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The Effects of a Typical Training Run on Overuse Running-related Injury Risk Factors In Recreational Runners

Sherveen Riazati

PhD

2020

The Effects of a Typical Training Run on Overuse Running-related Injury Risk Factors In Recreational Runners

A thesis submitted in partial fulfilment of the requirements of
Northumbria University for the degree of
Doctor of Philosophy

by

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ABSTRACT

Running has increased in popularity over recent decades to become one of the five most popular recreational activities worldwide. With this rise in popularity, there has however been a concomitant increase in rate of running related overuse injuries with epidemiology studies reporting 7.7 injuries every 1000 hours of running.

Patellofemoral pain and iliotibial band syndrome are the most common RROI accounting up to 17% and 8%, respectively. Runners experiencing either injury share common gait signatures of excessive hip adduction. Running induced fatigue has been shown to reduce strength in numerous muscle groups important for initiating and regulating gait, notably increased hip adduction. These fatigue induced changes to gait have been examined during prolonged or continuous runs, often to exhaustion. Runners however do not typically perform runs to exhaustion during their regular training, rather they perform high intensity interval training or medium intensity continuous running. The level of fatigue induced by these typical training sessions, or its impact on gait is unknown. The aim of this thesis was to examine the effect of fatigue on risk factors associated with development of running related injuries during typical training runs. Acceptable to excellent relative and absolute reliability for risk factors were reported. The absolute reliability enabled an alternative statistical approach to be alongside traditional, group level, P values. This alternative statistical approach used minimum detectable change to detect 'real changes' in risk factors post-run. Following two typical running sessions, fatigue induced a changes in running related overuse injury risk factors were found. There was a significant ($P < 0.05$) reduction in muscle strength (12%) following high intensity interval training session and medium intensity continuous run (10.6%) in both the hip and knee musculature. Force reduction was accompanied by increased maximum hip adduction angle and range of motion ($P < 0.05$). Fatigue increased coordination variability significantly ($P < 0.05$) in nearly all variables for hip and knee couplings. Individual

assessment showed that the high intensity interval training run induced gait changes in more runners, a finding not observable in group assessment. The fatigue induced changes following training runs could potentially increase the risk of RROI development. This risk however, can only be considered detrimental if still present immediately prior to the next training session. Recovery of strength, kinematic and coordination variability at 24-h following a high intensity interval run was then examined. To fully assess recovery kinetics, evoked electrical stimulation was used to examine the extent of central (voluntary activation) and peripheral (knee extension maximum voluntary contractions and quadriceps twitch potentiation) fatigue immediately post and 24-h after high intensity interval training session. The results not only corroborated those in the previous findings of the thesis, but showed decrements in both central and peripheral drive. Collectively, immediately post, runners exhibited a reduction in hip musculature strength (8.1%), voluntary activation (6.8%), both remaining significantly ($P < 0.05$) impaired at 24-h. The changes were also accompanied by increased maximum angle and RoM for hip adduction immediately post training run and at 24-hr post. Coordination variability was again increased with fatigue and remained increased at 24-h in those who remained fatigued. The most noteworthy finding was that while collectively there were signs of lack of recovery, on an individual level most runners had recovered within 24-h, while only a few did not and still exhibit impaired gait. Only four runners were identified to be at risk of injury development following fatigue induced changes to risk factors and impaired neuromuscular function following a typical training run. This thesis demonstrated that fatigue induced during a typical training session causes changes to gait. For a minority of runners these changes are still evident 24-h after training placing them at an increased risk of running related overuse injury development.

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CHAPTER 8

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LIST OF SYMBOLS AND ABBREVIATIONS

24-h	Twenty Four Hours
AE	Ankle Eversion
AI	Ankle Inversion
AP	Ankle Pronation
AS	Ankle Supination
CA	Coupling Angle
CAV	Coupling Angle Variability
CRP	Continuous Relative Phase
CRPV	Continuous Relative Phase Variability
DST	Dynamical Systems Theory
FF	Fore Foot
FFx	Forefoot Flexion/Extension
FFy	Forefoot Abduction/Adduction
FFz	Forefoot Inversion/Eversion
FO	Foot-off
Fx	Foot Flexion/Extension
Fy	Foot Abduction/Adduction
Fz	Foot Inversion/Eversion
GMED	Gluteus Medius
HIIT	High intensity interval training
HABD	Hip Abduction
Hy	Hip Abduction/adduction
HADD	Hip Adduction
Hy	Hip Abduction/adduction

HE	Hip Extension
HF	Hip Flexion
Hx	Hip Flexion/Extension
HER	Hip External Rotation
HIR	Hip Internal Rotation
Hz	Hip Internal/External Rotation
IC	Initial Contact
ICC	Interclass Correlation Coefficient
IT Band	Iliotibial Band
ITBS	Iliotibial Band Syndrome
KF	Knee Flexion
KE	Knee Extension
KABD	Knee Abduction
KADD	Knee Adduction
KIR	Knee Internal Rotation
KER	Knee External Rotation
KF	Knee Flexion
KE	Knee Extension
La	Lactate Threshold
LTP	Lactate Turnpoint
Max angle	Maximum Angle
MVC	Maximum Voluntary Contraction
MICR	Medium Intensity Continuous Run
MDC	Minimum Detectable Change
NMF	Neuromuscular Function
Px	Pelvis Flexion/ Extension

Py	Pelvis Abduction/Adduction
Pz	Pelvis Rotation
PFP	Patellofemoral Pain
$Q_{tw,pot}$	Quadriceps Twitch Amplitude
RF	Rear Foot
RFx	Rearfoot Flexion/Extension
RFy	Rearfoot Abduction/Adduction
RFz	Rearfoot Inversion/Eversion
ROM	Range of Motion
RROI	Running Related Overuse Injury
SEM	Standard Error of Measurement
sLTP	Speed of Lactate Turnpoint
SSC	Stretch Shortening Cycle
$s\dot{V}O_2 \max$	Speed of Maximal Oxygen Uptake
TER	Tibial External Rotation
THx	Thigh Flexion/Extension
THy	Thigh Abduction/Adduction
THz	Thigh Internal/External Rotation
TIR	Tibial Internal Rotation
TibX	Tibia Flexion/Extension
TibY	Tibia Abduction/Adduction
TibZ	Tibia Internal/External rotation
VA	Voluntary Activation
$\dot{V}O_2 \max$	Maximal Oxygen Uptake

Publications arising from this thesis

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Riazati S, Caplan N, Matabuena M and Hayes PR (2020) Fatigue Induced Changes in Muscle Strength and Gait Following Two Different Intensity, Energy Expenditure Matched Runs. *Frontiers in Bioengineering and Biotechnology*. 8:360. doi: 10.3389/fbioe.2020.00360

DECLARATION

I declare that the work contained in this thesis has not been submitted for another award and that is all my own work. I also confirm that this work fully acknowledges opinion, ideas and contribution from the work of others.

Any ethical clearance for the research presented in this thesis as been approved. Approval has been sought and granted by the Faculty of Health and Life Sciences Ethics committee for each study.

Name: Sherveen Riazati

Signature:

Date: 8th June 2020

CHAPTER 1 - INTRODUCTION

1.1 Introduction

Recreational running participation has increased since the 1970's (Scheerder *et al.* 2015) and is one of the five most popular sports in the world (Hulteen *et al.* 2017). The growing popularity of club recreational running has, in part, been due to community organised, small, weekly, 5 km running events such as the Parkrun (Wiltshire *et al.* 2017). The growth in the sport has been met with an increase in running related overuse injuries (RROI). Injuries can have a significant negative economic consequence through mental well-being, direct health care costs and loss of paid work (Junior *et al.* 2016).

Recreational runners often take part in competitions ranging from 5 km up to a marathon (2019 Running USA; Parkrun, 2019). To be able to sustain or improve performance for a race, recreational runners train as often as 6 sessions per week (Enoksen *et al.* 2011; Zinner *et al.* 2018). Performance of the races has long been down to three key physiological determinants: $\dot{V}O_2$ max, running economy and maximal steady state (Joyner, 1991). An alternative model was proposed by Paavolainen *et al.* (1999) that included neuromuscular capacity incorporating neural control, running mechanics and muscle force and elasticity. Neuromuscular function and gait changes have been found after a marathon (Nicol *et al.* 1991b), however this remains an under researched area, with no evidence from typical training sessions.

Epidemiological studies have reported running related injury incidence rates of 20% to 70% (Buist *et al.* 2010), and 2.5 to 33.0 injuries every 1000 hours of running (Vidabeck *et al.* 2015). Lower extremity injuries have been reported to occur most frequently, rates range between 19.4% and 79.3%, with the knee (7.2% to 50%) being the most common site of injury (Van Gent *et al.* 2007). The occurrence of knee injuries is mainly due to overuse, where patellofemoral pain (PFP) and iliotibial band syndrome (ITBS) have been identified as the most common RROI (Taunton *et al.* 2002).

Running related overuse injuries are multifactorial with several identified risk factors, e.g., hip and knee muscular strength, altered running kinematics and coordination variability (Buist *et al.* 2010; Hamill *et al.* 2012). Furthermore, they exhibit a distinct running gait profile or signature, primarily characterised by an increased hip adduction angle (Ferber *et al.* 2011; Powers *et al.* 2017). While there is a link between muscular strength and kinematic abnormalities amongst injured runners (Powers, 2010), there is no consensus on whether injuries are the cause or the consequence of muscular strength deficits and abnormal mechanics. The most common risk factor of overuse injury development in runners has been identified as weak hip musculature, primarily in the two most common injuries (Noehren *et al.* 2007; Powers, 2010). Poor muscular strength is found alongside abnormal running mechanics in injured compared to healthy runners (Bazett-Jones *et al.* 2013; Derrick *et al.* 2002; Dierks *et al.* 2010). There is however a limited amount of information examining both muscular strength and changes to kinematics during runs, and no evidence on their subsequent recovery.

Fatigue has been identified as an extrinsic factor contributing to the development of RROI (Rolf, 1995), yet only a handful of studies have examined the effect of acute fatigue on risk factors healthy runners. Willson *et al.* (2015) observed an increase in hip adduction angle in both male and female runners while other studies observed little increase to no change in hip frontal kinematics (Dierks *et al.* 2010; Bazett-Jones *et al.* 2013; Brown *et al.* 2016). These studies however used runs to exhaustion, often performed at the same absolute running speed for all participants. The use of absolute intensities can result in runners performing in different physiological domains resulting in different mechanisms of fatigue (Burnley and Jones, 2018). Moreover, runners seldom perform continuous runs to exhaustion during training, although they do undertake fatiguing high intensity interval training (HIIT) (Laursen, 2010). In trained runners, these HIIT sessions are more effective than continuous runs at moderate intensities at improving critical aspects of running performance i.e. $\dot{V}O_2$ max (Bacon *et al.* 2013). Billat *et al.* (1999)

found that frequent use of HIIT sessions (3 or more times per week) led to symptoms of overtraining. Despite their undoubted importance, endurance athletes typically use HIIT sessions judiciously, only accounting for 10-15% of weekly training volume (Laursen, 2010). The remaining training being performed at lower intensities to facilitate recovery, often continuously e.g. medium intensity continuous runs (MICR) (Laursen, 2010). It is not known whether HIIT sessions invoke greater changes in gait than continuous running and therefore potentially pose a greater risk of developing RROIs.

To better understand the complexity of gait biomechanics that contribute to the development of RROIs, coordination variability has been used in recent years. Coordination variability is examined through the coordination of coupling joints, where the motion of one joint can influence another (DeLeo *et al.* 2004). There are currently three suggested methods for examining coordination variability (Hamill *et al.* 2012), however only two have been used in running (Miller *et al.* 2008; Brown *et al.* 2016); continuous relative phase and coupling angle through vector coding (Miller *et al.* 2010). Hamill *et al.* (2012) proposed that deviating from an optimal coordination variability, defined as a coordination state where the two joints remain stable, healthy and unchanged, to be a risk factor for injury with injured runners presenting a reduced coordination variability. Similarly, a very high coordinative variability can contribute to the development of overuse injuries. Only two studies have examined the effect of fatigue on coordination variability using dynamical system theory applications finding, both increased and decreased coordination variability following a run to exhaustion (Brown *et al.* 2016; Miller *et al.* 2008).

At present there is a dearth of knowledge examining fatigue induced changes to gait following typical training runs performed by recreational runners. The need to examine typical training runs was further highlighted by the framework leading to RROI proposed by Bertelsen *et al.* (2017). Their framework outlined the relationship between the cumulative load experienced

during a training session, which is determined by the magnitude of the load experienced per stride and its distribution over tissue structure, with the aetiology of an overuse injury. In this model, when the cumulative load exceeds the tissues ability to tolerate it an injury occurs.

Bertelsen's *et al.* (2017) framework identified a possible pathway to running related overuse injury development, however it does not provide a mechanistic explanation of the reduction in tissue load tolerance during a run or how this can cause a RROI. For a better understanding of the aetiology of RROI, a multifactorial approach, where multiple risk factors are examined is required.

While the reliability of gait kinematics has been examined under various settings and conditions (McGinley *et al.* 2009), its reliability in a fatigued condition is unknown. Unlike kinematics, the reliability of coordination variability has not been examined either fatigued or non-fatigued. To detect a meaningful change, sometimes referred to as a 'real change', requires the use of the minimum detectable change (MDC) statistic. This is a confidence interval based upon absolute reliability, which when exceeded indicates a real change (Weir 2005). Its use offers the potential to identify individuals who have experienced a real change, compared to null-hypothesis testing which only identifies between differences groups.

1.2 Aims

To date, the effect of fatigue developed during typical training sessions on muscle function and gait kinematics has not been investigated. Both of these variables have been linked to running related overuse injuries. In an attempt to maximise the utility of any findings from this thesis, early masters age group runners were selected as they have had the highest increase in running participation (Willy and Paquette, 2019).

The primary aim of this thesis was to assess the effect of fatigue, accumulated during typical training sessions, on risk factors associated with frequently occurring running related overuse injuries. In order to achieve this aim, the thesis examined:

1. the between-day reliability of neuromuscular and kinematic risk factors associated with running related overuse injuries at both the beginning and end of two typical, but different intensity, training runs (*chapter 4*).
2. changes in muscle strength, kinematics and coordination variability from the beginning to end of typical, but different intensity, training runs
3. different statistical approaches for the assessment of fatigue resulting from typical, but different intensity, training runs. (*Chapter 6*).
4. the time course of recovery for neuromuscular and kinematic risk factors associated with running related overuse injuries. (*Chapter 7*)

CHAPTER 2 - REVIEW OF LITERATURE

This review will start by examining the popularity of running and training practices before moving on to examine determinants of running performance, the role of the stretch shortening cycle, identifying mechanisms that bring about fatigue, how they affect the stretch shortening cycle and the time-course of recovery. Specific attention will also be given to detailed gait events during running, changes to gait with fatigue and coordination variability of joint couplings during running measured through dynamical systems theories. The final sections will explore incidence rates of running related overuse injury, identifying the most common running related overuse injuries and the potential risk factors of these injuries.

2.1. Running Overview

Running is recognised as a good form of promoting health, social experience and performance enhancement; motives that have attracted diverse populations of all ages and genders.

Recreational running can be characterised as a mass movement, being a social expression of the counterculture of the 1960's, where running was largely distanced from club-organised setting and became an independent activity (Scheerder *et al.* 2015). Thanks in part to the mass movement towards recreational running, running is now pursued by millions worldwide (Scheerder *et al.* 2015). In Europe approximately 12% of the population regularly run (Scheerder *et al.* 2015). The Parkrun, a free, weekly, timed 5km run started in 2004 in a single location in the UK with 13 participants; now there are approximately 105,000 runners per week in 20 countries (Parkrun, 2019). Globally, running is one of the most participated sports in the world, it has been identified as one of the top five most popular global recreational activities (Hulteen *et al.* 2017). In 2016, nearly 42 million people in the USA took part in some form of running event with 507,600 runners finishing a marathon, compared to 25,000 in 1976 (2019 Running USA). One of the main attractions for recreational runners in events such as 5k, 10k, and marathons is

to complete the race in the least time; to achieve this goal runners train regularly (Parkrun, 2019; 2019 Running USA).

2.1.1 Physiological Determinants of Running Performance

Endurance running performance has been attributed to three main physiological parameters:

maximal oxygen uptake ($\dot{V}O_2 \text{ max}$), fractional utilisation of $\dot{V}O_2 \text{ max}$ / maximal steady state and running economy (RE) (Bassett and Howley, 2000; di Prampero, 2003; Joyner and Coyle, 2008).

$\dot{V}O_2 \text{ max}$ is the highest rate at which oxygen can be utilized during whole body exercise (Basset and Howley, 2002). The percentage of $\dot{V}O_2 \text{ max}$ sustained over a distance is known as fractional utilization (Maughan and Leiper, 1983). The ability to maintain a high percentage of $\dot{V}O_2 \text{ max}$ is an important determinant of performance and is related to the percentage of $\dot{V}O_2 \text{ max}$ where maximum steady state occurs (Jones, 2006; Sjodin and Svedenhag, 1985). During incremental exercise, a curvilinear relationship exists between exercise intensity and the accumulation of blood lactate. This relationship is used to identify lactate threshold (LT) and lactate turnpoint (LTP) (Figure 2.1), the latter used as a measure of maximum steady state (Jones, 2006; Jones and Carter, 2000; Smith and Jones, 2001). Both LT and LTP are highly trainable, with aerobic training they occur at a higher percentage of $\dot{V}O_2 \text{ max}$ (Hawley, 2002). Running economy (RE) is the oxygen cost of running at a given speed. In homogeneous groups of runners RE is considered a better predictor of endurance performance than $\dot{V}O_2 \text{ max}$ (Saunders *et al.* 2004).

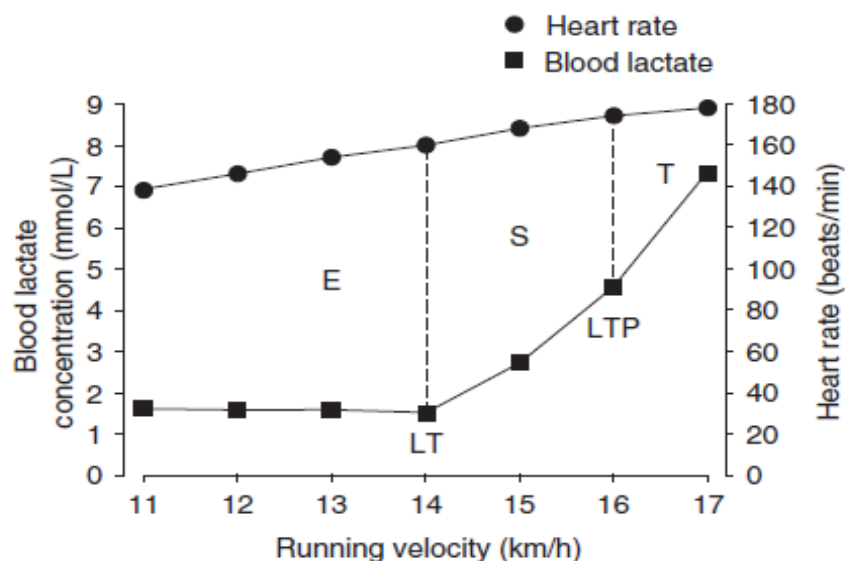


Figure 2.1. Blood lactate and heart rate responses of a competitive club runner during incremental test identifying lactate threshold (LT) and lactate turnpoint (LTP). The easy (E), steady (S) and tempo (T) running training zones are associated with exercise intensity. Figure adapted from Midgley *et al.* (2007)

2.1.2 Training to Improve Performance

In order to improve running performance, runners seek to use the most effective training methods (Midgley *et al.* 2006). There are two main forms of training to improve endurance running performance, moderate intensity continuous running (MICR) and high intensity interval training run (HIIT) (Enoksen *et al.* 2011). High intensity interval training elicits both oxygen transport and utilization adaptations to improve $\dot{V}O_2$ max, when maintained at maximal, or near maximal, oxygen uptake (85%-95% of $\dot{V}O_2$ max) (Enoksen *et al.* 2011; Wen *et al.* 2019). Medium intensity continuous runs are commonly used to train maximum steady state, or at intensities between 50% – 80% of $\dot{V}O_2$ max (Enoksen *et al.* 2011). The MICR is also typically performed at speeds between LT and LTP identified in Figure 2.1 as zones E and S, enabling long distance training with less fatigue (Enoksen *et al.* 2011).

2.2 Neuromuscular Capacity

Paavolainen *et al.* (1999) proposed a model of running performance identifying the role of neuromuscular performance and capacity as a running performance determinant (Figure 2.2).

The model includes neural control, muscle force and elasticity, and running mechanics. By comparison with the metabolic determinants of running performance, the neuromuscular components have received far less attention. Each of these three components will now be considered in greater depth.

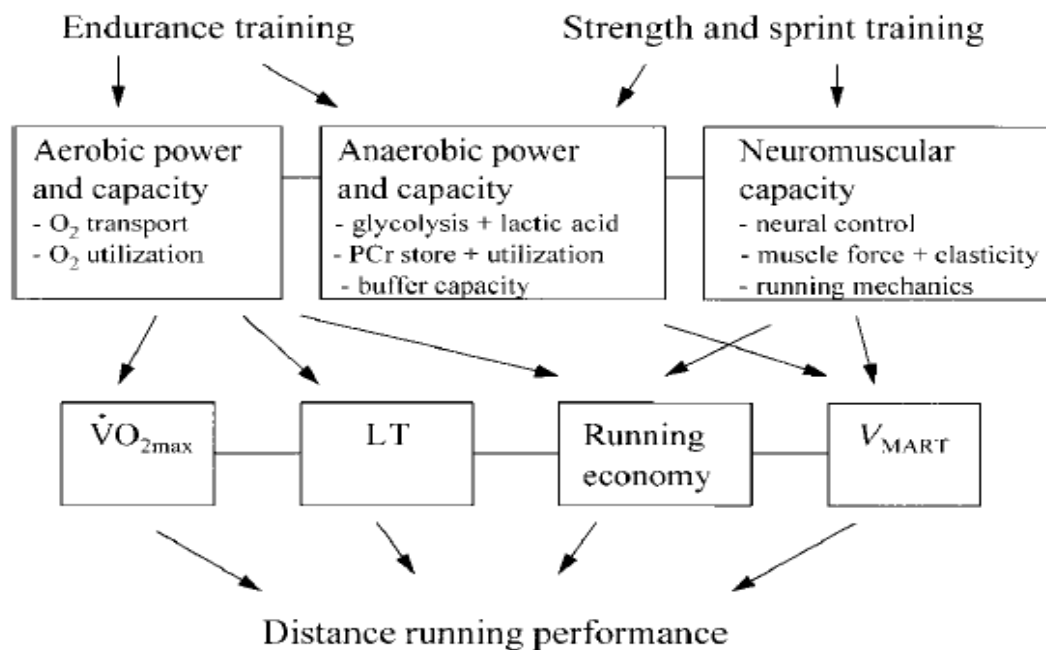


Figure 2.2. Model adapted from Paavolainen *et al.* (1999) identifying neuromuscular function and its influence on running mechanics as determinants of distance running performance in endurance athletes.

2.2.1 Neural Control

The pathway of muscle activation begins in the motor cortex where the voluntary activation of motor neurons transmits an action potential to the motor neurons in the spinal cord. From there,

the action potential is relayed to the motor end plate, releasing acetylcholine across the neuromuscular junction. The resultant action potential depolarises the sarcolemma, resulting in the release of calcium ions from the sarcoplasmic reticulum into the sarcomere. Ca^{2+} released in this process binds with troponin enabling actin and myosin cross-bridges to form and produce force; the amount of force produced being proportional to the number of cross-bridges formed (Allen *et al.* 2008; Gandevia, 2001; Nicol and Komi, 2010). The sequence of signal transmission from the neuromuscular junction to the generation of force at the cross-bridges is known as excitation-contraction coupling (Gandevia, 2001). Events within the brain and spinal cord are referred to as central, while events distal to the motor neuron are called peripheral (Bigland-Ritchie and Woods, 1984; Allen *et al.* 2008; Nicol and Komi, 2010).

2.2.2 Muscle Force and Elasticity

Locomotion activity such as running are best described through a mechanical system combining both the elastic recoil of the muscle-tendon unit with the contractile muscular work described as a stretch-shortening cycle (SSC) (Heglund and Cavagna, 1985; Nicol and Komi, 2010). A SSC task is characterized by the coupling of an eccentric and subsequent concentric contraction. Norman and Komi (1979) identified SSC as consisting of a three phase process (Figure 2.3), i) pre-activation of lower limb extensor muscles prior to ground contact to in readiness to absorb the impact ii) the active braking or stretch phase, which occurs during the first part of the stance phase iii) a concentric action of the muscles or shortening action, during the second half of the stance phase, which is involved in propulsion (Komi, 1984).

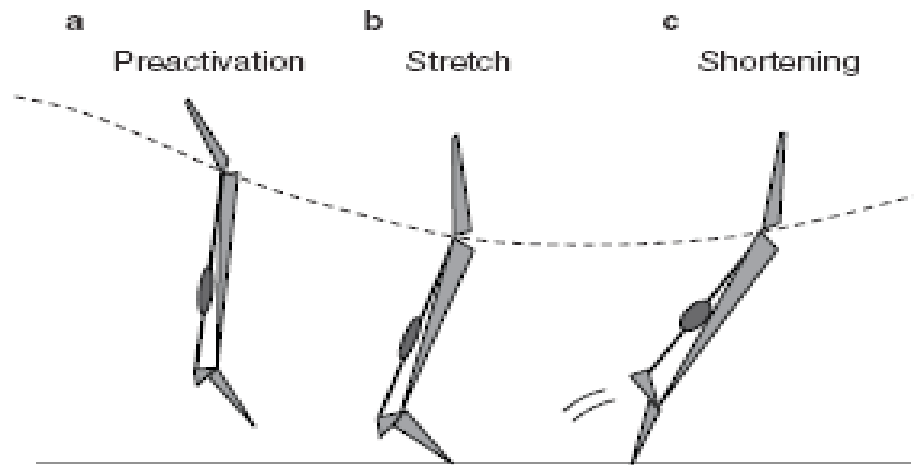


Figure 2.3. Stretch-shortening cycle during human locomotion, incorporating the musculo-skeletal components of the lower limb (Komi, 2000; pp. 1198).

The mechanisms of SSC allows for more work to be completed in the concentric phase when compared to an isolated concentric contractions due to the utilisation of the stored elastic energy from the eccentric phase (Cavagna *et al.* 1965; Komi, 2000). In addition, the stretch-reflex mechanism contributes to the potentiation of SSC performance. The stretch-reflex potentiates muscle performance, as the rapid changes in muscle contractions favour the contribution of spindle-mediated reflex responses to muscle force generation (Komi, 2003). The increased excitability from the muscle spindles and desensitisation of the Golgi tendon organs, (GTO) located in the extrafusal fibres of muscle-tendon unit, allow optimisation of the neuromuscular system. As muscle tension reaches a point where there is a risk of damage to the muscle-tendon unit, the GTOs inhibit the motor neurons innervating the agonist muscle, facilitating the antagonist motor units. The muscle spindles, which lie parallel to the intrafusal muscle fibres, respond to the eccentric action that threaten the integrity of the muscle-tendon unit structure, immediately countering it by initiating a contraction of the agonist muscle. The stretch reflex

evoked by the GTO and muscle spindle to protect the muscle-tendon unit, is identified as one of the mechanisms behind SSC (Flanagan and Comyns, 2008; Trimble *et al.* 2000). Another contribution of stretch reflex is its role in regulation of muscle stiffness by varying the amount of elastic energy stored in series-elastic component (Komi, 2000).

2.2.3 Running Mechanics

While there has been considerable research on metabolic costs of running, factors relating to mechanical elements are relatively unexplored, particularly with fatigue. Running is a complex movement pattern that involves the conversion of muscular forces utilised by all major joints in the body (Saunders *et al.* 2004). Running performance is not just dependent on physiological aspects, as running gait and biomechanical factors such as ground contact, step length, and lower extremity kinematics, and neuromuscular performance play a role in running performance (Paavolainen *et al.* 1999).

Chapman *et al.* (2012) suggested that running economy in elite middle and long distance runners could be largely influenced by ground contact time. Additionally, lower leg kinematics and spatiotemporal parameters such as knee flexion angle, stride length and stride frequency have been shown to have an effect on running economy, a critical determinant of endurance running performance (Bassett and Howley, 2000; Jones, 2006; Williams and Cavanagh, 1987). Peak hip flexion and knee RoM have been reported to be predictors of oxygen uptake as they are associated with vertical oscillation of the body (Sinclair *et al.* 2013; Williams and Cavanagh, 1987). An increase in the vertical oscillation of centre of mass has been associated with reduced running economy, while slowing of centre of mass in the early stance phase have been found to improve RE (McMahon *et al.* 1987; Saunders *et al.* 2004).

Mechanical changes that influence performance are however either the cause or consequence of neuromuscular function factors. Paavolainen *et al.* (1999) introduced a model (Figure 2.2) showing the effect of neuromuscular capacity as a performance determinant. The model indicates that neuromuscular capacity encompasses three factors: neural control, muscle force and elasticity, and running mechanics.

Running biomechanics is investigated by examining joint or body segment kinematics (e.g. position and displacement). Running mechanics have been used extensively in understanding the aetiology of RROI, however this section will first outline the key kinematic events within running gait before examining differences between healthy and injured runners.

2.2.3.1 Gait analysis

The first recorded discussion on human movement was made by Aristotle in 384-322 B.C., while the first experiments and theories were not made until Giovanni Alfonso Borelli in the 1600s (Baker, 2007). The first modern gait analysis was performed by Jules Etienne Mary (1830-1904) (Baker, 2007). Prior to technological advancements enabling motion capture or videography through computer assistance, Jules Etienne Mary performed gait analysis mainly through using still images. The first three dimensional gait analysis was performed by Otto Fischer (1861-1917) (Baker, 2007). Only in recent decades has gait analysis been made available for use in both clinical and research settings alike. With advancements in technology, gait analysis is now more reliable, accurate, and allows for frame by frame observation (Switaj and O'Connor, 2008). Gait analysis through three-dimensional motion capture will be the primary tool used in this thesis for examining hip and knee movements during running.

2.2.3.2 Gait Cycle

Running is a sequence of repeated movements, this patterns is referred to as the gait cycle. It is best explained when divided into phases and each phase broken down into events (Figure 2.4) (Novacheck, 1998). In order to describe the gait cycle there are two common terms used, a step and a stride, with the latter being the focus of this thesis. Cavanagh and Williams (1982), defined a stride as consecutive contacts of the same foot, with a step defined as successive contacts of opposite feet; a step is therefore half of a stride.

