sustained in habitually resistance-trained marathon runners and traditionally running-trained marathon runners.
Methods

Healthy male runners between 20 and 50 years were included in the study. Participants were required to have completed at least one marathon in the 12-month period prior to the study. Runners forming the “traditionally running-trained” group were required to be participating in regular endurance running training only. Runners in the “habitually resistance-trained group” were required to be performing resistance training in addition to regular endurance running training. Runners with any injury at the time of recruitment or runners who reported a calf injury within the six-month period prior to the study were excluded. Participants with any medical abnormalities detected during screening were also excluded from the study. Eight marathon runners participating in habitual resistance training plus standard running training and eleven marathon runners participating in traditional running training only were recruited for this study. Runners who met the criteria attended two testing sessions at least three days apart. During the first session, informed consent was obtained and the Physical Activity Readiness Questionnaire (PAR-Q) was completed to ensure participants could safely complete physical testing. A questionnaire was completed to determine relevant training and injury history. Body mass, height and the sum of seven skinfolds were recorded. Muscle architecture measurements, including fascicle length, pennation angle, thickness and volume, were performed via imaging ultrasound. Participants were then familiarised with the physical testing procedures. In the second testing session, calf muscle flexibility and endurance were assessed; and isokinetic testing was performed for the left and right triceps surae.

Results

There were no significant differences in descriptive characteristics between groups. Participants in the habitually resistance-trained group performed in an average of two hours (range 0.5-2.5 hours) of resistance training of between one to four sessions per week. Participants combined upper and lower body training in the form of circuit training, body weight training, core and proprioceptive training. Resistance training sessions were performed at a varied intensity for load (light to high) according to an estimated 1RM. Participants in the habitually resistance-trained group had completed a significantly greater number of 21.1 km races compared to the traditionally running-trained group (p < 0.05); but there were no other differences in running training or competition history between groups. There were also no significant differences in the number of reported injuries between groups. Average pennation angle was significantly increased in the habitually resistance-trained group compared to the traditional running-trained group (p < 0.05). No other significant differences in architectural measurements were identified. There were no significant differences in calf muscle flexibility, strength, power or endurance between the two groups. However, the small sample size limits the interpretation of the study findings.
Conclusion

Wide variability in habitual resistance training patterns were identified. While pennation angle was significantly greater in the habitually resistance-trained group; no differences in all other architectural measurements; or calf muscle strength, power, endurance or flexibility between groups were identified. However, one of the key findings emerging from this study is the variable resistance training practices in endurance runners; and that resistance training practices were not aligned to current evidence-based guidelines for resistance training. Resistance training has a critical role in enhancing endurance running performance, injury prevention and rehabilitation. Future research should investigate the knowledge, attitudes and practices of endurance runners regarding resistance training; to facilitate the development of appropriate education interventions, and to effectively disseminate evidence-based training guidelines to lay communities.
CHAPTER 1: INTRODUCTION AND SCOPE OF THESIS

1.1 INTRODUCTION

Training interventions use the overload principle to cause muscle adaptation during exercise. The overload principle refers to the regular application of a specific exercise that enhances physiologic function to create a training response to the load applied \(^3\). The type of training and the way training is performed causes specific changes in the metabolic or physiologic functions of muscle. This is known as exercise training specificity. Anaerobic stress during strength-power training such as part of a resistance training programme will induce different adaptations to a muscle when compared to aerobic stress during endurance training such as during a long slow run. Specific training will therefore create the necessary adaptations to the muscle to enhance the capacity of the muscle to perform those actions \(^3\).

It has been reported that runners incorporate mostly long slow runs in preparation for marathons \(^5\). Runners also incorporate interval and hill training to improve strength; however the addition of resistance training has been shown to further enhance running performance \(5,6\). Resistance training programmes involve lifting, lowering or pushing an external weight by a muscle or a group of muscles to improve strength and power \(^3\). The resistance training programme can also be performed at a lower level of intensity to increase muscle endurance and motor control, which has been seen to decrease the reoccurrence of overuse injuries in runners \(^7\).

Ultrasound studies have analysed muscle architecture to understand the adaptation in muscle structure during resistance training. Muscle architecture is described by the arrangement of the muscle fibres relative to the central tendon. The alignment can determine how much force and the speed of action the muscle can produce during contraction due to this arrangement. Therefore this arrangement of muscle fibres will determine the function of a muscle. Resistance training has been associated with an increase in muscle thickness and pennation angle \(^8\) which is reflective of the ability of the muscle to produce higher amounts of force \(^9\). To achieve these beneficial effects of resistance training it is required that these programmes are performed regularly at a high intensity to achieve a level of muscle adaptation \(^4\). This will also ensure that the muscle adaptation achieved through resistance training is maintained.

While it is known that compliance is often low to specific rehabilitation interventions \(^10,11\), it is unclear whether similar issues may be associated with regular or habitual resistance training.
In addition, evidence-based guidelines for resistance training exist, but it is unclear whether runners are routinely incorporating evidence-based resistance training into marathon training programmes. If runners are performing habitual resistance training, it is also unknown if the resistance training is of sufficient magnitude or intensity to induce a loading response in the calf muscle structure or function and if this may be linked to injury.

Therefore, this study will examine the effects of habitual resistance training compared to traditional running training on gastrocnemius muscle structure and function in marathon runners.

1.2 AIMS AND OBJECTIVES

1.2.1. Aim

The aim of this study was to evaluate gastrocnemius muscle structure and function in marathon runners who performed habitual resistance training in addition to regular endurance training, compared to marathon runners who performed traditional endurance running training only.

1.2.2. Specific Objectives

- To describe the demographic and training characteristics of habitually resistance-trained marathon runners and traditionally running-trained marathon runners.
- To determine if there were differences in gastrocnemius endurance, power and flexibility between habitually resistance-trained marathon runners and traditionally running-trained marathon runners.
- To evaluate if there were differences in the gastrocnemius muscle structure and architecture in habitually resistance-trained marathon runners compared to traditionally running-trained marathon runners.
- To establish if there were any differences in the number of calf injuries sustained in habitually resistance-trained marathon runners compared to traditionally running-trained marathon runners.
1.2.3. Significance of this Study

Marathon running is a popular sport worldwide, with numerous marathon events being hosted annually internationally and in South Africa. The increasing number of runners participating in marathons has also shown an upward trend of running-related injuries, specifically of the calf muscle. The triceps surae is predominantly more active during the push-off phase of gait and injury to this muscle can prevent runners from participating in marathon events. Calf injuries are more commonly reported in the gastrocnemius muscle due to a sudden overstretch or overuse during long periods of running.

The findings in this study will establish whether the current training practices of a habitually resistance-trained runner or a traditionally running-trained runner will have an impact on muscle function, structure and/or injury patterns. This may be used to develop interventions for marathon runners.

1.3 PLAN OF DEVELOPMENT

A comprehensive review of the literature in marathon running, calf injuries, marathon running and resistance training will be presented in Chapter 2. This review assisted with the final development of the cross-sectional descriptive study presented in Chapter 3. The study will be summarised and relevant conclusions will be made in Chapter 4.
CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

There has been an increase in runners participating in marathons as there are many health benefits from regular cardiovascular exercise as well as an improved lifestyle. Running marathons and training for these events involves high running loads to condition the runner for endurance running. The overload principle in training refers to this adaptation of muscle, enhancing physiologic and metabolic function in response to the high loads induced on the body. The type of training performed will further enhance the adaptation of metabolic and physiologic function of a muscle, this is known as exercise training specificity. Training loads have also been seen to alter muscle architecture due to the increased demands and type of muscle force required during training. This arrangement of muscle fibres can determine how much force and the speed of action the muscle can produce during contraction.

Traditionally runners prepare for marathons with training sessions of long slow running. Interval training and hill training are also used to build up strength and speed, however the addition of resistance training has been shown to enhance running performance. Resistance training programmes involve lifting, lowering or pushing an external weight by a muscle or a group of muscles to improve strength and power. Performing resistance training programmes at a low intensity will increase muscle endurance and motor control which has been seen to decrease the reoccurrence of overuse injuries in runners.

This review introduces marathon running and the epidemiology of running related injuries. The types of injuries are then discussed with a specific focus on the triceps surae as the calf has been identified as one of the most commonly injured parts of the lower leg. The review further investigates factors related to calf injury focussing on anatomical and physiological factors associated with calf injury. The anatomy and structure of the triceps surae is then discussed as well as muscle architecture. Traditional running training and habitual resistance training is then reviewed. Finally the instrumentation used in this study is reviewed.

Data was sourced from sports medicine and science literature incorporating medical literature sourced through online databases including PubMed, CINAHL, PEDro and Google Scholar.

2.2 MARATHON RUNNING

Marathon running is classified as an endurance sport, and is defined as running many kilometres over extended periods of time using aerobic metabolism. Marathon distances are typically over 42.2 kilometres (km) and further distances are classified as ultra-distances. Many events host a half marathon distance of 21 kilometres as an alternative option to the marathon distances, which has encouraged more runners to participate in endurance events. Marathon running has grown substantially as a popular sport and thousands of runners participate throughout the year, with up to 49,365 finishers recorded at the New York marathon in 2015. Not only have runners progressed their training to participate in marathon running as a sport, more people are taking up running programmes to improve their general health.

2.3 EPIDEMIOLOGY OF RUNNING INJURIES

Despite the popularity and health benefits to marathon running, the injury rate is high. Due to the load of running marathons the lower body is exposed to a repetitive action, which may cause a repetitive strain on bones, muscles and tendons. In a systematic review on running related injuries, the occurrence rate ranged from 19% to 79%. Lower leg injuries accounted for 9% to 32% of injuries. The most commonly reported running related injuries occur at the knee, calf and Achilles tendon.

Running related injuries may occur both during training for, and competing in marathon events. A retrospective study done on masters and younger runners found 2.8 injuries per athlete over a period of eleven months, and overuse injuries were more common than acute injuries at 0.07 per 1000 km run. In a survey of 694 male marathon runners preparing for the Rotterdam marathon, 58% reported an injury during the year leading up to the race. The injury incidence rate was calculated as 3.2 injuries per 1000 hours of running. It has been found more accurate to document running related injury to every 1000 hours of training done rather than weekly mileage as this allows for evaluation of injury according to the exposure to running. Nielsen et al. (2012) further found a frequency of running injuries was reported at 2.5 to 7.4 injuries per 1000 hours of running.

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1 Masters runners are runners over the age of 40 years old.
2.3.1 Epidemiology of Calf Muscle Injuries in Runners

From the lower leg injuries reported during running there is a high occurrence of calf injury. During the Rotterdam marathon, 18% of 694 male runners reported calf muscle injuries. Prior to the race the most common injury was the knee (27%) and one month prior to the race an increase in knee injuries were reported (30%). However post marathon, more runners complained of calf injury (34%). At initial contact, runners reported calf injuries of 14% which steadily increased to 20% one month prior to the race \(^{23}\). Similarly, in a recent study, an incidence of 19% of running injuries was reported from runners participating in the Amgen Singelloop Breda 2009 marathon (Netherlands). The areas reported as most injured were mainly of the knee (27%), calf muscle (20%) and hip (18%) \(^{25}\).

Furthermore, in a survey of 2 886 runners, 46% of runners reported an injury with a significantly increased amount of hamstring, calf and Achilles injury (p < 0.001) in the masters group compared to the younger running group \(^{26}\).

2.3.2 Nature of Calf Muscle Injuries in Runners

Muscle injury to the gastrocnemius muscle has been described as the “classic tennis leg” \(^{14}\), which occurs when there is a strain or tear of the musculotendinous junction of the medial head of the gastrocnemius muscle. A strain to the gastrocnemius results in immediate pain and limitation to running. Gastrocnemius strains are more commonly seen than soleus strain or the least common, plantaris \(^{1}\). Injury to the soleus is referred to as the soleus syndrome, which is as a deep-seated pain to the gastrocnemius muscle, which worsens over time with walking and running activities \(^{12,14}\).

Apart from calf muscle strains reported in the literature, there is also a prevalence of 9.5% of chronic running related calf injuries namely medial tibial stress syndrome (MTSS) \(^{27}\). Medial tibial stress syndrome is a common complaint amongst runners and recent studies have shown that MTSS is caused by excessive bony resorption due to repetitive overload of the tibial cortex \(^{12,27,28}\). Soleus may also cause excessive traction via its anatomical attachment onto the tibial border during periods of contraction and stretching \(^{28}\).

Another common complaint is chronic exertional compartment syndrome \(^{28,29}\). During running a build-up of intramuscular interstitial fluid during prolonged exercise occurs causing increased intramuscular pressure. When there is limited space between intramuscular compartments due to poor expansion this can cause elevated intramuscular pressure (>15mm Hg pre-exercise, >30mm Hg 1 min post exercise, >20 mm Hg 5 min post exercise) \(^{28,29}\).
The increased intramuscular pressure can cause capillary restriction and result in decreased blood flow to the calf muscle which can cause possible cell death due to hypoxia, a build-up of lactate and poor aerobic metabolism of the calf muscle. The anterior compartment of the lower leg is more commonly affected than the lateral, deep and superficial compartments.

**2.3.3 Anatomical and Physiological Predisposing Factors to Calf Injuries**

There are a number of factors that may predispose to calf injuries including extrinsic factors (such as weekly distance, training surface, training speed) and intrinsic factors (such as decreased flexibility, increased ankle pronation, muscular imbalances or muscle weakness, previous injury and age). A combination of factors can co-exist which may predispose to calf injury. Currently the most consistent factors for increased risk of injury in runners are previous running injury and total weekly training volume. The injury risk is lower for experienced runners as the injury threshold increases due to the maturation of a runner with increased hours of training. Most of these factors associated with musculoskeletal and vascular running injuries can be understood through the knowledge of anatomy, physiology and biomechanics.

The biomechanical factors that have been proposed to cause calf injuries include excessive pronation of the ankle joint during stance phase of gait which causes an eccentric strain of the tibialis posterior and anterior muscles of the calf. Ferber et al. (2009) has further categorised risk factors for overuse injuries into two groups: atypical foot pronation and poor hip stability and control during running. These intrinsic factors are beyond the scope of this literature review. A focus on anatomy and physiology is presented below.

Due to the gastrocnemius arrangement across two joints, this muscle is commonly more injured than the soleus muscle, which only runs across one joint. The mechanism of injury is usually due to a sudden stretch of the muscle during acceleration as the foot is forced into dorsiflexion while the knee is fully extended or with sudden knee extension with the foot fixed in dorsiflexion. The gastrocnemius muscle is predominantly made up of fast twitch fibres responsible for fast and powerful movements. Therefore a combination of the anatomical arrangement and the fibre type predispose the muscle to injury. Alternatively an eccentric contraction in the presence of forced muscle stretch can also cause injury. The medial head is more frequently torn due to the higher force directed during toe-off phase.

Apart from the anatomical arrangement of the gastrocnemius muscle another explanation for the frequent injury of this muscle is due to neuromuscular fatigue. Alteration in neuromuscular control including muscle imbalances, altered muscle timing, muscle fatigue and muscle weakness have all been associated with musculoskeletal injury.
The overloading of endurance running results in neuromuscular fatigue which is the disruption of the neural inputs from the central nervous system (CNS) to the motor unit. The muscle function declines with prolonged activity into this fatigue state predisposing the runner to an overstretch during a period of eccentric muscle contraction.

Decreased flexibility has been proposed as an intrinsic factor for muscle injury however there is a lack in literature to support this. The proposed mechanism of increased muscle stiffness and flexibility is due to regular training. Increased muscle stiffness has also been seen in delayed onset muscle soreness (DOMS), a temporary condition of minor muscle damage due to unaccustomed exercise or excessive muscle loading. There is an increase in muscle tension due to muscle spasm and inflammation.