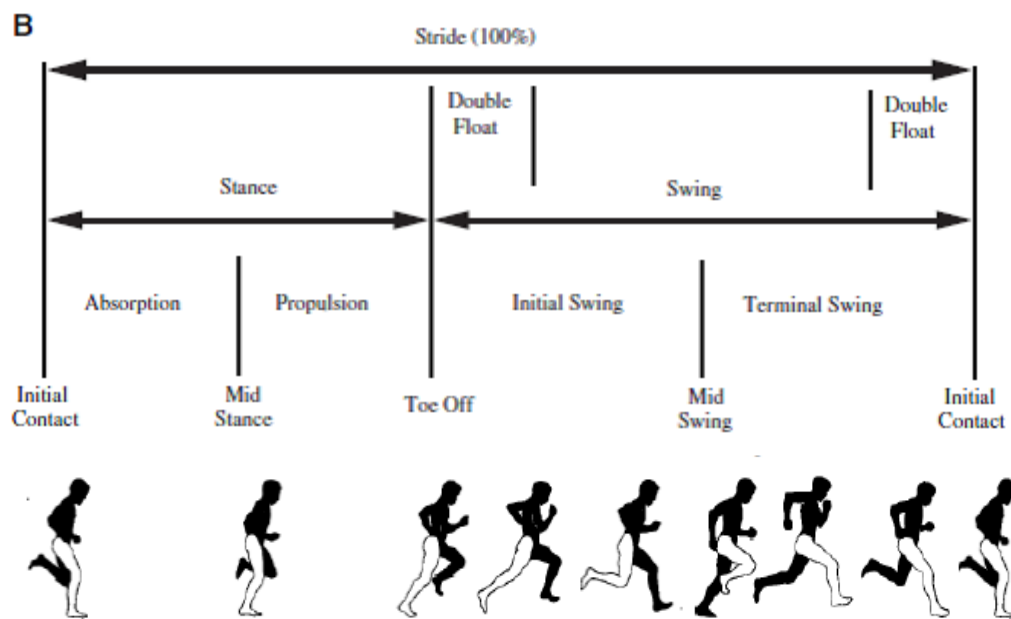


Figure 2.4. Gait cycle and associated events adapted from Novacheck, 1989.

The stance phase begins with the heel making contact with the ground and ends at toe off, when the same foot leaves the ground. Stance phase can be divided in two halves or sub-phases of absorption – where the body absorbs the energy from contact with the ground, commencing at initial contact up to the middle of stance) and propulsion – where centre of mass of the body is

propelled upwards and is referred as the propulsion phase. The second phase of stride cycle, the flight phase, begins with foot take-off and ends when the foot makes initial contact (Novacheck, 1998). This thesis is focused on the events of the stance phase as the majority of pathological issues associated with the lower extremities become apparent during the stance phase, as the joints are undergoing their greatest stress due to the weight-bearing load placed on them.

The stance phase begins with the initial ground contact. At the time of contact with the ground, the foot lands in front of centre of mass, tending to be in a supinated position, while the leg swings toward the line of progression in the midline, at this point, in the frontal plane, the leg is at 8° to 14° of functional varus (Dugan and Bhat, 2005). At initial contact, hip adductors provide stability to the lower limb and remain active throughout the rest of stance (Dugan and Bhat, 2005). After initial contact the foot tends to progress into dorsiflexion due to limited plantar flexion (Novacheck, 1998).

The absorption or weight acceptance phase, is important as ground reaction forces exceed two times body weight, as the position and acceleration of the centre of mass determine the magnitude and direction of the ground reaction force (Cavanagh and LaFortune, 1980). Towards mid-stance, dorsiflexion continues through mid-stance reaching up to 20° while the foot is fixed to the ground, maximum dorsiflexion occurs when the centre of gravity passes anterior to the base of support (Dugan and Bhat, 2005; Novacheck, 1998). While the foot is progressing through the cycle an extension moment occurs as the centre of mass shifts from behind the knee at initial contact to in front of the knee. This extension of the lower limb is controlled by the hamstrings while the shift of the tibia is controlled by the gastrocnemius and soleus muscles (Novacheck, 1998). The tibialis posterior muscles along with plantar flexors control the pronation that takes place when the centre of mass passes front of the base of support (Novacheck, 1998). The end of the absorption phase of stance is signalled by the point of maximum pronation and beginning of propulsion, with a shift in ground reaction force traveling

anteriorly through the knee joint and stabilised through co-contraction of the quadriceps and hamstrings (Cavanagh and LaFortune, 1980; Dugan and Bhat, 2005; Novacheck, 1998).

At start of the stance phase, the hip is in a flexed position before moving into extension for the remainder of the stance phase (Novacheck, 1998). Adduction and internal rotation movements of the hip occur in both the transverse and frontal planes during the absorption phase of the stance, with abduction and external rotation taking place from mid-stance until toe-off. During the early part of the swing phase, the hip begins to extend, reaching maximum extension at around 78% of the entire gait cycle. The hip then moves back into flexion, placing the leg in position for the initial contact (Novacheck, 1998). Hip internal rotation continues at small degrees within the swing phase and hip abduction is observed during the initial part of the swing phase before moving into adduction during terminal of swing.

When considering hip frontal mechanics in isolation during gait, hip adduction is the result of either the thigh abducting relative to the pelvis with the pelvis elevating on the contralateral side, or a combination. At the initial ground contact, the hip is adducted approximately 7 degrees in males and 11 degrees in females (Willson *et al.* 2012). Between initial contact and mid-stance, the hip begins to abduct until toe-off, reaching a maximum abduction angle of about 8 degrees during the swing phase. Hip frontal angle is then returned to neutral when the foot descends prior to start of the next stride or initial contact.

In the absorption phase of stance, the knee is in flexion and by mid-stance it reaches maximum knee flexion (Novacheck, 1998). The knee then starts to move into extension at the propulsion phase, until maximum knee extension is reached at toe-off (Novacheck, 1998). The knee returns to flexion at the onset of swing, reaching maximum flexion at close to 75% of the way through the gait cycle before going into extension towards end of the swing phase, the knee reaches maximum extension before the foot makes contact (Novacheck, 1998).

During initial ground contact, the ankle is in dorsi-flexion, reaching maximum dorsiflexion at end of the absorption phase of stance (Ounpuu, 1994; Novacheck, 1998). In the propulsion phase of the gait, the ankle joint plantar-flexes, reaching maximum plantar-flexion early in the swing phase (Novacheck, 1998, Ounpuu, 1994). For the remainder of the swing phase, the ankle moves into dorsi-flexion preparing the foot for initial ground contact; the amount of dorsiflexion depends on the type of stride pattern (Novacheck, 1998; Ounpuu, 1994).

2.2.3.2.1 Stride length and Stride frequency

Stride frequency is identified as the number of strides completed over a specified time. Stride length and stride frequency are components of running velocity, where the product of stride length and stride frequency produce velocity. A change in velocity can be influenced by a change in either stride length or stride frequency, which can affect physiological variables. Runners tend to select a stride length that minimises metabolic costs (Cavanagh and Williams, 1982; Hamill *et al.* 1995). Stride length also influences running kinematics, with increases in stride length increasing joint range of motion during stance (Derrick *et al.* 1998). Stride length has also been shown to increase with fatigue by as much as 3 cm (Derrick *et al.* 2002; Gerlach *et al.* 2005; Hanon *et al.* 2005). Furthermore, alterations in stride length have been shown to have an effect on ground reaction forces, with a longer stride increasing loading rate (Willson *et al.* 2015). By manipulating stride length and frequency, Mercer *et al.* (2003) found that only stride length had an effect on shock attenuation. Stride frequency has a cause and effect relationship with contact time, as an increase can lead to a decrease in stride frequency and vice-versa (Nummela *et al.* 2007).

2.2.3.2.2 Contact time

Ground contact time has been recognized as one of the most important spatiotemporal parameters in running. Changes in contact time have been associated with an inability to maintain performance (Hayes and Caplan, 2014). Hasegawa *et al.* (2007) found a relationship between contact time and performance during a half-marathon; runners with a shorter contact time had a higher finishing. Shorter contact time has been linked with lower energy cost through better utilization of stored elastic energy from eccentric contraction phase of the SSC (Kyröläinen *et al.* 2001; Paavolainen *et al.* 1999). Shorter ground contact times have also been associated with economical runners as result of shorter braking phases allowing for optimization of SSC (Butler *et al.* 2003; Nummela *et al.* 2007). Contact time is also speed dependent, faster running has been associated with a decrease in contact time allowing for sufficient time to swing the leg into position (Weyand *et al.* 2000).

2.3 Fatigue

Despite being a topic for research since the 18th century there is still no unanimous definition of fatigue. Definitions of fatigue are often context specific, three widely used definitions are i) a decrease in performance capacity of muscles, during or after an activity, usually evidenced by a failure to maintain or develop a certain expected force or power (Asmussen, 1979); ii) any reduction in force generating capacity of the neuromuscular system, including the ability to maintain a constant sub-maximal force (Bigland-Ritchie and Woods, 1984); iii) “a reduction in the maximum force generating capability of the muscle” (Gandevia 2001). It is this final definition that will be used in this thesis. Fatigue can occur at multiple points along the chain of events identified in section 2.2.1 that results in voluntary force production.

2.3.1 The effects of fatigue on neuromuscular capacity

This section of the literature review will now consider the effects of fatigue on the neuromuscular capacity and its sub-components identified in Paavolainen *et al*'s (1999) model (sect 2.2). During any type of training run, fatigue has the potential to influence any of the neuromuscular capacity factors of neural, muscle force and elasticity, and gait, individually or collectively which can influence performance. The following sections review the effect of fatigue on each of the three components of neuromuscular capacity.

2.3.1.1 Neural Factors

An impairment to neuromuscular capacity can be either through the central or peripheral nervous systems. Central fatigue constitutes decrements at or proximal to neuromuscular junction while peripheral decrements occur at or proximal distal to neuromuscular junction (Taylor *et al.* 2006).

2.3.1.1.1 Central Fatigue

An exercise induced reduction in voluntary activation, that is the inability to fully recruit the active muscle, is defined as central fatigue (Taylor *et al.* 2006; Gandevia, 2001). Impaired voluntary activation is the result of reduction in descending cortical output from the motor cortex or efficacy of output (Gandevia, 2001; Taylor *et al.* 2006). The decrement in voluntary activation, or central fatigue, involves spinal and supraspinal factors that are associated with a reduction in motoneuron activation (Lattier *et al.* 2004). The spinal level is well understood and known to be caused by alterations to excitability of the motoneuronal pool (Gandevia, 2001). Supraspinal fatigue is related to a sub-maximal output from the motor cortex due to inhibition occurring within the motor cortex (Gandevia *et al.* 1996), its process is however not so well understood. Gandevia (2001), explained that the likely cause of the inhibition for the central motor derive are the group III-IV muscle afferents. Previous studies however have been unable

to examine the effect of group III-IV muscle afferents in central fatigue (Amann *et al.* 2013; Amann and Dempsey, 2008; Blain *et al.* 2016). Apart from group III-IV afferents, Goodall *et al.* (2012) suggested impaired brain oxygenation may induce voluntary activation decrements.

2.3.1.1.2 Peripheral Fatigue

Underlying mechanisms causing peripheral fatigue could result from a combination of metabolic and structural changes. Raastad and Hallén, (2000) identified increased concentrations of hydrogen ions and inorganic phosphate, along with a reduction in creatine phosphate concentration as possible metabolic causes. An immediate increase in inorganic phosphate concentration is the result of hydrolysis of adenosine tri-phosphate and dephosphorylation of phosphocreatine at the onset of muscular contraction (Allen *et al.* 2008; Cady *et al.* 1989; Coupland *et al.* 2001). As exercise continues, there is an increase in hydrogen ion concentration resulting from glycolysis becoming the primary energy source (Allen *et al.* 2008; Raastad and Hallén, 2000). The exercise induced increases in hydrogen ions and inorganic phosphate can lead to disrupted excitation-contraction coupling (Garland and Kaufman, 1995). Raastad *et al.* (2000) suggested that the changes in excitation contraction coupling can affect the release of Ca^{2+} thereby reducing cross-bridge formation. High concentrations of inorganic phosphate can inhibit the release of Ca^{2+} from the sarcoplasmic reticulum, reduce myofibril sensitivity to Ca^{2+} , and reduce the number of active cross-bridges inhibiting muscle force production (Lattier *et al.* 2004).

2.3.1.2 The effect of fatigue on muscle force and elasticity

Long distance running involves a series of repeated, sub-maximal SSCs and therefore repeated sub-maximal impact loads. Cumulatively, these repeated SSCs can contribute to fatigue

followed by recovery process that can last several days (Komi, 2000). The fatigue experienced from repeated sub-maximal SSCs can be multi-factorial, encompassing mechanical, neural and metabolic processes (Nicol and Komi, 2010).

Stretch shortening cycle fatigue results in reversible damage of muscle tissue, reduced reflex activity and altered muscle performance (Komi, 2000; Avela, 1996). The decrements have been associated with a reduced tolerance to ground impact and reduced muscle strength (Avela *et al.* 1999; Horita *et al.* 1996; Nicol *et al.* 1991a). It has also been suggested that when the speed of muscular contraction is similar in running and jumping activities, then so too is the elastic behaviour of the leg extensor muscles (Bosco *et al.* 1987). In the majority of studies investigating SSC fatigue, jumping tasks have been employed because of their relationship with running performance (Hennessy and Kilty, 2001) and their ease of measurement (Nicol and Komi, 2006). Based on a review by Nicol and Komi (2010), similar decrements in maximal voluntary contraction (MVC) are found following jumping (~22%) and running (26%) protocols. Studies using a high number of jumps or rebound exercises have been shown to produce a decline in voluntary activation and alterations to jump parameters (Kuitunen *et al.* 2004). Following maximum leg rebounds, Kuitunen *et al.* (2002, 2004) reported a 30% reduction in MVC. Skurvydas *et al.* (2000) reported a 23% reduction in MVC following 100 intermittent drop jumps and a 20% reduction following continuous drop jumps. Kuitunen *et al.* (2002) also reported decrease in muscle activation for the jumping parameters of braking phase activation, pre-contact activation, push-off phase activation as result of fatigue following drop jumps from 35 cm and 55 cm heights. Similarly, following a marathon, Avela *et al.* (1999) reported fatigue induced changes to sledge jump performance of increase in contact time, push-off time; along with decreases in take-off velocity, impact force, and push-off force.

Within studies examining running protocols however, the decrement in MVC are duration and intensity dependent, the results also vary depending on the muscle group examined. Most studies have used an MVC following a marathon or ultramarathon, these are races and therefore presumably performed to exhaustion. These runs however, are not typically performed by runners during their weekly training sessions (Enoksen *et al.* 2011). Millet *et al.* (2002) reported a 30% reduction in MVC following a 65km ultramarathon run. Similarly, Place *et al.* (2004) reported a 28% reduction in knee extensor MVC following a 5-hour treadmill run at 55% of the speed at $\dot{V}O_2$ max and Millet *et al.* (2003) reported a 24% reduction in MVC following a 30km running race. Shorter distance runs, while still inducing a considerable reduction in MVC, have shown less effect. Lepers *et al.* (2000) examined knee extensor strength during multiple contractions following a 2-hour run at 75% of $\dot{V}O_2$ max. They reported a reduction of 19% in MVC, and also found that force production during eccentric contractions was 6% lower than concentric contractions. The loss of eccentric function was attributed to the inability to maintain stretch-loads, altered muscle stiffness and SSC efficacy, however no difference in neural input to the knee extensors during concentric and eccentric contractions was found. Davies and White, (1982) reported a 9% reduction in triceps surae MVC following a 1-hour treadmill run at approximately 70% of $\dot{V}O_2$ max.

Compared to MVC, twitch interpolation has not been examined widely within SSC exercises. Unlike maximal voluntary contraction, jumping and running have been shown to differently effect peripheral drive, examined through twitch potentiation. Studies examining jumping SSC exercises have reported a reduction in peak twitch torque ranging between 13 – 70% (Nicol and Komi, 2006), while increases in twitch torque of 18% (Place *et al.* 2004) and 16 % (Millet *et al.* 2002) were reported in long duration runs. Millet *et al.* (2002) contested that twitch response might not be a good representation of peripheral fatigue, because potentiated twitch can increase the stiffness of the muscle-tendon unit. They also suggested that twitch response could be run

duration dependent. Runs of less than 1-hour and distances below 30 km have induced a reduction in twitch potentiation of 13% and 8%, respectively. (Davies and White., 1982; Millet *et al.* 2002). Repeated maximal sprints (12 x 30 m) reduced quadriceps twitch potentiation by 24% (Goodall *et al.* 2015) which is greater than that seen in continuous sub-maximal running .

Neural activation failures and loss of muscular strength are evident in SSC exercises as participants fatigue. Kuitunen (2004) examined VA during 100 maximal drop jumps on a sledge ergometer. They reported that as the number of drop jumps increased, VA decreased, suggesting that during SSC exercise the contribution of central fatigue to MVC force loss increases. During running however, the reported VA is similar with studies examining different durations.

Voluntary activation decreases have been reported after a 64 km ultramarathon (13%) (Millet *et al.* 2002), 30 km run (10.7%) (Millet *et al.* 2003), 24 hour treadmill run (33%) (Martin *et al.* 2010), 5 hour treadmill run (16%) (Place *et al.* 2004) and repeat sprints (9%) (Goodall *et al.* 2014). In these studies the intensity of the run is not described in detail, however the origin and extent of neuromuscular fatigue are exercise intensity dependent (Burnley and Jones, 2016). In runs below LT, the origin of fatigue is mostly central while during heavy domain exercise (between LT and LTP), fatigue can have both central and peripheral origins (Burnley and Jones, 2016). Both Millet *et al.* (2002) and Millet *et al.* (2003) were performed at race paces. Runners of Martin *et al.* (2010) and Place *et al.* (2004) performed a 24 hour treadmill run at 39% of $\dot{V}O_2$ max and 55% of maximal aerobic velocity respectively. While all studies exhibited both peripheral and central fatigue, the variations in VA findings could have been intensity dependant. The effects of fatigue on both central and peripheral drive as a result of a typical training runs remain unexamined.

2.3.1.2.1 Recovery from fatiguing SSC activity

The time course of recovery following SSC exercise has not been examined as extensively as fatigue immediately after SSC activity. Recovery processes following SSC activity have been described as a biphasic, where recovery up to 2 hours following exercise is known as the acute phase and recovery up to seven days is identified as delayed recovery (Figure 2.6) (Nicol and Komi, 2010). Nicol and Komi (2010) also outlined that recovery duration may take up to 8 days.

It is the eccentric phase of the SSC induced muscle damage that causes the prolonged decrements following SSC exercise (Horita *et al.* 1996).

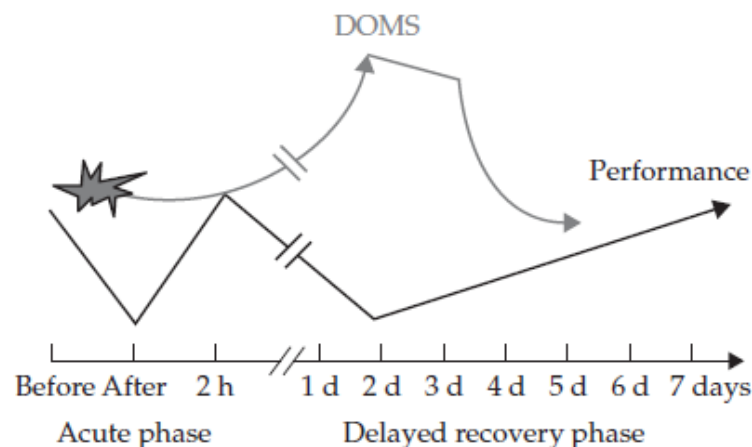


Figure 2.5. Schematic representing the biphasic model and inclusion of DOMS post exhaustive stretch shortening cycle exercise reproduced (from Nicol and Komi 2010)

Systematic attempts have been made to examine the time-course of recovery from running as a function of exercise duration and/or intensity. Avella *et al.* (1999) examined MVC at 2-hours, 2-days, 4-days, and 6-days following a marathon run. They reported significant reductions in force immediately post and 2-hours following the marathon, with a return to baseline by day 2. Their study also examined stretch-reflex activity during sledge ergometer jumps. Immediately after the run, there was significant drop in stretch reflex, at 2-hours the runners had partially recovered but were still significantly below baseline. The stretch reflex response remained close to the

immediately post-run values at day 2, and were still not fully recovered at day 6. A similar trend was observed in Horita *et al.* (1999), following exhaustive sub-maximal leg rebounds. They reported significantly reduced stretch reflex function immediately post, partial recovery at 2-hours, followed by further reductions close to immediately post-run values at day 2 and day 4. Running has been shown to impair SSC function, however mainly through prolonged runs or races to exhaustion. At present little is known about if a typical training session induces impairments to SSC function or if any decrements cause or accompany mechanical alterations to running gait.

2.3.1.3 Gait changes with fatigue

With the progression of fatigue during a run, runners tend to exhibit mechanical changes to their running gait, these changes can depend on their training and experience level (Clansey *et al.* 2012). Generally, the effects of fatigue on gait have been conducted through competitive races e.g. a marathon (Nicol *et al.* 1991a) or prolonged runs to exhaustion on a treadmill (Dierks *et al.* 2008). While kinetic and kinematic changes have been observed with fatigue (Derrick *et al.* 2002; Dierks *et al.* 2011; Mizrahi *et al.* 2000) only a few studies having supported this with a direct measurement of muscular strength pre and post running run (Bazett-Jones *et al.* 2013; Dierks *et al.* 2008; Nicol *et al.* 1991b) to understand possible links between gait and muscle strength.

During a run, changes in running speed and spatiotemporal parameters have been reported to be affected by fatigue. Towards the end of the run, as fatigue accumulates, runners have been found to increase contact time and decrease running velocity to lower metabolic cost (Nummela *et al.* 2007). At the end of a run to exhaustion or a race, studies have reported decreased stride frequency and increase in contact time (Gazeau *et al.* 1997; Hanley *et al.* 2011; Hayes and

Caplan, 2012). Changes in contact times have been associated with SSC fatigue. Horita, (2000), reported longer contact times and reduced eccentric muscular strength with time progression during rebound exercises. The longer contact times may be indicative of reduced ability to tolerate impact (i.e. braking action) (Nicol and Komi, 2010).

Nicol *et al.* (1991a), reported increased ground contact time and knee flexion angle following a marathon as a result of a reduction in the ability to tolerate repeated eccentric loads. They also suggested that in order to maintain speed, greater muscular work was required at push off phase. Similarly, during a fast 10 km treadmill run, increased flight times and shorter contact times were attributed to coping with the demands of the constant speed and contributed to a decrease in vertical force at each stride (Hanley and Mohan, 2014).

Changes to knee sagittal plane kinematics have been the most common finding during a run to exhaustion, however contrasting results are reported (Table 2.1). Mizrahi *et al.* (2000) observed a reduction in knee flexion angle at the end of a run performed for 30 minutes at anaerobic threshold, while Derrick *et al.* (2002) observed increased knee flexion angles following runs to exhaustion at 3200 meter race pace. Abt *et al.* (2011) observed no significant change to knee flexion angle following a run to exhaustion.

The lack of consistent results when examining kinematics during different runs can be largely attributed to using an absolute exercise intensity and different exercise durations. With the exception of Mizrahi *et al.* (2000), where runs were performed at 5% above the speed of anaerobic threshold, other studies were performed at either the same speed for everyone or a self-selected speed. This can lead to participants running in different exercise domains, whereby within the same study it is possible that not all runners are at steady state. An alternative approach would be to set a relative intensity based around the maximum steady state (Hayes *et*

Table 2.1. Studies examining kinematic changes during prolonged or exhaustive running

Study	Population	Task	Kinematic variables	Findings
Mizrahi <i>et al.</i> 2000	14 male healthy runners	30 minutes treadmill running above anaerobic threshold	Stride frequency Maximum KF and flexion at different phases of stance at start and end of run	Significant findings start vs end: KF preceding heel strike: 13.6° vs 8.1° KE Preceding heel strike: 13.8° vs 17.2°
Derrick <i>et al.</i> 2002	10 recreational runners	Treadmill running to volitional exhaustion at velocity equal to 3200 meter time trial performed week prior to examination.	Stride length KF angle at IC and Max	<i>P</i> values not reported. Significant findings start vs end: KF max: 127.7° vs 123.8°, KF at IC: 164.9° vs 160.5°
Hayes <i>et al.</i> 2004	6 sub elite male middle distance runners	Treadmill running to exhaustion at $\dot{V}O_{2max}$	Hip ROM, Maximum KF and extension	No significant difference pre to post
Abt <i>et al.</i> 2011	12 healthy competitive Runners	Treadmill running to exhaustion	Max KF	No significant findings

Table 2.1. Continued

Study	Population	Task	Kinematic variables	Findings
Clansey <i>et al.</i> 2012	21 trained male distance runners	overground running pre and post fatiguing treadmill runs at lactate threshold	HADD	End vs Start group x Exhaustion $P < 0.001$
Koblbauer <i>et al.</i> 2013	17 novice healthy runners	Treadmill running fatiguing protocol	Peak HF HE KF KE dominant vs non-dominant fatigue vs non-fatigue	No significant findings
Brown <i>et al.</i> 2014	20 healthy female runners	Overground running pre and post treadmill fatiguing run	Peak angles of HF HADD HIR KF KABD KIR ADF AE for Dominant vs non-dominate leg	No significant findings
Willson <i>et al.</i> 2015	18 females and 17 male healthy runners	Treadmill running to exhaustion	HADD RoM	Female vs male post exhaustion $P < 0.001$ female 10.3° - 11.4° Male 14.8° - 16.3°

al. 2011). Training status might also affect the level of fatigue, studies using trained or elite runners showed no changes in knee Kinematics (Abt *et al.* 2011; Hayes and Caplan, 2014). Two of the four studies identified in Table 2.1 that examined novice or recreational runners found reduced knee flexion angles (Derrick *et al.* 2002; Mizrahi *et al.* 2000). The two studies that observed no significant change in KF angle had performed runs at self-selected speeds (Brown *et al.* 2014; Koblbauer *et al.* 2013).

2.3.2 Measurement of Fatigue

To measure fatigue, the extent of muscle strength has been widely examined pre and post exercise during maximal voluntary contraction. The measure however does not provide a direct measurement of central and peripheral fatigue. This section will outline some of the main measurements and how they provide an insight into fatiguing processes.

2.3.2.1 Maximal Voluntary Contraction

The examination of fatigue following exercise has been typically performed using a maximal isometric voluntary contraction of a specific muscle group. Maximum voluntary activation is a standardised method of measuring muscular strength following exercise and used to measure the extent of an overall or global fatigue (Goodall *et al.* 2012; Millet *et al.* 2011).

2.3.2.2 Evoked Electrical stimulation

To examine the extent of voluntary activation during a voluntary muscle contraction (MVC), twitch interpolation has been a common method of choice (Millet *et al.* 2011).

Twitch interpolation involves delivering a supramaximal electrical stimulation delivered to

a motor nerve of the muscle group under investigation during an MVC compared to at rest (Figure 2.5) (Millet *et al.* 2011). The extent to which electrical stimulation increases force production beyond the voluntary force, identified as superimposed twitch (Figure 2.5), can be used to quantify central fatigue, because the loss of force was due to an inability to activate the muscle and not contractile failure (Taylor *et al.* 2008).

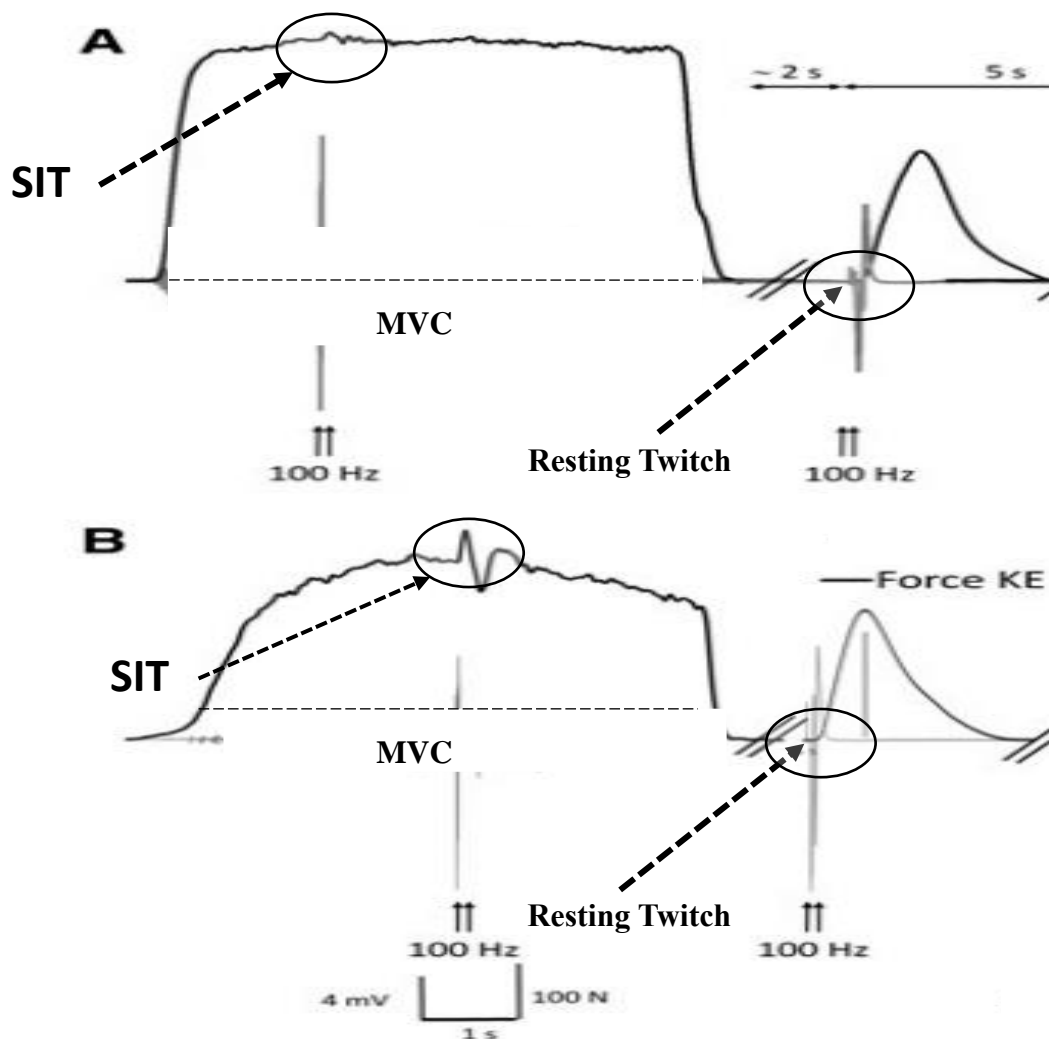


Figure 2.6. Illustration of evoked electrical stimulation technique adapted and modified from Millet *et al.* (2011) representing superimposed twitch (SIT) taken during an MVC and following potentiation twitch (Resting Twitch) at rest (A) and at fatigue (B).

The motor nerve is again stimulated at rest following a voluntary contraction (Figure 2.5). The resultant amplitude of the evoked potentiation twitch force is used to extrapolate voluntary activation and also provides a means to measure contractile function (Millet *et al.* 2011). Hodgson *et al.* (2005) suggested that twitch potentiation is the increase in the sensitivity of the actin-myosin complex to Ca^{2+} released from the sarcoplasmic reticulum as result of phosphorylation of myosin regulatory light chains. Reductions in potentiated twitch force represent impairments that are the result of metabolic and/ or mechanical disturbances; both have a negative influence on contractile function. The superimposed twitch obtained during MVC and subsequent potentiation twitch at rest allows for the examination of voluntary activation.

2.4 Dynamical System Theory

Dynamical systems theory (DST) application was introduced within biomechanics to examine the interactions of joints and segments for RROI, (Hamill *et al.* 1999; Heiderscheit, 2000). Dynamical systems theory can provide an insight into motor control coordination capabilities under different conditions. The idea was first introduced by Bernstein (1967) to help understand the complexities required to perform a movement task. He proposed that the degrees of freedom in a given control system behave in a non-linear dynamical system. The complexity is the product of the dimensionality and the number of elements in a system (Bernstein, 1967). The coordinative structures have the ability to reduce the degrees of freedom through the use of groups of muscles over joints and acting as single unit (Tuller *et al.* 1982). Coordinative structures are independent and adjust spontaneously to control parameters that dictate the response (Fitch *et al.* 1982). This in turn allows the ability to combine coordination structure to perform complex movements with relative simple adjustment of input parameters (Fitch *et al.* 1982).

Kelso (1979, 1984, 1991, 1995) presented the first valid construction of DST for coordination by observing the inter-segmental coordination of oscillating fingers. He identified frequency of movement as a control parameter and the relative phase between the two oscillating fingers as an application to examine coordination. Through relative phase, Kelso was able to observe variability with the shifts in the coordinative state in accordance defining a system that was in non-equilibrium. Kelso was also able to observe a shift from out-of-phase to in-phase, where coordination patterns switched to in-phase with increased frequency. Van Emmerik *et al.* (1999) suggested that the failure to shift from coordination patterns could be suggestive of a pathological locomotion pattern during walking. They found less coordinative variability in the thorax and pelvis during walking between patients with Parkinson's disease when compared to healthy individuals.

Hamill *et al.* (1999) suggested that DST could be used for investigating the interaction between two joints or segments of the lower extremity instead of isolated joint kinematic examination. Unlike Kelso (1984), where relative phase was considered as a potential order parameter, Hamill *et al.* (1999) suggested that through continuous relative phase (CRP), velocity can be used as a control parameter and implemented to evaluate movement patterns in a continuous manner. With CRP, however, there are limitations to be considered; it is thought to be valid for assessment of sinusoidal movements but requires normalisation making the measure more suited for the lower extremity (Peters *et al.* 2003). Details exploring measurement of coordination using CRP will be discussed in sections 2.6.1. Considering the limitations associated with CRP, vector coding involving the quantification of angle-angle diagrams was developed as another form of nonlinear dynamics assessment. Coupling angle (CA) through vector coding was introduced by Heiderscheit (2000) containing spatial information; a contrast to position and velocity signals of CRP. Both CRP and CA enable the assessment of variability of coordination between two joints, however each measure different parameters. Continuous relative

Table 2.2. Studies that have examined the running related overuse injuries through applications of dynamical system theory (DST) methods of continuous relative phase variability (CRPV) and coupling angle variability (CAV). flexion/extension movements are indicated by X, abduction/adduction movements are indicated as Y and internal/external rotation movements are indicated as Z for lower extremity segments and joints.

Study	Population	Tasks	Comparison	DST Method	Couplings	Findings
Hamill 1999	Participants with Q-angle $>15^\circ$, Q-angle $<15^\circ$	Overground running and treadmill running	Low Q-angle - High Q-angle	CRP, CRPV	$Th_x - Tib_z$, $Th_y - Tib_z$, $Tib_z - Ft_z$	No finding between groups in CRP and CRPV
Heidercheit 2002	8 female PFP 8 female healthy	Treadmill running	Injured vs non-injured leg	CAV	$TH_z - Tib_z$, $TH_x - Tib_x$, $K_z - A_z$, $K_x - A_z$,	$ThZ - TibZ$ Q1 19° injured leg vs 27° healthy leg $P = 0.02$ $THz - TibZ$ Q1 19° PFP vs 23° healthy
Ferber <i>et al.</i> 2005	11 various injures 11 healthy	Overground running	Various orthotic conditions.	CA, CAV	$K_x - A_x$ $Tib_z - A_z$	No significant findings
Dierks and Davis 2007	Healthy Runners 20 Males 20 Females	Overground Running	Descriptive	CRP, CRPV, CA, CAV within 4 different period of stance	$RF_z - Tib_z$, $RF_z - K_x$, $Tib_z - K_x$, $Tib_z - K_z$, $RF_z - K_z$	Descriptive: within subject and group CRP, CRPV, CA, CAV
Miller <i>et al.</i> 2008	8 ITBS 8 Healthy	Exhaustive run over treadmill running	Injured vs healthy	CRP, CRPV	$Th_y - Tib_z$, $Th_y - F_z$, $Tib_z - F_z$, $K_x - F_y$, $K_y - F_z$	$Kx - Fy$ CRPV end 18.6° ITBS vs 15.3° Healthy $P = 0.003$ $TibZ - Fz$ end 13.3° ITBS vs 24.2° Healthy $P = 0.004$ $Kx - Fy$ start ITBS 18.6° vs 15.3° $P = 0.02$ $THy - Fz$ end 30.5 ITBS vs 33.1 Healthy $P = 0.03$

Table 2.2. Continued

Study	Population	Tasks	Comparison	DST Method	Couplings	Findings
Miller <i>et al.</i> 2010	18 Healthy Females 4 healthy males 5 healthy males	Walking and running		CAV, CRPV	A _z - FF _x , A _z - FF _z , A _y - FF _y , Th _y - Tib _x	Q1 - Q5 CAV>CRP in Ax-FFx, Az- FFz Q5 Ay-Ffy
Hein <i>et al.</i> 2012	18 healthy runners	Overground barefoot running		CRPV	H _x - K _x , Hy- K _x , K _x - A _z , K _x - A _z	No differences
Cunningham <i>et al.</i> (2014)	19 PFP 11 healthy runners	treadmill running	Healthy vs PFP	CAV	K _y - A _z , K _y - A _x , K _x - A _z , K _x - A _x , K _z - A _z , K _z - A _x , K _x - A _x , K _z - A _z , K _z - A _x	Q1 K _x -A _x 7.9° PFP vs 6.1° healthy <i>P</i> = 0.020 Q2 K _z -A _z 16° PFP vs 10.1° healthy <i>P</i> = 0.49 Q2 K _z -A _x 10.3° PFP vs 7.0° healthy <i>P</i> = 0.038 Q4 K _y -A _x 10.6° PFP vs 6.2° healthy <i>P</i> = 0.010 Q5 K _y -A _z 23.5° PFP vs 14.6° healthy <i>P</i> = .008 Stance K _y -A _x 6.9° PFP vs 4.5° healthy <i>P</i> = 0.008 Stride K _y -A _z 14.8° PFP vs 11.6° healthy <i>P</i> = 0.031
Hafer <i>et al.</i> 2017	10 ITBS 10 Healthy	Treadmill run to exhaustion		CA, CAV	P _y - Th _y , Th _x - Tib _z , Th _x - Tib _z , Tib _z - Rf _y	No significant findings

phase examines temporal and spatial characteristics of joints through the entire movement cycle, whereas CA involves quantification of an angle-angle diagram (Miller *et al.* 2010).

Dynamical systems theory techniques of CRP and CA facilitate the investigation into the effect of coordination variability in locomotion, especially during activities involving complex movements such as running, which requires high coordination between the musculoskeletal and nervous system.

Dynamical systems theory techniques of CRP and CA facilitate the investigation into the effect of coordination variability in locomotion, especially complex movements such as running, which requires high coordination between the musculoskeletal and nervous systems. Coordination variability in running is natural as it is difficult to replicate movement stride to stride without any variations (Heiderscheit, 2000). Kelso (1995) suggested that when coordination is no longer stable the relative phase pattern will alter, and this alteration is indicated by an increase in coordination variability before settling on a new pattern. Latash and Huang (2015) referred to instability when a system such as motor system or processes that modulate coordinated movements, is unable to return to a certain state following small perturbations.

Coordination variability, usually measured as the standard deviation of the coordination measure (Kelso, 1995; Turvey, 1990), has historically been ignored as noise, however, more recently it has been recognised as an intrinsic characteristic. Hamill *et al.* (2012), along with Stergiou and Decker (2011), suggested the presence of an optimal coordination variability and that a rise or reduction could be associated with abnormal or unhealthy motor behaviour.

Evaluation of coordination variability of a complex task such as running will allow for further understanding of how a runner will navigate and respond to the environment through their motor control system (Hamill *et al.* 2012; Stergiou *et al.* 2006). Stergiou *et al.* (2006)

suggested that optimal coordination variability is associated with mature and healthy states where rigid and unchanging is characterised as low coordination variability, while high coordination variability represents instable and noisy systems.

Dynamical systems theory is still a relatively new and underutilised approach in the investigation of the aetiology of RROI. There have been a few studies examining the effects of runs to exhaustion on lower extremity joints and segments (Brown *et al.* 2016; Miller *et al.* 2008). Each study employed different method of investigating coordination variability between continuous relative phase variability (CRPV) (Miller *et al.* 2008) and coupling angle variability (CAV) through modified vector coding (Brown *et al.* 2016). This thesis will employ both methods of CRPV and CAV to examine coordination variability, as both applications employ different parameters for examination and provide different information. Both approaches will be used to see if there is consistent information as result of fatigue in healthy runners and how this aligns with other kinematic findings.

2.4.1 Continuous Relative Phase

Rosen (1970) suggested that the behaviour of complex movements can be described by way of plotting a joint's position against its velocity. A dynamical systems theory was developed by Kelso (1985, 1988, 1995) and was advanced by Hamill *et al.* (1999) that would allow for exploration in instability that can be used to distinguish unrelated movement patterns.

Continuous relative phase allows for measurements and comparison coordination patterns throughout many cycles. While CRP allows for continuous assessment throughout the entire stride cycle, it also maintains velocity (temporal) and angular (spatial) characteristics of segment data. CRP's popularity was a result of the ability to analyse control parameter relationships with specific coordination patterns and their variability and to examine the

abrupt changes observed in coordination. When examining human hand movement, Kelso (1991) showed that there are phase transitions within cycles of movement. There is an asymmetrical mode called out-of-phase, which is replaced by a symmetrical in-phase mode signalling simultaneous activity, in-phase. A model on these sudden phase transitions was first created by Haken (1985) and again tested by Kelso (1995) where an abrupt change was seen as participants' movements of index fingers shifted toward in-phase movement from out-of-phase with increase in movement frequency.

There are a few forms of techniques that can be used to calculate CRP, but the common principle is by calculating the phase angle. Phase angle is calculated when normalised data of a joint/segment angle are plotted by its angular velocity against its displacement (Hamill *et al.* 1999). The obtained phase angle of the joint/segment is then subtracted by a distal segment phase angle. This will allow for assessment of coupling for two joints throughout a cycle, providing a continuous measure of coordination with complex movements such as running (Hamill *et al.* 1999; Millet *et al.* 2010). Through normalisation, the frequency effects of the segments or joints on the phase angles can be reduced. However, there are limitations to be considered with calculation of CRP as it is better suited for sinusoidal oscillators, movement in a sine wave pattern. To give CRP the capability to assess segments or joints that move in a non-sinusoidal pattern, the phase portrait should be normalised so that the resulting trajectories are circular (Fuchs *et al.* 1996), this ensures that phase portraits of different signals are comparable and clear of artefacts caused by frequency. Kurz and Stergiou (2002) explained the goal of normalisation is to transform the segments or joints that displacement of the signal so that its angular velocity fall in a range between -1 and 1, suggesting that the normalised data have the potential to inappropriately represent segment data. Peters *et al.* (2003) showed that normalisation is a necessary step to cut the effects of frequency when comparing sinusoidal signals, however there are limitations with CRP due to its normalisation techniques

for measuring relationship of two non-sinusoidal oscillators (Diedrich and Warren, 1995), as it influences the way data are interpreted. The reason for the debates with normalisation is the way the data is interpreted and explained. In this thesis, the normalisation method of choice is -180° to 180° , where zero indicates in-phase movement while both values of -180° and 180° indicate anti-phase movement.

Continuous relative phase or dynamical systems theory applications are, however, gaining more attraction as a tool to investigate coordination variability, as what was once considered noise is now a measure of flexibility and stability (Hamill *et al.* 1999). Continuous relative phase variability is obtained by calculating standard deviation point by point over the course of the region of interest of a cycle (Hamill *et al.* 2012). Continuous relative phase variability has recently been used as a tool to examine aetiology of running related overuse injuries.

Davids *et al.* (2003) suggested that an increase in coordination variability can be reflective of an athlete not being able to adapt to tasks and could be an indicator in loss of complexity. Low coordination variability has been suggested to be presented with persons with knee injuries and that a person with high or low variability that deviates from an optimal state can be predisposed to injury risk.

CRP Calculation:

For the purpose of this thesis, CRP coupling relationships of the hip and knee joints were examined during treadmill running. Full calculation steps can be seen in section 3.5.1.

2.4.2 Coupling Angle

Sparrow *et al.* (1987) first introduced an approach to measure relative motion through vector coding. The approach was later applied in biomechanics by Hamill *et al.* (2000) as coupling

angle (CA) through modified vector coding, a form of angle-angle plots. Coupling angle allows for measurement of coordination of two oscillating joints of two adjacent points in consecutive time series relative to the right horizontal. Within CA, proximal the segment/joint angle is plotted on the horizontal axis and the distal segment/joint angle on the vertical axis of the angle-angle diagram. Coupling angles are directional in nature, and mean coupling angles are computed using circular statistics suggested by Batschelet (1981). When introducing the technique, the equations are not presented by Hamill, however it was suggested that the values should fall within $0^{\circ} - 360^{\circ}$ range. Based on the guidelines for interpreting results by Hamill *et al.* (2000), a brief description of the interpretations given by Hamill is warranted that further explain the nature of the oscillators' movement patterns. Values of 0° , 90° , 180° and 270° signal a movement of one oscillator, with values 0° and 180° signalling the distal oscillator is stationary and the proximal oscillator is in motion, whereas values of 90° and 270° signal that the proximal oscillator is stationary and distal oscillator is in motion. For values of 45° , 135° , 224° , and 315° signal equal movement between the two examined oscillators as values of 45° and 225° signal equal movement in the same direction and 135° and 315° signal equal movement in the opposite direction. Chang *et al.* (2008) later proposed expanded coordination phases compared to Hamill, the intervals best represented the schematics in 45° increments and is represented in Table 2.3 and Figure 2.7.

A limitation with CA has been the availability of the techniques in the literature for determining the means of calculations, first reported by Heiderscheit, (2000) and Heiderscheit *et al.* (2002). The equation given, however, did not provide outcome measures of values in the suggested range, rather from -90 to 90 , requiring further procedure that were not explained (Chang *et al.* 2008; Needham *et al.* 2014). While some studies employed a modified technique through absolute values of the outcome values causing a range of $0-90$, no explanation on the reasoning and of the procedure were provided (Dierks and Davis, 2007; Ferber *et al.* 2005).

Needham *et al.* (2014) was the first to outline a step-by-step procedure for measuring coupling angle (see equations 5-12) that would provide an outcome measure based on the suggestions of Hamill. Similar to CRP, coordination variability can be examined through CA through standard deviation of the mean coupling angle. Full calculation procedures of CA and CAV are described in section 3.5.2.

Table 2.3. Coupling Angle Definitions reproduced from Chang *et al.* (2008).

Anti-phase	$112.51^{\circ} \leq y < 157.51^{\circ}, 292.51^{\circ} \leq y < 337.51^{\circ}$
In-phase	$22.51^{\circ} \leq y < 67.51^{\circ}, 202.51^{\circ} \leq y < 247.51^{\circ}$
Rearfoot phase	$0 \leq y < 22.51^{\circ}, 157.51^{\circ} \leq y < 202.51^{\circ}, 337.51^{\circ} \leq y < 360.1^{\circ}$
Forefoot phase	$67.51^{\circ} \leq y < 112.51^{\circ}, 247.51^{\circ} \leq y < 292.51^{\circ}$

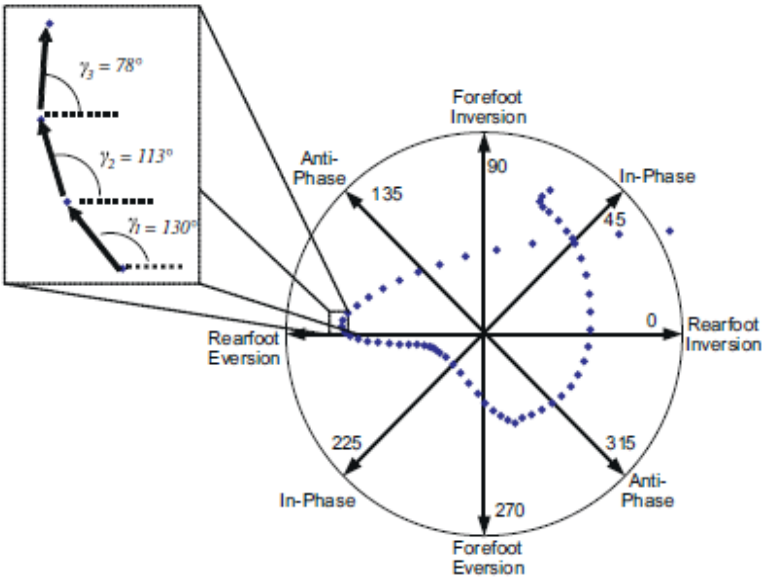


Figure 2.7. Coupling angle interpretation reproduced from Chang *et al.* (2008).

2.4.3 Coordination Variability

For the purpose of this thesis, only coordination variability for the couplings of the hip and knee in the sagittal and frontal plane movements will be examined. Hamill *et al.* (2012) explained that examination of coordination variability offers information on RROI. Seay *et al.* (2011) was able to distinguish injured and non-injured runners with low back pain based on coordination variability. Hamill *et al.* (2012) observed that injured runners are less able and adaptable to use all the degrees of freedom associated with running, hence why it is expected to observe reduced coordination variability. What remains unknown, however, is the effect of fatigue on coordination variability. There are limited studies on coordination variability and possible effects when fatigued. In the case of Brown *et al.* (2016), the study observed statistical significance ($P < .05$) of increased coupling angle variability for one of the interactions between hip and knee, while observing increased coordination variability in all other interactions for both injured and non-injured runners following a run to exhaustion. Miller *et al.* (2008) performed a run to exhaustion and examined CRVP in injured and non-injured runners. While the study did not find any significant alterations in the examined interactions, the authors purposed that the increased coordination variability observed could have been due to muscle dysfunction. Ferber and Pohl (2011) observed increased coordination variability in joint couplings of healthy participants following locally induced muscular fatigue. The findings of these studies present a possibility for use of coordination variability to not just be used to discriminate from injured and non-injured, but also fatigue in both healthy and injured runners.

2.5 Running Related Over Injuries

Various definitions have been used when investigating RROI with no consensus of the definition (Table 2-2). A common characteristic of RROI has been any pain or physical complaint to the lower extremities or lower back region as a result of running activity, resulting in an alteration to running program or stopping from running for a duration (Buist *et al.* 2010, 2008). Acute injuries, blisters, cuts or scrapes did not fall under the definition. One factor to be considered for the classification of RROI is the duration a runner is unable to run or requires alterations to their training programs. Across a number of studies a range of days has been used for their analyses, from a full cessation in running for as little as one day (Buist *et al.* 2010; Lun *et al.* 2004; M Van Middelkoop *et al.* 2008) up to one week (Lysholm and Wiklander, 1987; Hreljac, 2005; Buist *et al.* 2008). In a report by Yamato, Saragiotto and Lopes, (2015), a consensus definition of RROI was provided: “Running-related musculoskeletal pain in the lower limbs that causes a restriction or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training session or that requires the runner to consult a physician or other health professional”. This consensus however has not always been used when defining RROI in recent epidemiology studies (Linton and Valentin, 2018).

2.5.1 Running Related Overuse Injury Incidence Rate

Running injury rates across a wide range of studies vary from 19.4% to 92.4%, the differences in findings can be explained through the differences in study designs, running populations, and differing definitions of RROI (Table 2-3).

While running has continued its growth in global popularity, running related overuse injuries have been a concomitant consequence. A yearly survey conducted by runningUSA.com

Table 2.4. Epidemiology studies examining running related overuse injury populations and incident rates

Study	Population	Injury Definition	Running related injury incident and rate
Satterthwaite <i>et al.</i> 1999	1357 runners participating in marathon	injuries and health problems post marathon	92.40%
Lysholm and Wiklander, 1987	60 competitive runners of two clubs	Any injuries that markedly hampered training or competition for at least one week	28%
Taunton <i>et al.</i> 2003	2002 recreational runners	Experiencing pain only after exercise, during exercise, and restricting distance or speed, pain preventing all running.	29.50%
Lun <i>et al.</i> 2004	87 recreational runners	Any musculoskeletal symptom of the lower limb that required a reduction or stoppage of a runners normal training	79%
Van Middelkoop <i>et al.</i> (2008)	694 male running taking part in 2005 Rotterdam Marathon	A self-reported injury on muscle, joints, tendons, or bones of the lower extremists that participants attributed to running	28.10%
Buist <i>et al.</i> 2008	250 graded training programme, 236 standard training programs. Healthy runners	Healthy runners with no injury to the lower extremities 3 months prior to participation	20.8 % for graded programme and 20.3% for standard programme
Buist <i>et al.</i> 2010	629 novice and recreational runners	Any musculoskeletal pain of the lower limb or back causing a restriction in running for at least 1 day	30.1/1000 hours of running
Junior <i>et al.</i> 2013	191 recreational runners	Any pain of musculoskeletal origin attributed to running by runners themselves that prevented at least one training session	31% and 10/1000 of running

reported that of the 6,800 runners that responded, 75% experienced a running related injury within the previous 12-month period. In addition 50% curtailed their training for more than 4 days due to these injuries (Running USA, 2017). In a review, Videbaek et al. (2015), found that recreational runners sustain 7.7 RROI per 1000 hours of running. In another review by Van Gent *et al.* (2007) examining incidence rates across prospective, cross sectional, retrospective, and randomised clinical trials, reported incidence rate of 19.4% to 79.3%.

2.6 Risk Factors for running related overuse injury

Ryan *et al.* (2006) defined an injury risk factor as “a variable that, while not proven to be causative, is considered to be associated with onset of injury”. The aetiology of RROI remains complex and to be fully elucidated. Rolf, (1995) split identified risk factors into intrinsic and extrinsic. Factors such as distance, duration, frequency, shod running, footwear and running surface have been labelled as extrinsic factors (Hreljac, 2005; Van Gent *et al.* 2007; Junior *et al.* 2013). Intrinsic factors for running related injuries include age, gender, mass, running technique, muscular weakness, previous injury, anatomical structure, flexibility, and fatigue (Lun *et al.* 2004; Taunton *et al.* 2002; Van Middelkoop *et al.* 2008). While extrinsic factors such as footwear have been popular topics of investigation, intrinsic factors such as the influence of fatigue on running kinematics have received limited attention.

Epidemiology studies have identified that the most common site of RROI is in the lower extremities (Buist *et al.* 2010; Van Gent *et al.* 2007; Taunton *et al.* 2002; Van Middlekoop, 2009). Overuse injuries to the knee are the most prevalent as they represent the highest rate of incidence in runners, 14%-42.1%, lower leg injuries account for 9%-35.5%, and foot and ankle account for 14%-33.6% (Buist *et al.* 2010; Hespanhol Junior *et al.* 2013; Malisoux *et al.* 2015; Taunton *et al.* 2002; Van Middlekoop, 2009). For both males and females, the knee has been identified as the most common site of overuse injury with 13-36% and 22-35%, with the two

most common running related overuse injuries being patellofemoral pain (PFP) and iliotibial band syndrome (ITBS) (Lun *et al.* 2004; Taunton *et al.* 2003).

2.6.1 Predictive Risk Factors

Both PFP and ITBS share common risk factors of impaired hip muscular strength and altered running mechanics that can contribute to injury development. Figure 2.8 shows the complexity of PFP and the contribution to injury development as result of the identified risk factors (boxes 1.2a.2a and 1.2a.2) in this section.

2.6.1.1 Impaired Hip Muscle Strength

A weakness in the hip musculature has been reported in runners that exhibit the two common RROIs, prominently the abductors and external rotators as they control the frontal plane movements of the femur (Noehren *et al.*, 2007; Dierks *et al.* 2008; Powers, 2010). Intervention studies focusing on improving hip muscular strength in both PFP and ITBS runners have shown to effectively reduce pain and improved running mechanics (Earl 2011; Ferber 2011). Hip musculature (e.g. gluteus maximum, glutes medius and gluteus minimus) is activated during loading to overcome the large external hip adduction moments (Novacheck, 1998). The structural characteristics of the gluteus medius (GMED) are suited to the production of a large torque which can support frontal plane alignment during the early stance phase in running (Semciw *et al.* 2016). The GMED has been identified to be the largest of the hip abductors (glutes medius, gluteus minimus, and tensor fascia lata) for both volume and cross-sectional area; indicators of muscle force generation capability (Flack *et al.* 2014). This enables the generation of large abduction torques required to maintain frontal plane movement (Dostal *et al.* 1986; Flack *et al.* 2014). Additionally, the posterior fascicles along with distribution of nerve

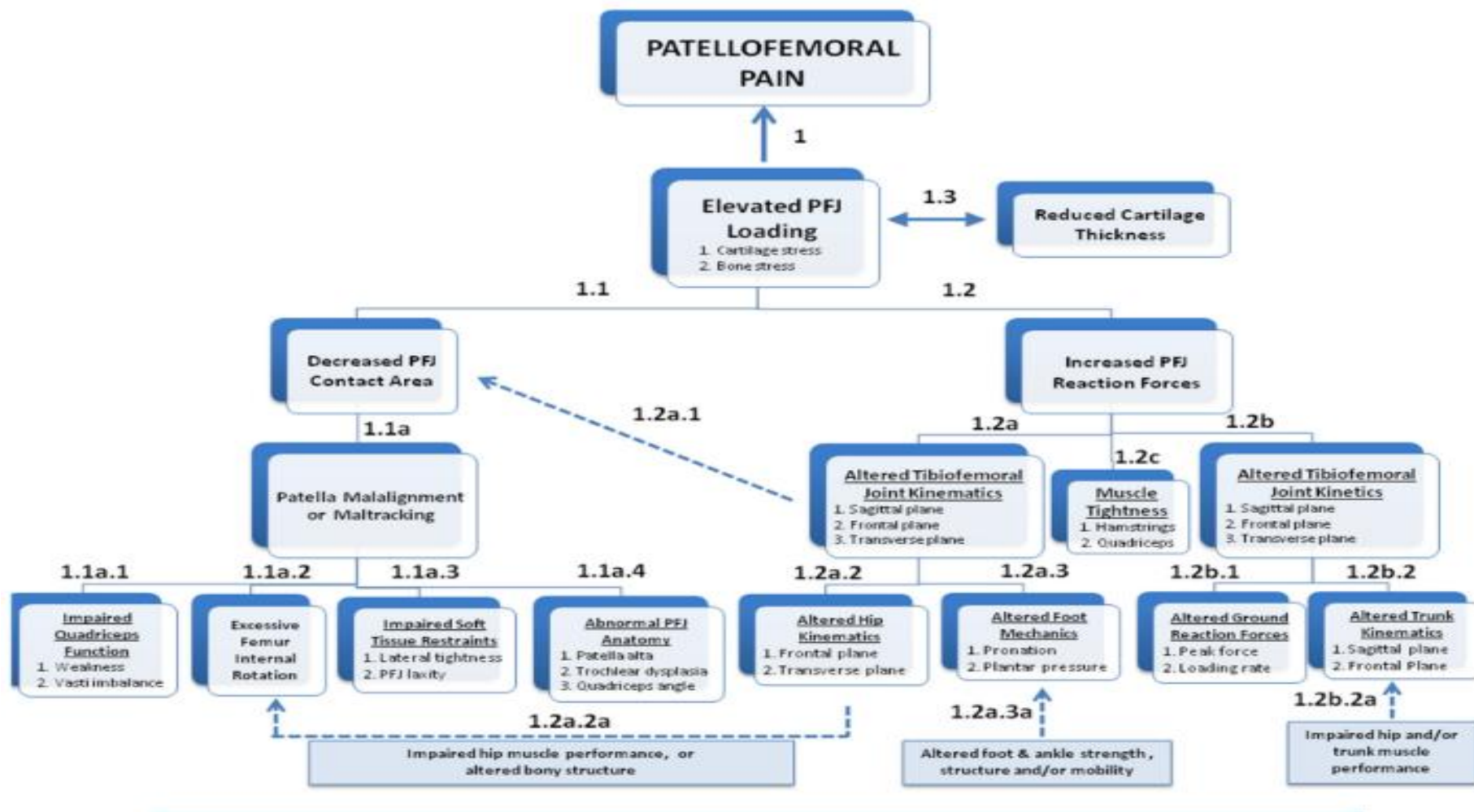


Figure 2.8. Schematic overview of a pathway of factors that contribute to Patellofemoral Pain adapted from Powers *et al.* (2017).

branches of the GMED, are structures that allow both concentric abduction and eccentric adduction actions (Flack et al. 2014). Gluteal muscles, primarily the GMED, play an important role in reducing power generation and absorption at the ligaments, bone to bone contact forces, and tendons (Novacheck, 1998). During the stance phase, gluteus medius acts as the prime mover by contracting eccentrically producing hip abductor moment during the absorption phase as the ground reaction force falls medial to the hip (Novachek, 1998). This is followed by hip abduction through concentric contraction and power generation during the propulsion phase. The swing phase also plays a role in the stability of the hip. During late swing, GMED goes through pre-activation to prepare for stance to control frontal plane movements (Chumanov *et al.* 2012).

The role of the IT band is to control hip adduction movement by acting as a lateral stabilizer through eccentric contractions (Fredericson *et al.* 2000; Noehren *et al.* 2013). It has two separate functional components, the iliopatellar band and the iliotibial tract, the latter is a continuation of the IT band and inserts into Gerdy's Tubercle on the tibia (Terry *et al.* 1986). Iliotibial band originates at gluteus maximum, gluteus medius, and tensor fascia lata muscles and is attached distally to the supracondylar tubercle of the femur and the lateral intramuscular septum with additional fibre attachments to the lateral boarder of patella (Birnbaum *et al.* 2004; Muhle *et al.* 1999).

2.6.1.2 Altered Running Mechanics

Increased hip frontal plane movements have been found in runners with PFP when compared to healthy runners. In a prospective study by Noehren *et al.* (2013), where 400 runners were tracked for injury development, greater hip adduction angle was identified as the primary risk factor in occurrence of RROI. Runners with PFP typically exhibit excessive maximum hip adduction of 2.2° (Noehren et al., 2013). Following a run to exhaustion Dierks *et al.* (2008)

found a significant relationship in maximum hip adduction angle between healthy runners and those with PFP as result of fatigue.

When comparing injured to healthy runners, injured runners have increased hip adduction angle and weak hip abductors, resulting in an inability to resist the movement (Ireland *et al.*, 2003; Powers, 2010). The inability of the gluteus medius muscle to counter the external adduction moment, arising from either insufficient strength or neuromuscular dysfunction, can induce an increased hip adduction angle (Noehren *et al.* 2007). This change in kinematics, brought on by GMED dysfunction, has been suggested as a major contributor common RROI (Niemuth *et al.* 2005; Willson *et al.* 2011).

Increased hip adduction angle can contribute to stresses at the patellofemoral joint by rotating the femur laterally, bringing the femur in close contact with the patella, causing a shift in force distribution. There are two primary forces working on the patella, quadriceps force vector and patellar tendon force vector (Powers, 2003). Patellar reaction forces are the sum of the force vectors of the quadriceps and patella ligament; a contraction of the quadriceps creates a force vector acting on the patella, the offset in force vectors are defined by quadriceps angle (Powers, 2003; Powers *et al.* 1999). During knee flexion beyond 20°, the quadriceps angle can result in forcing the patella against the lateral femoral condyle, a 10° increase in quadriceps angle can result in a 45% increase in peak contact pressure and patellofemoral joint stress, an aetiology frequently associated with PFP (Huberti and Hayes, 1984; Powers, 2010; Powers *et al.* 2017; Wirtz *et al.* 2012). With an increase in knee flexion angle, load magnitudes also increases, whereas reduced knee flexion has been suggested to be a compensatory strategy to reduce knee pain by reducing compressive patellofemoral forces during running (Dierks *et al.* 2011; Powers *et al.* 2017).