In the presence of an overuse injury, the mechanism is not related to a specific event such as sudden stretch in muscle strains. Overuse injuries, such as MTSS, are related to the overloading of musculoskeletal structures due to the repetitive action of landing and propulsion of the running gait. There are two proposed mechanisms for the development of MTSS. The first mechanism is due to continuous contraction of the posterior tibial, soleus and flexor digitorum muscles, which produce repetitive stress on the tibia leading to periosteal inflammation. The second mechanism is due to a reduction of bone remodelling as a result of repetitive strain on the tibia from continuous muscle strain and the vertical ground reaction force experienced during landing.

2.3.4 Summary of the Literature: Epidemiology of running injuries

Marathon running is a popular sport however there is a reported injury incidence of 19% to 79%. Lower leg injuries account for 9% to 32% of running injuries and the calf is reported as one of the most common sites of injury. Currently the only significant factors associated with running injury are weekly distance and previous injury. Understanding the anatomical and physiological implications of these factors can help one gain more insight into the incidence of injuries.

Due to the anatomical two-joint arrangement of the gastrocnemius muscle the mechanism of calf strains is often reported as a result of a sudden stretch during acceleration or due to sudden eccentric contraction of the muscle during lengthening. In the calf, muscle strains are more common in the gastrocnemius medialis muscle also known as the “classic tennis leg.”

During a prolonged period of running, a muscle under neuromuscular fatigue can be vulnerable to a sudden stretch while eccentrically contracting.
Repetitive training can also result in increased muscle stiffness which may predispose the calf to injury \(^{30}\). Other injuries also seen are overuse lower leg injuries namely medial tibial stress syndrome (MTSS) and chronic exertional compartment syndrome (CECS) \(^{27,29}\).

These overuse injuries are due to overloading of the musculoskeletal structures during repetitive contraction of the surrounding muscles or due to inadequate bony remodelling under overload and strain. Biomechanical factors such as atypical foot pronation and poor hip stability are also risk factors to cause overuse injuries in the calf \(^{28,29,34}\). Understanding these biomechanical factors is beyond the scope of this literature review. The anatomical structure and functional aspects of calf architecture of the calf will be further discussed.

2.4 CALF MUSCLE ANATOMY, FUNCTION AND ARCHITECTURE

2.4.1 Calf Muscle Anatomy and Function

The calf muscle complex is made up of the superficial gastrocnemius muscle (medial and lateral heads), the deeper soleus muscle of the posterior and superficial compartment of the lower leg and plantaris muscle. This group is also known as triceps surae.

The medial head of gastrocnemius originates from the medial condyle to fuse with the smaller lateral head before joining the soleus aponeurosis to the Achilles tendon \(^{28}\). Similarly, plantaris is also a biarticular muscle but it is a weak contributor to plantarflexion and labelled a vestigial muscle \(^{1}\).

The soleus muscle originates from the posterior margins of the tibia and fibula and runs downwards to join the gastrocnemius and plantaris muscles to insert onto the calcaneus via the common Achilles tendon \(^{1}\). The muscle fibres of soleus insert onto the most distal part of the Achilles tendon. The Achilles tendon inserts onto the posterior superior aspect of the calcaneus allowing the triceps surae unit to work together functionally and plantarflex the ankle during gait and locomotion \(^{37}\).

2.4.2 Calf Muscle Fibre Type

Despite the gastrocnemius and soleus muscles having a similar mechanism of function they behave differently according to the speed of muscle contraction performed by each muscle. Each muscle is made up of a predominant type of muscle fibre, which determines this speed of contraction \(^{35}\).
The gastrocnemius muscle is mainly made up of fast twitch fibres (type 2) enabling the muscle to be used for faster powerful movements. The soleus muscle comprises mostly of slow twitch muscle fibres (type 1) and provides more stability and postural control 14,28,37.

2.4.3 Calf Muscle Architecture

Muscle architecture is described by the arrangement of the muscle fibres relative to the central tendon. The alignment can determine how much force and the speed of action the muscle can produce during contraction due to this arrangement. Therefore this arrangement of muscle fibres will determine the function of a muscle 9. Muscle architecture along with fibre type distribution and the cellular make-up of muscle ensures length-force and force-velocity relationships during muscle contraction 9,38.

The calf muscle has been described as multipennate, which is a series of bipennate muscles that fuse towards the insertion, the Achilles tendon aponeurosis. The bipennate arrangement is descriptive of the muscle fibres arranged at several angles in relation to the axis of force generation 9,14,39. The fibres of the soleus muscle deviate more towards an oblique direction than the gastrocnemius muscle 40. Pennate muscles are able to exert significantly more contractile force compared to non-pennate muscles due to the pennation angle and the physiological cross-sectional area (PCSA). Physiological cross sectional area and pennation angle are reflective of the force-generating capacity of the calf muscle due to the maximum number of acto-myosin cross bridges that can be activated in parallel during contraction 41.

Apart from PCSA and pennation angle, fascicle length and muscle volume can also describe the ability of a muscle to produce force 42. These components of muscle architecture are discussed below: pennation angle, fascicle length, muscle thickness, muscle volume and PCSA.

2.4.3.1 Pennation angle

Pennation angle is the angle measured between the insertion of the muscle fibre to the deep aponeurosis. An increased pennation angle allows for more sarcomeres to be in parallel with each other, which will provide more force during muscle contraction 38,42. The pennation angle varies by a few degrees with ankle ROM. As ankle ROM moves from -15° to +30°, the pennation angle increases for gastrocnemius medialis (GM) from 17.8° ± 2.1° to 25.2° ± 2.0°, in gastrocnemius lateralis (GL) from 9° ± 1.3 to 15° ± 2.0 and in soleus (SOL) from 21.3° ± 3.2 to 33.3° ± 3.3 43. This change of pennation angle during GM contraction was confirmed in another study which resulted in angles varying from 20° to 45° 44.
Previously it was thought that pennation angle remained constant with contraction however these recent studies using real time ultrasound have confirmed that the angle does change with contraction. The change in this parameter is important in accurately estimating muscular forces in mathematical models of the musculoskeletal system 43,44.

2.4.3.2 Fascicle Length

The muscle fascicles of the gastrocnemius run between the superficial and deep aponeurosis. As ankle ROM moves from -15° to +30° the fibre length decreases in GM from 53 mm ± 3 mm to 36 mm ± 1.5 mm in GL from 83 mm to 55 mm and in SOL from 42.5 mm ± 3 mm to 27.6 mm ± 3.6 mm 43. The length of a fascicle allows for an increased number of sarcomeres in series. During muscle contraction the total power generated by the increased number of sarcomeres results in increased force velocity when compared to a shorter fascicle with a smaller number of sarcomeres in series 9,38,42.

2.4.3.3 Muscle thickness

Muscle thickness is the distance between the superficial and deep aponeuroses. Muscle thickness has been seen to increase during sprinting and resistance training due to the increased diameter of a muscle fascicle in response to training 41. Thickness has also been recorded to change with muscle contraction and length changes in the muscle which should be considered during mathematical calculations in estimating loads in the musculoskeletal system 40.

2.4.3.4 Anatomical Cross-Sectional Area

Anatomical cross-sectional area (ACSA) is measured in an axial plane to the longitudinal axis of the muscle, but unlike the PCSA it does not give an indication to the amount of force the muscle can generate. A change in ACSA (such as during muscle hypertrophy) is therefore not reflective of a change in PCSA from training or a lack of training 41. Anatomical cross sectional area is important to measure in order to calculate muscle volume from ultrasound imaging.

2.4.3.5 Muscle Volume

Volume is an important measure to determine PCSA, which is a measure of the maximum force produced by a muscle. Exercise training increases the size of a muscle fibre and therefore increases muscle volume 3.
Volume measurements are important to observe the hypertrophic changes in muscle fibres. Measurements are done in vitro using ultrasound or MRI for accuracy. 

2.4.3.6 Physiological Cross-Sectional Area

Physiological cross-sectional area (PCSA) is defined as the magnitude of muscle fibre area perpendicular to the longitudinal axis of individual muscle fibres multiplied by the cosine of angle of pennation. Muscle PCSA is therefore proportional to the amount of force produced by the muscle fibres and determines the maximum force generated by a single muscle fibre relative to the CSA irrespective of fibre type. PCSA is calculated from the ratio of volume to fascicle length. Physiological cross-sectional area can therefore be used to describe how much force a muscle is capable of producing.

2.4.4 Summary of Literature: Calf muscle anatomy, function and architecture

Triceps surae is a collective term for lateral and medial gastrocnemius, soleus and plantaris and together these muscles plantarflex the foot due to the anatomical arrangement of the muscle fibres. The plantaris muscle is a weak plantarflexor and labelled a vestigial muscle and therefore the gastrocnemius and soleus muscle are the main contributors to plantarflexion. Muscles are described according to the anatomic arrangement and fibre type as well as muscle architecture. The gastrocnemius is a two joint muscle with a multipennate arrangement of the muscle fibres of which enables the muscle for bigger force production. The gastrocnemius muscle is described as a fast acting powerful muscle due to a predominant make-up of fast twitch fibres whereas the soleus is a slow acting muscle with comprising of slow twitch fibres making it more favourable for postural stability. Together these muscles are dominant during the push-off phase of gait.

Muscle architecture is described by the arrangement of the muscle fibres relative to the central tendon. The alignment can determine how much force and the speed of action the muscle can produce during contraction due to this arrangement. Therefore this arrangement will determine the function of a muscle. Components of muscle architecture include pennation angle, fascicle length and muscle thickness. Each component describes the force-generating capacity of a muscle during contraction. Anatomical cross-sectional area is measured using ultrasound imaging to determine muscle volume. The PCSA is calculated from volume calculations and describes the maximum force generated by a single muscle fibre irrespective of the fibre type. Understanding muscle architecture provides more information of the structure and function of muscle.
2.5 TRAINING FOR MARATHON RUNNING

2.5.1 Traditional Running Training

2.5.1.1 Overview of Traditional Running Training

Training programmes for traditional running training have been developed to improve running performance based on maximum oxygen consumption (VO$_{2\text{max}}$), lactate threshold and running economy as these are the most important physiological components of long distance running performance$^5$. Running training therefore mostly incorporates training sessions of long slow distances interspersed with shorter sessions of high intensity training or interval training to achieve these adaptations$^5,46$.

Training frequencies are constant at approximately six to eight sessions per week for elite runners and training sessions vary between training intensity and duration to reach a threshold where physiological adaptation occurs due to the training load$^5$. The training load is determined by a combination of intensity, duration and frequency. Training intensity is determined using maximum race pace as a maximum speed and calculating the required pace to train at to achieve the necessary overload creating a physiological stress on the body and training adaptation$^5$.

Once a runner has achieved a base level of running endurance, pace tempo or transitional training (also known as interval training) is started. Intervals during training sessions consists of a number of increased running bursts at a higher intensity alternated with short rest intervals of running at a slower pace$^46$. These training zones of increased intensity can be measured using heart rate monitors to establish the necessary training intensity to maintain the required exercise load. Heart rate is a direct physiological measure to reflect the amount of strain on the body through training at a level to achieve optimum adaptation to the training load$^5$.

To maintain the maximum required training load over a period of time runners have introduced periodisation into their training protocol. Periodisation determines time periods of high training loads followed by time periods of low training loads to allow the necessary adaptation due to physiological strain without causing overtraining$^47$. Periods of higher training loads (increased frequency, increased duration and increased intensity) are essential to increase VO$_{2\text{max}}$ and lactate thresholds, whereas running economy is seen to improve with years of running training. Therefore periodisation is a crucial part of running training$^5,47$. 
2.5.1.2 Adaptations associated with Traditional Running Training

Endurance running training creates adaptation to the pulmonary, cardiovascular and neuromuscular systems to improve the efficiency of the delivery of oxygen to mitochondria and the metabolism within the cells. The enhancement and co-ordination of these systems improve $VO_{2\text{max}}$, running economy and lactate threshold which are used as parameters in training and to rate running performance $^5$.

Maximum oxygen consumption ($VO_{2\text{max}}$) is the maximal rate of aerobic expenditure and will increase when there is an increase in cardiac output and higher usage of oxygen in skeletal muscle increase. Cardiac output is increased due to increased stroke volume due to an enlarged left heart ventricle, increased myocardial contractility and end-diastolic volume that occurs with training. The heart is therefore able to pump more oxygenated blood to skeletal muscle. Oxygen transport is possible due to increases in haemoglobin availability in blood and improved arterial oxygen saturation via ventilation $^{47}$.

The act of running increases neuromuscular activation to skeletal muscle increasing the number of muscle fibre recruitment and hypertrophy of type 1 muscle fibre (slow twitch fibre) $^{47}$. There is an increase in the number of mitochondria in muscle cells to improve the oxidative capacity of skeletal muscle. Further metabolic changes seen are an increase in fat metabolism and conservation of muscle glycogen. Prolonged sessions of moderate intensity exercise (>1 hr. at 65% of peak oxygen uptake) performed repeatedly for at least several weeks increases skeletal muscle oxidative capacity and alters substrate utilization during exercise resulting in improved endurance capacity $^{46,47}$.

During interval training anaerobic energy systems are utilised to provide higher demands of muscle metabolism during these short bursts of energy. The adaptations seen during training are: an increased levels of anaerobic substrates (ATP, PCr, free creatine and glycogen), increased number of enzymes available in glucose catabolism and an increased capacity to generate high levels of blood lactate during high intensity training $^3$. The physiological benefits of this type of training include: enhanced lactate thresholds, improved specific neurological patterns of muscle fiber recruitment and higher levels of fatigue resistance $^{46}$. 


2.5.2 Resistance Training

2.5.2.1 Overview of Resistance Training

Muscle overload is reached when a muscle is trained at its current maximal force-generating capacity. This is achieved through resistance training which is commonly lifting a weight, pushing or pulling a resistive pulley, band or machine, or using body weight exercises. Resistance training increases muscle strength, power, speed, endurance and motor performance. The type of strength training programme determines the type of muscular adaptation and this will affect the outcome. A practical way to achieve muscle overload is through progressive resistance exercise. Typical programs use the optimal number of sets of exercises and repetitions without rest to achieve the desired training specificity. Table 2.1 provides a summary of evidence-based guidelines for progressive resistance exercise.

Table 2.1: Evidence-based recommendations for resistance exercise.

<table>
<thead>
<tr>
<th>FITT-VP</th>
<th>Evidence based recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Each major muscle group trained 2-3 days/week</td>
</tr>
<tr>
<td>Intensity</td>
<td>• 60-70% 1RM for novice to intermediate to improve strength.</td>
</tr>
<tr>
<td></td>
<td>• ≥80% 1 RM for experienced strength trainers to improve strength.</td>
</tr>
<tr>
<td></td>
<td>• 40-50% 1RM for older individuals.</td>
</tr>
<tr>
<td></td>
<td>• &lt;50% 1 RM to improve muscle endurance.</td>
</tr>
<tr>
<td>Time</td>
<td>• No specific time duration has been identified.</td>
</tr>
<tr>
<td>Type</td>
<td>• Resistance exercises for each muscle group recommended.</td>
</tr>
<tr>
<td></td>
<td>• Multi-joint exercises recommended for all adults.</td>
</tr>
<tr>
<td></td>
<td>• Single joint exercises targeting major muscle groups included in program.</td>
</tr>
<tr>
<td>Repetitions</td>
<td>• 8-12 repetitions recommended to improve strength and power in adults</td>
</tr>
<tr>
<td></td>
<td>• 10-15 repetitions effective in improving strength and power for middle age to older adults.</td>
</tr>
<tr>
<td></td>
<td>• 15-20 repetitions recommended for muscle endurance</td>
</tr>
<tr>
<td>Sets</td>
<td>• 2-4 sets recommended for adults to improve strength and power.</td>
</tr>
<tr>
<td></td>
<td>• ≤ 2 sets effective to improve muscle endurance.</td>
</tr>
<tr>
<td>Pattern</td>
<td>• Rest intervals of 2-3 minutes between each set.</td>
</tr>
<tr>
<td></td>
<td>• Rest ≥ 48 h between sessions for any single muscle group is recommended.</td>
</tr>
<tr>
<td>Progression</td>
<td>• A gradual progression of greater resistance, and/or more repetitions per set and/or increasing frequency is recommended.</td>
</tr>
</tbody>
</table>

Table adapted from American College of Sport Medicine’s Guidelines for Exercise Testing and Prescription.

2.5.2.2 Adaptations associated with Resistance Training

The initial response to resistance training includes increased motor unit recruitment and synchronisation of motor units due to a neuromuscular adaptation. The increased motor neuron excitability and central nervous system activation lower neural inhibitory reflexes and Golgi tendon organs all contribute to increased muscle strength. Increased muscle tension stimulates the process of muscle hypertrophy and the change in size is seen after three weeks of regular training.
Further metabolic changes of specific slow twitch and fast twitch fibre types are seen after four to eight weeks of specific training. The hypertrophic changes in muscle create adaptation to muscle architecture which will determine the force generating capacity of the muscle 42.

In a study comparing a resistance training group performing strength training (higher loads and low repetitions) to a resistance training group performing endurance training (lower loads and higher repetitions), it was seen that maximal aerobic power and time to exhaustion was increased in the group performing endurance training 6. This group had significantly increased muscle endurance suggesting that this group is more adapted for submaximal prolonged contractions such as during marathon running 6.

The benefits of strengthening programmes focussing on muscle endurance have further been seen in injured groups of marathon runners. Overuse injuries have been linked with hip muscle weakness of the hip abductors and hip flexor muscles and this is commonly seen in runners with iliotibial band syndrome (ITBS). Strengthening programmes targeting hip musculature for six weeks has been implemented to treat ITBS and help return runners to running 7. These changes have further been seen in Snyder et al (2009) who demonstrated that a six-week training programme using closed chain and open chain hip rotational exercises was associated with a 13% increase in hip abductors strength and a 23% increase in hip external rotator muscle strength 48. Joint range of motion, eversion velocity, eversion angle at heel strike and peak joint moments were also measured prior to the six-week training programme in this study. There was a decrease in ankle eversion ROM, an increase in hip adduction ROM and a decrease in hip internal rotation ROM. These biomechanical improvements have been postulated to decrease joint loading, which may decrease overuse injury 48. Therefore the increased time to exhaustion as seen by Campos et al (2002) will assist in maintaining good biomechanical alignment as seen by Snyder et al (2009) 6,48.

2.5.3 Muscle Architecture Adaptations to Training for Marathon Running

Resistance exercise and endurance training both have an effect on muscle architecture. Muscle thickness and CSA have seen to increase in response to all forms of training 42,49. The maximum force produced of a single muscle fibre is in proportion to increase of CSA therefore indicating that the maximum force produced will be increased in the muscle 42.

In a study comparing sprinters and endurance runners, there was a significant difference in muscle thickness between the two groups where sprinters had a significant increase of PCSA. In this study the sprinters not only had an increase in muscle thickness but also had significantly increased fascicle length 49.
Fascicle length is proportional to the velocity of the muscle contraction due to the increased number of sarcomeres in series. This allows for rapid force-generation and maximal power production during joint movements. Therefore the rate of muscle shortening is in proportion to sprint running performance. Differences in maximum shortening velocity are proportional to different muscle fascicle lengths as well as the pennation angle.

Pennation angle has an important effect on the force-generating capacity. An increased fibre angle allows more sarcomeres in parallel, which allows for more muscle force however when the angle is over 45° this does not apply. Interestingly when comparing endurance runners to sprinters, the endurance runners had a significantly increased pennation angle whereas the sprinters had significantly increased muscle thickness and increased fibre length. Similarly Blazevich et al. (2003) found a decreased fibre pennation angle in a sprint-jump training group compared to a conventional resistance-training group. Fascicle length was also similarly to be increased in the sprint-jump training group and unchanged in the conventional resistance-training group. A longer fascicle therefore does not co-exist with an increased pennation angle due to the importance of whether sarcomeres are in parallel to produce more force or if sarcomeres are in series to produce more power.

Muscle architecture adaptation therefore seems to occur in response to different training methods. Resistance training has been shown to increase muscle cross-sectional area within ten weeks of training but not for endurance training in a study comparing ten weeks of resistance training of the lower body to 10 weeks of endurance cycling in 18 previously male athletes. Strength was measured with a dynamometer and muscle morphology was measured with ultrasound and MRI (magnetic resonance imaging). Although both groups increased leg press strength, there were no significant changes for PCSA, ACSA and pennation angle for the endurance cycling group. However, the resistance-training group had significant increases in PCSA, ACSA and pennation angle. Farup et al. (2012) further concluded that there is a close relation between pennation angle and muscle hypertrophy. In contrast, Abe et al. (2000) found that pennation angle is similar between sprinters and a control group but increased in distance runners. This greater pennation angle in distance runners may be due to a shorter fascicle length and increased PCSA. There may be an increase in muscle thickness but ACSA is not related to pennation angle as discussed earlier in this review.

Further studies have looked at the effect of eccentric training on muscle architecture to assess whether higher loads applied during eccentric training have superior adaptations to muscle architecture. Reeves et al. (2009) compared an eccentric training group to a conventional resistance training group and found that both groups had adaptations in muscle architecture.
The eccentric group had significantly greater fascicle length increases and increased 5RM strength in the leg press and knee extension exercise than the conventional training group. However the pennation angle showed a greater increase in the conventional training group than the eccentric training group. Therefore this study illustrates that higher loads during eccentric training will enhance the force velocity of muscle contraction (increased fascicle length) and conventional training enhances the force-generating capacity of a muscle (increased pennation angle). Currently there is limited evidence to support which type of resistance training is effective for marathon running.

2.5.4 Summary of the Literature: Training for Marathon Running

Training for a marathon may include traditional running training as well as habitual resistance training programmes. Traditional running training involves running sessions of long slow runs interspersed with interval running training to augment physiological adaptation and improve VO$_{2\text{max}}$, running economy and lactate threshold. Training intensity, frequency and duration are principles used to achieve training specificity in traditional running training. The load of endurance running creates a stress on the body to induce changes in pulmonary, cardiovascular, neuromuscular and metabolic systems. Resistance training uses muscle overload to create physiologic adaptation to improve the force generating capacity of a muscle. This is achieved through a progressive resistance exercise programme. The benefits of resistance training are increased muscular strength, power, speed and endurance. Implementing a resistance training programme focusing on high repetitions and lower loads significantly increases muscle endurance, maximal aerobic power and time to exhaustion when compared to a group performing strength training (higher load with lower repetitions). The benefits of a resistance training programme has further been implemented to enhance muscle endurance of the hip musculature and improve biomechanical factors that are normally associated with injury.

An increase in ACSA and muscle thickness is seen as an adaptation to all types of training. Sprinting training further increases PCSA and fascicle length to allow for more speed. Pennation angle has been seen to increase in endurance running and with conventional strength training but not with speed training. A similar trend is seen in eccentric training when compared to conventional resistance training. Fascicle length increases during eccentric training whereas fibre angle increases during conventional resistance training. Currently there is limited evidence to support which type of resistance training results in the optimal adaptation in muscle architecture for marathon running.
2.6 INSTRUMENTATION

Several measurements are needed to assess the different components of muscle structure i.e. muscle architecture and muscle function i.e. flexibility, strength, endurance and power. The instrumentation used includes: ultrasound imaging for muscle architecture, inclinometer readings for muscle flexibility, calf heel raise test for muscle endurance and isokinetic dynamometry for muscle strength and power.

2.6.1 Ultrasound Imaging

There are a larger number of studies using ultrasound to assess muscle architecture in the literature than other forms of muscle imaging such as MRI\textsuperscript{9,39,40,43,45}. MRI is the gold standard to measure muscle volume however it is expensive to use\textsuperscript{45}. Ultrasound is a favourable measuring tool as it is inexpensive, non-invasive, shows real-time display and it is quick to use\textsuperscript{51}. The use of ultrasound to measure muscle architecture for the calf muscle specifically is also well recorded in the literature\textsuperscript{17,41,49,50}.

In a systemic review on the measurement of fascicle length and muscle thickness, it was found that ultrasound has moderate reliability for fascicle length (Intra Class Coefficient > 0.6 and coefficient variance of <10%) and for pennation angle (ICC > 0.7 and coefficient variance <14%)\textsuperscript{52}. Validity studies were also compared and it was found that fascicle length and pennation angle (ICC >0.7) are accurate in studies where ultrasound was performed with muscles in a relaxed state\textsuperscript{52}. More studies have also shown reliability for muscle thickness and cross-sectional area measurements\textsuperscript{51}. Despite the accuracy and reliability of ultrasound, measurement errors do exist and the standardisation of procedures is imperative to be accurate when using ultrasound as a measuring tool. Measurement errors are avoided when: generous amounts of gel are used; measurements are done on at the same anatomical locations in standardised positions and muscles are relaxed\textsuperscript{51}. Other problems seen in ultrasound measurements are the technique of using the ultrasound probe. Holding the probe perpendicularly to the deep aponeuroses within the distal end of the GM belly and using the alignment for subsequent longitudinal imaging helps minimise probe-orientation related errors\textsuperscript{53}.

2.6.2 Flexibility of Gastrocnemius and Soleus

The ability of the ankle to dorsiflex sufficiently is a requirement during walking and running as the foot prepares for heel strike (or less for runners who have a forefoot strike) before the stance phase of gait\textsuperscript{54}. Any limit in the ability of the triceps surae to stretch will decrease ankle dorsiflexion due to the anatomical attachment of these muscles via the Achilles tendon.
A decrease in dorsiflexion range is associated with plantar heel pain as well as overuse injuries of the lower limb. The normal range of motion for dorsiflexion has been described as 11°-25° and flexible range is described as 25°-32°.

Ankle dorsiflexion is measured in a lunge weight-bearing position with either the back knee extended (gastrocnemius) or the back knee flexed (soleus) and has been seen to be a reliable method. An inclinometer is used to measure ankle dorsiflexion range and this tool shows good reliability when compared to a goniometer. It is inexpensive and easy to use and has good reliability in both experienced and novice raters.

### 2.6.3 Calf raise test

The calf raise test is used to measure muscle endurance of the calf muscle and reliability has been established with an ICC of 0.78-0.84. The performance of the test is important to determine the accuracy of the results and an appropriate estimation of fatigue needs to be used to terminate the test. A standardised testing protocol is used and the Borg scale is used to terminate the test.

The Borg scale is an affordable and practical tool that uses the rate of perceived exertion (RPE) to determine levels of fatigue. Scherr et al. (2013) conducted a cohort study on 2560 study participants to determine validity of the Borg scale. In this study a strong relationship was seen for RPE and heart rate (r= 0.74, p<0.001) and RPE and blood lactate levels (r = 0.83, p<0.001). Therefore the use of the Borg scale is an effective measure to determine an estimation of fatigue during a calf raise test.

### 2.6.4 Isokinetic dynamometry

Isokinetic dynamometry is a reliable measuring tool for assessing torque in the ankle joint. In a recent study it has been confirmed that high ICC values (0.90 – 0.98) exist for reliability of peak torque and average work using the cybex norm dynamometer. Test-retest reliability has further been seen specifically for the ankle joint. The ICC for plantarflexion were 0.37-0.95 for different testing positions and no testing position was seen to be more superior to another position. Isokinetic dynamometry has also been seen to be reliable to measure peak torque in plantarflexors following Achilles tendon rupture.

Measurement errors also exist in isokinetic dynamometer and the need for standardization is essential for reliability. Accuracy depends on whether the dynamometer is precise, the test protocol is standard, the measurements are reproducible and on the person performing the test.
Furthermore, to produce accurate peak power measurements it has been seen that a constant angular velocity needs to be set during testing. An increase in angular velocity decreases the torque production at the calf. Therefore the highest torque measurements are set at 30° per minute for the calf 62,67.

2.6.5 Summary of the Literature: Instrumentation

Several measurements are needed to assess the different components of muscle structure i.e. muscle architecture and muscle function i.e. flexibility, strength, endurance and power. The instrumentation used includes: ultrasound imaging for muscle architecture, inclinometer readings for flexibility, calf heel raise test for muscle endurance and isokinetic dynamometry for muscle strength and power.

Muscle architecture is measured using ultrasound imaging. Ultrasound is a favourable measuring tool as it is inexpensive, non-invasive, shows real-time display and it is quick to use 51. Ultrasound imaging has moderate reliability and validity for fascicle length and pennation angle 52. More studies have also shown reliability for muscle thickness and cross-sectional area measurements 51. Muscle flexibility is measured using an inclinometer and uses a method described to measure ankle dorsiflexion. This has been seen to be a reliable method 59–61. Muscle endurance is measured using the calf raise test and reliability has been established 62. A standardised testing protocol is used and the Borg scale is used to terminate the test 62,63. The final instrument used for muscle function is to test gastrocnemius strength and power. Isokinetic dynamometry is a reliable measuring tool for assessing torque in the ankle joint 65. Similarly to ultrasound imaging a standardised protocol is used to avoid any measurement errors during testing.

2.7 SUMMARY OF THE LITERATURE

Marathon running is an endurance sport defined as running many kilometres over an extended period of time using aerobic metabolism 18. There is a substantial growth in the sport and many people take up the sport to improve general health and lifestyle 20. Despite these health benefits there is a high prevalence of running related injury in the lower limb of 9% to 32% of all injuries 21. The frequency of lower limb injury is reported as 2.5 to 7.4 injury per 1000 hours of running 15. Of the lower limb injuries reported the calf area has been reported as a commonly injured area. The number of runners reporting injury to the calf is recorded as 18% - 46% during and post marathon events 25,26,68.

The most common calf injury during running is a muscle strain of the gastrocnemius medialis muscle 12,14.
The gastrocnemius muscle forms part of the triceps surae and is predominant during the push-off phase of gait. Therefore during running there is a repetitive load on the gastrocnemius medialis muscle. Currently the most consistent factors for injury in runners is previous injury and total weekly distance run. Other factors associated with calf muscle injury are intrinsic factors (decreased flexibility, muscular weakness or imbalance, increased ankle pronation) and extrinsic factors (training speed and training surface).

Understanding the anatomical and physiological effects of these factors can provide insight into running related injury. The gastrocnemius medialis muscle is vulnerable to overstretch due to its anatomical arrangement across two joints. The muscle is predominantly made up of fast twitch muscle fibres which generate fast powerful movements and therefore contributes to the vulnerability of overstretch during sudden acceleration. Neuromuscular fatigue and increased muscle stiffness from overuse during endurance running will further increase the risk of muscular strain during a sudden eccentric stretch on the muscle.

Muscle architecture is described by the arrangement of the muscle fibres relative to the central tendon. The alignment can determine how effectively the muscle will produce force and force velocity during contraction due to this arrangement. Therefore this arrangement will determine the function of a muscle. Pennation angle and PCSA are reflective of the force generating capacity of a muscle whereas fibre length presents the force generating velocity of the muscle. Muscle thickness and PCSA are seen to increase in all forms of training. Resistance training increases pennation angle and PCSA due to the increase in muscle thickness and fibre hypertrophy in response to muscle overload. Currently ultrasound imaging is used to measure muscle architecture and MRI is the gold standard to measure muscle volume. Ultrasound is more convenient to use and cheaper than the use of MRI for measuring volume and has also shown good accuracy and reliability as a measuring tool. Muscle function is further determined through the assessment of physical tests to measure calf flexibility muscle endurance, strength and power.