The attachments of the IT band can cause tension, inducing greater eccentric demands from gluteal musculature during increased hip adduction movement (Noehren *et al.* 2007). In

addition, when loaded, the IT band can cause the patella to tilt and rotate more laterally due its insertion on the lateral boarder of the patella through the iliopatellar band of the lateral retinaculum (Merican and Amis, 2009). The displacement can increase the relative load causing tissue stress and over load. An increase in hip adduction can increase the load placed on the IT band altering the patellar position, causing it to be displaced laterally, exacerbating anterior knee pain (Herrington and Law, 2012; Noehren *et al.* 2007; Powers, 2010). While it is unknown whether drop in hip abductor strength is the result or cause of ITBS, there is consistent evidence showing a relationship between the two (Fredericson *et al.* 2000; Niemuth *et al.* 2005; Noehren *et al.* 2007; Noehren *et al.* 2006).

2.6.2 Overview

Running related overuse injuries are multifactorial and complex with many factors contributing to their development (Figure 2.8). The two anterior knee pain overuse injuries however share the common pathologies of decreased strength of the hip musculature, primarily hip abductor strength, along with abnormal running mechanics of greater hip adduction angles. While both risk factors are observed in conjunction of each other, it is unknown which is causative (Powers, 2010; Noehren *et al.*, 2013). The effect fatigue during a typical-training runs on risk factors has yet to be examined. There is a lack of knowledge on whether healthy runners exhibit these risk factors as fatigue develops while running, if so that would place them at an increased risk of potential RROI development.

2.7 Conclusion

Running research has primarily focused on physiological determinants of performance, while neuromuscular function has received less attention. Neuromuscular function has been shown to

be affected by fatigue with impaired muscular strength, SSC function and stretch reflex activity. These fatigue induced changes in healthy runners have been correlated with changes in running gait, in particular hip adduction angle, leading to a gait similar to that exhibited by runners suffering from PFP or ITBS. Studies that have induced fatigue have generally used extreme exercise, for example exhaustive runs or races. On a day to day basis runners do not train in this way and yet still, from time to time, get injured. Currently, there is no information on how runners respond to typical running sessions.

CHAPTER 3 - GENERAL METHODS

3.1 Introduction

This chapter will provide a brief overview of data collection methods employed within multiple experiments within this thesis.

3.2 Ethical approval

Institutional ethical approval was obtained for all original research studies (chapters 4, 5, 6, and 7) from Northumbria University Faculty of Health and Life Sciences Ethics Committee in accordance with the Helsinki declaration. Each participant was given an information sheet outlining the purpose and procedures of the study (Appendix 1). They were then provided with time to ask questions about the study. Lastly, participants provided a written informed consent to participate (Appendix 2).

3.3. Participants

Participants were recruited through local running clubs via social media and e-mail (see appendices for recruitment poster). To be eligible to take part, they had to have competed in an organised race within the past two years, be part of an affiliated running club, and had not experienced any type of lower extremity injury that prevented them from running for more than a week in the past 6 months. Participants were identified as ineligible if they had experienced any cardiovascular or neurological conditions, or if they were allergic to adhesive material. Medical history was pre-screened via a self-reported questionnaire and eligible participants provided informed written consent prior to testing sessions. Participants between the age of 35 and 50 were recruited to represent the popular age group that participates in weekly Parkrun, running races, and club running (Parkrun, 2019; Runningusa, 2017; Schreeder, 2015). While

runners from this age group represent the largest population of runners, they have not been given attention in research for examination of risk factors on potential development of RROIs.

As part of the inclusion criteria, the runners that were recruited in this thesis runners were required to be active club runners, participating in organised club training sessions. Most clubs typically designate one or two weekly session to interval sessions, fartlek training or hill work with continuous running forming the other training sessions. In addition, the runners were required to have participated in a race with in the past two years. The majority of them had a profile on nationally run websites (runbritanrankings.com; thepowerof10.info) that records personal bests in races of five kilometre (5K), ten kilometre (10K) and half marathon (HM) (See table 3.1). They were also required to be running a minimum of 20 km per week. Training volume however as not recorded.

Table 3.1. Representing participant times in minutes : seconds for five-kilometer (5k), ten-kilometer (10K) and half marathon (HM) races.

Sex	Races		
	5K	10K	HM
Female	21:51	47:49	105:56
Male	19:58	43:55	99:38

Once the consent form and health questionnaire were given and confirmation of inclusion criteria was met, the runners were then taken to an adjacent room for a series of initial Participants were then familiarised with the muscular strength test measures (See section 3.2) before the treadmill runs.

3.4 Laboratory

All data collection was performed in Northumbria University Gait Laboratory (Figures 3.1 and 3.2). Prior to this thesis, the university gait lab was void of a treadmill, therefor the addition of

one required certain adjustments. Pilot sessions revealed that both treadmill and camera set up were not effectively arranged for optimum marker recognition and image error for calibration. The treadmill required modification where front handles were removed to ensure recognitions of the hip markers and placement in room was trialled before final location was designated (See figures 3.2 and 3.3). Cameras were also re-ordered within the lab to ensure each foot fall was captured. Various camera configurations were trialled, the final configuration resulted in at least five cameras being able to record each marker; exceeding the manufacturer's recommendation of at least three. Only cameras 4, 6, and 8 did not assist in marker recognition, the final camera set up is represented in figure 3.2. Each camera was then adjusted for strobe, with the goal to have a minimum of three cameras capture each marker. The adjustments also made for low image errors for calibration resulting in high quality motion capture.



Figure 3.1. Northumbria University Gait Laboratory, view from work station.

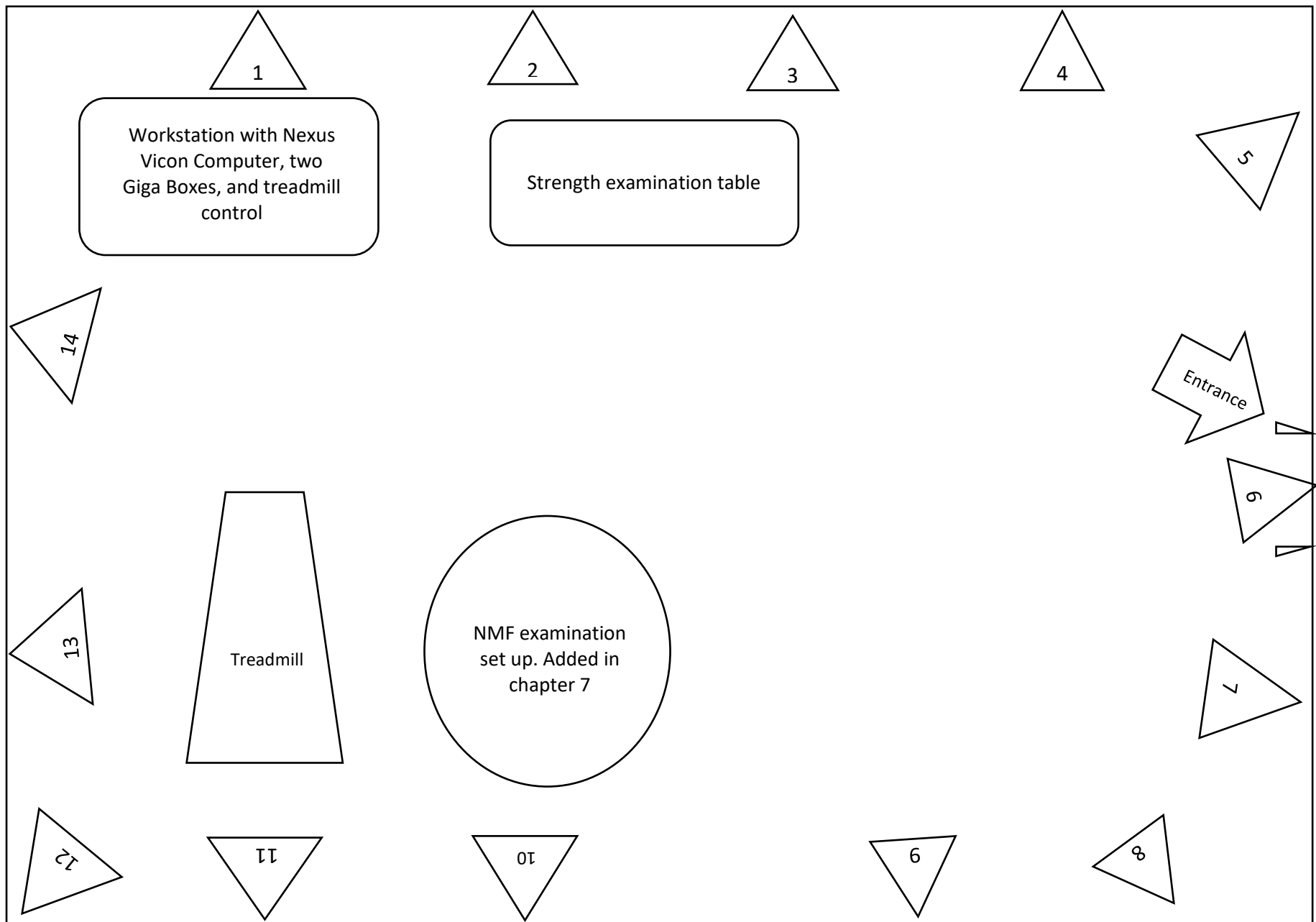


Figure 3.2. Overhead layout of Northumbria University Gait Laboratory

3.5 Preliminary Session

Once the consent form and health questionnaire were given and confirmation of inclusion criteria was met, the runners were then taken to an adjacent room for a series of initial Participants were then familiarised with the muscular strength test measures (See section 3.2) before the treadmill runs.

3.5.1 Kinanthropometric Measurements

Initial measurements of mass and stature were recorded using Seca scales and stadiometer (Seca Ltd, Birmingham, UK) at start of the preliminary session. Measures of leg length, knee breadth and ankle breadth were also recorded, these measures were required for the motion capture software. All Kinanthropometric measures were taken according to ISAK guidelines.

3.5.2 Treadmill Familiarisation

As part of the familiarisation participants practiced stepping on and off the treadmill (ELG2, Woodway, Germany) to replicate elements of the sub-maximal test and due to modifications made to the treadmill to facilitate motion capture (Figure 3.3).



Figure 3.3. Modified treadmill employed in this thesis

Participants then performed a 5-minute warm-up run to familiarise them with the treadmill and equipment used for expired gas collections. During the familiarisation, participants were given a minimum of 5 trials practicing stepping off and back on the treadmill. The treadmill speed was increased after each dismount and stepping back on the treadmill to mimic the sub-maximal testing. Once familiarised, participants proceeded to complete an incremental treadmill tests to determine maximum steady state and $\dot{v}O_2$ max.

3.5.3 Calibrations

3.5.3.1 *Gas analyser*

Expired gas analysis was measured by Cortex Metalyser 3B (Leipzig Germany). The equipment was calibrated prior to each sub-maximal and maximal test using MetaSoft Studio (Leipzig, Germany). The Cortex Metalyser calibration process was according to manufacturer's instructions. An hour before calibration, the gas analyser was turned on. The first step was to perform calibrate the O₂ and CO₂ analysers. This required a two point calibration process using ambient air and a sample gas of 15% O₂ and 5% CO₂ for gas analysis. The final step required volume calibration using five valid inspired and expired air strokes through three-litre syringe.

3.5.3.2 *Biosin*

Prior to blood lactate processing, the Biosin diagnostics equipment (Biosen C-line, EKF diagnostics, Germany) was calibrated according to manufacturer's recommendations; this was performed before each sub-maximal assessment.

3.5.4 Sub-max treadmill test

The sub-maximal test consisted of taking a 20 μl sample of capillary blood from the finger tips at the end of a series of incremental 4-minute stages at 0% gradient, separated by 60-s recovery (Smith and Jones, 2001). Stages increased by 1 $\text{km}\cdot\text{h}^{-1}$ until lactate turnpoint (LTP) was exceeded; defined as the second, sustained, increase in blood lactate. The initial test speed was set according to the participant's current performance level. Between stages, participants were required to stand astride the treadmill belt while a fingertip capillary blood sample was taken for analysis of blood lactate concentration. The capillary blood sample was then analysed using the Biosin diagnostics for a real time lactate reading. The blood lactate levels and heart rate were recorded at each stage and plotted against running speed (RS) to identify LT and LTP. $\dot{V}\text{O}_2$ and $\dot{V}\text{CO}_2$ were recorded breath by breath during the final minute of each stage. They subsequently were 60s averaged and used to determine energy expenditure of the typical runs in this thesis (chapters 4, 5, and 6), further explain in section 3.7.2.

3.5.5 Maximal Treadmill Test

Following a 15-min recovery period after the sub-maximal test, participants completed a $\dot{V}\text{O}_2$ max test, the initial speed was set at 4 $\text{km}\cdot\text{h}^{-1}$ below the speed at LTP (sLTP) with a 0% gradient. In order to mimic outside running, maximal tests are typically ran at 1% gradient (Jones and Doust, 1996). A decision was made to use 0% gradient as a 1% gradient could affect gait mechanics e.g. flight time. The treadmill speed increased speed by 0.5 $\text{km}\cdot\text{h}^{-1}$ every 30 seconds; the test concluded at volitional exhaustion, typically lasting 6-8 minutes. Heart rate was recorded for each 30s stage during the session. A 30 second average of the breath by breath data was used, with the highest averaged $\dot{V}\text{O}_2$ value attained regarded as $\dot{V}\text{O}_2$ max (Billat *et al.* 2001). A secondary step verification phase using Midgley *et al.*'s (2006) data analysis approach to confirm a plateau of the test.

3.6 Training Runs

The duration and speed of each run was individualised based on $\dot{V}O_2$ max and sub-maximal gas exchange measures. Prior to each run, the speed (s) were pre-programmed through the interface attached to the treadmill. For the MICR, the treadmill was programmed for both duration and running speed; the treadmill began at a slow pace, gradually accelerating until desired running speed was reached and the test commenced. In the HIIT, the treadmill was pre-programmed for the duration and running speed of both the repetitions and recovery. There was a brief transition from recovery to run at the start of each repetition as the treadmill speed increased rapidly to the required pace. Acceleration was complete within 2 seconds of the repetition. For chapters 4, 5, and 6, the training runs were randomised to control for any possible influence on performance. Runners were made aware of the run-type they would be performing on the day of examination.

3.6.1 HIIT speed and duration

The HIIT session was a modification of the protocol used by James and Doust (2000) that caused fatigue in club runners. It consisted of six repetitions of 800 meters, run at $1 \text{ km} \cdot \text{h}^{-1}$ below the speed at $\dot{V}O_2$ max ($s\dot{V}O_2$ max), with a 1:1 work: rest ratio. The recovery was active with participants walking at $4 \text{ km} \cdot \text{h}^{-1}$; the recovery walking speed was chosen to set a standard across all runners.

The repetition speed was determined from a regression equation generated by plotting the averaged final minute $\dot{V}O_2$ for each 4-minute stage against RS from sub-maximal test. This relationship was extrapolated up to $\dot{V}O_2$ max to identify the speed at $\dot{V}O_2$ max ($s\dot{V}O_2$ max). The speed of the repetitions was identified as $1 \text{ km} \cdot \text{h}^{-1}$ under $s\dot{V}O_2$ max. To determine the repetition duration, the speed of the repetition was converted from $\text{km} \cdot \text{h}^{-1}$ to $\text{m} \cdot \text{s}^{-1}$. The 800 meters was then divided by the speed in $\text{m} \cdot \text{s}^{-1}$ to give a total time in seconds.

3.6.2 Calculation of energy expenditure

The total energy expenditure (EE) of the HIIT session was calculated from the sum of the energy expenditure of the repetitions and recoveries. The EE for both repetitions and recovery was calculated for using the RER values and $\dot{V}O_2$ –RS relationship from the sub-maximal test. From this relationship the EE for was calculated as an energy cost per minute ($\text{kJ}\cdot\text{min}^{-1}$) using the method of Shaw *et al.* (2013) based on the respective speeds for the repetition and recovery. This was then multiplied by the total time for the repetition or recovery and then multiplied by the number of repetitions / recoveries to provide a cumulative total.

3.6.3 MICR speed and duration

The MICR speed was the mid-point between the speeds at LT and LTP. The $\dot{V}O_2$ and RER values for running at the MICR speed were determined by interpolating the $\dot{V}O_2$ –RS relationship and used to calculate the energy cost per minute ($\text{kJ}\cdot\text{min}^{-1}$) (Shaw *et al.* 2013). The MICR duration was calculated by dividing the total energy expenditure of the HIIT by the energy cost per minute at the speed of MICR.

3.7 Muscular Strength

Participants were first familiarised with muscular strength procedures prior to treadmill testing of preliminary session. A hand held dynamometer (HHD) Lafayette Manual Muscle Tester (Lafayette Instruments, IN, USA) was used to measure isometric hip flexion, extension, internal and external rotation strength along with isometric knee flexion and extension strength. The HHD was calibrated by the manufacturer prior to use. In order to remove tester strength bias, the participant's tested limb was secured to an examination table via a non-elastic strap (Thorborg 2011). To further secure the HHD, a velcro strap was used to attach the device against the tested limb (Figure 3.4).



Figure 3.4. Hand held dynamometer and immovable strap used in hip and knee muscular strength measures.

The participants were asked to perform one set of three maximal effort trials for each movement in a ramped 5-second protocol, exerting maximum force against dynamometer in the final 3 seconds. All three trials were recorded with the highest reading used for analysis. There was a 30 second rest between each effort and the tests were performed in the order described below. The protocol was similar to that of Bazett-Jones *et al.* (2011). Strength measures were recorded in Newton's and normalised to body mass (kg), as suggested by Bazett-Jones (2011). The point of attachment of the HHD for each test was marked with indelible ink for post-test measures.

Hip Abduction (HABD): Participants were positioned lying on their side with two pillows placed between their legs to place the hip in a neutral 0 degrees of abduction and adduction. The HHD was placed 7cm proximal to the lateral condyle. The participants then abducted the testing leg against the HDD, ensuring to avoid either pushing down on the table or bending the leg.

Hip Adduction (HADD): participants were placed in a side-lying position with the tested leg in 0 degrees of adduction and knee extended against the table, the non-tested leg was crossed over in front of the testing leg in a figure-4 position. The HHD was placed 5cm proximal to the medial

epicondyle. The participant then pushed against the HHD by adducting the tested leg, keeping the leg straight and not pushing down on the table to aid force exertion.

Hip Extension (HE): participants lay prone with their knee passively flexed at 90 degrees to ensure no recruitment of the hamstrings. The HHD placed was placed on popliteal fossa of the knee. The participant extended the hip by pushing upwards, the test was considered a fail if the participant knee was in extension.

Hip Flexion (HF): participants sat with both their hip and knee flexed at 90 degrees. HHD was placed proximally to the superior pole of the knee. The participant then lifted the thigh against the HHD and the test was considered a fail if the participant extended the knee and was unable to keep the back straight.

Hip external rotation (HER): participants were seated with their hip and knee flexed at 90 degrees. A foam block (10.16cm x 15.24cm x 22.86cm) was placed in between their legs to keep a neutral space between the participant's legs and to prevent unnecessary movement. The HHD was placed 5cm proximal to the medial malleolus. The participant was asked to push through the ankle and bring the tested leg inward towards the midline of the body. The test was considered a fail if the participant was not able to keep the tested knee at 90 degrees.

Hip internal rotation (HIR): participants were seated with their hip flexed at 90 degrees. A foam block was placed in between their legs to keep a neutral space between the participant's legs and to prevent unnecessary movement. The HHD was placed 5cm proximal to the lateral malleolus. The participant was asked to push through the ankle and bring the tested leg outwards away from the midline of the body. The test was considered a fail if the participant was not able to keep the tested knee at 90 degrees.

Knee Extension (KE): participants were seated with knee and hip flexed at 90 degrees. HHD was placed proximal of anterior talotibial joint, the participant extended the knee against the HHD. The test was considered invalid if the participant was unable to keep his or her back straight.

Knee Flexion (KF): participants lay supine, the tested leg was placed in a 30 degree flexion by resting the ankle on a foam block. The HHD placed 5cm proximal to the posterior talotibial joint. The participant then flexed the knee against the HHD.

3.8 Motion Capture

Running motion for measuring kinematics and coordination variability was the primary component of the experiments in this thesis.

3.8.1 Motion Capture System

The Gait Laboratory housed a 14-camera 3D Vicon MX optoelectronic motion capture system (Vicon Nexus; Vicon Motion Systems Ltd. Oxford, England). The camera system is comprised of 12 T20 and 2 T40 (cameras 5 and 14; Figure 3.3) near-infrared cameras that were captured via Giganet MX boxes. The cameras only captured the motion of specific reflective markers placed onto the runner. The data were recorded within computer designed for Vicon use, only. The captured 2D marker trajectories from each camera were then reconstructed into 3D trajectories and analysed used Vicon Nexus 2.0 software.

Prior to each data collection session, the cameras were calibrated to examine extrinsic parameters and camera pose with respect to the laboratory global co-ordinate system (Richards *et al.* 2008). A filtration of the room was performed, prior to calibration, through masking of each camera to remove unwanted interference or reflections that could influence data collection. In cases where high reflection was seen, the object was manually removed or covered. Following masking of the cameras, a T-shaped wand with five 14mm markers, was moved throughout the room centred around the anticipated capture volume (treadmill) until each camera captured a minimum of 5000 frames. Target calibration image error was less than 0.25mm, if image error values were greater than desired, the process was repeated until the target error was achieved.

Camera calibration allowed the motion capture system to identify each camera location. This was achieved by placing the T-wand in the centre of the laboratory in order to assign the volume origin of the global co-ordinate system of the laboratory.

3.8.3 Marker Placement

High visibility fluorescent tape covered 25mm diameter reflective spherical markers (Vicon Motion Systems Ltd. Oxford, England) that reflect the near-infrared light emitted from the MX cameras were placed on specific anatomical landmarks.

Reflective markers were placed according to the Vicon lower limb Plug-in Gait model (Nexus 2.5 Documentation) bilaterally on: the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, condyles of the femur, lateral shank, lateral malleoli, base of the 2nd metatarsal, and calcaneus (Figure 3.5). Throughout, the markers were carefully placed by the same researcher; both the markers and their bases were secured with double sided tape. The area of the placement for thigh, knee and shank were shaved if required. Custom made wand markers (40 mm in length) were used for the thigh and shank.

Pilot testing highlighted the need for strict securing of the markers as they were falling off during the runs due to repeated impact and accumulation of sweat, particularly during high running speeds. To overcome this problem, the base of the wand markers was separated from the

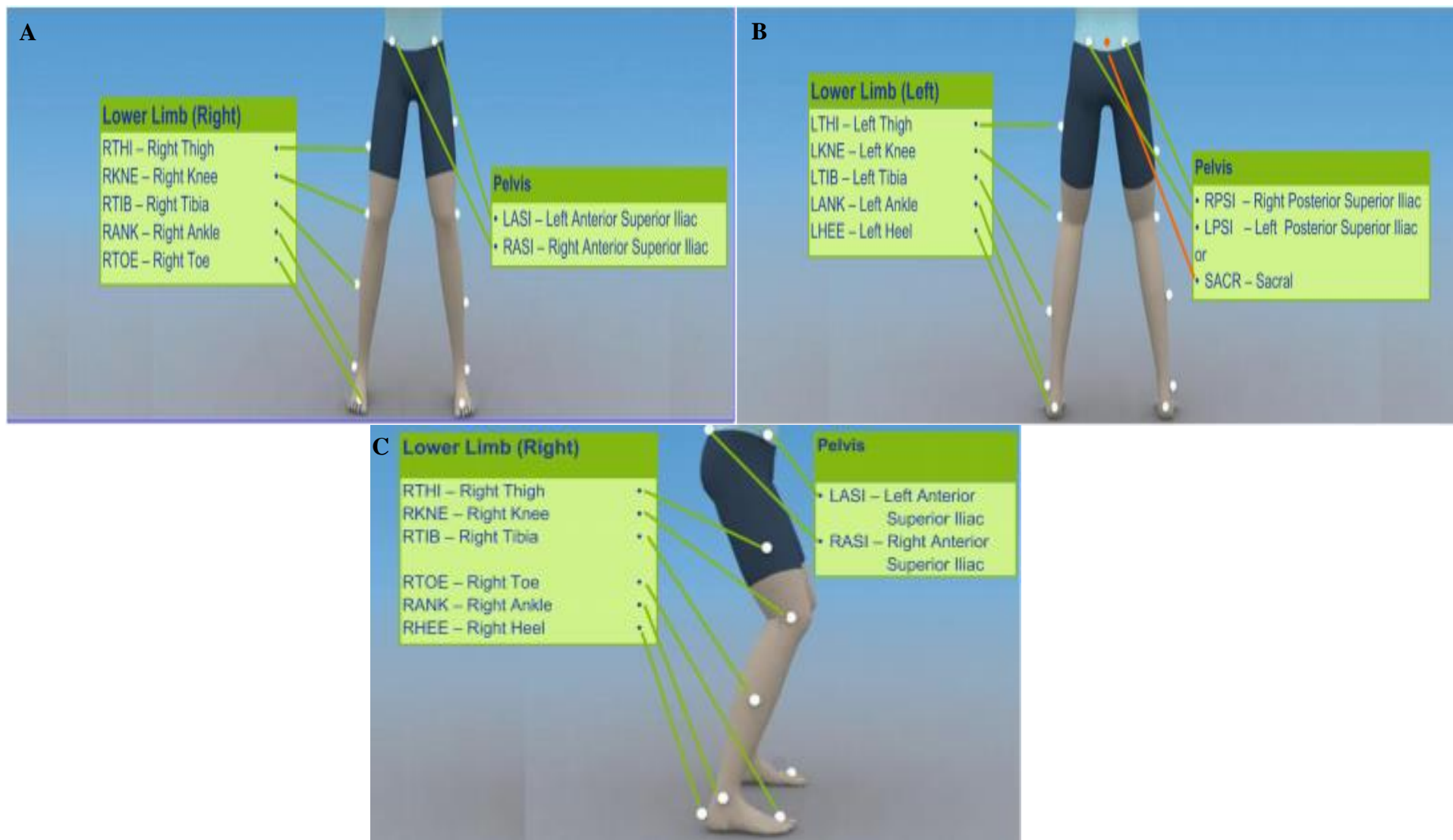


Figure 3.5. Lower Body Plug-in Gait marker placement from A) front B) back and C) side view. Images taken from Vicon (2018).

spheres, this was also done for the knee marker. Prior to marker placement, landmarks (skin) were sprayed with adhesive pre-tape spray used on athletic taping procedures (Muller, Tufner, Germany). The pre-tape spray aides in sticking of the tape to the skin for longer periods and is water resistant, thereby combating sweating. The bases of the makers were then taped on to the skin and were also taped down to provide increased security. Participants were then given compression leggings to wear over the marker bases to provide additional security. A small opening was made in the leggings over each base, to attach the spheres of the reflective marker to its base. The toe, heel and ankle markers were secured using kinesiotape to minimise movement restriction. The posterior and anterior super iliac spine markers were taped around the hip using soft adhesive tape to avoid impeding hip movement while ensuring they remained in place throughout the run.

3.8.4 Static Capture

Following marker placement, participants were first instructed to stand still in front of the treadmill, the middle of the capture volume where all unlabelled markers were visible in the 3D

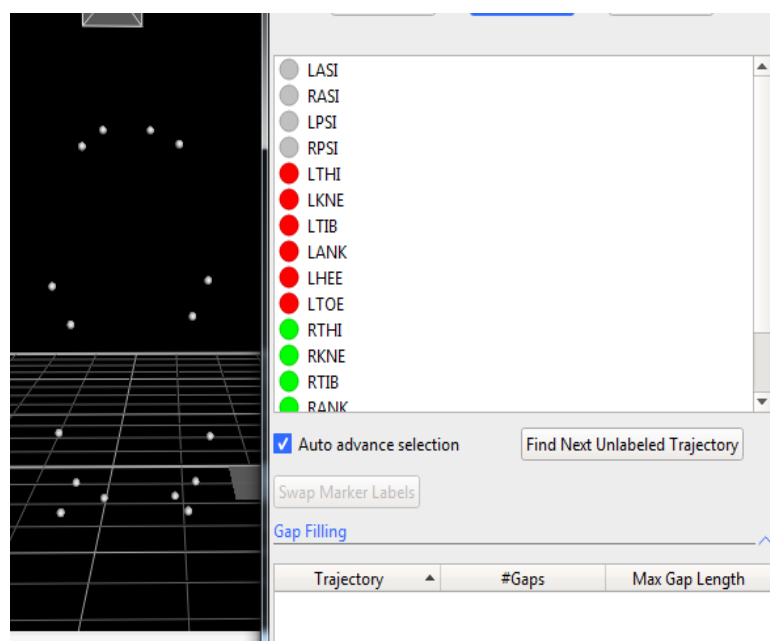


Figure 3.6. Post static capture marker identification

perspective view of Vicon Nexus software. They stood with hands across their chest and feet shoulder width apart, ensuring all markers were visible to the cameras. Static capture was recorded for three seconds and then reconstructed in the software for marker identification (Figure 3.6).

3.8.5 Data Capture

For all running protocols, motion capture was recorded for 25 seconds, and later analysed for kinematic variables and coordination variability. Based on pilot testing, the motion capture was recorded at two time points: after the first 30 seconds, to allow time for participants to acclimatise to the treadmill belt speed, and during the first 30 seconds of the final minute of each run or repetition. This allowed a five second time window to provide a countdown for participants before end of each run to avoid exaggerated running mechanics. For chapters 4, 5, and 6 data was captured at a 500 Hz sampling rate. In chapter 7 the capture rate was reduced to 250 Hz to reduce file size. This decision to lower sampling rate eliminated occasional freezing of the system thereby enhancing data processing.

3.8.6 Data Processing

The captured trials of each run were first constructed through the system via the reconstruct and label pipeline, where markers were labelled automatically. This action was followed with identification of gaps in marker trajectories that occur due to the inability to reconstruct markers in some frames. This was rectified through manual gap filling per manufacture recommendation (Vicon, 2018).

In order to identify the stance phase, the initial contact and toe-off were identified semi-manually on motion capture software. Initial contact was identified as the first contact of the heel

assessed by the location of the heel marker in the Z-axis, and foot-off was identified by using the heel marker in respect to horizontal position in the Z-axis. This action was performed for the first two strides, and the remaining strides were autocorrelated through Vicon Nexus 2.0 software. Individual events were then double checked manually for correct identification.

Once all the stride events had been identified, the captured trajectories were processed using a fourth order Butterworth filter via dynamic plug-in gait model with 6 Hz cut-off frequency based on the recommendation of van den Bogert (1996). All processed raw files were exported from Vicon Nexus into Excel as a comma delimited format and prepared for data extraction.

The raw data with identified events were then transferred into a custom written script for the identification of gait characteristics. A stride was counted as an initial contact of the right leg to the next initial contact of the same leg. Stride frequency was calculated as number of strides per minute, and contact time was calculated as the time difference between initial contact and foot off.

3.8.6.1 Kinematics and Spatiotemporal Parameters

For each sampled stance phase, maximum (Max) and range of motion (RoM) angles at the knee and hip in the sagittal and frontal plane were identified, then averaged, before being exported from the processed raw data. The transverse planes of motion was extrapolated for chapters 4 and 5 only to provide an overall reliability of motion capture and stride count required for motion capture. At each joint, maximum angle was taken as the peak value within each stance phase, and RoM was determined from the difference between the maximum and minimum angles within the stance phase. Spatiotemporal parameters of contact time, stride length, and stride frequency were also taken from each stance phase and then averaged.