Through the use of physical testing and ultrasound imaging, valuable information can be gathered regarding calf muscle structure and function to develop an understanding of how training effects the calf muscle. This information can further be used to develop training programmes and preventative strategies for running-related injuries.
CHAPTER 3: GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN HABITUALLY RESISTANCE-TRAINED MARATHON RUNNERS AND TRADITIONALLY RUNNING-TRAINED MARATHON RUNNERS: A COMPARATIVE ANALYSIS

3.1 INTRODUCTION

Marathon running is a popular sport and thousands of runners participate in marathons worldwide\textsuperscript{20}. Running far distances per week causes an overload to the muscles and joints of the body which can lead to injury\textsuperscript{15}. The stress from training stimulates muscle to adapt according to the overload principle and exercise specific training further enhances the required metabolic and physiologic functions of the muscle to meet the demands of the type of training\textsuperscript{3}. Resistance training has been seen to increase muscle strength, power and endurance\textsuperscript{3}. Ultrasound studies have confirmed a structural change in the muscle architecture due to resistance training\textsuperscript{17,49,50}. These changes are specifically an increase in muscle thickness and pennation angle, which are reflective of increased force production of a muscle\textsuperscript{17,49,42}. Due to these effects, resistance training programmes are used to facilitate training\textsuperscript{50}, improve exercise performance\textsuperscript{6}, and rehabilitate runners with overuse injuries and help them return to running\textsuperscript{48}.

Despite the benefits of rehabilitation programmes there is currently poor compliance to these programmes\textsuperscript{10,11}. The outcome of a training programme is dependent on good compliance to achieve the muscle adaptations needed to meet the training demand and requires regular and consistent training\textsuperscript{4}. There is currently limited literature on the effects of habitual resistance training in marathon runners.

Therefore, the aim of this study was to evaluate gastrocnemius muscle structure and function in marathon runners who performed habitual resistance training in addition to regular endurance training, compared to marathon runners who performed traditional endurance running training only. Specific objectives have been stated in Section 1.2 (page 2).
3.2 METHODS

3.2.1. Research Design and Participants

This study had a descriptive cross-sectional design. Twenty male marathon runners were recruited for this study from local running clubs. Runners were required to either be participating in regular endurance running training only, or to be performing habitual resistance training in addition to regular endurance running training.

3.2.2. Inclusion Criteria

This study included healthy male runners between 20 and 50 years. Runners were required to have completed at least one marathon in the 12-month period prior to the study. Runners forming the "traditionally running-trained" group were required to be participating in endurance running training only. Runners in the "habitually resistance-trained group" were required to be performing resistance training in addition to endurance running training. We purposefully did not specify specific inclusion criteria for resistance training, as one of the main objectives of this study was to describe habitual resistance training patterns of marathon runners.

3.2.3. Exclusion Criteria

To facilitate homogeneity between groups, female runners were excluded from this study due to the influence of testosterone on exercise-associated muscle adaptation. Runners with any injury at the time of recruitment or runners who reported a calf injury within the six-month period prior to the study were excluded. Runners with any medical abnormalities detected during the pre-test screening, such as neurological impairment, muscular disorders or untreated cardiovascular disorders were also excluded from the study. Any participant with a medical condition or injury identified at screening was excluded from further testing and referred to an appropriate medical practitioner for further investigation.

3.2.4. Sample Size Determination

Data from a previous study that used ultrasonography to measure fascicle length were used to ensure that the sample size would provide sufficient statistical power. Fascicle length was selected to determine the required sample size, as this was one of the main outcome measures for this study. Required sample size for fascicle length was calculated using a smallest meaningful difference of 9 mm, and a standard deviation of 7 mm.
With statistical significance accepted as $p < 0.05$, groups of 11, 14, and 17 participants provided 80%, 90% and 95% statistical power for fascicle length respectively.

3.2.5. Ultrasound Training

Training was received on all ultrasound measurements and imaging techniques. Further training was received on the specific ultrasound model (Logique) from a representative of the company. The measurements as described in Section 3.2.8 were practiced on four volunteers and a total of 15 hours were completed (five hours under supervision during training). Clinicians guided in ultrasound training for four hours were found more skilful than self-trained clinicians in ultrasound use.

3.2.6. Feasibility Study

Five runners who had similar inclusion and exclusion factors were recruited to do a feasibility study to determine intra-rater reliability of ultrasound measurements (Appendix I). The data recorded from the feasibility study were not included in the final data analysis of the study. The questionnaire has previously been validated. The intra-rater reliability for Achilles tendon elongation was poor, and therefore this measurement was removed from the study.

3.2.7. Participant Recruitment

Runners were recruited from running clubs in the Boland and Helderberg area through advertisements on running club websites, social media club and newsletters via email (Appendix II). The investigator also attended running events, time trials and social long club runs to hand out flyers and recruit runners.

3.2.8. Measurement Instruments

3.2.8.1. Informed Consent Form

Each participant completed an informed consent form before any testing started (Appendix III). The consent form included a description of the study and the testing procedures to be performed as well as information on the risks and benefits of the testing procedures. The right for any participant to withdraw from the study at any time was made clear.
3.2.8.2. Physical Activity Readiness Questionnaire

To screen each participant for their general health and any underlying medical condition the revised Physical Activity Readiness Questionnaire (PAR-Q) (Appendix IV) was completed prior to testing during the first testing session. There were no participants detected with any underlying health pathology and no referral was necessary.

3.2.8.3. Training and Injury History Questionnaire

During the first testing session a questionnaire was completed by each participant, which gave information on personal details, injury history, training history and competition history (Appendix V). This questionnaire was previously assessed for validity and reliability.

3.2.8.4. Anthropometry Measurements

Body composition was described as body mass, body fat and stature. Body mass (kg) was measured on a calibrated scale (Seca model, 708 Germany) and stature (cm) was measured with a stadiometer (Seca model, 708 Germany). The sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, calf, thigh and abdomen) was calculated. The sum of four skin folds (biceps, triceps, subscapular and suprailiac) was used to calculate the value of body density. Body density was then converted into body fat percentage. Validity for these tests has been shown previously.

3.2.8.5. Ultrasound Imaging

Ultrasound imaging was performed using a Logique model 5419804, 20V 5A, 12L RS to analyse the different components of the gastrocnemius muscle architecture. The participant was positioned in prone with the gastrocnemius muscle relaxed in ankle plantarflexion for the initial part of the imaging. A standard testing position has been shown to have correlations greater than 0.8 in healthy participants when measuring components of muscle architecture such as: thickness, fascicle length, pennation angle. All measurements were first recorded on the right and then on the left medial gastrocnemius muscle. The medial gastrocnemius was used as it is the most commonly injured portion of the gastrocnemius. The intra-tester reliability was done during the feasibility study (Appendix I).
3.2.8.6. **Gastrocnemius Muscle Belly Length**

Firstly, the distal and proximal musculotendinous junctions of the medial gastrocnemius were located using ultrasound in a mid-sagittal plane and these points were marked with a non-permanent marker on the skin surface. The length of the gastrocnemius muscle was measured as the distance between these two points.\(^{45}\)

3.2.8.7. **Muscle Thickness**

Three images were recorded of the medial gastrocnemius muscle belly halfway between the proximal and distal musculotendinous junction. Muscle thickness was measured using a measuring tool on the ultrasound machine using the perpendicular distance between the two muscle aponeuroses.\(^{76}\) Three measurements were taken and the average recorded. Figure 3.1 illustrates an example of an image taken to measure muscle thickness, fascicle length and the pennation angle.

![Figure 3.1.](image)

*Figure 3.1. An example of an ultrasound image to measure muscle thickness (small dash), fascicle length (long dash) and pennation angle (solid line).*

3.2.8.8 **Fascicle Length**

Using the same mid-belly images, fascicle length was measured tracing the fascicle from the superficial to deep aponeuroses in a straight line. This method has previously been proven reliable.\(^{79}\)
If the fascicle length extended past the border of the scanned image, the length was roughly calculated by tracing the line to the point where it would connect with deep or superficial aponeuroses. Three fascicles were measured and the average was recorded.

3.2.8.9 **Pennation Angle**

The angle between a single fascicle and its insertion onto the deep aponeurosis was measured on the mid-belly scans using the measuring tool on the ultrasound machine programme. Three angles were measured and the average was recorded.

3.2.8.10 **Muscle Volume**

The muscle between the proximal and distal musculotendinous junctions was scanned in the axial plane varying from four to six images. Each scan was evenly spaced, 30 mm apart, using a grid on the surface. Each image was then stitched together using an imaging programme (ImageJ 1.46r; National Institute of Health, USA) and the area was calculated on the programme (Figure 3.2.). Using the following formula, the volume between each serious of stitched images was calculated:

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

where \( a \) and \( b \) were the ACSA of the two consecutive stitched 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.

![Figure 3.2.](image)

**Figure 3.2.** This figure illustrates how six separate images was stitched together using an imaging programme to calculate muscle volume.

3.2.8.11 **Physiological Cross-sectional Area**

The following formula was used to measure physiological cross-sectional area using the average fascicle length \( (l_f) \) and total muscle volume, as measured above:

\[ PCSA (mm^2) = \frac{V}{l_f} \]

---

28
3.2.9 Muscle Flexibility

Muscle length of the gastrocnemius and soleus was tested using an inclinometer secured to the distal fibula lateral to the ankle for each participant. Gastrocnemius flexibility was tested with the participant in standing with the leg to be tested in hip extension and the knee in extension. This position was maintained as the participant stepped forward with the opposite leg while maintaining the heel of the tested leg on the ground. Once full stretch was reached the ankle dorsiflexion angle was measured on the inclinometer. To test soleus flexibility, the participant was instructed to stand with the leg to be tested in hip extension, knee flexion and full ankle dorsiflexion. The angle of ankle dorsiflexion was recorded as the lower leg moved forwards over the foot. The right leg was measured first and repeated on the left leg and each test was done three times. The average measurement was then taken. Reliability has been 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.

3.2.10 Muscle Endurance Test

The single leg calf raise test was used to test endurance of the musculotendinous unit (MTU) of the calf complex. The participant stood on one leg with the knee extended and raised and lowered the heel from the floor into full ankle plantarflexion ROM at a rate of 60 raises per minute using a metronome as a guide of speed. Verbal encouragement was given to ensure good performance. The right leg was tested first, followed by the left leg. The test was stopped if the participant could not maintain the speed, or if three consecutive heel raises of full ROM were not performed due to fatigue or if the participant reported muscle fatigue according to the Borg scale once they reached 19 (near maximal effort). The Borg scale was used to assess the rate of perceived exertion (RPE) (Appendix VI). To calculate the repetitions performed accurately and ensure quality of the movement the test was video recorded. The number of repetitions was counted from the video analysis and this was repeated three times to reduce error. A normal range was considered 36 to 45 repetitions and any significant difference between the two sides was noted.

3.2.11 Muscle Strength and Power Tests

Muscle strength and power was evaluated on the Humac norm Cybex machine. The participant was positioned in prone with the knee in extension and the foot secured on the plate as well as stabilizing the thigh to ensure isolated ankle movement. The machine was set up according to each individual to ensure the footplate was able to move freely without limiting movement. The cybex was set to a continuous speed at 30 degrees per second and the participant was instructed to “push the foot into the plate as hard as they could and pull back again.”
The participant was able to have three practice repetitions before the test was performed. Five repetitions were performed for the test. The best score for strength (peak torque) and average power per repetition (watts) was used for this study. This method of testing muscle strength and power has been proven reliable and valid \(^{65-67}\).

3.2.12 Testing Procedure

The protocol was submitted to the University of Cape Town, Faculty of Health Sciences Human Research Ethics Committee (HREC) for review. Once formal ethical approval was granted (HREC REF: 767/2015) (see Appendix VII), the researcher commenced with ultrasound training and the feasibility study. Once these components had been successfully completed, the formal research procedures were initiated. Runners were recruited through various platforms. Runners that responded to the advertisement contacted the investigator via email or telephone. This allowed the investigator to check that runners met the inclusion criteria before setting up testing appointments with each runner. Runners who met the criteria were required to attend testing at the Stellenbosch Academy of Sport in Stellenbosch for two testing sessions of at least three days apart. During the first session informed consent was obtained, followed by the completion of the PAR-Q to ensure runners were safe to participate as well as the training and injury history questionnaire. Anthropometry measurements (mass, height and skinfolds) were then performed followed by the ultrasound imaging by the same investigator. The runner was then instructed on the muscle flexibility and muscle endurance tests and they had the opportunity to practice the test. The first testing session took one hour. The strength and power tests were not done during the first testing session however each participant had three practice rounds of each test on the humac norm during the second testing session before the final test was performed. The strength and power testing was conducted by a biokineticist trained in the use of the Cybex humac norm machine. The second testing session took 40 minutes.

3.2.13 Statistical Analyses

Statistica software (Statsoft, Inc. 2016 STATISTICA) (Data analysis software system, version 13, www.statsoft.com) was used for statistical analyses. Normality was assessed using the Shapiro Wilkes test. An independent t-test was used for numerical data to assess for changes in descriptive variables between the habitually resistance-trained group and the traditional running-trained group. Frequency tables were used to describe categorical data obtained from the questionnaire and the Pearson’s chi square test was used to assess for any differences in categorical data between the two groups. Odds ratios were used to determine any associations between types of habitual resistance training or injury incidence between groups. Statistical significance was accepted at \(p < 0.05\).
3.2.14 Ethical Considerations

The study adhered to the ethical principles outlined in the Declaration of Helsinki 87. The proposal was given formal ethical approval by the University of Cape Town, Faculty of Health Sciences Human Research Ethics Committee (HREC REF: 767/2015) (see Appendix VII). An informed consent form was given to each participant to complete upon recruitment and before any testing commenced (Appendix II). The consent form included a description of the study and information on the purpose of the project as well as the testing procedure. Any risks and benefits of their involvement were explained and participants were given the right to withdraw from the study at any stage. All data were kept in a file and locked in a cupboard only accessible by the primary examiner. Data was then captured onto spreadsheets using the primary examiner’s personal computer protected by a security password.

3.2.15 Risks to Participants

Risks were explained to each participant before signing the informed consent form. There were no physical risks associated with the ultrasound imaging or anthropometrical assessment. There was a risk of musculoskeletal injury due to the nature of the physical tests and therefore participants were able to practice the physical tests before final testing. This enabled them to familiarise themselves to help decrease the risk of muscle injury. Each test was explained carefully to ensure the participant understood how to perform the tests and was advised to stop at any point of discomfort. None of the participants were injured during the testing procedure.

3.2.16 Benefits to Participants

Participants were given feedback on the structure of their gastrocnemius muscles during the ultrasound evaluation and they also received the results from the muscle flexibility, power and endurance tests once all the data was captured. Each individual was also given feedback on anthropometrical measurements and the investigator advised runners on tips to promote fat loss and improve muscle function according to these results. Each runner was also given a running guide to educate them on strengthening exercises, flexibility exercises and tips to improve diet and hydration (Appendix VIII).
3.3 RESULTS

3.3.1 Participants

Twenty runners were recruited for this study. The habitually resistance-trained group consisted of eight runners and the traditionally running-trained group consisted of 12 runners. One runner failed to return for the second session of testing in the traditionally running-trained and data from this participant were not included in the analysis. Therefore, the traditionally running-trained group consisted of 11 runners. No runners were excluded following the screening tests. The sample group is summarised below in Figure 3.3.

Figure 3.3: Summary of the study sample.

3.3.2 Descriptive Characteristics

The descriptive characteristics of participants in both groups are shown below in Table 3.1. There were no significant differences seen between the two groups for these variables.
Table 3.1: Descriptive characteristics of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>33.5 ±4.8</td>
<td>33 ± 7.5</td>
<td>0.19</td>
<td>0.85</td>
<td>4.46 – 8.72</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>77.9 ±10.6</td>
<td>80.8 ± 9.2</td>
<td>-0.62</td>
<td>0.55</td>
<td>7.47 – 14.61</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>179.9 ± 6.4</td>
<td>177 ± 3.8</td>
<td>1.14</td>
<td>0.27</td>
<td>4.18 – 8.17</td>
</tr>
<tr>
<td>Body mass index</td>
<td>24 ± 2.7</td>
<td>25.8 ± 2.2</td>
<td>-1.54</td>
<td>0.14</td>
<td>1.96 – 3.84</td>
</tr>
<tr>
<td>Sum of 7 skinfolds</td>
<td>61 ± 17.4</td>
<td>75.7 ± 21.7</td>
<td>-1.63</td>
<td>0.12</td>
<td>15.27 – 29.88</td>
</tr>
<tr>
<td>Fat percentage</td>
<td>16.9 ± 3.5</td>
<td>18.4 ± 5.4</td>
<td>-0.74</td>
<td>0.47</td>
<td>3.25 – 6.36</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>64.6 ± 6.6</td>
<td>65.6 ± 5.6</td>
<td>0.72</td>
<td>0.72</td>
<td>4.60 – 9.01</td>
</tr>
</tbody>
</table>

3.3.3 Training History

3.3.3.1. Habitual Resistance Training

Table 3.2 illustrates the resistance training sessions that were completed by participants in the habitually resistance-trained group as part of their routine training.

Table 3.2: Resistance training sessions completed by participants in the habitually resistance-trained group (n = 8). Data are presented as mean ± SD, and minimum and maximum ranges.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training hours per month</td>
<td>8.6 ± 4.4</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>Training months per year</td>
<td>11.1 ± 2.4</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Average RPE per session</td>
<td>7.5 ± 0.8</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Rate of perceived exertion (RPE) is measured as a 1–10 Borg scale.

Table 3.3 shows resistance training patterns of participants in the habitually resistance-trained group. All runners incorporated upper body and lower body training in their programmes. The group mostly did circuit training (n=5), body weight training (n = 8), core and proprioception training (n = 4). More than half of the group trained consistently throughout the year (n = 6).
Table 3.3: Individual resistance training patterns of participants in the habitually resistance-trained group (n = 8). Resistance training data are described for individual participants (R1 – R8).

<table>
<thead>
<tr>
<th>Resistance training variables</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower body</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Upper body</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Upper + Lower body combined</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Circuit training</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Body weight training</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Power training</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Isometric training</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Core</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Proprioception training</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Average Intensity for training sessions</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>Split sessions high and moderate</td>
<td>Split sessions moderate and light</td>
<td>moderate</td>
<td>moderate</td>
<td>light</td>
</tr>
<tr>
<td>Repetition and sets</td>
<td>8-10 reps 1-3 sets</td>
<td>12-15 reps 3 sets</td>
<td>8-12 reps 1 set</td>
<td>Split sessions 6-8 reps 3 sets 10-12 reps 3 sets</td>
<td>Split session 6-8 reps 3 sets</td>
<td>8-10 reps 1-2 sets</td>
<td>8-10 reps 1 set</td>
<td>10 reps 2 sets</td>
</tr>
<tr>
<td>Supervised</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Hours per session</td>
<td>2.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.75</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Session/week</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Average RPE</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Consistent through year</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Abbreviations: Yes (Y); No (N); Repetitions (reps)

Notes:
1. The split sessions are split into two different training sessions with different repetition and set ranges.
2. Consistent through the year refers to whether resistance training was performed regularly for 12 months of the year.
3. Upper and Lower body combined refers to whether training of muscle groups of the lower body and upper body were done together in one session.
4. Intensity levels: high = ≥80% of 1R, moderate = 60-70% 1RM, light <50%.

3.3.3.2. Running Training

There were no significant differences in weekly running training variables between groups (Table 3.4).
Table 3.4: Weekly running training variables of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are presented as mean ± standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weekly training (km)</td>
<td>54.1 ± 13.6</td>
<td>50 ± 8.9</td>
<td>0.74</td>
<td>0.47</td>
</tr>
<tr>
<td>Maximum weekly training (km)</td>
<td>84.1 ± 25</td>
<td>74.8 ± 14.3</td>
<td>0.95</td>
<td>0.36</td>
</tr>
<tr>
<td>Minimum weekly training (km)</td>
<td>16.5 ± 16.1</td>
<td>19 ± 8</td>
<td>-0.40</td>
<td>0.70</td>
</tr>
<tr>
<td>Running sessions per week (days)</td>
<td>4 ± 1</td>
<td>5 ± 1</td>
<td>-0.47</td>
<td>0.64</td>
</tr>
</tbody>
</table>

The type of running training performed by each group is presented in Table 3.5. There were no significant differences between the two groups in any of the types of running training.

Table 3.5: Type of running training performed by participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are presented as numbers (n).

<table>
<thead>
<tr>
<th>Type of running training</th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>X²</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Long slow runs</td>
<td>11</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Speed</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Hills</td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Intervals</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

3.3.4 Competition History

Table 3.6 shows the competition history in the one year prior to the study for participants in both groups. There was a significant difference of the number of 21.1km races completed between group, with participants in the habitual resistance training group having completed significantly more 21.1 km races (p = 0.00007).
Table 3.6: Number of races completed by participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n=8)</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of 10km races during previous year (n)</td>
<td>2 ± 3</td>
<td>6 ± 10</td>
<td>- 1.47</td>
<td>0.16</td>
</tr>
<tr>
<td>Number of 21.1km races in previous year (n)**</td>
<td>2 ± 2</td>
<td>10 ± 4</td>
<td>-5.42</td>
<td>p = 0.00007</td>
</tr>
<tr>
<td>Number of 42.2km races in previous year (n)</td>
<td>2 ± 1</td>
<td>2 ± 1</td>
<td>-0.98</td>
<td>0.34</td>
</tr>
</tbody>
</table>

** p < 0.01

Table 3.7 illustrates the average running speeds for 5 km, 10 km, 21.1 km and 42.2 km race distances. There were no significant differences in running speeds for any of the race distances between groups.

Table 3.7: Average running speeds (min.km⁻¹) across different race distances of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11).

<table>
<thead>
<tr>
<th>Race distance</th>
<th>Traditionally running-trained group (n=11) (min.km⁻¹)</th>
<th>Habitually resistance-trained group (n=8) (min.km⁻¹)</th>
<th>X²</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 km</td>
<td>4:00</td>
<td>4:00</td>
<td>4.29</td>
<td>0.37</td>
</tr>
<tr>
<td>10 km</td>
<td>4:00</td>
<td>4:30</td>
<td>2.82</td>
<td>0.59</td>
</tr>
<tr>
<td>21.1 km</td>
<td>5:00</td>
<td>5:30</td>
<td>4.67</td>
<td>0.32</td>
</tr>
<tr>
<td>42.2 km</td>
<td>5:30</td>
<td>6:30</td>
<td>4.30</td>
<td>0.37</td>
</tr>
</tbody>
</table>

3.3.5 Running Injuries

3.3.5.1. Injury History

Table 3.8 summarises running-related calf injuries reported in the 12-month period preceding the study. There were no significant differences in the number of injuries reported between the two groups (OR = 0.35; 95% CI's: 0.05-3.02).
Table 3.8: Running-related calf injuries over the previous 12-month period of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as numbers, with Odds ratio and 95% confidence intervals (95% CI).

<table>
<thead>
<tr>
<th>Running related calf injury</th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>Odds ratio</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>9</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>2</td>
<td>3</td>
<td>0.35</td>
<td>0.05 - 3.02</td>
</tr>
<tr>
<td>Totals</td>
<td>11</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.6 Injury Nature and Site

Figure 3.2 illustrates the nature and site of running-related injuries recorded by participants in both groups. A total of 15 injuries were reported in the 12-month period preceding the study. The most common site of injury was the calf muscle (n = 5), followed by the knee, specifically the iliotibial band (n = 3) and anterior knee pain (n = 1); and then the foot (n = 2). Injuries to the Achilles tendon and ankle, and muscular strains of the upper leg were also reported.

![Figure 3.2: Nature and site of running-related injuries](image)

3.3.7 Ultrasound Measurements

3.3.7.1. Architecture of the Gastrocnemius

Table 3.9 shows the architectural measurements that were performed using ultrasound. Measurements were performed for the left and right legs.
An average of both legs was calculated. There were significant differences in pennation angle (right leg) \( (t = -2.16, p = 0.045) \) and in pennation angle (average) \( (t = -2.20, p = 0.042) \) between groups showing a greater pennation angle in the habitually resistance-trained group. There were no other significant differences between the two groups in muscle belly length, thickness or fascicle length.

### Table 3.9: Ultrasound architectural measurements of participants in the habitually resistance-trained group \( (n = 8) \) and the traditionally running-trained group \( (n = 11) \). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group ( (n=11) )</th>
<th>Habitually resistance-trained group ( (n = 8) )</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemius muscle belly length (right) (mm)</td>
<td>195.9 ± 17.7</td>
<td>186.5 ± 31.7</td>
<td>0.83</td>
<td>0.42</td>
<td>20.9 – 64.55</td>
</tr>
<tr>
<td>Gastrocnemius muscle belly length (left) (mm)</td>
<td>198.3 ± 16.3</td>
<td>195 ± 22.3</td>
<td>0.38</td>
<td>0.71</td>
<td>14.7 - 45.4</td>
</tr>
<tr>
<td>Gastrocnemius muscle belly length (average) (mm)</td>
<td>197.1 ± 16.3</td>
<td>190.8 ± 26</td>
<td>0.66</td>
<td>0.52</td>
<td>17.2 – 52.8</td>
</tr>
<tr>
<td>Pennation angle (right) (°) *</td>
<td>28.3 ± 5.5</td>
<td>34 ± 5.8</td>
<td>-2.16</td>
<td>0.045</td>
<td>3.8 – 11.8</td>
</tr>
<tr>
<td>Pennation angle (left) (°)</td>
<td>27.2 ± 3.9</td>
<td>29.9 ± 4.3</td>
<td>-1.44</td>
<td>0.17</td>
<td>2.8 – 8.7</td>
</tr>
<tr>
<td>Pennation angle (average) (°)</td>
<td>27.7 ± 4.3</td>
<td>31.9 ± 3.7</td>
<td>-2.20</td>
<td>0.041</td>
<td>2.5 – 7.6</td>
</tr>
<tr>
<td>Fascicle length (right) (mm)</td>
<td>43.9 ± 7.6</td>
<td>41.3 ± 7.7</td>
<td>0.73</td>
<td>0.48</td>
<td>5.1 – 15.8</td>
</tr>
<tr>
<td>Fascicle length (left) (mm)</td>
<td>42.3 ± 6.8</td>
<td>40.5 ± 6.7</td>
<td>0.56</td>
<td>0.58</td>
<td>4.4 – 13.7</td>
</tr>
<tr>
<td>Fascicle length (average)</td>
<td>43.1 ± 6.9</td>
<td>21.2 ± 6.9</td>
<td>0.68</td>
<td>0.51</td>
<td>4.6 – 14.0</td>
</tr>
<tr>
<td>Thickness (right) (mm)</td>
<td>20.8 ± 2.5</td>
<td>21.7 ± 3.2</td>
<td>-0.68</td>
<td>0.50</td>
<td>2.1 – 6.5</td>
</tr>
<tr>
<td>Thickness (left) (mm)</td>
<td>18.9 ± 3</td>
<td>20.7 ± 4.1</td>
<td>-1.10</td>
<td>0.29</td>
<td>2.3 – 8.4</td>
</tr>
<tr>
<td>Thickness (average)</td>
<td>19.8 ± 2.6</td>
<td>21.2 ± 3.2</td>
<td>-0.95</td>
<td>0.35</td>
<td>2.3 – 7.0</td>
</tr>
</tbody>
</table>

* \( p < 0.05 \)

### 3.3.7.2. Volume of Gastrocnemius

Gastrocnemius volume measurements are shown in Table 3.10. Measurements were performed for the left and right legs. An average of both legs was calculated. There were no significant differences in gastrocnemius volume measurements between groups.
Table 3.10: Gastrocnemius volume measurements of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (right) (cm³)</td>
<td>263.3 ± 67.4</td>
<td>274 ± 93.3</td>
<td>-0.29</td>
<td>0.35</td>
<td>61.7 – 189.9</td>
</tr>
<tr>
<td>Volume (left) (cm³)</td>
<td>265.4 ± 74.4</td>
<td>253.8 ± 83.4</td>
<td>0.32</td>
<td>0.75</td>
<td>55.1 – 169.73</td>
</tr>
<tr>
<td>Volume (average) (cm³)</td>
<td>264.4 ± 69</td>
<td>263.9 ± 87.1</td>
<td>0.01</td>
<td>0.99</td>
<td>57.6 – 177.3</td>
</tr>
</tbody>
</table>

3.3.7.3. Physiological Cross-sectional Area

There were no significant differences in physiological cross-sectional area of the left leg, right leg or average measurements between groups (Table 3.11).

Table 3.11: Physiological cross-sectional area measurements of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiological cross sectional area (right) (cm²)</td>
<td>61 ± 14.9</td>
<td>63.7 ± 15.2</td>
<td>-0.39</td>
<td>0.7</td>
<td>10.1 – 31</td>
</tr>
<tr>
<td>Physiological cross sectional area (left) (cm²)</td>
<td>61.9 ± 13.9</td>
<td>63.7 ± 16.5</td>
<td>-0.26</td>
<td>0.8</td>
<td>10.9 – 33.5</td>
</tr>
<tr>
<td>Physiological cross sectional area (average) (cm²)</td>
<td>61.5 ± 13.2</td>
<td>63.7 ± 15.2</td>
<td>-0.34</td>
<td>0.74</td>
<td>10.4 – 31.9</td>
</tr>
</tbody>
</table>

3.3.8 Physical Tests

3.3.8.1. Gastrocnemius and Soleus Flexibility

The measurements for gastrocnemius and soleus flexibility are illustrated in Table 3.12. Measurements were performed for the left and right legs. An average of both legs was calculated. There were no significant differences in flexibility measurements between the two groups.
Table 3.12: Gastrocnemius and soleus flexibility of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemius flexibility (right) (°)</td>
<td>33.9 ± 7.4</td>
<td>34.4 ± 4.8</td>
<td>-0.17</td>
<td>0.87</td>
<td>3.18 – 9.79</td>
</tr>
<tr>
<td>Gastrocnemius flexibility (left) (°)</td>
<td>34.8 ± 6.3</td>
<td>37.8 ± 10.7</td>
<td>-0.75</td>
<td>0.46</td>
<td>7.07 – 21.75</td>
</tr>
<tr>
<td>Gastrocnemius flexibility (average) (°)</td>
<td>34.3 ± 4.4</td>
<td>36.1 ± 7.2</td>
<td>-0.65</td>
<td>0.53</td>
<td>4.76 – 14.65</td>
</tr>
<tr>
<td>Soleus flexibility (right) (°)</td>
<td>34.3 ± 8.2</td>
<td>33.9 ± 5.1</td>
<td>0.14</td>
<td>0.89</td>
<td>3.38 – 10.4</td>
</tr>
<tr>
<td>Soleus flexibility (left) (°)</td>
<td>34.6 ± 6.8</td>
<td>35.4 ± 8.9</td>
<td>-0.21</td>
<td>0.84</td>
<td>5.91 – 18.2</td>
</tr>
<tr>
<td>Soleus flexibility (average) (°)</td>
<td>34.5 ± 4.9</td>
<td>34.6 ± 6.9</td>
<td>-0.05</td>
<td>0.96</td>
<td>4.54 – 13.96</td>
</tr>
</tbody>
</table>

3.3.8.2. Isokinetic Dynamometry

Peak torque and muscle power measurements of the calf muscle are shown in Table 3.13. Measurements were performed for the left and right legs. An average of both legs was calculated. There were no significant differences in peak torque or muscle power measurements between groups (p > 0.05).