All kinematic and dynamical systems theory were processed using custom written scripts in Matlab (2018a, The Mathworks, Inc. Natick, MA, USA).

3.8.6.2 Joint Calculations

Vicon Plug in Gait dynamic model was run to produce X, Y and Z coordinates for virtual hip, knee and ankle joint centres (Davis *et al.*, 1991), where angles for each joint of interest and planes of motion were extrapolated. A description of hip, knee, and ankle joint calculation based on lower extremity Plug in Gait Model is provided below (Vicon, 2018).

3.8.6.2.1 Hip

Hip flexion/extension was calculated based on the Y-axis of the pelvis which passes through the hip joint centre. Hip flexion was identified as the positive value, as the projected sagittal thigh and pelvic axis, where the knee was in front of the body. Hip abduction/adduction was calculated between the long axis of the thigh and frontal axis of the pelvis (pelvis X-axis). Adduction angle is identified as the positive value for the leg moving inward. Hip rotation is measured between the sagittal axis of the thigh and pelvis projected into the plane perpendicular to the long axis of the thigh (pelvis Z). Hip internal rotation was identified as a positive value where the thigh had rotated internally.

3.8.6.2.2 Knee

Knee flexion/extension was identified as the thigh Y-axis, defined as the plane between sagittal shank axis – that is projected into the plane perpendicular to the knee flexion, and the sagittal thigh axis – the angle with a positive value is identified as knee flexion angle. Knee abduction/adduction, the angle between the long axis of the shank and the thigh (the thigh X-axis) measured in the plane of the knee flexion axis and ankle centre, where a positive value indicates an outward bend of the knee, or varus. Knee rotation was measured about the long axis of the shank, as the angle between sagittal axis of the shank and the thigh projected into the long

axis of the shank (the thigh Z axis). Internal rotation of the knee was identified by a positive value.

3.8.6.2.3 Ankle

For the ankle, dorsiflexion and plantar flexion were identified as the angles between the foot vector and the sagittal axis of the shank, where a positive value identifies dorsiflexion (Y-axis of the tibia). Inversion and eversion are described through the X-axis of the tibia, projected posteriorly from the ankle joint centre along the long axis of the foot. Ankle rotation as defined as the tibia Z-axis projected upward from the ankle joint centre, a cross product of X and Y-axes.

3.8.6.3 Continuous Relative Phase

To allow for phase angle calculation, φ , phase plots were constructed for each joint motion by plotting angular position (horizontal axis) against angular velocity (vertical axis). Normalisation of the phase plots for every trial was required and outlined in equations 1 and 2. θ represents joint angle and i for each data point within the stance phase.

$$\text{Angle (Horizontal axis): } \theta_i = \frac{2*[\theta_i - \min(\theta_i)]}{\max(\theta_i) - \min(\theta_i)} - 1 \quad \text{Equation 1.}$$

$$\text{Angular velocity (vertical axis): } \omega_i = \frac{\omega_i}{\max\{\omega_i\}} \quad \text{Equation 2.}$$

The normalisation process applied normalised the x-axis to represent a minimum value of -1 and maximum value of 1, with the horizontal axis in the middle of the range. In equation 2, ω_i represents angular velocity at each data point i , with the largest magnitude of angular velocity being normalised to 1 for one stance phase. The normalised phase plots for each stance phase in the cycle defined the phase angle, φ , as the angle between the right horizontal and a

line drawn from the origin to a specific data point (Hamill *et al.* 1999), as outlined in equation 3.

$$\varphi = \tan^{-1} \frac{\omega(t)}{\theta(t)} \quad \text{Equation 3.}$$

Continuous relative phase was calculated as the difference between the normalised phase angles (equation 4) for the hip and knee of interest.

$$CRP(t) = \varphi_{proximal}(t) - \varphi_{distal}(t) \quad \text{Equation 4.}$$

Continuous relative phase was represented as a range from 180° to -180° with 0° indicating that the examined joints were moving in-phase. An increase in CRP indicated that joints were moving out of phase until reaching 180° or -180° anti-phase. Continuous relative phase also examined which coupling joints had a larger phase angle; a positive angle indicated that the proximal joint had greater phase angle while a negative angle is indicative of a higher distal joint phase angle. Continuous relative phase variability, defined as standard deviation of the calculated CRP. It was used to indicate the variation in CRP over a number of strides and thereby the stability of the gait.

3.8.6.4 Coupling Angle through Vector Coding

Coupling angle was calculated for each instant (i) for the normalised data of the stance phase. Coupling angle, γ_i , was calculated based on consecutive angles of the proximal and distal joints outlined in equations 5 - 12. As explained in section 2.7.2 there are normalisation ranges to be considered, for the purposes of this thesis a range of 0°-360° was employed, with all angles corrected (equation 8). The average coupling angle was calculated based on average horizontal

and vertical components at each instant through circular statistics (equations 8-9) and corrected again (equation 10) to provide the selected range (Hamill *et al.* 2000, Needham *et al.* 2014). The length of average coupling was represented as \bar{r}_i and coupling angle variability was calculated using equation 11 and 12.

$$\gamma_i = \tan^{-1} \left(\frac{\theta_{D(i+1)} - \theta_{Di}}{\theta_{P(i+1)} - \theta_{Pi}} \right) \frac{180}{\pi} \quad \theta_{P(i+1)} - \theta_{Pi} > 0 \quad \text{Equation 5.}$$

$$\gamma_i = \tan^{-1} \left(\frac{\theta_{D(i+1)} - \theta_{Di}}{\theta_{P(i+1)} - \theta_{Pi}} \right) \frac{180}{\pi} + 180 \quad \theta_{P(i+1)} - \theta_{Pi} > 0 \quad \text{Equation 6.}$$

$$\gamma_i = \left\{ \begin{array}{ll} \gamma_i = 90 & \theta_{P(i+1)} - \theta_{Pi} = 0 \text{ and } \theta_{D(i+1)} - \theta_{Di} > 0 \\ \gamma_i = -90 & \theta_{P(i+1)} - \theta_{Pi} = 0 \text{ and } \theta_{D(i+1)} - \theta_{Di} < 0 \\ \gamma_i = -180 & \theta_{P(i+1)} - \theta_{Pi} < 0 \text{ and } \theta_{D(i+1)} - \theta_{Di} = 0 \\ \gamma_i = Undefined & \theta_{P(i+1)} - \theta_{Pi} = 0 \text{ and } \theta_{D(i+1)} - \theta_{Di} = 0 \end{array} \right\} \quad \text{Equation 7.}$$

$$\bar{x}_i = \frac{1}{n} \sum_{i=1}^n \cos \gamma_i \quad \text{Equation 8.}$$

$$\bar{y}_i = \frac{1}{n} \sum_{i=1}^n \sin \gamma_i \quad \text{Equation 9.}$$

$$\bar{\gamma}_i = \left\{ \begin{array}{ll} \tan^{-1} \left(\frac{\bar{y}_i}{\bar{x}_i} \right) \cdot \frac{180}{\pi} & x_i > 0, y_i > 0 \\ \tan^{-1} \left(\frac{\bar{y}_i}{\bar{x}_i} \right) \cdot \frac{180}{\pi} + 180 & x_i < 0 \\ \tan^{-1} \left(\frac{\bar{y}_i}{\bar{x}_i} \right) \cdot \frac{180}{\pi} + 360 & x_i > 0, y_i < 0 \\ 90 & x_i = 0, y_i > 0 \\ -90 & x_i = 0, y_i < 0 \\ Undefined & x_i = 0, y_i = 0 \end{array} \right. \quad \text{Equation 10.}$$

$$\bar{r}_i = \sqrt{\bar{x}_i^2 + \bar{y}_i^2}$$

Equation 11.

$$CAV_i = \sqrt{2 \cdot (1 - \bar{r}_i)} \cdot \frac{180}{\pi}$$

Equation 12.

CHAPTER 4 – RELIABILITY OF RISK FACTORS OF RUNNING RELATED OVERUSE INJURIES

4.1 Introduction

While the aetiology of running related overuse injuries remains unclear, there is a common consensus that risk factors e.g. weak muscular strength at the hip, excessive knee valgus or hip abduction angle and altered coordination variability (Hamill *et al.* 2012; Powers, 2010). In order to have confidence in the detection of injury risk factors, the validity and reliability of the measures must be known (O'Donoghue, 2012).

Hand held dynamometers (HHD) have been utilized extensively in previous studies to examine strength of both hip and knee muscle for examining aetiology of RROI (Bazett-Jones *et al.* 2013; Fredericson *et al.* 2000). Hand held dynamometers have shown to be useful because they are relatively small in size, easy to use, and affordable. Previous studies have however reported inconsistent reliability scores as the measure depends on experiment set up, placement of HHD on tested limb and position of the participant at time of the test (McMahon *et al.* 1992; Wikholm and Bohannon, 1991). Katoh and Yamasaki (2009) compared muscular strength reliability with and without the use of a resistant belt, reporting that a resistance belt the interclass correlation scores are higher (0.61- 0.95) compared to without (0.21- 0.88). Similarly, Thorborg *et al.* (2011) reported tester bias when not using a non-elastic strap to secure the HHD.

The reliability of kinematic assessment has been overwhelmingly performed using overground running (Ferber *et al.* 2002; Kadaba *et al.* 1989). There are, however, certain limitations when using overground running. For example, consecutive strides cannot be recorded and it requires running along a runway at between $\pm 5\%$ to 10% of designated running speeds (Brown *et al.* 2016; Crowell and Davis, 2011). In contrast, treadmill running can provide standardised conditions with a fixed speed and motion capture calibration volume making for a more reproducible testing environment (Riley *et al.* 2008). Treadmill running also enables the recording of consecutive strides and detection of the time course of any changes (Riley *et al.* 2008; Brown *et al.* 2016).

To date, only one study has examined and reported acceptable kinematic reliability during treadmill running (Noehren *et al.* 2010). The reliability of kinematic data collected towards the end of a run, when athletes might be fatiguing, has yet to be established. The presumption is that reliability remains unchanged. Furthermore, while treadmill running has been used previously for investigating RROI (Bazett-Jones *et al.* 2013; Brown *et al.* 2016; Noehren *et al.* 2011), there is limited knowledge of the reproducibility and measurement error for detecting abnormal kinematics.

Coordination variability is examined through the use of applications of DST allowing the assessment of the interaction of one joint acting on another. The applications of continuous relative phase and vector coding coupling angle were introduced to provide further insight into running injuries (Hamill *et al.* 2012). While both methods have been shown to be valid and a popular choice within biomechanics (Miller *et al.* 2010), their reliability remains unexamined. To date, no study has examined the measurement error associated with either DST applications. As coordination variability will be a strong component in assessment of effect of fatigue on gait this thesis, it's between day reliability requires consideration. Similar to kinematics, its reliability needs to be examined at multiple time points during data capture to ensure stable data and reliable fatigue response.

4.1.1 Aims

To ensure reliable data collection for the experiments of this thesis, the principle aims of this chapter were to examine between-day reliability of the protocols of future studies of this thesis:

- i) muscular strength assessment of the hip and knee using a HHD
- ii) treadmill running kinematics and DST applications during two different intensity, energy expenditure matched, runs
- iii) to examine both running gait and DST applications at both start and end of the runs.

4.2. Methods

4.2.1 Participants

Following a power analysis and subsequent institutional ethical approval, 20 healthy, experienced, club distance runners, (N=10 male; N=10 female) were recruited (Table 4.1).

Inclusion criteria is described in chapter 3 section 3.3.

Table 4.1. Descriptive characteristics of participants, training runs, speeds, durations, $\dot{V}O_{2\max}$, speed at lactate turnpoint (sLTP), percentage of $\dot{V}O_{2\max}$ at sLTP (% at sLTP), represented as mean \pm standard deviation.

	Female (<i>n</i> = 10)	Male (<i>n</i> = 10)
Age (years)	42.2 \pm 4.0	43.8 \pm 4
Height (cm)	164.6 \pm 6.0	181.2 \pm 7.9
Mass (kg)	58.5 \pm 6.2	77.3 \pm 6.5
HIIT Speed (m·s ⁻¹)	3.9 \pm 0.3	4.6 \pm 0.3
HIIT rep duration (min:sec)	03:24 \pm 13(s)	02:47 \pm 16(s)
MICR Speed (m·s ⁻¹)	3.3 \pm 0.2	3.6 \pm 0.4
MICR duration (min:sec)	32:15 \pm 02:01	25:53 \pm 03:40
$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	53.6 \pm 5.4	60.5 \pm 4.4
sLTP (m·s ⁻¹)	3.3 \pm 0.2	3.7 \pm 0.4
% $\dot{V}O_2$ max at LTP	81.4 \pm 5.5	72.7 \pm 8.1

4.2.2 Procedure

All sessions were conducted at the same time of day to minimise diurnal variation (Reilly and Garrett, 1998). Participants were asked to wear the same footwear throughout and follow their habitual dietary regimen, while refraining from high volume or intensity training 48 hours prior to testing.

4.2.2.1 Preliminary Testing

Initial measurements of mass, height and kinanthropometric measures were taken as described in chapter 3, section 3.5.1.

Participants completed maximal and submaximal tests to determine speeds and duration of the training runs, this was collected as described in chapter 3, sections 3.5.4 and 3.5.5.

4.2.2.2 HIIT and MICR

Participants completed maximal and submaximal tests to determine the speeds and duration of the training runs, as described in chapter 3, sections 3.6.

4.2.2.2 Reliability trials

4.2.2.2.1 Muscular Strength

Hip and knee muscular strength reliability was examined prior to the two training runs. The data collected from the four trials was then used to assess both relative and absolute reliability. The procedure is described in section 3.7.

4.2.2.2.2 Kinematics and Coordination Variability

Reliability of kinematic variables along with coordination variability was assessed using two different types of run; a high intensity interval training (HIIT) and a medium intensity continuous running (MICR). The duration and speed of each run was individualised based on $\dot{V}O_{2\max}$ and LTP, a full description of the procedure for kinematic measures can be found in chapter 3, section 3.6.

Reliability of coordination variability of interactions between sagittal (flexion/ extension) and frontal (abduction/ adduction) planes of motion for the hip and knee joint couplings were examined for CRPV and CAV. Data for both CRPV and CAV were collected and processed as described in chapter 3, section 3.8.6.2 and 3.8.6.3.

4.2.3 Motion Analysis

Running kinematics were captured via a 14-camera 3-dimensional kinematic analysis system (MX; Vicon Motion Systems Ltd., Oxford, England) sampling at 500 Hz. Marker trajectories were recorded for 25 seconds at the end of the first minute and the final minute of each run.

Motion capture description can be found in chapter 3, sections 3.8.

4.2.4 Data Processing

Motion capture data was processed as described in chapter 3, section 3.8.6.

4.2.5 Statistical analysis

4.2.5.1 Relative Reliability

Relative reliability was reported through intraclass correlation coefficients for repeated measures (ICC (3,1)). An ICC of <0.50 was considered poor, while between 0.5 and 0.75 was considered moderate and between 0.75 and 0.90 was considered good, with excellent reliability >0.90 (Koo and Li, 2016).

4.2.5.2 Absolute Reliability

Absolute reliability was expressed as standard error of measurement (SEM), representing a combination random and systematic error (Weir, 2005), expressed as

$$SEM = SD(\sqrt{1-ICC})$$

Equation 4.1.

where SD denotes standard deviation of all scores. To be able to compare strength absolute reliability to previous works, percentage of SEM expressed from the mean (SEM%) was derived.

Minimum detectable change (MDC) was calculated to estimate the minimum amount of change needed to be 95% confident that a real change had occurred and calculated as

$$\text{MDC} = \text{SEM} \times 1.96 \times \sqrt{2} \quad \text{Equation 4.2.}$$

Coefficient of variation calculated as

$$\text{CV} = (\text{SD}/\text{mean}) \times 100 \quad \text{Equation 4.3.}$$

4.3. Results

4.3.1 Muscular Strength

4.3.2.1 Relative Reliability

Good reliability values were observed from muscular strength measures at the hip and the knee ranging from (0.77 – 0.88; Table 4.2) with the lowest ICC value observed at hip extension (0.77).

4.3.2.2 Absolute Reliability

In only hip extension and knee flexion measures the SEM value exceeded 10% of the mean. The lowest measure was observed in hip abduction (6.2%)

Table 4.2. Standard error of measurement (SEM; $\text{kg}\cdot\text{kg}^{-1}$), Percentage of SEM expressed as the mean (SEM%). and minimum detectable change (MDC; $\text{kg}\cdot\text{kg}^{-1}$) values for strength measures of hip and knee musculature.

Muscular Strength measures	ICC	SEM	SEM %	MDC
Hip Abduction	0.84	0.031	6.2%	0.087
Hip Adduction	0.86	0.031	9.7%	0.086
Hip Internal Rotation	0.81	0.023	9.8%	0.064
Hip External Rotation	0.84	0.014	7.2%	0.086
Hip Flexion	0.81	0.035	8.7%	0.098
Hip Extension	0.77	0.038	11.6%	0.106
Knee Extension	0.86	0.043	8.6%	0.118
Knee Flexion	0.88	0.030	11.4%	0.183

4.3.2 Kinematics and Spatiotemporal Parameters

4.3.2.1 Relative Reliability

There was considerable variation in the reliability of kinematic variables with scores ranging from poor to excellent ICCs (0.46 – 0.94) for all three planes of motion (Table 4.3). Range of motion produced better reliability for the knee and hip compared to maximum angle values in all planes of movement (Table 4.3). Within joints and planes of motions, there were limited differences in ICC values when comparing the start or end of either run intensity. All spatiotemporal parameters showed good to excellent ICCs (0.78 – 0.97) with the lowest ICC value was observed in SF at HIIT_{start} (Table 4.4).

4.3.2.2 Absolute Reliability

In Kinematics, the SEM ranged from 1.0° - 5.5° , with the highest values observed in transverse planes of motion (1.8° – 5.7°), while sagittal (1.4° – 3.7°) and frontal (1.0° – 5.0°) produced similar values. There were no differences observed between HIIT and MICR for SEM for either

Table 4.3. Comparison of Intraclass Correlation Coefficients (ICC), Standard Error of Measurement (SEM; deg), Minimum Detectable Changes (MDC; deg), Coefficient of variation percentage (CV%), for maximum angles (Max) and range of motion (RoM) of stance phase in sagittal and frontal planes of motion for Knee and Hip in High Intensity Interval Training run (HIIT) start and end; and Medium Intensity Continuous Run (MICR) start and end.

<i>Sagittal</i>		ICC	SEM	MDC	CV %	<i>Frontal</i>		ICC	SEM	MDC	CV %	<i>Transverse</i>		ICC	SEM	MDC	CV %
Knee Max	<i>HIIT start</i>	0.90	2.0	5.5	2.4	<i>HIIT start</i>	0.50	3.0	8.3	3.0	3.0	<i>HIIT start</i>	0.88	4.0	11.1	3.8	
	<i>HIIT end</i>	0.80	2.9	8.0	2.4	<i>HIIT end</i>	0.46	5.0	13.9	8.1	8.1	<i>HIIT end</i>	0.86	4.7	13.0	3.0	
	<i>MICR start</i>	0.91	2.0	5.5	3.6	<i>MICR start</i>	0.86	2.7	7.5	2.8	2.8	<i>MICR start</i>	0.83	4.5	12.5	4.0	
	<i>MICR end</i>	0.74	3.7	10.3	2.2	<i>MICR end</i>	0.82	3.7	10.3	2.6	2.6	<i>MICR end</i>	0.83	4.2	11.6	3.1	
Knee RoM	<i>HIIT start</i>	0.92	1.7	4.7	4.1	<i>HIIT start</i>	0.47	1.6	4.4	13.1	13.1	<i>HIIT start</i>	0.63	2.9	8.0	5.2	
	<i>HIIT end</i>	0.81	2.5	6.9	3.7	<i>HIIT end</i>	0.68	1.3	3.6	11.9	11.9	<i>HIIT end</i>	0.81	2.6	7.2	5.9	
	<i>MICR start</i>	0.94	1.5	4.2	5.3	<i>MICR start</i>	0.57	2.4	6.7	13.9	13.9	<i>MICR start</i>	0.63	3.4	9.4	5.3	
	<i>MICR end</i>	0.94	1.9	5.3	2.4	<i>MICR end</i>	0.75	1.4	3.9	10.6	10.6	<i>MICR end</i>	0.63	3.3	9.1	4.7	
Hip Max	<i>HIIT start</i>	0.85	2.9	8.0	2.7	<i>HIIT start</i>	0.74	1.8	5.0	6.8	6.8	<i>HIIT start</i>	0.82	4.8	13.3	11.1	
	<i>HIIT end</i>	0.88	2.6	7.2	2.5	<i>HIIT end</i>	0.73	2.3	6.4	7.0	7.0	<i>HIIT end</i>	0.79	4.8	13.3	15.9	
	<i>MICR start</i>	0.88	2.9	8.0	4.1	<i>MICR start</i>	0.73	1.0	2.8	6.3	6.3	<i>MICR start</i>	0.91	4.8	13.3	14.4	
	<i>MICR end</i>	0.72	3.6	10.0	2.3	<i>MICR end</i>	0.75	1.0	2.8	2.3	2.3	<i>MICR end</i>	0.86	5.7	15.8	15.6	
Hip RoM	<i>HIIT start</i>	0.74	1.9	5.3	2.6	<i>HIIT start</i>	0.76	1.2	3.3	6.0	6.0	<i>HIIT start</i>	0.61	2.6	7.2	10.9	
	<i>HIIT end</i>	0.88	1.6	4.4	2.4	<i>HIIT end</i>	0.78	2.1	5.8	6.8	6.8	<i>HIIT end</i>	0.53	3.3	9.1	11.4	
	<i>MICR start</i>	0.86	1.4	3.9	6.0	<i>MICR start</i>	0.78	2.0	5.5	7.8	7.8	<i>MICR start</i>	0.46	4.6	12.8	9.7	
	<i>MICR end</i>	0.88	1.5	4.2	6.8	<i>MICR end</i>	0.93	1.2	3.3	5.7	5.7	<i>MICR end</i>	0.66	2.8	7.8	10.7	

Table 4.4. Comparison of intraclass Correlation Coefficients (ICC), Standard Error of Measurement (SEM), Minimum Detectable Change (MDC), for spatiotemporal parameters of Stride Frequency (SF), Stride Length (SL), and Contact Time (CT) in High Intensity Interval Training run (HIIT) start and end; and Medium Intensity Continuous Run (MICR) start and end.

		ICC	SEM	MDC
SF (strides/minute)	<i>HIIT start</i>	0.78	2.8	7.9
	<i>HIIT end</i>	0.90	1.1	3.8
	<i>MICR start</i>	0.87	2.3	6.3
	<i>MICR end</i>	0.89	1.4	3.8
SL (m)	<i>HIIT start</i>	0.95	0.027	0.074
	<i>HIIT end</i>	0.96	0.026	0.072
	<i>MICR start</i>	0.96	0.026	0.073
	<i>MICR end</i>	0.97	0.023	0.064
CT (s)	<i>HIIT start</i>	0.91	0.008	0.023
	<i>HIIT end</i>	0.96	0.006	0.016
	<i>MICR start</i>	0.90	0.009	0.025
	<i>MICR end</i>	0.86	0.007	0.018

RoM or maximum angles, in the sagittal or frontal planes. Maximum angles for the transverse planes of motion produced the highest SEM values of all three planes. Examination of the coefficient of variation found no differences between MICR and HIIT, or between time points for all joints and planes. Within the sagittal plane, CV values ranged from 2.2 to 6.8% and between 2.3 to 13.9% within the frontal plane. RoM values for the knee joint produced the highest CV. The transverse plane produced the highest CV of the three planes for the maximum angles of hip, with a range from 3.0 to 15.9%, hip_{max} and RoM producing the highest values. Within spatiotemporal parameters, only in SF was there a difference between start and end, with end of both HIIT and MICR showing lower measurement error compared to start (Table 4.4). The comparison between the start and end of the runs in kinematics found similar SEM values, this was consistent across run type and plane of movement (Table 4.4).

4.3.3 Coordination Variability

4.3.3.2 Relative Reliability

The ICC values do not allow for comparison between CRPV and CAV as both applications produce similar relative reliability (Table 4.5). Both coordination variability applications produced good to moderate relative reliability with ICC values ranging from (0.73 – 0.92).

Table 4.5. Comparison of Intraclass Correlation Coefficients (ICC), Standard Error of Measurement (SEM; deg), Minimum Detectable Changes (MDC; deg), for Continuous Relative Phase Variability (CRPV) and Coupling Angle Variability (CAV) of high intensity interval training (HIIT) and medium intensity continuous run (MICR) at both beginning and end.

			CRPV			CAV		
			ICC	SEM	MDC	ICC	SEM	MDC
Hip _{flex/ext} - Knee _{flex/ext}		<i>HIIT start</i>	0.77	2.5	6.9	0.79	2.8	7.8
		<i>HIIT end</i>	0.89	2.7	7.5	0.89	0.8	2.2
		<i>MICR start</i>	0.84	3.8	10.5	0.77	2.1	5.8
		<i>MICR end</i>	0.82	6.8	18.8	0.84	2.6	7.2
Hip _{flex/ext} - Knee _{abd/add}		<i>HIIT start</i>	0.88	2.6	7.2	0.78	1.7	4.7
		<i>HIIT end</i>	0.88	3.6	10.0	0.73	0.5	1.4
		<i>MICR start</i>	0.86	4.5	12.5	0.78	1.6	4.4
		<i>MICR end</i>	0.86	5.1	14.1	0.80	2.8	7.8
Hip _{abd/add} - Knee _{flex/ext}		<i>HIIT start</i>	0.89	8.4	23.3	0.84	0.9	2.5
		<i>HIIT end</i>	0.89	2.8	7.8	0.91	0.2	0.6
		<i>MICR start</i>	0.83	7.4	20.5	0.75	0.7	1.9
		<i>MICR end</i>	0.89	6.5	18.0	0.75	0.7	1.9
Hip _{abd/add} - Knee _{abd/add}		<i>HIIT start</i>	0.92	3.2	8.9	0.76	1.8	5.0
		<i>HIIT end</i>	0.81	1.9	5.3	0.81	0.7	1.9
		<i>MICR start</i>	0.86	3.7	10.3	0.83	1.2	3.3
		<i>MICR end</i>	0.78	9.7	26.9	0.73	1.9	5.3

4-3.3.2 Absolute Reliability

For CRPV SEM ranged from 1.9° - 9.7°, with CAV having lower SEM values ranging from 0.2° - 2.8° (Table 4.5). In either of the two applications, both run-types produced similar SEM values at the start and end of the runs.

4.4. Discussion

The aim of this chapter was to determine the between-day reliability and measurement error of muscular strength, treadmill running kinematics and coordination variability captured for two different running speeds at both the start and end of each run. The results of this chapter demonstrate good to excellent reliability for measures employed to examine running related risk factors of injury. There were minimal differences in the reliability of the two-energy expenditure matched running speeds even though they differed in physiological demand. Furthermore, regardless of time point of data collection, the reliability of the captured kinematics and coordination variability remained good to acceptable.

The reliability of muscular strength measures were consistent with previous studies (Bazett-Jones *et al.* 2011; Katoh and Yamasaki, 2009). The lowest measurement error percentage was observed in hip abduction strength measure at 6.7%. The examination of hip abduction strength is imperative in this thesis to assess risk of injury from typical training runs; the low error provides confidence in this measure. Hip abduction weakness has been identified as a primary risk factor with runners exhibiting either PFP and ITBS (Noehren *et al.* 2007; Dierks *et al.* 2008).

The lack of consistency in procedure amongst previous studies has made comparison of approaches for examining hip and knee musculature strength difficult. There are various factors that influence the measurement e.g., fixation system of the device, devices, and position

(Chamorro *et al.* 2017). This can be seen in the 11.4% SEM% value reported in this chapter for knee flexion, this is lower than lower than the reported 21% by Arnold *et al.* (2010) and 14% of Lu *et al.* (2007), however higher than the 1% reported by Kelln *et al.* (2008). The three studies however differed in protocol of participant position during the test. The testing procedures for the hip musculature which included the placement of HHD on tested limb was replicated from study of Bazett-Jones *et al.* (2011). There was however a difference in the method for securing the HHD against the tested limb as they study used hard foam to fit the HHD, while this chapter used a velcro strap. This resulted in lower ICC values for all hip measures apart from hip abduction strength compared to Bazett-Jones *et al.* (2011). Based on a review by Chamorro *et al.* (2017), the absolute reliability of in this experiment set up is in line with the measurement errors reported by previous studies.

For kinematics, knee maximum angles in the frontal plane and hip range of motion in transverse plane produced the lowest ICC values. The ICC values however were used for the calculation of absolute reliability (SEM and MDC) and therefore accounted for in all subsequent analyses and data interpretation. For all three joints and planes of motion, the SEMs were similar to previous studies using the Plug-in-Gait (PiG) model and the reliability values obtained were similar to previously reported studies examining running kinematics (Noehren *et al.* 2010; Stief *et al.* 2013). McGinley *et al.* (2009) reported that for majority of studies, SEM values fall between 2° and 5°. For the majority of variables in this chapter, the SEM was below 5°, apart for three variables. The SEM values across all three planes of motion for both knee and hip joint were between 1.2° and 5.7°, again in line with previous studies (McGinley *et al.* 2009).

This chapter concurs with the view of McGinley *et al.* (2009) that reliability studies should provide absolute reliability measures, allowing the determination of MDC. They also suggested that SEMs should not exceed 5°, as large measurement errors could reduce the sensitivity in the

variables and decrease feasibly to detect meaningful change in gait (McGinley *et al.* 2009). This does, however, raises the question of how to best detect changes in gait due to fatigue, injury, or other abnormalities. SEM is the expected error within a measurement 67% of the time, while MDC is a confidence interval identifying the amount of change required to be sure that a change is real, rather than due to measurement error. All but three of the SEM values were below 5°, resulting in MDC values of as high as 15.8° (Table 4.3). Based on previous recommendations, this may be too insensitive to detect most kinematic changes.

Noehren *et al.* (2014), used kinematics to distinguish between injured and non-injured runners during treadmill running. They used an MDC score of 2.3° for maximum hip rotation angle based on a previously reported ICC score ($r = 0.98$) (Ferber *et al.* 2002) rather than their own reliability. The ICC value they used was higher than this study ($r = 0.91$) but was determined from over ground not treadmill running. This thesis contends that running modes should match and that researchers should utilise their own reliability scores.

The results of this chapter suggest that for most variables the use of both CRPV and CAV are reliable. To date, this is the first study to examine reliability of either DST application. Between the two applications, CRPV had better overall ICC values, however absolute measurement error was much lower in CAV (Table 4.4). The reliability assessments of the two measures however should not be compared against one another as each measure is fundamentally different. Each application incorporates a different set of variables for calculation, with CRP containing spatiotemporal signals and CAV containing only spatial. Similarly, Miller *et al.* (2010) suggested that the two applications should not be compared to one another as each measure might provide different perspectives.

The measurement errors obtained in this chapter might have been influenced by factors that were outside testing protocols and require consideration. An inherent contributor could be attributed to

the normalisation process of each application; a necessary element of calculation steps of DST applications. Each application can be normalised to different ranges with the potential to induce different measurement error. For example, this chapter employed a 180° , -180° range for normalisation of CRP; however, there are options to perform normalisation in $[0^\circ, 360^\circ]$ or $[0^\circ, 180^\circ]$ instead (Lamb and Stöckl, 2014). The ranges will have their own interpretation of mean values of each stride and these different normalisation procedure require further study.