Table 3.13: Peak torque and muscle power measurements of the calf muscle of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Torque (right) (Nm)</td>
<td>104.4 ± 20.5</td>
<td>112 ± 21.6</td>
<td>-0.78</td>
<td>0.44</td>
<td>15.7 – 30.6</td>
</tr>
<tr>
<td>Peak Torque (left) (Nm)</td>
<td>112.4 ± 18.7</td>
<td>111.6 ± 19.9</td>
<td>0.08</td>
<td>0.94</td>
<td>14.1 – 27.6</td>
</tr>
<tr>
<td>Peak Torque (average) (Nm)</td>
<td>108.4 ± 17.7</td>
<td>111.8 ± 19.6</td>
<td>-0.40</td>
<td>0.69</td>
<td>13.6 – 26.7</td>
</tr>
<tr>
<td>Power (right) (W)</td>
<td>34.4 ± 7.7</td>
<td>34.8 ± 8</td>
<td>-0.11</td>
<td>0.92</td>
<td>5.8 – 11.3</td>
</tr>
<tr>
<td>Power (left) (W)</td>
<td>36.3 ± 5.8</td>
<td>34.4 ± 9.2</td>
<td>0.55</td>
<td>0.59</td>
<td>5.5 – 10.8</td>
</tr>
<tr>
<td>Power (average) (W)</td>
<td>35.3 ± 5.9</td>
<td>34.6 ± 8.4</td>
<td>0.23</td>
<td>0.82</td>
<td>5.2 – 10.1</td>
</tr>
</tbody>
</table>
3.3.8.3. Calf Endurance

Calf endurance, measured as the number of repetitions during the calf raise test is shown in Table 3.14. Measurements were performed for the left and right legs. An average of both legs was calculated. There were no significant differences in calf endurance between the groups.

Table 3.14: Calf endurance, measured as the number of repetitions during the calf raise test of participants in the habitually resistance-trained group (n = 8) and the traditionally running-trained group (n = 11). Data are expressed as mean ± standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traditionally running-trained group (n=11)</th>
<th>Habitually resistance-trained group (n= 8)</th>
<th>t-value</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calf raise (right)</td>
<td>35.7 ± 5.8</td>
<td>35.4 ± 9.4</td>
<td>0.10</td>
<td>0.92</td>
<td>5.50 – 10.76</td>
</tr>
<tr>
<td>Calf raise (left)</td>
<td>37 ± 5.8</td>
<td>35.9 ± 7.5</td>
<td>0.37</td>
<td>0.72</td>
<td>4.84 – 9.46</td>
</tr>
<tr>
<td>Calf raise (average)</td>
<td>36.4 ± 5.5</td>
<td>35.6 ± 7.7</td>
<td>0.24</td>
<td>0.81</td>
<td>4.78 – 9.36</td>
</tr>
</tbody>
</table>

3.3.9 Summary of Results

In both groups the marathon runners were similar in age, 33 ± 4.8 in the traditionally running-trained group and 33 ± 7.5 in the habitually resistance-trained group. Both groups also showed similar body composition for mass, stature and therefore similar body mass index. Both groups were comprised of a mix of experienced runners and novice runners.

The habitually resistance-trained group performed on average 8.6 hours of resistance training per month for 11.5 months of the year. The type of resistance training was mostly circuit training, body weight training with little power and isometric training. More than half of the group did core and proprioception training as part of their resistance training programmes. Most of the runners incorporated upper body muscle groups and lower body muscle groups in their training sessions. Only one runner did not do upper body training. The programmes varied in intensity (light to high) as well as repetition ranges and number of sets performed. The frequency of raining varied from one to four sessions per week.

Both groups had similar running training programmes and averaged 50 ± 8.9km to 54 ± 13.6km per week with a maximum weekly training load of 84.1km (traditionally running-trained group) and 74.8km (habitually resistance-trained group). All the runners did long slow runs as part of their training whereas interval and hill training was not performed by all the runners. There were no significant differences between the groups in the type of running training. The only significant difference between the groups in competition history was the number of races run by the habitually resistance-trained group for 21.1km (p < 0.000071).
The area of injuries reported was the highest for the calf, followed by the knee and then the foot. Both groups reported injuries to the calf area and there were no significant differences in injury incidence between the groups.

There were no significant differences between groups in gastrocnemius muscle length, fascicle length or muscle thickness. The right pennation angle (t = -2.16, p = 0.045) as well as the average pennation angle (t = -2.20, p = 0.041) was significantly higher in the habitually resistance-trained group. There were also no significant differences in gastrocnemius volume and physiological cross-sectional area between groups. Lastly, there were no significant differences in gastrocnemius and soleus muscle flexibility; or calf muscle strength, power and endurance between groups.

3.4 DISCUSSION

3.4.1 Participants

3.4.1.1 Sample Size

For this study to have 80% statistical power, a sample size of 11 participants was required. We fell short of this requirement for the habitually resistance-trained group. Button et al (2013) highlighted the issues associated with small sample sizes that may lead to unreliable findings. These issues include a low probability of determining true effects, which was potentially the main limitation of the small sample size in this study. We have tried to be cognisant of the small sample size throughout the discussion of the results of this study; and recognise that the study findings should be interpreted with caution.

3.4.1.2 Descriptive Characteristics

In both groups, the runners were all males similar to other studies analysing the effects of resistance training and no females were recruited for the study. In another study comparing males in a resistance training group to males in an endurance training group there was a significant increase in body mass for the resistance group after 10 weeks of progressive training. Resistance training is known to increase muscle size and mass however in this study there was no significant difference between the habitual resistance training group and the traditional running training group for age, mass, stature, BMI, body fat percentage or lean body mass. Muscle hypertrophy occurs when resistance training is done at a high enough intensity to cause the physiologic adaptation to the muscle load.
The lack of differences seen may be suggestive that the runners in the habitually resistance-trained group did not train at a high enough intensity to create this change. The type of resistance training performed in the habitually resistance-trained group also varied which may also explain the lack of muscle adaptation.

3.4.2 Training and Competition History

3.4.2.1 Habitual Resistance Training

Apart from one runner, the runners in the habitually resistance-trained group incorporated upper and lower body training into their training programmes. The lower body muscle groups focussed on were hamstrings, gluteals, quadriceps and calves and the upper body muscles groups focussed on were triceps, biceps, lattissimus dorsi and trapezius. According to the recommended guidelines for resistance training these muscle groups should be trained two to three days per week. The runners in this group performed one to four training sessions per week incorporating upper body and lower body muscle groups. The exercises were generalised and not specific to one muscle group. The runner who did four sessions per week focussed on one muscle group per session and divided his training sessions into chest/traps, back, legs, arms/shoulders i.e. one group trained once per week. The runner who only did lower body training did two sessions per week only focussing on the lower body muscle groups. The training sessions for the habitually resistance-trained group did not follow the recommended guidelines.

The type of resistance training exercises varied from multi-joint exercises to single-joint exercises for all the participants. Only two runners reported a high intensity training session per week whereas the other runners reported exercises of moderate to light intensity. According to the guidelines 60 – 80% of 1RM is needed to increase strength with a repetition range of 10 to12 with two to four sets done per exercise. The runners performed the recommended range of repetitions but the amount of sets done was either too low or at the minimum required amount of two sets. Four runners performed more than two sets per exercise at a varied intensity of light to high however there was no specific rating of the weights used or calculated according to 1RM as stated in the guidelines. This may explain the lack in muscle hypertrophy as the weights used were possibly too low.

A trainer supervised three of the runners and their training was progressed whereas the other five runners followed a program without any progression. According to the ACSM’s guidelines, progressive resistance exercise is needed to create adaptation and therefore the runners not following a progressive programme will not observe the desired changes in muscle.
The runners in the habitually resistance-trained group did not follow the recommended guidelines for frequency of training sessions per muscle group, recommended training intensity and progression of exercises. This can explain the lack of differences seen in the physical muscle testing and other ultrasound measurements between the two groups. From the previous literature seen on resistance training it is expected to see differences in physical muscle testing and ultrasound imaging\(^6,8,42\).

3.4.2.2 Traditional Running Training

All participants did long slow runs as part of their marathon training. In the habitually resistance-trained group, six runners did speed work, all runners did hill training and three runners did interval training. In the traditionally running-trained group, six runners did speed work, eight runners did hill training and seven runners did interval training. Some runners in the traditionally running-trained group did not do any other running training apart from long slow runs. There were no statistically significant differences between the groups. The habitually resistance-trained group however did do less interval training than the traditionally running-trained group and this was most likely due to the addition of resistance training in their weekly training schedule. The traditionally running-trained group did an average of 4 ± 1 running sessions per week whereas the habitually running-trained group did 5 ± 1 per week. There were no differences seen between the two groups for weekly average distance per week as well as minimum and maximum distance run per week.

The runners in both groups were below the recommended number of six to eight running sessions per week and only some of the runners performed interval training according to the recommended endurance running programs as seen in the literature\(^5,46\). The runners in both groups did not train at the recommended level of intensity to create the physiological adaptation to endurance running due to the shortfall in the number of running training sessions and the loss of the training intensity achieved with interval training. Therefore there were no differences seen between the two groups.

3.4.2.3 Competition History

The habitually resistance-trained group ran a significantly higher number of 21.1 km races than the traditionally running-trained group. There is no apparent reason for this as there was no significant difference between the two groups for the number of 10 km or 42.2 km races run in the previous 12 months. There was also no significant difference between the two groups for the running speed of 5km, 10km, 21.1km and 42.2km races. These results are different from the literature as it would be expected to see an increase in muscle power output in the habitually resistance-trained group\(^49\).
3.4.3 Injury History

In this study 5 out of the 19 runners reported to have running related calf injuries in the previous 12 months. Of these calf injuries reported, two were runners in the traditionally running-trained group and three were runners in the habitually resistance-trained group. There was no significant difference between the two groups. The high number of calf injuries (26%) for the study sample is similar to a recent prospective study by van Poppel (2016) who followed up on marathon runners for 12 months after the Amgen Singelloop Breda marathon (2009). During the marathon 7.8% injuries were reported and calf (20%) was reported as the second highest area injured to the knee during the Amgen Singelloop Breda marathon (2009) 68.

3.4.4 Ultrasound Measurements

3.4.4.1 Architecture of the Gastrocnemius

Studies have previously shown a change in muscle architecture due to resistance training 17,50. In this study the only significant difference seen in the habitually resistance-trained group was an increased pennation angle (right) and pennation angle (average) of the gastrocnemius medialis muscle. Most of the runners who participated in the study were right foot dominant however there is a lack of evidence seen in the literature to link handedness to muscle architecture and strength.

There were no other significant differences seen for muscle architecture. Duclay et al (2009) documented an increase in muscle thickness as well as pennation angle after a group of males completed seven weeks of resistance training compared to a control group 89. Muscle thickness has previously been seen to increase in resistance training, however in the current study only the pennation angle was increased 41. The lack of differences seen in muscle thickness may be due to that there was no control group used as a comparison in this study and both groups were distance runners. Abe et al (2000) found a similar finding for muscle thickness in a study comparing sprinters to distance runners and a control group. There was only an increase in muscle thickness in the sprinting group whereas the distance running group and control group had no significant change in muscle thickness 49. No other studies have compared marathon runners who do habitual resistance training to a group of runners who do traditional running training only. Therefore it is difficult to compare the results of this study to the literature. The lack of differences in muscle thickness seen may also be due to variability in the resistance training seen in the habitually resistance-trained group. As discussed in Section 3.4.2.1, only one runner trained at a high and moderate intensity twice per week with the recommended amount of repetitions and sets to induce muscle hypertrophy 4.
Therefore the majority of the runners in the habitually resistance-trained group potentially did not perform resistance training at the required level to create the adaptations seen in muscle architecture in previous studies \(^8,17\).

Previously a lack of differences seen in studies has been due to measurement errors when using ultrasound to measure muscle architecture. Failure to maintain the ultrasound probe perpendicular to the muscle has been seen to alter the true image of a fascicle and will result in a false recording of the correct length of the fascicle \(^53,90\). In addition, recent in vivo findings have shown that ankle position can alter the length of fascicles through range of motion. To reduce measurement errors in this study the testing position was standardised \(^51\) and the investigator was trained to correctly position the probe for measurements during three training sessions. Further, the feasibility study showed good intra-rater reliability for all ultrasound measurements included in this study.

### 3.4.4.2 Volume

In this study, there were no significant differences in volume measurements between groups. In a study comparing 11 males undergoing 14 weeks of heavy loaded resistance training there was an increase in muscle volume of \(10.3\text{cm}^3 \pm 2.2\%\) \(^41\). A heavy load is classified as a high intensity according to the ACSM’s guidelines \(^4\) and will create muscle adaptation when applied to resistance training. In the current study, runners performed mainly moderate intensity training at one to three sets per exercise. This is suggestive that the load was too low to create muscle adaptation.

Measurement errors have also been documented when measuring volume, using ultrasound, which may affect results. MRI is the gold standard to measure volume however it is costly and not easily accessible. Ultrasound has been found to be reliable and valid was therefore used to measure volume in this study \(^38,45,69\). The measurement errors previously seen when using ultrasound to measure volume are due to possible compression of the muscle from the ultrasound probe on the skin and failure to keep the ultrasound probe perpendicular to the skin. To measure volume, the method used involves measuring equal sections throughout the muscle. In this study measurements were kept 30 mm apart using a grid as a marker to keep the images standard and minimal compression was ensured during measurements however this was challenging at times. To ensure the reliability of the use of ultrasound this method was thoroughly practiced by one examiner to ensure the reliability of this measurement.
3.4.4.3 Physiological Cross-sectional Area

Despite the significant increase of pennation angle in the habitually resistance-trained group there was no difference of physiological cross-sectional area (PCSA) between the two groups unlike previous findings when comparing a resistance training group to an endurance cycling group. Both pennation angle and PCSA are proportional to the force generating capacity of a muscle. Aagaard et al (2001) evaluated the effects of 14 weeks of resistance training in 11 males with no previous resistance training. There was an increase of muscle fibre CSA as well as an increase of pennation angle. Histochemical analysis was used to evaluate the change in fibre CSA. Training intensity has been linked to changes in muscle fibre CSA in a study comparing resistance training performed at low repetitions, intermediate repetitions, high repetitions and a control group. A significant increase in maximum strength and fibre CSA was observed for the low repetition group.

The studies mentioned above did not measure PCSA in addition to fibre CSA. Other studies have suggested that the current method to calculate PCSA may be unreliable. In the current study, PCSA is calculated using a formula dividing volume with fascicle length assuming that fascicle length stays constant. Fascicle length has been seen to change with muscle length changes and therefore this method of calculating PCSA may be inaccurate. This is the current method to calculate PCSA.

3.4.5 Physical Tests

3.4.5.1 Gastrocnemius and Soleus Flexibility

There were no significant differences in gastrocnemius and soleus flexibility between groups in this study. The normal range of motion for dorsiflexion has been described as 11° to 25° and flexible range is described as 25° to 32°. The runners in the sample size varied dorsiflexion flexibility from 33.9° to 37.8°. These ranges are higher than the ranges reported by Moseley et al (2001). An increase in passive stiffness has been documented in the literature in individuals who participate in resistance training and running. A decrease in ankle dorsiflexion range has previously been seen in runners with plantar heel pain or overuse injuries of the lower limb. The runners in the current study did not report any current injury or in the few months prior to the study. This supports the expectation that there would be no differences between the two group or lack of flexibility.
3.4.5.2 Isokinetic dynamometry

Previous studies seen using isokinetic dynamometry for the ankle plantarflexors tested maximal voluntary contraction (MVC) (isometric) whereas in this study, full range peak torque as well as power was measured. The average MVC recorded by Duclay et al (2009) was 120.12 ± 6.77 Nm in the resistance trained group and 113.75 ± 9.69 Nm for the control group. In this study, there were no differences in calf muscle strength or power measurement between groups, most likely due to the different training protocols followed by the runners in the habitually resistance-trained group and the absence of training at the recommended level to enhance the muscle strength and power.

3.4.5.3 Calf Endurance

Previous studies have observed that endurance runners have significantly increased calf endurance when compared to low activity individuals; however in this study both groups consisted of endurance runners and no significant differences in calf endurance were detected. Buchholtz (2013) reported an average of 33 ± 8 repetitions in endurance runners which is similar to the findings in this study of an average of 36.05 ± 6.3 between the two groups. In the habitually resistance-trained group there was also only one runner who reported to train at a light intensity. Light intensity is aimed at enhancing muscle endurance according to the ACSM’s training guidelines. Training muscle to enhance muscle endurance has been seen to improve aerobic power and time to exhaustion. Therefore the absence of differences between the two groups may be due to the poor training specificity for muscle endurance in the habitually resistance-trained group.

3.4.6 Limitations of this Study and Recommendations for Future Research

There are a few limitations to this study. The main limitation of this study was that we were unable to recruit the minimum number of runners required to ensure sufficient statistical power, according to the prospective power analysis that was performed. We were unable to recruit sufficient runners meeting the inclusion and exclusion criteria from the local running clubs. Runners were recruited in the Stellenbosch/Helderberg region of the Western Cape. This is an urban/rural region, with a small town and few recreational running clubs. The study was not funded and we were therefore unable to offer any reimbursement for travel expenses for potential participants. We also excluded female runners in an attempt to facilitate homogeneity between groups. We believe that all of these factors contributed to the difficulties experienced in recruiting runners for this study. We recognise that the study was under-powered as a result of difficulties experienced with recruitment.
Due to the physiologic and metabolic adaptation that needs to take place over time with progressive resistance training and traditional running training this study is limited by the design. A long-term prospective study would need to be conducted to observe muscle adaptation to resistance training over time and whether there is an association to injury prevention.

It is clear from this study that there is variability amongst the resistance training performed in runners. Participants were required to retrospectively recall their training and rate it subjectively in terms of effort. It is possible that those reporting a moderate or high intensity effort were in fact training at a lower intensity that that required for adaptation. There is also a clear indication that runners may not be educated on resistance training principles and how to implement resistance training into their routine to get the desired results. Improving the knowledge of resistance training can allow runners to improve running performance and efficiency. Future research should investigate the knowledge and practices of runners performing resistance training more thoroughly. This can be further used to implement a standardised and specific resistance training intervention for marathon runners to improve muscular strength and endurance of the lower limb specific to endurance running.
CHAPTER 4: SUMMARY AND CONCLUSION

Marathon running is a popular sport with runners participating regularly in marathons at a local level as well as internationally. There are many health benefits to participate in running as a sport\textsuperscript{18}. Despite these health benefits there is a high prevalence of injuries sustained due to the cumulative effect of running a high amount of kilometres per week\textsuperscript{16}. The calf has been identified as a common area of injury and the gastrocnemius muscle is commonly strained during running activity\textsuperscript{12}. Currently high weekly mileage is associated with running injury due to overuse of muscle and joints\textsuperscript{13}. The overload principle is imposed during training to create a physiologic and metabolic adaptation in response to exercise and exercise training specificity refers to the specific adaptation caused due to the type of training imposed\textsuperscript{3}. Therefore resistance-training programmes are implemented to strengthen muscles for running training\textsuperscript{48}. There is limited literature to assess the role of habitual resistance training in marathon runners and there are limited studies evaluating the effect of habitual resistance training on the structure and function of the gastrocnemius muscle. Therefore the aim of this study was to determine the effects of habitual resistance training compared to traditional running training on gastrocnemius muscle structure and function in marathon runners. Based on the findings of this study, the study objectives described in Chapter 1.2.2 (page 2) may be addressed as follows:

To describe the demographic and training characteristics of habitually resistance-trained marathon runners and traditionally running-trained marathon runners.

The runners in both groups were of similar ages and body composition. The average weekly load for running training was 50 ± 8.9 km per week in the habitually resistance-trained group and 54 ± 13.6 km per week for the traditionally running-trained group. This is far below the threshold weekly mileage of training over 65km, which has been associated with an increased risk of injury\textsuperscript{21}. The habitually resistance-trained group performed in an average of two hours (range 0.5-2.5 hours) of resistance training in between one to four sessions per week. Participants combined upper and lower body training in the form of circuit training, body weight training, core and proprioceptive training. Resistance training sessions were performed at an average RPE of 8/10 and varied in intensity for load (light to high) however there was a lack of understanding of measuring weights according to 1RM\textsuperscript{4}. Habitual resistance training showed wide variability and was not consistently performed in accordance with evidence-based guidelines for training.
To determine if there were differences in calf muscle endurance, power and flexibility between habitually resistance-trained marathon runners and traditionally running-trained marathon runners.

There were no significant differences in calf muscle endurance, power and flexibility between groups. We recognise that the small sample size in this study may have resulted in a low probability of determining true effects. However, this finding suggests that habitual resistance training programmes in the sample group may not be sufficient to induce specific adaptations in calf muscle function. Further studies are required to confirm these preliminary findings.

To evaluate if there were differences in the gastrocnemius muscle structure and architecture in habitually resistance-trained marathon runners compared to traditionally running-trained marathon runners.

We identified that pennation angle (average and right leg) was significantly increased in the habitually resistance-trained group compared to the traditionally running-trained group. No other significant differences in architectural measurements were detected. The differences in pennation angle between groups concurs with previous literature 17, and indicates a potential structural adaptation to resistance training. However, this finding should be interpreted with caution, given the small sample size. We were also unable to identify architectural changes observed in previous studies, including muscle thickness, fascicle length, muscle volume, and physiological-cross-sectional area 17,41,49. These discrepancies may be partially attributed to the absence of a formal resistance-training intervention in our study compared to previous research; but also suggests that runners are not performing sufficient training to induce specific adaptations associated with resistance exercise.

To establish if there were any differences in the number of calf injuries sustained in habitually resistance-trained marathon runners compared to traditionally running-trained marathon runners.

The calf was a common injury site, with five calf injuries being reported. Unfortunately, the sample size is too small to draw any meaningful conclusions regarding associations between habitual resistance training and the incidence of running-related injuries. Further studies are needed to determine if habitual or unsupervised resistance training may reduce the risk of running-related injuries in marathon runners.
In conclusion, wide variability in habitual resistance training patterns was identified in the sample group. While pennation angle was significantly greater in the habitually resistance-trained group; no differences in all other architectural measurements; or calf muscle strength, power, endurance or flexibility between groups were identified. However, one of the key findings emerging from this study is the variable resistance training practices in endurance runners; and that resistance training practices were not aligned to current evidence-based guidelines for resistance training. Resistance training has a critical role in enhancing endurance running performance, injury prevention and rehabilitation. Future research should investigate the knowledge, attitudes and practices of endurance runners regarding resistance training; to facilitate the development of appropriate education interventions, and to effectively disseminate evidence-based training guidelines to lay communities.
REFERENCES


APPENDICES
APPENDIX I: FEASIBILITY STUDY

INTRA-RATER RELIABILITY OF MEASUREMENTS REQUIRED FOR DETERMINING THE DIFFERENCES BETWEEN TRADITIONALLY TRAINED MARATHON RUNNERS AND HABITUALLY RESISTANCE TRAINED MARATHON RUNNERS

BACKGROUND
The ability to measure a specific test accurately and repeatedly by one examiner is called intra-rater reliability. This is essential for the measurements and re-measurements of clinical tests of patient assessments and re-assessment to determine the response to treatment interventions during the healing phase.

AIM
The purpose of the feasibility study was to determine reliability of the measuring tools used in the research study.

SPECIFIC OBJECTIVES
The following are the specific objectives of the feasibility study:
- Intra-rater reliability of using ultrasound to measure muscle thickness, fascicle length and pennation angle
- Intra-rater reliability of using ultrasound to measure the length of gastrocnemius length using the proximal and distal musculotendinous junctions as reference points
- Intra-rater reliability of ultrasound imaging and calculating the volume of gastrocnemius
- Intra-rater reliability of the ultrasound imaging of the Achilles tendon compliance

PARTICIPANTS
Five marathon runners were tested in this study (n = 5). Two runners met the criteria for the habitually resistance-trained group and three runners met the criteria for the traditionally running-trained group.

TESTING PROCEDURE
All five runners completed an informed consent form and completed the training and competition questionnaire. Each runner was then tested in one session and each test was repeated three times. The principal investigator performed all the ultrasound imaging and measurements.
a) Ultrasound measurements: length of gastrocnemius, pennation angle, thickness, fascicle length

The ultrasound measurements were done using a Logique model 5419804, 20V 5A, 12L RS. The runner was positioned in prone lying with the gastrocnemius muscle relaxed. The medial gastrocnemius is measured due to it being the most commonly injured portion of the muscle of the triceps surae. The right side was tested first and then the left with each measurement taken three times.

• Gastrocnemius muscle belly length
The musculotendinous junction of the proximal and distal attachment was first identified using ultrasound imaging. The length of the medial gastrocnemius is accepted as a straight line over the skin between these two points.

• Pennation angle
The angle between a single chosen fascicle and its insertion onto the deep aponeurosis was measured as the pennation angle.

• Muscle thickness
Muscle thickness was calculated by measuring the perpendicular distance between the two aponeuroses. The distance was then measured electronically after the testing session on the ultrasound machine.

b) Ultrasound measurement: volume calculation
The muscle between the proximal and distal musculotendinous junctions was scanned in four to six evenly spaced axial plane sections, 30mm apart, using a grid as a position marker on the surface. Muscle volume is also known as anatomical cross sectional area (ACSA) (cm$^2$). This was calculated by stitching the adjacent scans together and measuring the area on an imaging programme (Image 1.46r; National Institutes of Health, USA). The volume between each of those sections was then calculated based on the following formula:

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

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 was calculated and added together to give the total volume of the gastrocnemius.
c) Ultrasound measurement: Achilles tendon compliance

The Achilles tendon was assessed with the foot positioned at 90° (neutral) and resting against a plate of the Humac norm Cybex while the ultrasound head was positioned accordingly to visualize the musculotendinous unit from above the tendon. The participant was then asked to push as hard as possible into the plate to achieve the maximal isometric contraction of plantarflexion and the elongation of the tendon was measured.

DATA ANALYSIS

Measurements were documented on independent data collection sheets and this information was transferred into an Excel spreadsheet (Microsoft Corporation, Redmond, USA).

STATISTICAL ANALYSES

Data were analysed using a spreadsheet that is designed for reliability testing. 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.

RESULTS

The following table illustrates the results of each measurements:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Typical error (95% CI)</th>
<th>ICC (95% CI)</th>
<th>Mean ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of gastrocnemius muscle belly (right) (mm)</td>
<td>1.20 (0.88-2.25)</td>
<td>1.00 (0.99-1.00)</td>
<td>220.5 ± 16.5</td>
</tr>
<tr>
<td>Length of gastrocnemius muscle belly (left) (mm)</td>
<td>0.50 (0.93-0.37)</td>
<td>1.00 (1.00-1.00)</td>
<td>217.4 ± 15.8</td>
</tr>
<tr>
<td>Thickness (right) (mm)</td>
<td>1.51 (1.11-2.82)</td>
<td>0.79 (0.37-0.91)</td>
<td>20.1 ± 3.2</td>
</tr>
<tr>
<td>Thickness (left) (mm)</td>
<td>0.62 (0.45-1.15)</td>
<td>0.98 (0.94-0.99)</td>
<td>19.9 ± 4.3</td>
</tr>
<tr>
<td>Pennation angle (right) (°)</td>
<td>4.14 (3.03-7.72)</td>
<td>0.98 (0.93-0.99)</td>
<td>45.9 ± 26.3</td>
</tr>
<tr>
<td>Pennation angle (left) (°)</td>
<td>3.31 (2.43-6.19)</td>
<td>0.98 (0.94-0.99)</td>
<td>43.9 ± 24.4</td>
</tr>
<tr>
<td>Fascicle length (right) (mm)</td>
<td>3.13 (2.29-5.84)</td>
<td>0.87 (0.59-0.95)</td>
<td>49.1 ± 8.2</td>
</tr>
<tr>
<td>Fascicle length (left) (mm)</td>
<td>2.54 (1.86-4.75)</td>
<td>0.89 (0.65-0.96)</td>
<td>49.2 ± 7.3</td>
</tr>
<tr>
<td>Volume (right) (cm³)</td>
<td>1.27 (0.89-4.21)</td>
<td>0.98 (0.83-0.99)</td>
<td>36.8 ± 8.50</td>
</tr>
<tr>
<td>Volume (left) (cm³)</td>
<td>0.45 (0.32-1.49)</td>
<td>0.99 (0.92-1.00)</td>
<td>39.7 ± 4.4</td>
</tr>
<tr>
<td>Achilles tendon elongation (right) (mm)</td>
<td>5.16 (3.71-11.54)</td>
<td>0.45 (-0.72-0.78)</td>
<td>17.4 ± 6.8</td>
</tr>
<tr>
<td>Achilles tendon elongation (left) (mm)</td>
<td>2.85 (2.05-6.39)</td>
<td>0.68 (-0.15-0.88)</td>
<td>14 ± 4.9</td>
</tr>
</tbody>
</table>
SUMMARY AND CONCLUSION
Intra-rater reliability is illustrated using typical error and 95% confidence interval as well as intra-class coefficient and its 95% confidence interval. Inter-rater reliability is accepted at $r \geq 0.7$. According to these results Achilles tendon elongation is the only measurement that is not reliable and was therefore removed from the testing protocol. All other measurements show good reliability.
Dear Runner

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 experienced marathon runners and novice marathon runners.

I am currently looking for experienced and novice marathon runners who are between 20 and 50 years of age, run at least three to five times 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 Stellenbosch Academy of Sport, on two separate occasions (total of two hours).

I have attached two study advertisements for interested participants who fit each testing group 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

Tracy Ellis
BSc Physiotherapy (UCT)
Tel: 083 611 5809
Email: elltracy@gmail.com

The original groups were recruited according to these advertisements. However, due to the difficulties experienced in recruiting participants to the novice and experienced groups; we amended the study objectives and inclusion criteria to those for the habitually resistance trained and traditionally running-trained groups.
EXPERIENCED MALE MARATHON RUNNERS WANTED FOR UCT RESEARCH

For a study evaluating the calf muscle structure and function in experienced endurance runners and novice endurance runners

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 experienced marathon runners compared to novice marathon runners. The study aims to provide information regarding the changes in the calf muscle following long distance running training over time and whether this predisposes to calf injury.

You will be required to attend two testing sessions of one hour each at the Stellenbosch Academy of Sport. 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, power, flexibility and endurance of the calf muscle will be completed.

Those interested in participating as experienced marathon runners should:

- be between the ages of 20 and 50 years
- be running at least 50 km per week over four to six training sessions each week for at least six months
- have run at least three marathons in the previous 12 months
- have run one marathon per year for the last five years

Benefits of participating in the study include

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

DEADLINE FOR APPLICATIONS: 31 March 2016

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

Tracy Ellis
Cell: 083 611 5809
Email: elltracy@gmail.com
NOVICE MALE MARATHON RUNNERS WANTED FOR UCT RESEARCH

For a study evaluating the calf muscle structure and function in experienced endurance runners and novice endurance runners

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 experienced marathon runners compared to novice marathon runners. The study aims to provide information regarding the changes in the calf muscle following long distance running training for more than three years of time and whether this predisposes to calf injury.

You will be required to attend two testing sessions of one hour each at the Stellenbosch Academy of Sport. 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, power, flexibility and endurance of the calf muscle will be completed.