Both kinematic and coordination variability assessment at different time points during a task is a popular method for examining the effects of fatigue on running kinematics. Previous studies have compared kinematics and coordination variability at the start and end of a run to examine gait changes either from fatigue or to differentiate the gait of runners with and without RROI (Derrick *et al.* 2002; Miller *et al.* 2008). The principle benefit of employing treadmill running is the collection of continuous data (Sinclair *et al.* 2013), enabling the time-course of changes to be better observed. Previous reliability studies have only recorded runners in a non-fatigued state, thereby assuming that measurement error is the same at the end of the run. This is the first study to examine this, finding little to no difference in reliability between the start and end of each run, this was true for both relative and absolute reliability.

The low SEM values in gait assessment suggest that the approaches taken in this chapter were successful in producing reliable results. Marker placement, along with skin and soft tissue artefacts, have been linked as sources of errors within motion analysis (Noehren, *et al.* 2010; Ferber *et al.* 2002), for example a 10mm displacement can cause up to 6° in the knee (Osis *et al.* 2016)..

The MDC values in this chapter provide further information on absolute reliability of kinematic and coordination variability assessments during treadmill running alongside strength, offering

clinicians and researchers parameters to detect if a real change has occurred within, or following, a running-task or training intervention (Stratford *et al.* 1998).

Conclusion

This chapter was the first to examine the reliability of treadmill running kinematics and coordination variability during two different run-types at two points in time. The results of this chapter suggest that treadmill running is a reliable method for examining kinematics and coordination variability regardless of speed and time point of capture during a given running task. Furthermore, this chapter is the first provide MDC for kinematic and coordination variability assessment during treadmill running and provides provisional guidelines.

CHAPTER 5 – THE NUMBER OF STRIDES REQUIRED FOR TREADMILL RUNNING GAIT ANALYSIS IS UNAFFECTED BY EITHER SPEED OR RUN DURATION

Publication arising as result of this chapter:

Riazati, S., Caplan, N., and Hayes, P. R. (2019). The number of strides required for treadmill running gait analysis is unaffected by either speed or run duration. *Journal of Biomechanics*. 97. doi:10.1016/j.jbiomech.2019.109366

5.1. Introduction

Through the analysis of kinematic and spatiotemporal running patterns, differences have been identified between injured and non-injured runners and changes within a run due to fatigue (Dierks *et al.* 2010; Miller *et al.* 2007; Willson *et al.* 2015). Commonly this is analysed using motion capture analysis to assess running mechanics during over ground and treadmill running. There are, however, methodological considerations that need to be made when designing studies investigating RROI or fatigue using motion analysis. With the underlying aetiology of RROI still uncertain, one approach has been to examine fatigue related changes in gait by comparing the beginning and end of a run (Dierks, 2010). To date no study has addressed whether stable data are achieved in the same number of strides as runners fatigue.

The most widely used approach for data capture has been overground running, usually requiring participants to run over a force platform while simultaneously being filmed. Using this approach, it is only possible to measure a single stride (Bazett-Jones *et al.* 2013; Brown *et al.* 2016, 2014), however the number ground contacts collected in an experiment may influence stability of the data collected (Bates *et al.* 1983). Multiple trials are therefore required to gather enough data for analysis. In these circumstances it is difficult to standardise the running speed with studies often allowing a speed variation of between $\pm 5\%$ to 10% of the designated running speed (Almonroeder and Benson, 2016; Bazett-Jones *et al.* 2013; Riley *et al.* 2008; Sinclair *et al.* 2013). Treadmill running by contrast enables continuous data collection at a constant speed. Running gait contains a natural variability, whose capture might provide insight into gait control, for example a reduction in coordination variability has been linked with injury (Hamill *et al.* 2012). Treadmill running therefore offers a more consistent environment to capture this variability.

While treadmill running offers a more consistent environment for data capture, less clear is the number of strides required to have a sufficiently stable gait to analyse kinematic parameters. A few studies have reported the number of consecutive strides required for assessing running kinematics with values ranging from 5-50 (Dierks *et al.* 2010; Esculier *et al.* 2015; Ford *et al.* 2013; Miller *et al.* 2007; Riley *et al.* 2007). No set criteria or guidelines exist for the number of successive strides required to establish stable kinematic or spatiotemporal values during treadmill running. These, kinematic and spatiotemporal parameters vary with running speed (Orendurff *et al.* 2018), again this has not been sufficiently well examined to provide guidelines.

5.1.1 Aims

The aims of this chapter were i) to determine the number of strides necessary to produce stable values for kinematic and spatiotemporal assessment during treadmill running; ii) to compared two different running speeds: a high intensity interval run (HIIT) and a medium intensity continuous run (MICR); iii) to compare values at the start and end of a run.

5.2. Methods

5.2.1 Research Design

Runners were filmed at the beginning and end of two runs in a pre-post, repeated measures crossover design. The two runs were matched for energy expenditure but differed in intensity. The recordings were used to identify the number of strides required to achieve stable kinematic and spatiotemporal values across different intensities and levels of fatigue.

5.2.2 Participants

Based on a power analysis and subsequent institutional ethical approval, for calculating kinematic variables 20 healthy, experienced, local club distance runners, (N=10 male; N=10 female) were recruited. A description of participant characteristics, treadmill speeds and run duration is provided in Table 5.1. Inclusion criteria is described in chapter 3 section 3.3.

Table 5.1. Descriptive characteristics of participants, training runs, speeds, durations, $\dot{V}O_2$ max, speed at lactate turnpoint (sLTP), percentage of $\dot{V}O_2$ max at sLTP (% $\dot{V}O_2$ max), represented as mean \pm standard deviation.

	Female (<i>n</i> = 10)	Male (<i>n</i> = 10)
Age (years)	42.2 \pm 4.0	43.8 \pm 4
Height (cm)	164.6 \pm 6.0	181.2 \pm 7.9
Mass (kg)	58.5 \pm 6.2	77.3 \pm 6.5
HIIT Speed (m·s ⁻¹)	3.9 \pm 0.3	4.6 \pm 0.3
HIIT rep duration (min:sec)	03:24 \pm 13(s)	02:47 \pm 16(s)
MICR Speed (m·s ⁻¹)	3.3 \pm 0.2	3.6 \pm 0.4
MICR duration (min:sec)	32:15 \pm 02:01	25:53 \pm 03:40
$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	53.6 \pm 5.4	60.5 \pm 4.4
sLTP (m.s ⁻¹)	3.3 \pm 0.2	3.7 \pm 0.4
% $\dot{V}O_2$ max at LTP	81.4 \pm 5.5	72.7 \pm 8.1

5.2.3 Procedure

Each participant completed two treadmill runs that mimicked different, typical, training intensities. One was a HIIT session, the other a continuous run, participants were given verbal encouragement throughout. The order of the training runs was randomised, all sessions were conducted at the same time of day to minimise diurnal variation (Reilly and Garrett, 1998).

Participants were asked to wear the same footwear throughout and follow their habitual dietary regimen, while refraining from high volume or intensity training within 48 hours of testing.

5.2.3.1 Preliminary Testing:

Initial measurements of mass, height and kinanthropometric measures were taken as described in chapter 3, section 3.5.1.

Participants completed maximal and submaximal tests to determine speeds and duration of the training runs, this was collected as described in chapter 3, sections 3.5.4 and 3.5.5.

5.2.3.2 HIIT and MICR

The duration and speed of each run was individualised based on $\dot{V}O_2$ max and LTP. For full description see chapter 3, section 3.6.

5.2.4 Motion Analysis

Running kinematics were captured via a 14-camera 3-dimensional kinematic analysis system (MX; Vicon Motion Systems Ltd., Oxford, England) sampling at 500 Hz. Marker trajectories were recorded for 25 seconds at the end of the first minute and the final minute of each run.

Description of motion capture can be found in chapter 3, section 3.8.

5.2.5 Data Processing

Motion capture data was processed as described in chapter 3, section 3.8.6.

5.2.6 Statistical analysis

Mean, standard deviation (SD) and 0.25 SD values were calculated from 30 consecutive strides for each kinematic and spatiotemporal variable. Sequential averaging was used on each individual (Bates *et al.* 1983; Hamill and McNiven, 1990) to calculate the cumulative mean (strides 1 and 2; strides 1, 2 and 3, and so on for all consecutive stride permutations) and mean deviation (difference between 30 stride mean and each cumulative mean). A stable mean was considered as the lowest stride count plus one stride from when the mean deviation fell below 0.25 SD criterion value (James *et al.* 2007). Using the individual stable mean scores, a group mean value was calculated along with an upper 95% confidence interval.

A repeated two-way ANOVA was used to test for differences in strides counts across exercise intensity and time for each variable. Sequential averaging was conducted using a custom written MATLAB script (R2018a, The MathWorks, Inc., Natick, Ma, USA); ANOVA was conducted using SPSS v22.0 (SPSS Inc., Chicago, IL, USA).

5.3. Results

There were no significant differences ($P>0.05$) in the number of strides required to reach a stable value between joints, planes of movement, intensity of run or beginning and end of run. Within spatiotemporal parameters (Table 5.2; Figure 5.1), the stride frequency required the lowest mean value of 12-14 strides and a 95% CI of 16-18 strides across the different speeds and time points. Ground contact time required a mean of 16-17 strides and a 95% CI of 20-21 strides across the same conditions. None of these differences were significant ($P>0.05$).

For the frontal plane kinematics, the mean stride count required for stability ranged from 12-17 strides; 12-19 strides were required in the sagittal plane kinematics; and 12-16 strides in the transverse plane (Tables 5.3 and 5.4 ; Figure 5.2). The stability of required stride count was

judged by upper 95% Confidence interval (CI). The 95% CI for the frontal plane required the highest stride count to achieve stability ranging from 17-21 strides, compared to 14-21 strides for the sagittal plane and 14-20 strides for the transverse plane.

Table 5.2. Stride Count for spatiotemporal variables represented as mean \pm Standard deviation (SD) and upper 95% confidence interval (U95% CI) for Stride Frequency (SF) and Contact Time (CT).

SF	Mean \pm SD	U95% CI	CT	Mean \pm SD	U95% CI
<i>HIIT start</i>	13 \pm 6	16	<i>HIIT start</i>	16 \pm 7	20
<i>HIIT end</i>	14 \pm 7	18	<i>HIIT end</i>	17 \pm 6	20
<i>MICR start</i>	12 \pm 7	16	<i>MICR start</i>	16 \pm 6	20
<i>MICR end</i>	14 \pm 7	18	<i>MICR end</i>	17 \pm 7	21

Stride frequency produced an average upper 95% CI stride count of 17
Contact time produced an average upper 95% CI stride count of 20

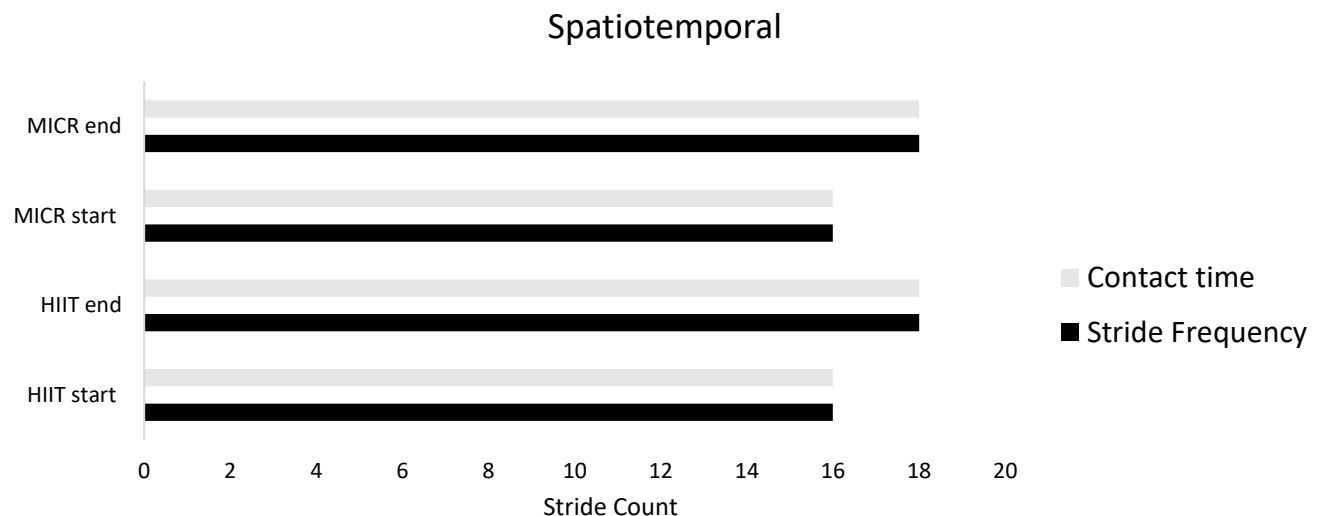


Figure 5.1. Stride count presented as 95% upper limit confidence interval for spatiotemporal parameter variables of Stride Frequency and Contact Time.

Table 5.3. Stride counts presented as mean \pm standard deviation (SD) and 95% upper limit confidence (U95% CI) at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the knee joint in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

		Frontal		Sagittal		Transverse	
		Mean \pm SD	U95% CI	Mean \pm SD	U95% CI	Mean \pm SD	U95% CI
Knee FS							
	<i>HIIT start</i>	17 \pm 7	21	17 \pm 6	20	16 \pm 7	20
	<i>HIIT end</i>	15 \pm 7	19	15 \pm 6	17	14 \pm 6	17
	<i>MICR start</i>	16 \pm 6	19	14 \pm 6	16	15 \pm 7	18
	<i>MICR end</i>	16 \pm 6	20	14 \pm 7	17	15 \pm 8	19
Knee Max							
	<i>HIIT start</i>	15 \pm 7	19	15 \pm 7	18	15 \pm 8	20
	<i>HIIT end</i>	14 \pm 6	18	14 \pm 5	16	15 \pm 6	17
	<i>MICR start</i>	13 \pm 6	17	12 \pm 6	15	13 \pm 6	16
	<i>MICR end</i>	16 \pm 6	20	14 \pm 9	18	15 \pm 6	18
Knee RoM							
	<i>HIIT start</i>	16 \pm 7	21	15 \pm 7	18	15 \pm 6	18
	<i>HIIT end</i>	15 \pm 7	20	13 \pm 7	16	12 \pm 6	15
	<i>MICR start</i>	15 \pm 7	20	16 \pm 7	20	16 \pm 7	19
	<i>MICR end</i>	15 \pm 6	18	15 \pm 7	18	15 \pm 7	18

Knee FS produced an average upper 95% CI stride count of 19 (frontal), 17 (Sagittal), and 18 (Transverse) for both run-types and time points of capture

Knee Max produced an average upper 95% CI stride count of 20 (frontal), 18 (Sagittal), and 19 (Transverse) for both run-types and time points of capture

Knee RoM produced an average upper 95% CI stride count of 20 (frontal), 18 (Sagittal), and 18 (Transverse) for both run-types and time points of capture

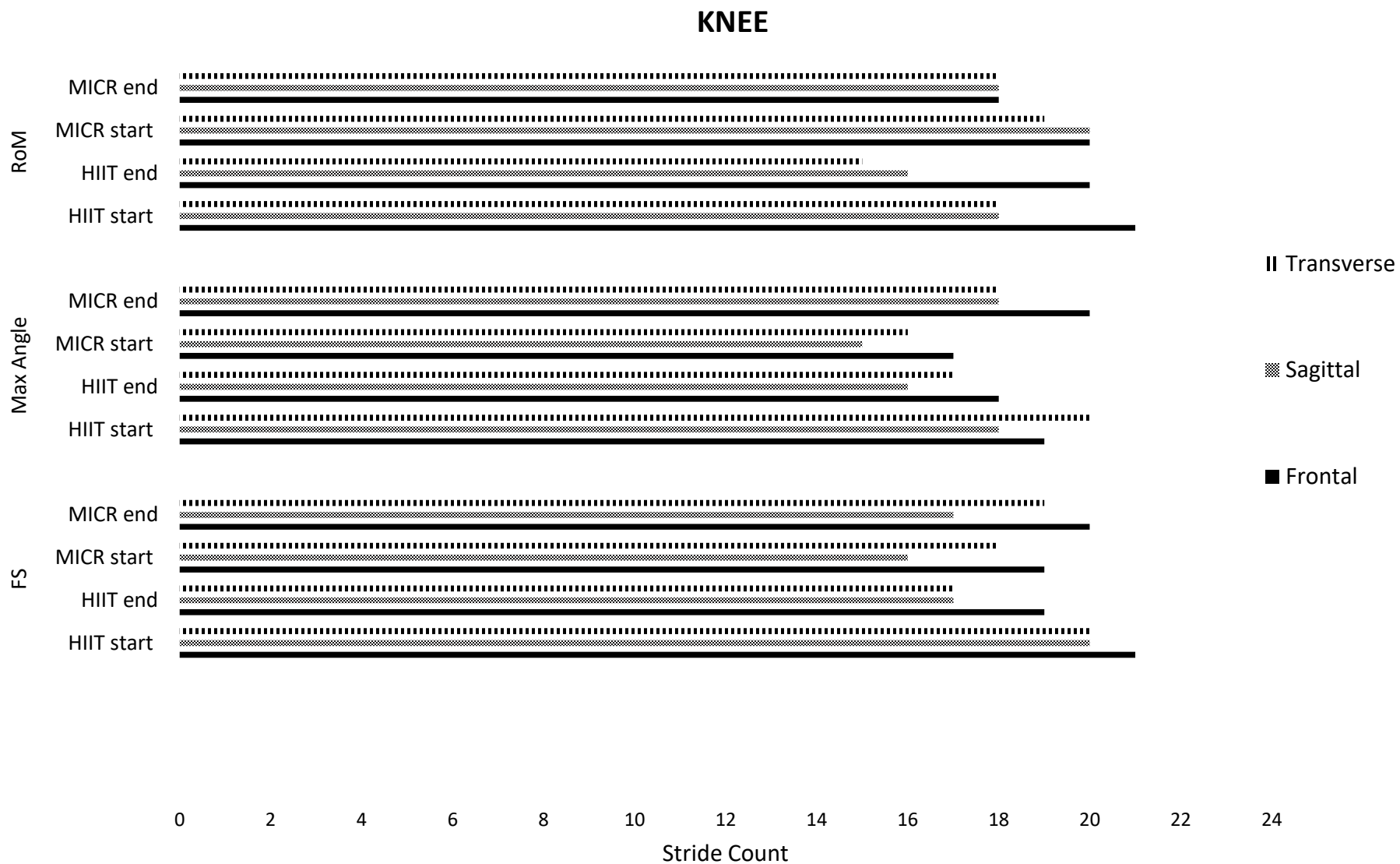


Figure 5.2 Stride count presented as 95% upper limit confidence interval for knee foot strike angle, maximal angle, and range of motion for sagittal, frontal, and transverse planes of motion.

Table 5.4. Stride counts presented as mean \pm standard deviation (SD) and 95% upper limit confidence (U95% CI) at foot strike (FS), maximum angle (Max), and range of motion (RoM); for the hip joint in the three planes of motion. At beginning and end of two run-types of high intensity interval training run (HIIT) and medium intensity continuous run (MICR).

		Frontal		Sagittal		Transverse	
		Mean \pm SD	U95% CI	Mean \pm SD	U95% CI	Mean \pm SD	U95% CI
Hip _{FS}							
	<i>HIIT start</i>	14 \pm 8	18	17 \pm 6	20	16 \pm 7	19
	<i>HIIT end</i>	15 \pm 6	20	12 \pm 6	14	15 \pm 6	18
	<i>MICR start</i>	14 \pm 7	18	16 \pm 8	19	12 \pm 5	14
	<i>MICR end</i>	16 \pm 6	20	13 \pm 5	15	16 \pm 5	18
Hip _{Max}							
	<i>HIIT start</i>	14 \pm 8	19	19 \pm 5	21	14 \pm 6	17
	<i>HIIT end</i>	15 \pm 6	20	15 \pm 6	18	14 \pm 5	16
	<i>MICR start</i>	16 \pm 6	20	13 \pm 8	16	16 \pm 7	19
	<i>MICR end</i>	16 \pm 6	19	15 \pm 6	18	14 \pm 6	17
Hip _{RoM}							
	<i>HIIT start</i>	16 \pm 7	20	15 \pm 7	18	14 \pm 5	16
	<i>HIIT end</i>	14 \pm 7	18	14 \pm 6	17	13 \pm 7	16
	<i>MICR start</i>	16 \pm 7	20	15 \pm 8	19	14 \pm 7	17
	<i>MICR end</i>	15 \pm 6	18	16 \pm 7	19	14 \pm 5	16

Hip_{FS} produced an average upper 95% CI stride count of 19 (frontal), 17 (Sagittal), and 17 (Transverse) for both run-types and time points of capture

Hip_{Max} produced an average upper 95% CI stride count of 20 (frontal), 18 (Sagittal), and 17 (Transverse) for both run-types and time points of capture

Hip_{RoM} produced an average upper 95% CI stride count of 19 (frontal), 18 (Sagittal), and 16 (Transverse) for both run-types and time points of capture

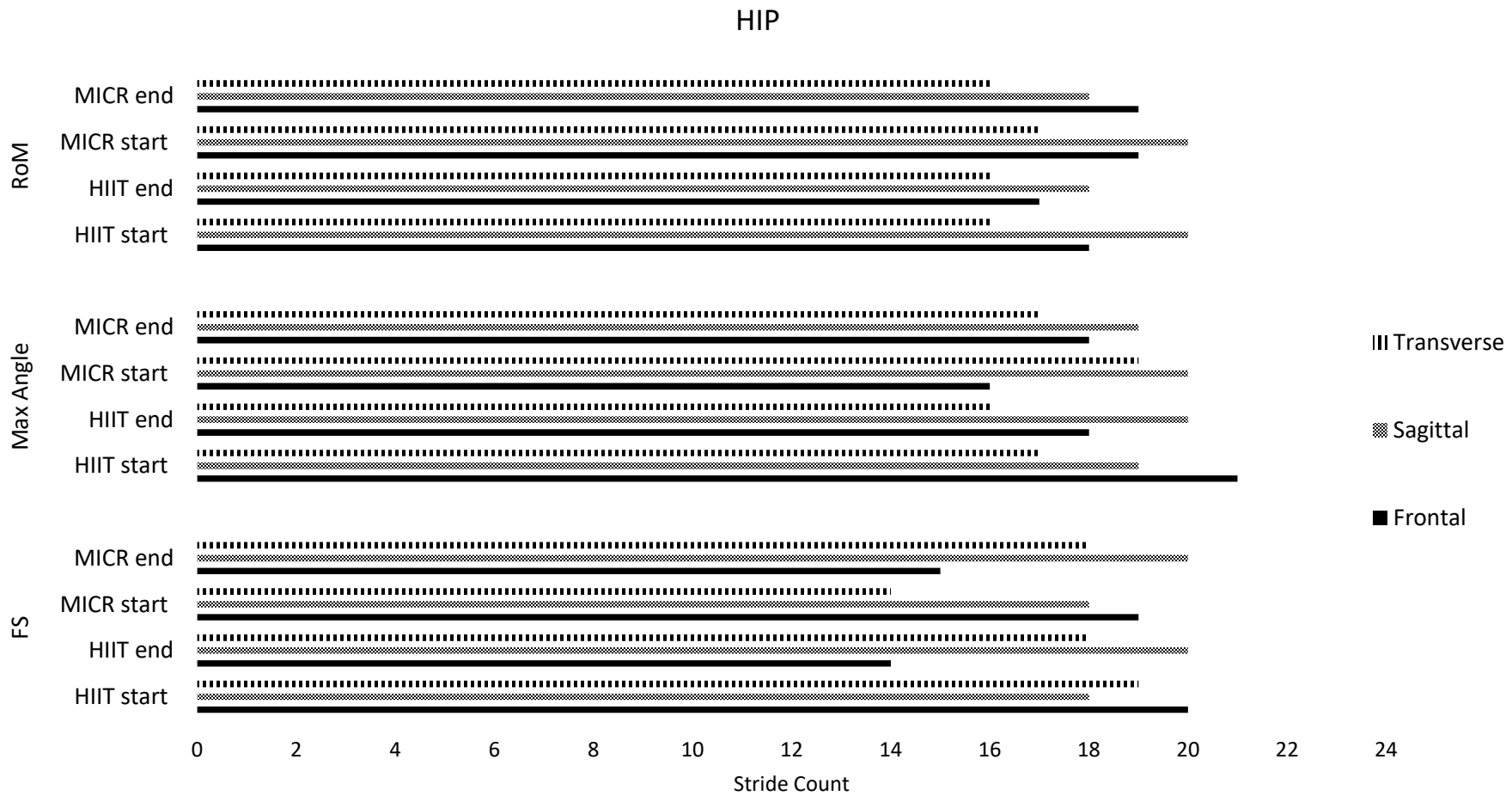


Figure 5.3 Stride count presented as 95% upper limit confidence interval for knee foot strike angle, maximal angle, and range of motion for sagittal, frontal, and transverse planes of motion.

5.4. Discussion

This chapter is the first to investigate the number of strides required to establish a stable mean value for stance phase kinematic and spatiotemporal analysis in all three planes in treadmill running. There were no differences for stable mean stride count between knee or hip joints in all three planes of motion. Nor were there any differences in any variable with HIIT or MICR regardless of whether measures were taken at the start or end of either run. This consistency of the required stride count irrespective of movement plane, running intensity or time point, provides confidence that a fixed number of ground contacts can be used in all circumstances.

When investigating the effect of fatigue on running gait, previous studies have compared kinematics and spatiotemporal parameters at start and end of a run; treadmill running is advantageous in this respect enabling the capture of continuous data to better observe the time-course of changes. These results provide confidence that as the stride count required remained unchanged throughout each run the quantity of data needed is the same at the start compared to end. In addition, we chose two relative intensities, rather than the more common approach of using absolute intensities. The use of relative intensities tailored for each participant based on their physiological profile could have contributed to the stability of the scores reported in this chapter. Using absolute intensities could cause greater variability in rates of fatigue and thus requires further examination.

Similar to time course changes, there was little difference for stable stride count between the three planes of motion or joints examined. The highest stride count of 19 was observed only in one variable, during HIIT_{start} for maximum hip angle in the frontal plane. For mean values, the transverse plane required fewer strides compared to the sagittal and frontal planes. This observation can be due to the limited movement allowed in transverse plane of motion for each

joint compared to frontal and sagittal where larger ranges of motion occurred. For simplicity and validity, this chapter recommend that a stride count of 20 is required, based on the upper 95% CI, as this would cover all variables examined.

The findings of this chapter could serve as a guideline for data analysis of treadmill running kinematics. The absence of clear guidelines regarding the number of strides required is borne out by the inconsistencies across previous studies. Noehren *et al.* (2012) along with Kellis and Liassou (2009) extracted five consecutive footfalls for data analysis, however both studies fall short of the 20 strides by Dierks *et al.* (2010) or 50 used by Esculier *et al.* (2015). Riley *et al.* (2008), established their own stable mean, however their method did not outline which joint or plane it represented. They found that 10-12 strides provided a stable mean but employed a more conservative 15 strides for kinematic assessment. Studies that have employed a low number of consecutive strides could have potentially ignored characteristics such as the natural variability. Jordan *et al.* (2006), observed that during treadmill running, fluctuations in running form exist but stride-to-stride variations tend to be low, less than 3% CV. Although small, such variations still require enough data to be captured to record them.

In overground running repeated trials are often performed within a 5 to 10% range of a designated speed (Almonroeder and Benson, 2016; Bazett-Jones *et al.* 2013; Riley *et al.* 2008; Schache *et al.* 2001). Furthermore, generally, only one foot strike per run is captured during each run, often from a relatively short run-up. In order for the foot strike to be considered acceptable, the runner must make contact with an embedded force plate, often requiring more attempts than valid trials. Treadmill running by contrast, while not an exact replica of outdoor running (Riley *et al.* 2008), does offer greater opportunities for kinematic assessment due to a more consistent speed and the ability to record consecutive foot strikes. In a recent review by Van Hooren *et al.* (2019), the authors conducted a meta-analysis of the studies comparing overground and treadmill

running finding the two methods are comparable when examining spatiotemporal, kinematics and kinetics. Similarly, Riley *et al.* (2008) also suggested that the two methods were similar when assessing kinematics. Additionally, because consecutive contacts can be recorded it is possible to examine the effects of fatigue on running kinematics. Overground running does not permit this due to the time taken to record a sufficient number of valid trials, during which time recovery is taking place.

The approach taken by this chapter for determining stride count during treadmill running was based on the sequential averaging method to establish a stable mean (Bates *et al.* 1983). How many reference trials to use appears to be an arbitrary decision. Bates *et al.* (1983) compared 10 and 20 reference trials, finding both identified eight non-consecutive trials were necessary for a stable mean in ground reaction force during running. To date there are no data for running kinematic or spatiotemporal values using sequential averaging. Similarly, the 0.25 SD criterion used is also an arbitrary value. James *et al.* (2007) compared sequential averaging with the use of ICCs and found lower stable values with ICCs, equating to the use a 0.6 SD criteria in sequential averaging. The 0.25 SD criterion has been criticised for being too conservative (Hamill and McNiven, 1990; James *et al.* 2007), alternatively this could be viewed as more rigorous; again the decision is arbitrary. The approach taken in this chapter has been to opt for a more conservative approach, recommending a minimum of 20 consecutive ground contacts be recorded. Moreover, we recommend that future studies perform, and report, their own sequential averaging for further consistency within motion capture research.

Conclusion

This chapter found a similar number of strides were required to achieve a stable stride count across the two joints and planes of motion during treadmill running. Furthermore, this value did not change with the intensity of run, or between the beginning or end of the run. We therefore recommend the use of the upper 95% confidence interval value of 20 strides found in this chapter as an initial guideline for examining kinematic and spatiotemporal variables during treadmill running.

CHAPTER 6 – FATIGUE INDUCED CHANGES TO GAIT FOLLOWING TWO ENERGY EXPENDITURE MATCHED TYPICAL TRAINING RUNS

Publication arising as result of this chapter:

Riazati S, Caplan N, Matabuena M and Hayes PR (2020) Fatigue Induced Changes in Muscle Strength and Gait Following Two Different Intensity, Energy Expenditure Matched Runs. *Frontiers in Bioengineering and Biotechnology*. 8:360. doi: 10.3389/fbioe.2020.00360

6.1 Introduction

To address the complexity of running related overuse injuries, this thesis has taken a multifactorial approach of examining the effect of typical training runs on risk factors. The results of chapter 4, provided a strong basis for examining the RROI risk factors of hip and knee musculature strength, kinematics, and coordination variability.

The aetiology of RROIs remains a particularly complex challenge. It has been suggested that there is a relationship between the loss of muscle strength and mechanical abnormalities linked with RROI e.g. increased maximum hip frontal plane angles (Noehren *et al.* 2007). Dierks *et al.* (2008) and Noehren *et al.* (2014) both reported a gait signature of increased hip adduction angle in conjunction with decreased hip muscular strength in runners with PFP and ITBS. This gait signature of injured runners is consistent with the proximal aetiology model proposed by Powers *et al.* (2010). Their model suggests that impaired muscular control at the hip causes an increased hip adduction angle providing a plausible mechanistic explanation for the gait signature of runners with PFP and ITBS. Strong supporting evidence for the proximal aetiology model can be found in a 2 year prospective study where runners who developed PFP had greater hip adduction angles than uninjured runners (Noehren *et al.* 2013). Despite the evidence for the proximal aetiology model, it remains unknown whether the injuries are the cause or consequence of the mechanical abnormalities and strength deficiency.