Those interested in participating as a novice marathon runners should:

- be between the ages of 20 and 50 years
- run at a moderate intensity at 30 minutes x 5/week or run at a vigorous intensity for 20 minutes x 3/week.
- have run at least one marathon in the previous 12 months

Benefits of participating in the study include:

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

DEADLINE FOR APPLICATIONS: 31 March 2016

If you are interested in taking part in the study and would like additional information, please contact:
Tracy Ellis
Cell: 083 611 5809
Email: elltracy@gmail.com
Dear Participant

I am a 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 marathon runners. Information about training and competition history will be obtained and physical tests will be conducted to test muscle flexibility, power and endurance. Information obtained within the study will be used to complete my mini-dissertation in part fulfilment of the MSc Exercise and Sports programme. This study has been given ethical approval by the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (HREC REF to be inserted).

There is a high incidence of calf injuries in marathon runners, which has led to prolonged time off running during training. The explanation for these injuries is not well understood and there is a lack of evidence. During running training there may be a change in the muscle function and structure, which may affect the intrinsic properties of the muscle such as muscle tightness and weakness. This study will investigate these factors.

You will be asked to attend a total of two appointments, lasting approximately an hour each, three to five days apart at the Stellenbosch Academy of Sport (SAS), Stellenbosch. For each session, you will be required to travel to SAS at your own cost as there is no funding for the study.

This study will be supervised by Dr Theresa Burgess and Kim Buchholtz 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. Ultrasound imaging will then 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. You will then be familiarised with all the muscle 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), the three muscle tests will be completed. The first test will test the flexibility of both of the muscles in the calf. This is done 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. The second test will test muscle strength and power using a Humac norm cybex machine, which will require you to sit in a chair that straps your leg into place and you will be asked to push against a resistance. 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.

The final test will test calf muscle endurance and will require you to stand on one leg and perform a calf raise until the muscle becomes too tired to continue. This test will be video recorded and the number of repetitions will be counted. The video will be used to capture the data and will be locked in a cabinet for the duration of the data analysis procedure. Once this has been completed, the video 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 callipers 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 flexibility, muscle strength and power 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 Humac norm cybex test, are performed below maximal performance and therefore the chances of injury are small.
The testing on the Humac norm cybex requires maximal effort, which has a higher chance of injury, however the testing procedure is conducted in such a manner to prevent injury from occurring by minimizing the amount of repetitions of the test with time in between to recover. 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.

What if something goes wrong?

The University of Cape Town (UCT) has insurance cover for the event that research-related injury or harm results from your participation in the trial. The insurer will pay all reasonable medical expenses in accordance with the South African Good Clinical Practice Guidelines (DoH 2006), based on the Association of the British Pharmaceutical Industry Guidelines (ABPI) in the event of an injury or side effect resulting directly from your participation in the trial. You will not be required to prove fault on the part of the University. The University will not be liable for any loss, injuries and/or harm that you may sustain where the loss is caused by:

- The use of unauthorised medicine or substances during the study
- Any injury that results from you not following the protocol requirements or the instructions that the study doctor may give you
- An injury that results from negligence on your part

By agreeing to participate in this study, you do not give up your right to claim compensation for injury where you can prove negligence, in separate litigation. In particular, your right to pursue such a claim in a South African court in terms of South African law must be ensured. Note, however, that you will usually be requested to accept that payment made by the University under the SA GCP guideline 4.11 is in full settlement of the claim relating to the medical expenses.

An injury is considered trial-related if, and to the extent that, it is caused by study activities. You must notify the study doctor immediately of any side effects and/or 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 you were taking part in the study. Your right in law to claim compensation for injury where you prove negligence is not affected. Copies of these guidelines are available on request.
Questions or Concerns:

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.

Tracy Ellis (Student researcher)
Physical Address: Stellenbosch Academy of Sport
1 Krige Street
Stellenbosch
7600
Tel number: 083 611 5809
Email: elltracy@gmail.com

Dr. T. Burgess Research (Supervisor)
Physical Address: Division of Physiotherapy
School of Health and Rehabilitation
University of Cape Town
Groote Schuur Hospital
Anzio Road
Observatory
7725
Tel number: 021 406 6171
Fax number: 021 406 6323
E-mail: theresa.burgess@uct.ac.za

Please contact Professor Marc Blockman, Chairperson of the Faculty of Health Sciences Human Research Ethics Committee, if you have any questions or concerns about your rights or welfare as a research participant:

Professor Marc Blockman
Chairperson, Faculty of Health Sciences Human Research Ethics Committee
Tel number: 021 406 6492
E-mail: marc.blockman@uct.ac.za

Consent statement:

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

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: PHYSICAL ACTIVITY AND TRAINING QUESTIONNAIRE

MSc Exercise and 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: Tracy Ellis
Tel number: 083 611 5809
Email: elltracy@gmail.com

Supervisor: Dr Theresa Burgess
Tel number: 021 406 6171
Fax number: 021 406 6323
E-mail: theresa.burgess@uct.ac.za
Please complete the following sections:

Section A  Personal Details
Section B  Competition History
Section C  Running Training
Section D  General Training History
Section E  Injury History
Section A: Personal details

Name:

Email address:

Date of birth:

Cell number:

Home number:

Height:

Weight:

Age:

Occupation:

Running Club (if applicable):
Section B: Competition history

Have you completed any of the following races in the last 12 months? How many completed in each category?

10 km   Yes ☐ No ☐ Number:

21.1 km Yes ☐ No ☐ Number:

42.2 km Yes ☐ No ☐ Number:

Ultra-distance (>50 km ) Yes ☐ No ☐ Number:

Which events?

2. What events are you currently training for?

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

<table>
<thead>
<tr>
<th>5km (including time trials)</th>
<th>10km</th>
<th>21.1km</th>
<th>42.2km</th>
<th>&gt;50km</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:45min/km - 4 min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4:01 min/km – 4:30min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4:31 min/km – 5 min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5:01 min/km – 5:30 min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5:31 min/km – 6 min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:01 min/km – 6:30 min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:31 min/km – 7min/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Section C: Running Training history

1. What is your current average training distance per week?
   
   0-40 km/wk  □
   41-50 km/wk □
   51-60 km/wk □
   61-70 km/wk □
   71-80 km/wk □
   81-90 km/wk □
   91-100 km/wk □
   100 km+/wk □

   Please specify: ______________

2a. In the last 12 months what distance did you complete in your greatest training week? □

2b. In the last 12 months what distance did you complete in your smallest training week? □

3. On how many days each week do you run? 1-7 □

4. How many times a week do you run training sessions with an average speed between the following amounts? Please indicate approximately how many hours these sessions add up to.
   
   3:45 min/km - 4 min/km  How often? hours/week □
   4:01 min/km – 4:30 min/km  How often? hours/week □
   4:31 min/km – 5 min/km  How often? hours/week □
   5:01 min/km – 5:30 min/km  How often? hours/week □
   5:31 min/km – 6 min/km  How often? hours/week □
   6:01 min/km – 6:30 min/km  How often? hours/week □
   6:31 min/km – 7 min/km  How often? hours/week □

5a. Have you had any rest periods during the year (longer than one week)? Yes No

5b. How long was this rest period? ______________
5c. What was the reason for this rest period?

6. Do you include the following in your running training?

<table>
<thead>
<tr>
<th>Training Type</th>
<th>Include</th>
<th>How Often?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low slow runs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed sessions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hill training</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interval training</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Section D: General Training

1. Do you do any other forms of training?  
   Yes ☐   No ☐

2. Which type?

   Cycling ☐  Swimming ☐
   Rugby ☐    Touch Rugby ☐
   Cricket ☐  Dancing ☐
   Martial arts ☐  Pilates ☐
   Yoga ☐    Resistance training ☐
   Hockey ☐  Canoeing ☐
   Horse riding ☐  Aerobics/ Step ☐
   Skating ☐  Volleyball ☐
   Walking ☐  Squash ☐
   Basketball ☐  Hiking ☐
   Tennis ☐  Soccer ☐
   Golf ☐    Badminton ☐

   Other:

3. For each form of training please write down the number of hours/wk

4a. Is this training consistent throughout the year?  ☐ Yes ☐ No

4b. If no, describe when you usually do the other forms of training

5a. Do you do any flexibility/stretch exercises regularly?  ☐ Yes ☐ No

5b. If yes, how often? Less than once a week ☐
   Once a week ☐
   2-3 times a week ☐
   4-5 times a week ☐
   6-7 times a week ☐
   After each training session ☐
Section E: Injury History

1a. Have you sustained any calf injuries while running in the last year?  Yes ☐  No ☐
1b. If yes, please describe
1c. Did you receive any treatment  Yes ☐  No ☐
1d. If yes, please describe
1e. Has this injury resolved?  Yes ☐  No ☐

2a. Have you sustained any other injuries while running in the last year?  Yes ☐  No ☐
2b. If yes, please describe each injury.

3a. Have you sustained any calf injuries during other sporting activities?  Yes ☐  No ☐
3b. If yes, please describe
3c. Did you receive any treatment  Yes ☐  No ☐
3d. If yes, please describe
3e. Has this injury resolved?  Yes ☐  No ☐

4a. Have you sustained any other injuries during other sporting activities in the last year?  Yes ☐  No ☐
4b. If yes, please describe each injury.

5a. Have your injuries resulted in time off training during the year?  Yes ☐  No ☐
5b. For each injury, please state length of time off training
APPENDIX VI: BORG SCALE

Borg Scale: Rate of Perceived Exertion (Borg, 1982)

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
20 October 2015

HREC REF: 767/2015

Dr T Burgess
Division of Physiotherapy
Health & Rehabilitation Sciences
F-45
OMB

Dear Dr Burgess

PROJECT TITLE: AN EVALUATION OF GASTROCNEMIUS MUSCLE STRUCTURE AND FUNCTION IN EXPERIENCED MARATHON RUNNERS AND NOVICE MARATHON RUNNERS (Mphil-candidate-T Ellis)

Thank you for submitting your study to the Faculty of Health Sciences Human Research Ethics Committee (HREC) for review.

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

Approval is granted for one year until the 30th September 2016.

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

(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

We acknowledge that the following student: - Tracy Ellis is also involved in this project.

Please quote the HREC reference no in all your correspondence.

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

Yours sincerely

[Signature]

PROFESSOR M BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS COMMITTEE
Federal Wide Assurance Number: FWA00001637.
Institutional Review Board (IRB) number: IRB00001938

Hrec/ref: 767/2015
**Principal Investigator to complete the following:**

1. **Protocol information**

<table>
<thead>
<tr>
<th>Date (when submitting this form)</th>
<th>05/11/2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>HREC REF Number</td>
<td>767/2015</td>
</tr>
<tr>
<td>Protocol title</td>
<td>Evaluation of gastrocnemius muscle structure and function in experienced marathon runners and novice marathon runners.</td>
</tr>
<tr>
<td>Protocol number (if applicable)</td>
<td>6742</td>
</tr>
</tbody>
</table>

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? A separate FHS016 must be submitted for each sub-study.

Principal Investigator: Dr. Theresa Burgess

Department/Office Address: F45.0 MB Groote Schuur Hospital

1.1 Does this protocol receive US Federal funding? □ Yes □ No

1.2 If the study receives US Federal Funding, does the annual report require full committee approval? □ Yes □ No

1.3 Has sponsorship of this study changed? If yes, please attach a revised summary of the budget. □ Yes □ No
ESSENTIAL TIPS FOR HAPPIER AND HEALTHY RUNNING

Running marathons results in many hours on your feet during the actual race as well as at each training run leading up to the event. Every time you land on your foot during the running action, your body has to absorb the force from the ground and your muscles have to contract to push you forwards to take the next stride. Each step requires energy to overcome these forces and to fuel your muscles to move your body forwards. Therefore during endurance running it is important to conserve your energy and use it wisely for an effortless and enjoyable race.

This is a guide to help you achieve effortless and energy efficient movement through the following topics:

- Lifestyle
- Strength training
- Mobility training

LIFESTYLE

I have put lifestyle on top of this list because what you do daily determines how you will perform in all your activities (work, studies, sport and training) as well as your state of mind (emotional well-being). Strength and mobility training are important too but it is not as effective without a good lifestyle. Having a good lifestyle will enhance your recovery after exercise and help you perform during training to achieve your running goals.

Figure 1:
Nutrition
Eating fresh is best. Stay away from preserved and ready cooked meals. Eat a large variety of wholesome fresh foods. Stay away from sugar and processed foods.

There are many views on correct nutrition and you should research and find what works for you to be healthy. I have included an evidenced based guide on sports nutrition from Yann Le Meur, a sport scientist (Figure 1).

Hydration
The total content of water in the body amounts to 60% however this changes constantly due to water loss during sweating or metabolic processes in our bodies. Therefore staying hydrated is essential. Water is what we are made up of so stick to water as much as possible. Drinks that are high in sugar are not recommended for hydration due to the negative effects of excessive sugar intake (high calorie intake, insulin spikes and gut problems). Look for sports drinks that are low in sugar but contain the essential electrolytes that are lost during excessive sweating such as: rehydrate, cytomax, peptosport. It is also important to remember that excessive amounts of coffee and tea will dehydrate you more.

Fascia
Different layers of connective tissue are found in the body and each layer has a role to connect, support and link different parts of the body. The deeper layers join, stabilize and enclose muscles, joints and ligaments. It also provides a supportive role and assists with energy transfer between different parts of the body. These layers of connective tissue are known as fascia. See more on www.anatomytrains.com. Fascia is very pliable and will adapt to positions that you put your body in.

Therefore if you maintain these positions too long it will become thickened and reinforce those patterns of movement. This becomes problematic when you move into other positions because the fascia becomes resistant to other directions of movement and changes the tensegrity of the tissues. This change in the tensegrity can cause injuries because it can change the normal mechanics of the joints of the body. It is therefore important to keep changing positions during work, studying, relaxing and in training. Keep moving to keep the fascia free and elastic and good conductors of energy. Healthy diet and good hydration will also assist in fascia well-being. Read more on keeping mobile here.
MOBILITY TRAINING
Static stretching and dynamic movements are all part of mobility training to maintain full movement at each joint and to prevent injury. Static stretching is used post exercise to get more length through muscles whereas dynamic movements are used pre-exercise to “warm up” muscles and prevent injury. Dynamic movements are also used to mobilize fascia, which we discussed previously (see the lifestyle section). Massage and foam rolling are other ways to prevent muscle stiffness and restricted movement, which can be used in conjunction with mobility training.

Figure 2


Here are three mobilizing techniques I often use to maintain fascia movement and joint range:

- Awesomiser
- Kneeling twists
- Walk stance reaching twists
- Scorpion rolls
STRENGTH TRAINING
If you want to run smoothly and effortlessly you need to train the muscles that will keep your pelvis to be stable as you step through and put weight on one leg while the opposite leg swings forward to take the next step (See the figure 3: PSS, ASS and LSS). You also need strength through the posterior kinetic chain to push your body forwards as you step forward onto your heel and push off from your toes to propel your body forwards (see figure 3: PSS and SSS).

STABILITY – the following exercises can be used to stabilize the pelvis
- Core activator
- Glute activator
- Oblique twist
- Anti twister
- Step ups
- Ninja walks
- Balance mini squats

STRENGTH/POWER – the following exercises strengthen the posterior chain to improve running speed.
- Split squat
- Single leg Deadlift
- Vertical jump
- Broad jump
- Running specific training – speed work and hill sprints

This guide will assist you with finding how you can move better to train better and therefore run better. Training is a continuous and on going process of development to reach your running goals. Many of these principles and exercises will need to be adapted to your programme over time as you improve and reach new levels of training.

Happy running!

Figure 3

https://physione.files.wordpress.com/2013/12/muscle-sling.jpg