The majority of studies that have examined the effect of fatigue on gait have used a prolonged continuous run or a continuous run to point of exhaustion (Brown *et al.* 2016; Dierks *et al.* 2010; Willson *et al.* 2015). Only two studies examined and reported reduced hip muscular strength following a run to exhaustion (Bazett-Jones *et al.* 2013; Dierks *et al.* 2008). Dierks *et al.* (2008) and Wilson *et al.* (2015) both reported increased hip frontal kinematics following the run to exhaustion. To date, no study has examined the effects of fatigue on hip and knee kinematics

following a typical training run, either MICR or HIIT. If the effects of fatigue induce kinematic changes that match the profile of runners exhibiting overuse injuries, then there is an increased risk of developing a RROI. In addition, only a limited amount of studies have taken a multifactorial approach to examine risk factors alongside kinematics (Bazett-Jones *et al.* 2013; Brown *et al.* 2016; Dierks *et al.* 2008; Dierks *et al.* 2010).

In addition to kinematic changes, running coordination variability has also been linked to RROI (Hamill *et al.* 2012). Hamill and colleagues proposed a model where either an increase or decrease in variability, from an optimal range, can lead to injury. The effect of fatigue on coordination variability in injured runners has only been examined by one study, where they reported both reduced and increased variability following a run to exhaustion (Miller *et al.* 2008). They suggested that the cause of the changes in coordination variability were due to muscle dysfunction, however they did not examine muscle strength.

6.1.2 Aims

The extent to which fatigue occurs in typical training runs and consequential changes in gait and gait variability are unknown, Given the multifactorial nature of RROI development a broader research approach is required. The purpose of this chapter was to observe changes in multiple risk factors i) muscular strength ii) kinematics and iii) joint coupling coordination variability at the beginning and end of a HIIT session and continuous run.

6.2. Methods

6.2.1 Research Design

This chapter employed a counter balanced cross-over design observing changes of muscle function, kinematics and running variability at the start and end of two typical, energy expenditure matched, running sessions.

6.2.2 Participants

Based on a power analysis and subsequent institutional ethical approval, 20 healthy, experienced, club distance runners, (N=10 male; N=10 female) were recruited. All runners that participated in this study train each run-type designed in this chapter at least once a week at their club and well trained based on their training profiles (See table 3.1). Table 6.1 shows participant characteristics, treadmill speeds and run duration. Inclusion criteria is described in chapter 3 section 3.3.

Table 6.1. Descriptive characteristics of participants, training runs, speeds, durations, $\dot{V}O_2$ max, speed at lactate turnpoint (sLTP), percentage of $\dot{V}O_2$ max at sLTP, represented as mean \pm standard deviation

	Female (<i>n</i> = 10)	Male (<i>n</i> = 10)
Age (years)	42.2 \pm 4.0	43.8 \pm 4
Height (cm)	164.6 \pm 6.0	181.2 \pm 7.9
Mass (kg)	58.5 \pm 6.2	77.3 \pm 6.5
HIIT Speed (m·s ⁻¹)	3.9 \pm 0.3	4.6 \pm 0.3
HIIT rep duration (min:sec)	03:24 \pm 13(s)	02:47 \pm 16(s)
MICR Speed (m·s ⁻¹)	3.3 \pm 0.2	3.6 \pm 0.4
MICR duration (min:sec)	32:15 \pm 02:01	25:53 \pm 03:40
$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	53.6 \pm 5.4	60.5 \pm 4.4
sLTP (m·s ⁻¹)	3.5 \pm 0.1	3.9 \pm 0.1
% $\dot{V}O_2$ max at LTP	81.4 \pm 5.5	72.7 \pm 8.1

6.2.3 Procedure

Each participant completed two treadmill runs that mimicked different, typical, training intensities. One was a HIIT session, the other a continuous run. All sessions were conducted at the same time of day to minimise diurnal variation. Participants were asked to wear the same footwear throughout and follow their habitual dietary regimen, while refraining from high volume or intensity training within 48 hours before testing.

6.2.3.1 Preliminary Testing

Initial measurements of mass, height and kinanthropometric measures were taken as described in chapter 3, section 3.5.1.

Participants completed maximal and submaximal tests to determine speeds and duration of the training runs, this was collected as described in chapter 3, sections 3.5.4 and 3.5.5.

6.2.3.2 HIIT and MICR

The duration and speed of each run was individualised based on $\dot{V}O_2$ max and LTP. For full description see chapter 3, section 3.6.

6.2.4 Muscular Strength

This chapter examined hip and knee muscular strength at pre and post both HIIT and MICR run. Hip and knee muscular strength reliability was examined prior to the two training runs. The full procedure of the data collected is described in chapter 3, section 3.7.

All tests were conducted in the same order: hip abduction, hip adduction, hip extension, hip flexion, hip external rotation, hip internal rotation, knee extension, and knee flexion.

6.2.5 Motion Capture

Running kinematics were captured via a 14-camera 3-dimensional kinematic analysis system (MX; Vicon Motion Systems Ltd., Oxford, England) sampling at 500 Hz. Marker trajectories were recorded for 25 seconds at the end of the first minute and the final minute of each run.

Description of motion capture can be found in chapter 3, sections 3.8.

6.2.6 Data Processing

Motion capture data was processed as described in chapter 3, sections 3.8.6.

6.2.7 Coordination variability

Variability of interactions between sagittal (flexion/ extension) and frontal (abduction/ adduction) planes of motion for the hip and knee joint couplings were analysed using CRPV and CAV. Data for both CRPV and CAV was collected and processed as described in chapter 3, section 3.8.6.2 and 3.8.6.3.

6.2.8 Statistical analysis

The data were checked for normality using Q-Q plots, all variables were deemed normally distributed. Mean and standard deviation were calculated for all variables. A 2 x 2 ANOVA with repeated measures were used to examine differences with time (start – end) and run-type (HIIT, MICR) for muscular strength, kinematics, and running variability. Effect sizes were calculated

according to Cohen, (1988) and interpreted as small (≥ 0.2), moderate (≥ 0.4), and large (≥ 0.8). The level of significance was set at $P < 0.05$. The level of significance was set at ≤ 0.05 . All statistical analysis was performed in SPSS v22.0 (SPSS Inc., Chicago, IL, USA).

Fatigue effects were considered to have occurred when individual runners experienced changes between start and end of each runs, greater than, or equal to, the minimum detectable change (MDC). The MDC were derived from reliability data of chapter 4.

6.3. Results

6.3.1 Muscular Strength

6.3.1.1 Group Assessment

Fatigue was evident following both run-types as all measures of muscular strength decreased with time following both run-types (Figure 6.1 and Table 6.2; $P < 0.05$). There were no differences between HIIT and MICR as no interaction for time or run-type were observed ($P > 0.05$). Similarly, effect size comparisons were marginally bigger following HIIT, as for HIIT this ranged from $d = 0.34$ to $d = 0.69$, and from $d = 0.27$ to $d = 0.58$ for MICR. The biggest difference in effect size between the two run-types was observed in hip adduction strength, with $d = 0.51$ in the HIIT compared to $d = 0.27$ for MICR.

Table 6.2. Hip and knee body mass-normalised ($\text{kg} \cdot \text{kg}^{-1}$) strength measures (Mean \pm SD) pre vs post and percentage change in High Intensity Interval Training run (HIIT) and Medium Intensity Continuous Run (MICR) runs.

		Mean \pm SD			Effect Size	Repeated measure ANOVA results (<i>P</i> value)		
	Run-type	Start	End	%		Time	Run-Type	Time x Type
Hip Abduction	HIIT	0.508 \pm 0.08	0.449 \pm 0.09	88.4%	$d = 0.69$	< 0.001	0.287	0.551
	MICR	0.490 \pm 0.09	0.437 \pm 0.09	89.2%	$d = 0.58$			
Hip Adduction	HIIT	0.344 \pm 0.09	0.301 \pm 0.08	87.5%	$d = 0.51$	< 0.001	0.233	0.150
	MICR	0.318 \pm 0.09	0.296 \pm 0.07	93.1%	$d = 0.27$			
Hip Internal Rotation	HIIT	0.199 \pm 0.04	0.178 \pm 0.03	89.4%	$d = 0.59$	< 0.001	0.218	0.927
	MICR	0.192 \pm 0.04	0.172 \pm 0.03	89.6%	$d = 0.57$			
Hip External Rotation	HIIT	0.249 \pm 0.06	0.227 \pm 0.05	91.2%	$d = 0.40$	0.002	0.094	0.871
	MICR	0.230 \pm 0.06	0.210 \pm 0.06	91.3%	$d = 0.33$			
Hip Flexion	HIIT	0.409 \pm 0.09	0.357 \pm 0.08	88.5%	$d = 0.64$	< 0.001	0.776	0.732
	MICR	0.403 \pm 0.08	0.357 \pm 0.07	88.6%	$d = 0.57$			
Hip Extension	HIIT	0.330 \pm 0.09	0.279 \pm 0.08	85.9%	$d = 0.60$	< 0.001	0.273	0.231
	MICR	0.321 \pm 0.11	0.262 \pm 0.11	84.5%	$d = 0.54$			
Knee Extension	HIIT	0.509 \pm 0.13	0.443 \pm 0.09	87.0%	$d = 0.59$	< 0.001	0.590	0.313
	MICR	0.482 \pm 0.13	0.433 \pm 0.09	89.8%	$d = 0.44$			
Knee Flexion	HIIT	0.258 \pm 0.11	0.222 \pm 0.10	86.0%	$d = 0.34$	< 0.001	0.512	0.654
	MICR	0.240 \pm 0.10	0.214 \pm 0.09	89.2%	$d = 0.27$			

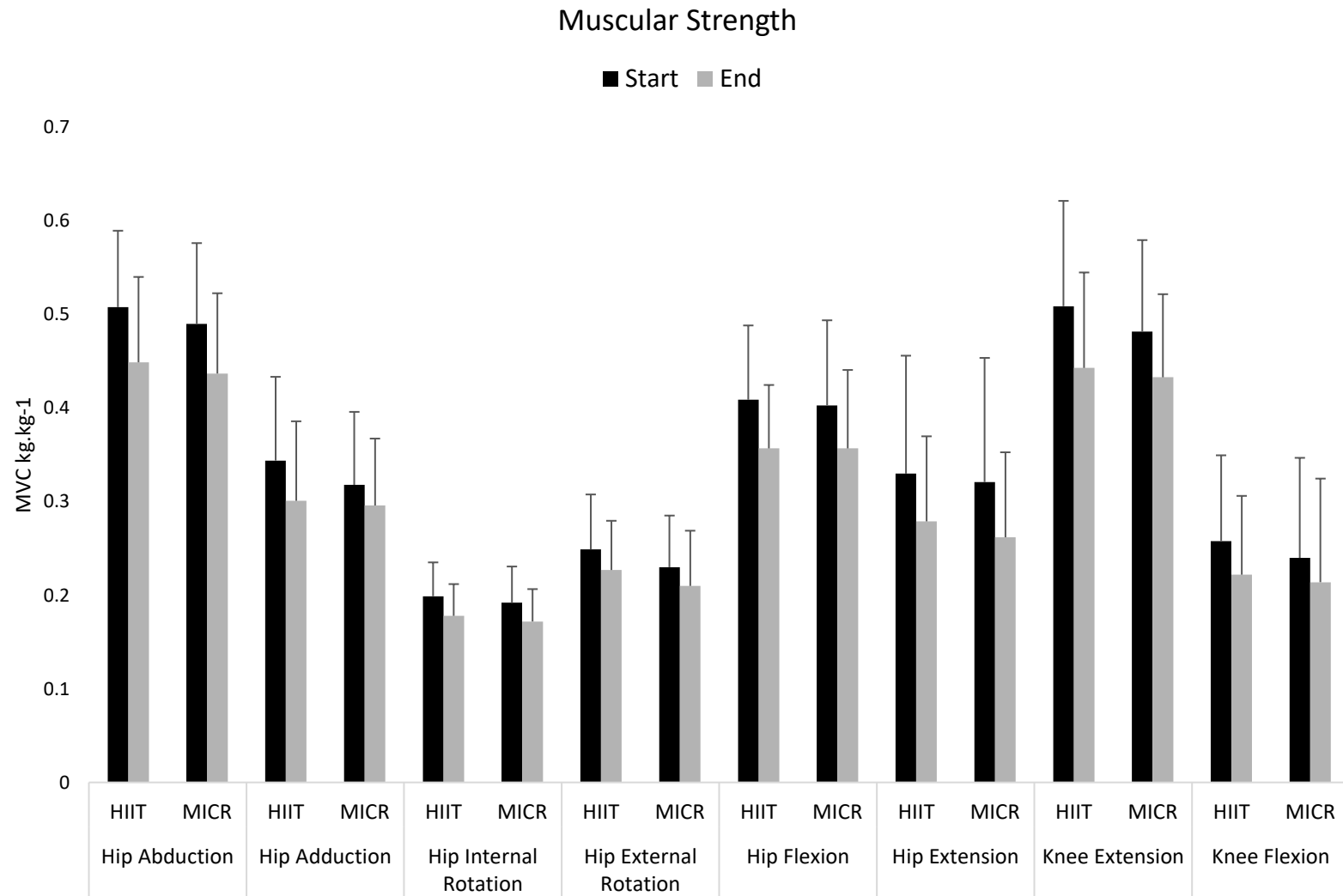


Figure 6.1. Figure representing changes in muscular strength at start compared to end following a High Intensity Interval Training (HIIT) session and a Medium Intensity Continuous Run (MICR).

6.3.1.2 Individual Assessment

Individual assessment (Figure 6.2) showed that more runners exhibited a drop in muscular strength greater than, or equal to, MDC in the HIIT compared to MICR run for all strength measures except hip flexion and external rotation. Hip abduction strength was reduced in five runners post HIIT and in three post MICR. For hip adduction strength, one runner experienced a reduction beyond MDC from HIIT but no runners post MICR. For hip adduction strength, one runner experienced a reduction beyond MDC from HIIT but no runners post MICR. Four runners experienced reduced hip internal rotation strength beyond MDC post HIIT and three runners post MICR. Four runners experienced reduced hip internal rotation strength beyond MDC post HIIT and three runners post MICR. Knee extension strength reduced beyond MDC for six runners post HIIT and two post MICR. A similar trend was seen in knee flexion, as four runners reduced strength above MDC post HIIT and two post MICR. For hip flexion, no runners exceeded MDC post HIIT, however two runners exceeded MDC post MICR. No runners experienced a reduced muscular strength beyond MDC for hip extension and hip external rotation after either run.

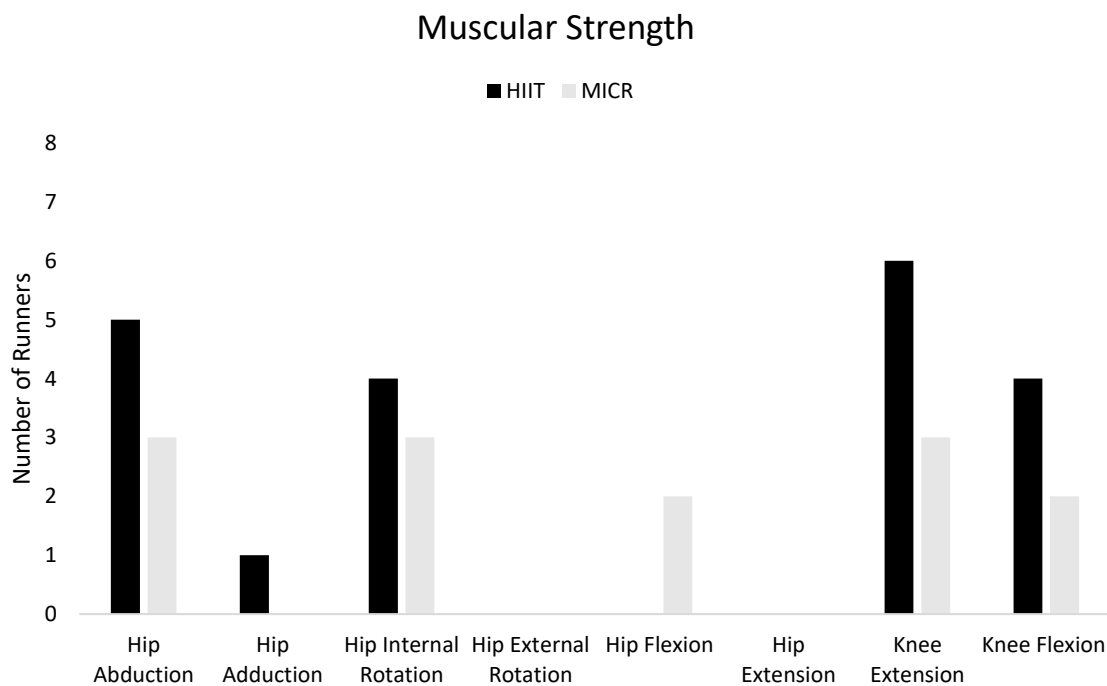


Figure 6.2. Number of runners that exceeded Minimum Detectable Change for muscular strength measures at the end of High Intensity Interval Training (HIIT) session and Medium Intensity Continuous Run (MICR).

6.3.2 Kinematics

6.3.2.1 Group Assessment

Both runs induced kinematic changes (Table 6.3) in the hip but no significant changes ($P > 0.05$) at in the knee joint. Hip frontal plane maximum ($F_{1,19} = 21.62$, $P < 0.001$) and RoM angles ($F_{1,19} = 11.57$, $P = 0.003$) increased significantly with time, and Post-hoc examination for hip frontal RoM revealed that the HIIT induced a greater effect ($d = 0.69$) compared to the MICR ($d = 0.43$; $P = 0.004$), while no effect for maximum angle between runs was observed. For hip sagittal plane, runners' RoM angles increased for both HIIT and MICR significantly with time ($P < 0.001$). There were also significant changes for time and run-type ($F_{1,19} = 6.52$, $P = 0.019$), with HIIT inducing a greater effect ($d = 0.73$) compared to the MICR ($d = 0.32$).

6.3.2.2 Individual Assessment

By contrast to the lack of significant differences at the knee, six runners showed increased maximum KF angle beyond the MDC at the end of the HIIT, while only two runners exhibited a similar change after MICR. For KF RoM angle, the number of runners were two and three for the HIIT and MICR respectively. Two runners exceeded MDC for maximum knee angle in the frontal plane after HIIT while no runners exceeded MDC post MICR. For hip sagittal plane maximum angle, MICR induced an increase above MDC in four runners compared to one at end of HIIT. For RoM angle of hip sagittal plane, a similar pattern occurred with more runners (four) experiencing an increase above MDC in MICR compared to HIIT (three). Maximum hip frontal plane angles showed that three runners exhibited a change above MDC for both HIIT and MICR. However, for hip frontal RoM angles, three runners exceeded MDC as result of HIIT, while no runners exceeded MDC post MICR (See Figure 6.3).

Table 6.3. Maximum and range of motion (RoM) angle for Hip and Knee sagittal and frontal plane of movements along with Spatiotemporal parameters of stride length (SL), Stride Frequency (SF), and Contact time (CT) represented as means \pm SD at start and end of High Intensity Interval Training run (HIIT) and Medium Intensity Continuous Run (MICR) runs.

Variables	Run-type	Mean \pm SD		ES	Repeated measure ANOVA results (<i>P</i> value)			
		Start	End		Time	Run-Type	Time x Type	
Maximum Angle (deg)								
Knee sagittal	HIIT	44.2 \pm 6.4	46.8 \pm 8.2°	<i>d</i> = 0.14	0.151	0.337	0.148	
	MICR	46.0 \pm 7.3	46.4 \pm 7.5°	<i>d</i> = 0.17				
Knee frontal	HIIT	-0.07 \pm 4.7	-0.45 \pm 6.3°	<i>d</i> = 0.10	0.817	0.933	0.737	
	MICR	0.69 \pm 7.1	1.06 \pm 7.7°	<i>d</i> = 0.05				
Hip sagittal	HIIT	49.2 \pm 7.0	51.5 \pm 7.1°	<i>d</i> = 0.33	0.429	0.071	0.055	
	MICR	47.8 \pm 13.4	47.0 \pm 7.0°	<i>d</i> = 0.07				
Hip frontal	HIIT	11.4 \pm 4.0	12.7 \pm 4.8°	<i>d</i> = 0.35	< 0.001	0.176	0.142	
	MICR	10.0 \pm 4.7	12.8 \pm 4.5°	<i>d</i> = 0.46				
RoM Angle (deg)								
Knee sagittal	HIIT	24.9 \pm 7.8	27.3 \pm 5.5	<i>d</i> = 0.23	0.097	0.275	0.189	
	MICR	26.8 \pm 8.6	27.3 \pm 5.3	<i>d</i> = 0.15				
Knee frontal	HIIT	4.4 \pm 1.9	5.0 \pm 2.1	<i>d</i> = 0.31	0.277	0.452	0.391	
	MICR	5.3 \pm 4.0	5.4 \pm 2.9	<i>d</i> = 0.03				
Hip sagittal	HIIT	50.1 \pm 4.1	53.1 \pm 4.9	<i>d</i> = 0.73	< 0.001	< 0.001	0.019	
	MICR	45.2 \pm 5.2	46.7 \pm 4.4	<i>d</i> = 0.32				
Hip frontal	HIIT	11.9 \pm 4.5	15.0 \pm 4.5	<i>d</i> = 0.69	0.003	0.573	0.004	
	MICR	12.2 \pm 4.1	14.0 \pm 3.4	<i>d</i> = 0.43				
Spatiotemporal								
SF (strides/minute)	HIIT	95.1 \pm 6.3	94.3 \pm 5.0	<i>d</i> = 0.14	0.550	< 0.001	0.516	
	MICR	88.2 \pm 4.9	88.1 \pm 4.7	<i>d</i> = 0.02				
SL (m)	HIIT	0.85 \pm 0.1	0.86 \pm 0.1	<i>d</i> = 0.10	0.859	< 0.001	0.225	
	MICR	0.78 \pm 0.1	0.78 \pm 0.1	<i>d</i> = 0.00				
CT (s)	HIIT	0.20 \pm 0.2	0.22 \pm 0.2	<i>d</i> = 0.10	0.026	< 0.001	0.088	
	MICR	0.24 \pm 0.3	0.25 \pm 0.3	<i>d</i> = 0.03				

Sagittal plane kinematics represent motion of flexion and extension as positive value indicate flexion and negative values indicate extension. Frontal plane kinematics represent abduction and adduction angles as positive values indicate adduction and negative value indicate abduction.

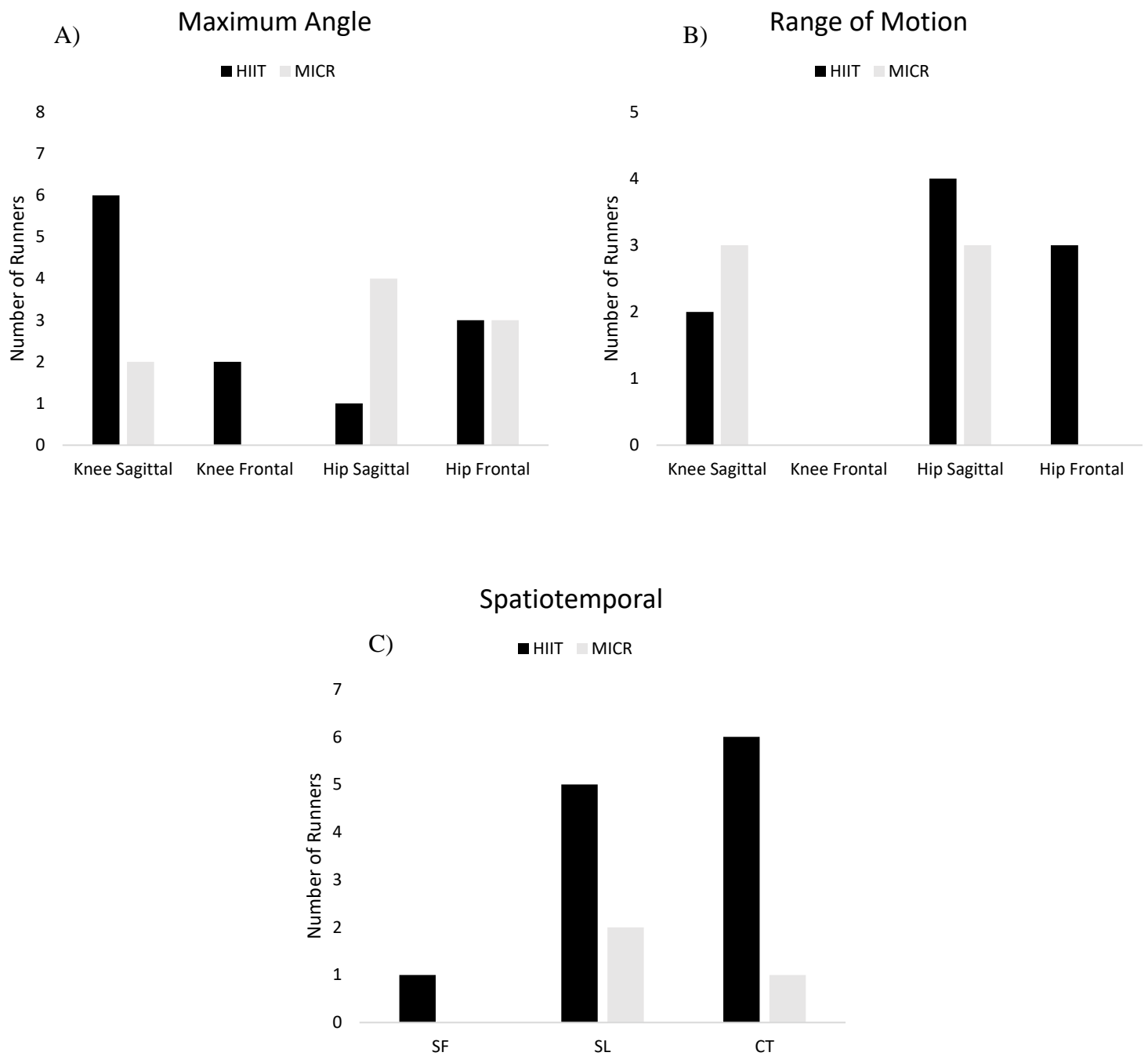


Figure 6.3. Number of runners that exceeded minimum detectable change for hip and knee sagittal and frontal planes of motion in A) maximum angle and B) Range of Motion and C) spatiotemporal parameters of Stride Frequency (SF), Stride Length (SL), and Contact Time (CT) at end of a High Intensity Interval Training (HIIT) session and a Medium Intensity Continuous Run (MICR).

6.3.3 Spatiotemporal

6.3.3.1 Group Assessment

For spatiotemporal parameters (Table 6.3), only CT showed a significant increase with time ($F_{1,19} = 5.86$, $P = 0.026$) however the magnitude of change was small (HIIT $d = 0.10$; MICR $d = 0.03$).

While the results did not show a significant difference between the two run-types, there is a trend towards CT being more affected in the HIIT than MICR. In either run-type, the results did not show an interaction with time or run-type by time for measures of SF or SL, however there was significant difference between run-type in SF ($F_{1,19} = 138.23$, $P < 0.001$) and SL ($F_{1,19} = 44.50$, $P < 0.001$) with post-hoc test showing the change in HIIT in both variables ($P < 0.001$).

6.3.3.2 Individual Assessment

The MDC assessment (Figure 6.3) revealed that HIIT caused a pre-post change beyond MDC in more runners compared to MICR for all spatiotemporal parameters. For SF, one runner exceeded MDC after HIIT but no runners after MICR. Five runners exhibited a reduced SL beyond MDC post HIIT compared with two for MICR. Six runners increased CT beyond MDC at the end of HIIT, with one runner experiencing an increase following MICR.

6.3.5 Coordination Variability

6.3.5.1 Group Assessment

Running variability in all joint couplings of hip and knee joints were increased significantly by time when assessed by CRPV (Table 6.4). The results also showed significant changes for time and run-types for all measures, with post-hoc tests showing HIIT having more effect compared to MICR in the increase in variability. For CAV, only the interaction of Hip_{abd/add} - Knee_{abd/add} exhibited no significant increase in variability. The Hip_{flex/ext} - Knee_{abd/add} interaction showed a significant interaction between time and run-type with post-hoc test showing the MICR ($d = 2.88$) being more effective than the HIIT ($d = 1.63$) in increasing variability of the runners.

6.3.5.1 Individual Assessment

In MDC assessment (Figure 6.4) for CRPV interactions of Hip_{flex/ext}- Knee_{flex/ext}, Hip_{flex/ext} - Knee_{abd/add}, and Hip_{abd/add} - Knee_{flex/ext}, all but one runner exceeded the MDC at the end of HIIT compared to 10 runners post MICR. In Hip_{abd/add} - Knee_{abd/add}, every runner exceeded the MDC at end of HIIT with 18 runners exceeding it following MICR. Thirteen runners exceed the MDC for CAV of Hip_{flex/ext}-Knee_{flex/ext}, post HIIT but only one runner following MICR. In Hip_{abd/add} - Knee_{flex/ext}, 19 runners exceed MDC at end of HIIT with 17 at end of MICR. Both HIIT and MICR caused nine runners to exceed MDC at the end for coupling interaction Hip_{abd/add} - Knee_{abd/add} but no runners for Hip_{flex/ext} -Knee_{abd/add}.

Table 6.4. Coordination variability examined through Continuous Relative Phase (CRP) and Coupling Angle (CAV) for the interaction between the knee and hip sagittal and frontal plane motions (means \pm SD) at start and end of High Intensity Interval Training run (HIIT) and Medium Intensity Continuous Run (MICR) runs.

Application	Couplings	Run-type	Mean \pm SD		ES	Repeated measure ANOVA results (<i>P</i> value)		
			Start	End		Time	Run-Type	Time x Type
CRPV (deg)								
	Hip _{flex/ext} - Knee _{flex/ext}	HIIT	15.2 \pm 13.3	78.8 \pm 9.8	$d = 5.44$	< 0.001	0.004	< 0.001
		MICR	21.7 \pm 6.7	36.4 \pm 8.3	$d = 1.94$			
	Hip _{flex/ext} - Knee _{abd/add}	HIIT	5.6 \pm 3.7	45.2 \pm 14.9	$d = 3.64$	< 0.001	0.232	0.004
		MICR	26.5 \pm 25.4	35.9 \pm 27.2	$d = 0.35$			
	Hip _{abd/add} - Knee _{flex/ext}	HIIT	13.4 \pm 9.4	77.4 \pm 9.3	$d = 6.84$	< 0.001	0.023	< 0.001
		MICR	22.1 \pm 26.0	41.9 \pm 34.4	$d = 0.64$			
	Hip _{abd/add} - Knee _{abd/add}	HIIT	5.4 \pm 3.4	46.4 \pm 14.9	$d = 3.79$	< 0.001	0.649	0.021
		MICR	12.5 \pm 11.3	41.3 \pm 12.1	$d = 2.46$			
CAV (deg)								
	Hip _{flex/ext} - Knee _{flex/ext}	HIIT	66.5 \pm 5.1	79.2 \pm 1.7	$d = 3.34$	< 0.001	< 0.001	0.258
		MICR	62.6 \pm 6.4	73.0 \pm 1.8	$d = 2.21$			
	Hip _{flex/ext} - Knee _{abd/add}	HIIT	67.9 \pm 5.0	73.9 \pm 1.4	$d = 1.63$	< 0.001	0.001	0.006
		MICR	62.2 \pm 5.6	73.7 \pm 0.7	$d = 2.88$			
	Hip _{abd/add} - Knee _{flex/ext}	HIIT	73.9 \pm 0.9	74.1 \pm 0.5	$d = 0.27$	0.077	0.147	0.279
		MICR	73.4 \pm 1.4	75.5 \pm 3.7	$d = 0.75$			
	Hip _{abd/add} - Knee _{abd/add}	HIIT	71.2 \pm 3.3	74.2 \pm 0.7	$d = 1.25$	< 0.001	0.184	0.162
		MICR	69.6 \pm 3.9	70.4 \pm 16.5	$d = 0.06$			

Flex/extension represent sagittal plane motions of flexion and extension and abd/add represent frontal plane motions of abduction and adduction angles

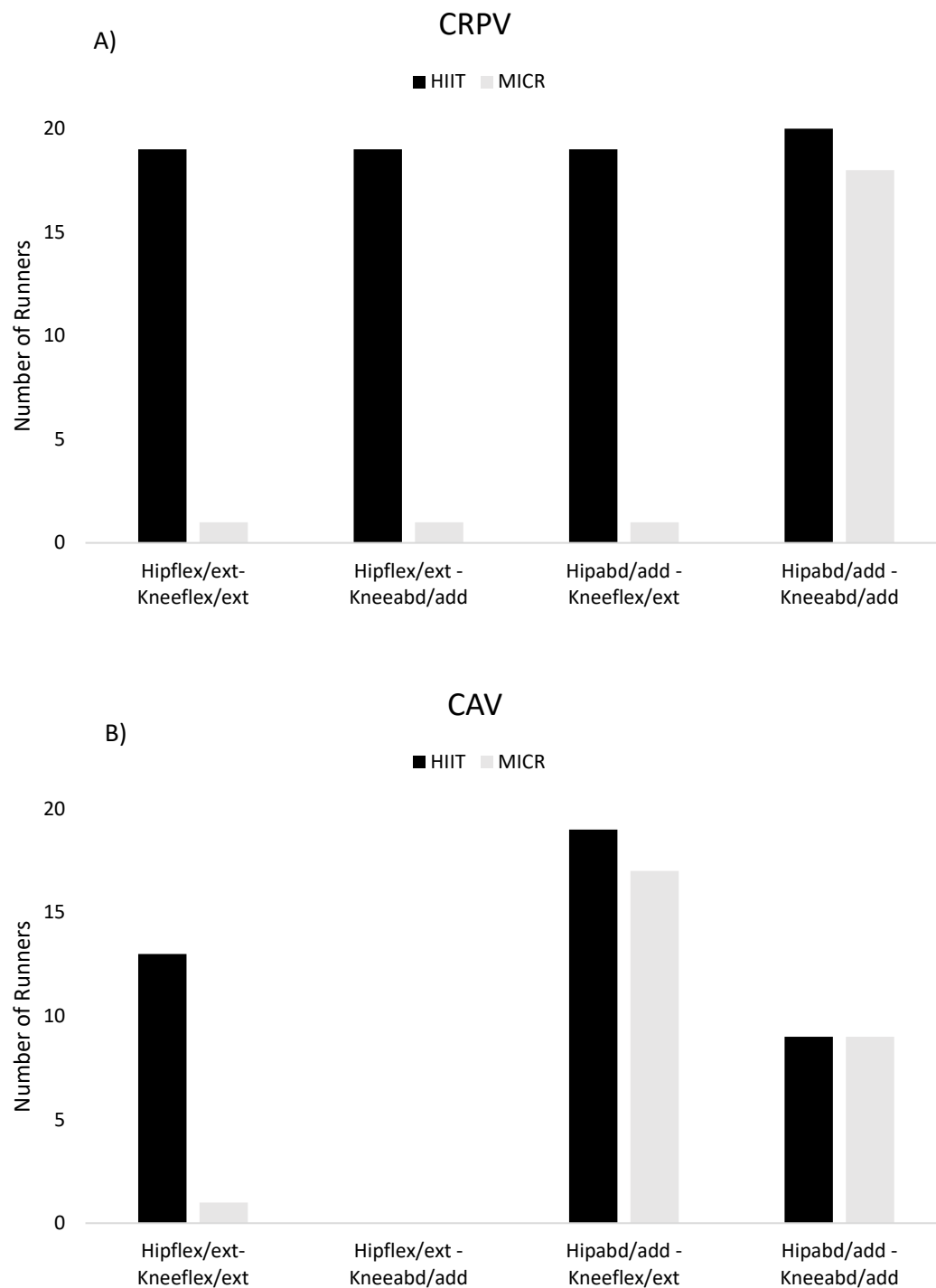


Figure 6.4. Number of runners that exceeded Minimum Detectable Change (MDC) for A) continuous relative phase variability (CRPV) and B) Coupling Angle Variability (CAV) at the end of a High Intensity Interval Training (HIIT) session and Medium Intensity Continuous Run (MICR).

6.4 Discussion

The purpose of this chapter was to investigate if changes in running gait occurred following two different intensity, energy expenditure matched, training runs. Furthermore, to see if any changes caused the gait to move towards the profile of runners with PFP and ITBS suggesting a potentially increased risk in the development of RROI. Following both HIIT and MICR, runners experienced a drop in strength in the hip and knee musculature. A novel finding was that both gait kinematics and coordination variability concurrently showed signs of exercise induced fatigue following HIIT. These changes in biomechanical profile were towards a gait more akin with runners suffering from PFP or ITBS thereby suggesting an increased risk of RROI development.

Potentially, the most noteworthy finding within the loss of muscular strength was the drop for hip abduction, with a reduction of 12.0% and 10.6% after HIIT and MICR respectively. While this chapter cannot identify causality, the loss of muscular strength at the hip could have contributed to gait alterations. Previous studies have associated reduced hip abductor strength with abnormal hip frontal plane kinematics (Noehren *et al.* 2007; Taylor-haas *et al.* 2014) with Dierks *et al.* (2008) finding a similar pattern to us in strength loss pre-post a run to exhaustion. The drop in muscular strength coincided with changes in running gait signature to be more like that of runners with PFP and ITBS. A loss of muscle strength could potentially indicate an inability to control gait or absorb impact force, either of which could potentially increase injury risk. A similar link between muscle function and injury risk was proposed by Bertelsen *et al.* (2017), their framework proposed that a reduction in structure specific load tolerance could lead to the development of RROI. This observation was more visible in the HIIT where greater changes in mechanics and coordination variability were observed. Interestingly both runs were matched for energy expenditure yet produced a similar drop in strength.

To avoid the problems of the self-selected running speeds used in many previous studies (Dierks *et al.* 2008, 2010; Bazett-Jones *et al.* 2013; Brown *et al.* 2016), we prescribed running speeds based on each individual's physiological capability. Using a self-selected but similar duration and speed as MICR used in this chapter but to exhaustion, Willson *et al.* (2015) found a corresponding increase in hip adduction RoM angle. Apart from Willson *et al.*'s (2015) study, results of this chapter differ from previous studies on hip kinematics as no differences in peak hip adduction angles have been observed at exhaustion (Dierks *et al.* 2010; Bazett-Jones *et al.* 2013; Brown *et al.* 2016). The runners in Dierks *et al.* (2008) performed their runs at lower speeds compared to runs of this chapter, albeit self-selected, finding no difference in peak hip adduction angle at the end. Dierks *et al.* (Dierks *et al.* 2010) observed minimal changes in RoM and maximum angles of hip adduction. Bazett-Jones *et al.* (2013) and Dierks *et al.* (2008) both examined hip strength alongside kinematics finding close to a 6% percent drop in hip abduction and 7% in hip external rotation following a run to exhaustion. Both of those studies only used MICR, this thesis has not identified a previous study utilizing a HIIT, this is the first study to have included a HIIT condition.

Unlike many previous studies, this chapter assessed quadriceps strength in conjunction with gait analysis, finding a loss of strength in both knee extensors and flexors at the end of each run. Runner's knee kinematics were less affected than the hip, with the knee frontal plane RoM angles the runners similar to those of Dierks (Dierks *et al.* 2008, 2010) but higher than Bazett-Jones *et al.*'s healthy runners (Bazett-Jones *et al.* 2013). While findings of this thesis were non-significant, the increase in maximum knee frontal angle after HIIT was of greater magnitude compared to MICR. These results could suggest that some runners may have been in dynamic knee valgus by the end of HIIT. Dynamic knee valgus is identified by a combination of increased hip adduction and knee abduction, however it can also be identified solely from increased hip adduction (Powers, 2010). The decrement of strength at both the knee and hip

musculature could have acted independently or synergistically to affect the runner's gait. With the increased hip adduction angle, the structures surrounding the knee would likely be under pressure, increasing patellofemoral joint stress, similar to the profile of runners with PFP (Powers *et al.* 2017).

Alterations to spatiotemporal parameters can also serve as a compensation strategy to accommodate for a reduced ability to tolerate load and produce force rapidly (Nicol and Komi, 2010). In this chapter, contact time was significantly increased in both run-types. Increased CT can be an indicator of fatiguing processes as greater work is required at the push-off phase (Nicol and Komi, 2010). The gait changes in this chapter concur with Nicol *et al.*'s (1991a) hypothesis that a loss of stretch shortening cycle function causes changes in knee flexion, stride length (SL) and ground contact time (CT). The inability of the runners to maintain short contact times can also suggest that the progression of fatigue has impaired the ability to maintain performance (Hayes and Caplan, 2014).

By the end of both HIIT and MICR, the runners had an increased demand for patterns of coordination between the joints and the associated movements. Miller and colleagues (Miller *et al.* 2008) examined CRPV finding non-significant increases and decreases in coordination variability from start to end of the run. They suggested that the alterations in coordination variability can be attributed to hip muscle dysfunction, although they failed to elaborate on this. The drop of hip and knee muscular strength in this chapter endorses this, as runners failed to remain stable at the end of both runs. Post-hoc tests revealed the increased coordination variability was greater post HIIT compared to MICR, with CRPV showing an interaction for run-type in all variables compared to one variable with CAV. As both runs were matched for energy expenditure, and exhibited similar drops in muscular strength, this suggests a non-metabolic mechanism was in operation. In line with Hamill and colleagues (Hamill *et al.* 2012) we suggest that as runners fatigued, the increased coordination variability reflects a loss of gait

control. Future studies are required that focus on the effect of fatigue on coordination variability, neuromuscular function and motor control.

Individual assessment

The use of P values has been heavily criticised, in particular their misuse for representing definite findings, with some journals no longer allowing their use (Greenland *et al.* 2016; Trafimow and Marks, 2015). Statistical significance considers whether the probability that a mean response has happened by chance or not, while providing no information on the magnitude of response. Runners however develop RROIs on an individual not collective basis. While not having a set criteria, Nicol *et al.* (1991a) reported that following a marathon, two individuals out of 7 showed a different kinematic profile that was contrary to the main group findings. Different analytical approaches can yield differing interpretations of the same data set.

To overcome the limitations of using P values and provide objective criteria, we examined the number of individuals who exceeded the MDC. Minimum detectable change provides a confidence interval based upon measurement error; those who exceed this confidence interval have a change in their score beyond measurement error, therefore it can be considered as a ‘real’ change. Individual assessment showed that not all runners were affected by the run-types. Those who exceeded the MDC developed a biomechanical profile more in line with injured runners seen in previous studies (Powers, 2010) which could represent an increased risk of developing running related overuse injury.

Individual assessment indicated that while all runners experienced a reduction in muscular strength, not many dropped by more than the MDC. Using P values identified a decrease that while not due to chance, may not be meaningful to all runners. The traditional statistical approach did not reveal a difference in strength loss for the different run-types, yet when using

MDC we were able to discern that more runners had a real change post HIIT compared to MICR, except in hip extension strength. This observation is supported by the larger effect sizes post HIIT compared to MICR.

Minimum detectable change values also revealed that in some variables, for example knee sagittal plane kinematics, runners experienced fatigue effects not revealed through using *P* values. Several runners exhibited an increase in knee sagittal plane angle above MDC at the end of both run-types, with HIIT affecting more runners than MICR. A similar observation was found for knee sagittal plane RoM, however more runners were affected during MICR than HIIT. The only measures where both *P* values and MDC analysis were similar was for hip frontal plane maximum angle and RoM, where the HIIT run had a greater effect on the runners.

P values did not yield a significant group effect in SL or SF, whereas the MDC assessment was able to show numerous runners experienced decreased SF and increased SL at the end of both run-types, with the HIIT affecting more runners. The observed changes in SF and SL have been associated with greater hip and knee moment at touchdown (Seay *et al.* 2011) and decreased leg stiffness (Morin *et al.* 2007). Similarly, the increase in contact time observed in this chapter may also suggest reduced muscle stiffness (Hayes and Caplan, 2014). Contact time did reveal a significant group change for time but not run-type, however twice as many runners exceeded MDC at end of HIIT compared to MICR. This observation may suggest that the HIIT induced a change in stiffness, providing a possible explanation on why runner's mechanics and coordination variability were affected more from the HIIT.

As the two run-types in this chapter were matched for energy expenditure, the suggestion based on individual assessment that more runners experienced fatigue inducing changes matching profile of injured runners during the HIIT compared to MICR requires further scrutiny. Further analysis of the data revealed an estimated average stride count during the HIIT was 1782

compared to 2279 strides in MICR. Although not directly measured, this suggests a greater loading rate per ground contact. An increased during HIIT concurs with previous work looking at loading rate (Dorn *et al.* 2012; Schache *et al.* 2011) causing a greater loading rate on the musculature and hip and knee joints potentially accelerating fatigue. This is further supported by Petersen *et al.* (2015) who found lower speeds decreased cumulative load (Petersen *et al.* 2015). Further work using an instrumented treadmill is required to examine the notion of differentiated accumulated load despite matching for energy expenditure.

Furthermore, each ground contact creates a collision or shock wave that is transmitted throughout the body. The process of absorbing this collision, or impact force, from each foot strike is called shock attenuation, which reduces the impact energy between the foot and head (Hamill *et al.*, 1995; Derrick *et al.*, 1998). Muscle and bone, along with other structural tissues, play a role in shock attenuation during ground contact. Fatigue induced changes to the running mechanics e.g. hip and knee flexion angle or stride length, can result in changes in shock absorption (Mercer *et al.* 2003; Derrick *et al.* 1998). The inability to absorb shock highlights the important role that muscles can play in absorbing impact energy (Mercer *et al.* 2003).

Grouped data showed little, to no, change in both run-types for stride length and knee flexion angle which would suggest no changes in shock attenuation (Derrick *et al.* 1998). Individual assessment however, suggests that the fatigue effects from the training-runs induced a change to shock attenuation strategies at the end of the run for several runners. Five runners experienced an increase in stride length compared to two in MICR. In the HIIT, the same runners also experienced an increase in knee flexion angle and reduced knee flexion strength. The increased knee flexion angle would suggest a change in mechanics to better absorb shock, as it may shift shock attenuation towards active muscles and away from passive tissues (Edwards *et al.*, 2012). Individual assessment showed that fatigue effects from the HIIT were greater than MICR, with more runners changing shock attenuation strategy. The greater changes in running mechanics

and strength following the HIIT suggest the extent of muscle dysfunction was greater, with some runners having an impaired tolerance to impact. This finding provides a basis for a more nuanced examination of fatigue effects on kinetics during typical-training runs.

The fatigue experienced during the HIIT run also induced increased coordination variability in more runners compared to MICR. Continuous relative phase variability revealed both a statistically significant difference and a greater number of runners beyond MDC for HIIT compared to MICR. For CAV, the only coupling that failed to see any runner change by less than MDC was (Hip_{flex/ext} - Knee_{abd/add}), while in all other couplings the number of runners beyond MDC was greater after HIIT than MICR. In line with hypothesis of this chapter, as runners fatigued, they were unable to maintain their co-ordination which could be seen as a potential precursor in overuse injury (Powers *et al.* 2010).

Implications

This chapter was able to show while fatigue from typical training runs induce changes in risk factors that contribute to development of common RROIs. Additionally, there were also differences between group and individual patterns of response when investigating fatigue effects on risk factors. The group findings can lead to further research into fatigue effects on injury development during different training run types and running population. On an individual level, the findings can lead to enhanced assessment of risk factors and identification of risk by clinicians, coaches and athletes. Through the use of MDC, individual runners can be identified as having had a ‘real change’ (or not) in RROI risk factors. Clinicians can use MDC to better assess whether a runner’s change to a risk factor was real or not for improved training or rehabilitation prescription. Coaches could identify individual athletes within a group for tailored training program which can enhance athlete performance and durability in a session.

Limitations

Strength measures of hip extension and knee flexion were met with some difficulties. Four runners experienced muscle cramping during post HIIT and MICR runs during examination procedures. During knee flexion exam, in one of the runners the examination could not be complete and left a void in the data. Similarly, for hip extension exam, in one runner only one measure was taken due to discomfort.

Conclusion

The main finding of this chapter was that runners exhibited fatigue induced changes in gait profile at the end of a typical training session. These changes are consistent with those seen in runners with PFP and ITBS and could represent a potential risk of developing a running related overuse injury. This was more prominent following high intensity interval training than moderate intensity continuous running despite an equal energy expenditure. Finally, different statistical approaches provided slightly different findings, based on the observation that injury risk was predominantly individual we would recommend the use of minimum detectable change alongside statistical significance testing for a more sensitive analysis. The contribution of these findings to development of RROI however is not critical unless there is inadequate recovery prior to the next session. This requires further examination.

CHAPTER 7 - TIME COURSE OF RECOVERY FROM A TYPICAL TRAINING RUN

7.1 Introduction

In chapter 6 several changes to running gait and gait variability were found in response to the fatigue experienced following HIIT and MICR, placing runners at an increased potential risk in developing a RROI. The key findings were that fatigue induced changes to gait that mirrored profiles of runners experiencing the most common overuse injuries of PFP and ITBS. This included increased maximum and RoM hip adduction angles, and increased coordination variability at the end of both run-types. Furthermore, this was accompanied by a loss of strength at the hip and knee musculature, with the HIIT having a larger effect and inducing changes in more runners. The fatigue induced changes showed that runners could potentially be at increased risk of injury development following these runs. Logically, these changes would increase the risk of injury development if they remained at the start the next run; although this has yet to be determined.

While chapter 6 identified fatigue as a decrement in strength, there was no evidence to identify its origin. During stretch-shortening cycle exercises such as running, there are rapid, short duration impact loads and active braking phases controlled by reflex and central neural pathways (Nicol *et al.* 2006). Impairments to neuromuscular function can occur in either contractile function (peripheral fatigue) or muscle activation (central fatigue) (Gandevia, 2001). Both of these mechanisms feature in intensive and exhaustive stretch-shortening exercise and provide a good basis to examine neuromuscular fatigue (Nicol *et al.* 2006).

Stretch shortening cycle recovery is biphasic by nature, suggesting the decrements in muscular strength and altered gait observed in chapter 6 may take several days to recover from exhaustive running (Nicol and Komi, 2006). The recovery kinetics from typical training sessions has not been investigated. If the observed effects of fatigue resulting from the runs in chapter 6 persist to the next training session, then based on Bertelsen's injury aetiology model (Bertelsen *et al.* 2017), a runner would be predicted to start a running session at a

lower capacity to tolerate load. This would place them at a risk of developing running related overuse injury. The time course of recovery from SSC fatigue related decrements following a typical running session may provide insights into potential risk in development of RROI in healthy runners.

To assess the time course of recovery of central and peripheral neuromuscular fatigue, a number of previous studies have utilized electrical stimulation of a motor nerve (Brownstein *et al.* 2017; Froyd *et al.* 2013; Škof and Strojnik, 2006). Nicol *et al.* (2003) reported impairments to neuromuscular function both acutely and for several days following a 10 km performed at self-selected pace. Studies examining the effect of running on neuromuscular function immediately and several hours post run have shown that there is a reduction in central and peripheral activation. The majority of studies however have used a marathon or ultra-distance run (Millet *et al.* 2003, 2002; Nicol *et al.* 1991b; Škof and Strojnik, 2006).

7.1.1 Aims

To date no study has investigated the time course of recovery for altered gait mechanics and muscle strength following a typical training run. Due to the larger effect on the risk factors examined in the previous chapter, this chapter focused solely on the HIIT run. It is unknown whether both peripheral and central fatigue are induced from a HIIT session alongside the previously observed risk factors in chapter 6. This chapter hypothesised that there would be changes in gait and neuromuscular function immediately post HIIT but insufficient evidence exists to hypothesise whether these changes will persist 24 hours later. The aim of this chapter was to examine the time course of recovery in the risk factors found in chapter 6, immediately following, and 24 hours after a HIIT session.

7.2.1 Research Design

This chapter employed a time-series design to observe changes in neuromuscular function, strength, kinematics and coordination variability during a standard paced run (SPR) pre, post, and 24-h post a typical training run. It was not feasible, nor appropriate, to run a HIIT session on consecutive days (James and Doust, 2000), therefore a standard paced run was introduced to examine the effects of the HIIT on kinematics and coordination variability immediately post and 24-h post.

7.2.2 Participants

Based on a power analysis and subsequent institutional ethical approval, 20 healthy, experienced, club distance runners, (N=10 male; N=10 female) were recruited. All runners that participated in this study were well trained (See table 3.1) and participated in at least one HIIT session or similar training type at least once a week, most weeks, at their running club. A description of participant characteristics, treadmill speeds and run duration is provided in Table 7.1. Inclusion criteria is described in chapter 3 section 3.3.

Table 7.1. Descriptive characteristics of participants along with both HIIT and standard pace run (SPR) speeds, and durations, represented as mean \pm standard deviation.

	Female (<i>n</i> = 10)	Male (<i>n</i> = 10)
Age (years)	43.2 \pm 4.5	43.0 \pm 5.0
Height (cm)	165.5 \pm 6.4	176.5 \pm 7.8
Mass (kg)	61.4 \pm 11.4	78.3 \pm 9.3
$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	52.5 \pm 6.2	55.3 \pm 5.0
HIIT Speed (m·s ⁻¹)	3.9 \pm 0.4	4.3 \pm 0.5
HIIT rep duration (min:sec)	03:24 \pm 20(s)	03:10 \pm 22(s)
SPR pace (m·s ⁻¹)	3.1 \pm 0.3	3.4 \pm 0.4

7.2.3 Procedure

Each participant attended three sessions, a preliminary session to determine the intensities for the HIIT and standard paced run, a HIIT session and follow up at 24-h post (Figure 7.1). The standard paced run (SPR) lasted 6-minutes based on James and Doust, (2000) who used same approach to measure fatigue post HIIT. The speed of the SPR was based upon the MICR speed used in chapter 6, which while at a steady state intensity was sufficient to examine possible kinematic alterations to the hip and knee joints sagittal and frontal plane motions. Recreational runners tend to perform a range of intensity runs to improve performance and are likely to perform a medium intensity continuous run the day following a high intensity session (Zinner *et al.* 2018). The SPR run was performed pre, immediately post, and at 24 hours (24-h) post HIIT. All sessions were conducted at the same time of day to minimise diurnal variation (Reilly and Garrett, 1998). Participants were asked to wear the same footwear throughout and follow their habitual dietary regimen, while refraining from high volume or intensity training within 48 hours before testing and also to refrain from any activity following the training run session prior to 24-h post assessment.

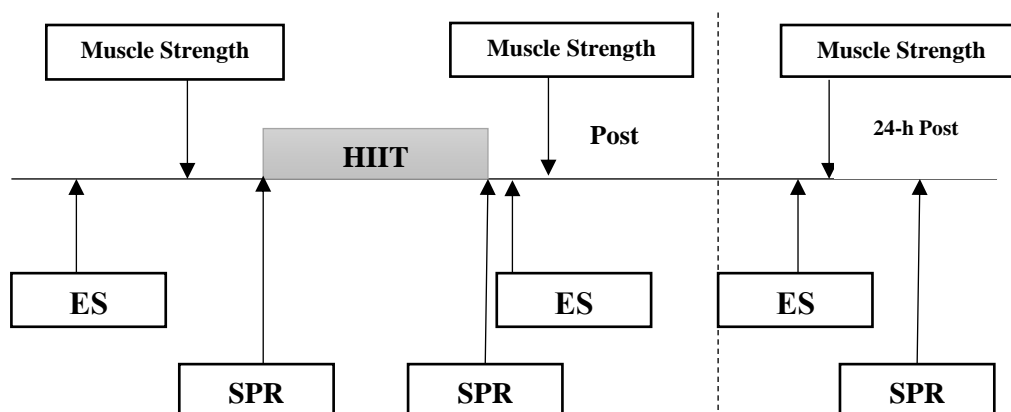


Figure 7.1. Testing procedure outlining timing of examination of the protocol containing electrical stimulation (ES), muscle strength, standard pace run (SPR) performed pre, post and 24-h post a high intensity interval training run (HIIT).

7.2.3.1 Preliminary Testing

Initial measurements of mass, height and kinanthropometric measures were taken as described in chapter 3, section 3.5.1.

Participants completed maximal and submaximal tests to determine speeds and duration of the training runs, this was collected as described in chapter 3, sections 3.5.4 and 3.5.5.

7.2.3.2 HIIT and SPR

The two runs used in this chapter were individualised based on the results of the $\dot{V}O_2$ max and LTP. This procedure was described in full in section 3.6.

7.2.4 Muscular Strength

Chapter 6 identified certain limitations with the examination of knee flexion and hip extension procedures causing discomfort during the post running session examination in some runners. For those reasons, knee flexion and hip extension were omitted from this chapter. This chapter examined hip strength only for hip abduction, hip adduction, hip flexion, hip external rotation, and hip internal rotation at pre, post, and 24-h post of HIIT. The full procedures of the data collected are described in chapter 3, section 3.7. All tests were conducted in the same order: hip abduction, hip adduction, hip flexion, hip external and internal rotation.

7.2.6 Motion Capture

Running kinematics were captured using a 14-camera 3-Dimensional motion analysis system (Vicon Nexus; Vicon Motion Systems Ltd. Oxford, England) sampling at 300 Hz.

For HIIT motion analysis was recorded for 25 s at the end of the first and start of the final minute. During the SPR, motion analysis was recorded for 25 s at the end of the first minute. Description of motion capture can be found in chapter 3, sections 3.8.

7.2.7 Data Processing

Motion capture data was processed as described in chapter 3, sections 3.8.6.

7.2.8 Coordination Variability

Coordination variability of interactions between sagittal (flexion/ extension) and frontal (abduction/ adduction) planes of motion for the hip and knee joint couplings were analysed using CRPV and CAV. Data for both CRPV and CAV was collected and processed as described in chapter 3.8.6.2 and 3.8.6.3.

7.2.9 Neuromuscular Function Assessment

This chapter added measures of neuromuscular function to identify central and peripheral components of fatigue. Electrical stimulation of the femoral nerve was used to assess the contribution of both central and peripheral mechanisms towards neuromuscular fatigue and recovery of the quadriceps, similar to those performed in our lab (Brownstein *et al.* 2017; Goodall *et al.* 2014). These measures were taken pre SPR, immediately post (within one minute of HIIT completion) and at 24-h post.

The set up for the experiment required modification of an isometric force chair in order to attach a force transducer (Figure 7.2). The modification of the isometric force chair required the placement of two 15mm thick, square, hollow, aluminium metal bars with length just exceeding the width of the chair (320 mm). There were two holes with radius of 10mm, at



Figure 7.2. Modified isometric strength chair with attached force transducer (circled).

each of the bars placed where the force transducer was attached to the tested leg. An additional modification enabled adjustment of the height of the load cell to be able to line up the load cell directly in line with participant's leg. Lastly, the ends and handles of the chair were covered with foam for comfort and to prevent possible injury from sharp ends.

The isometric force chair was situated near the treadmill to ensure a rapid examination of neuromuscular function following the HIIT session. Immediately following the HIIT, runners dismounted the treadmill and hip markers were taken off to connect electrodes for the motor nerve stimulation. This process took no longer than 30 seconds.

7.2.9.1 Maximal Voluntary Contraction

A load cell (RDP load cell model RLT; Wolverhampton, UK) was used to examine knee extensors (KE) maximal voluntary contraction (MVC). The load cell was powered by a switching mode bench power supply (Maplin, UK), and read on a LabChart 8 software (ADInstruments, Australia). The reading was converted from analogue to digital into LabChart via a 16-channel power lab (ADInstruments, Australia) (Figure 7.3).

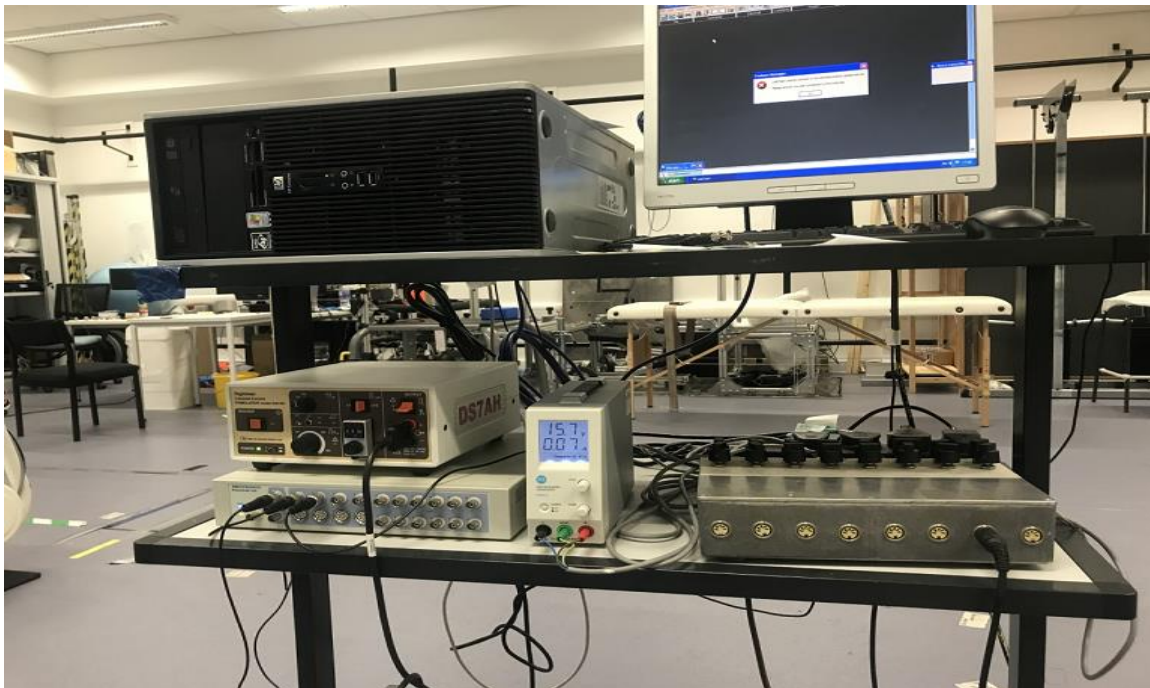


Figure 7.3. Complete set up for electrical stimulation procedure

Prior to use, the load cell was calibrated by attaching 5kg weights incrementally up to 40kg onto the load cell; the load cell was hung by a non-elastic rope that was attached to the ceiling of the lab. A perfectly linear relationship was found between load and voltage ($y = 761.51x + 1.1695$; $R^2 = 1$) (Figure 7.4). Following calibration, the load cell was attached to the isometric force chair and used to record muscle force (N) during maximum voluntary contraction (MVC) of the knee extensors.

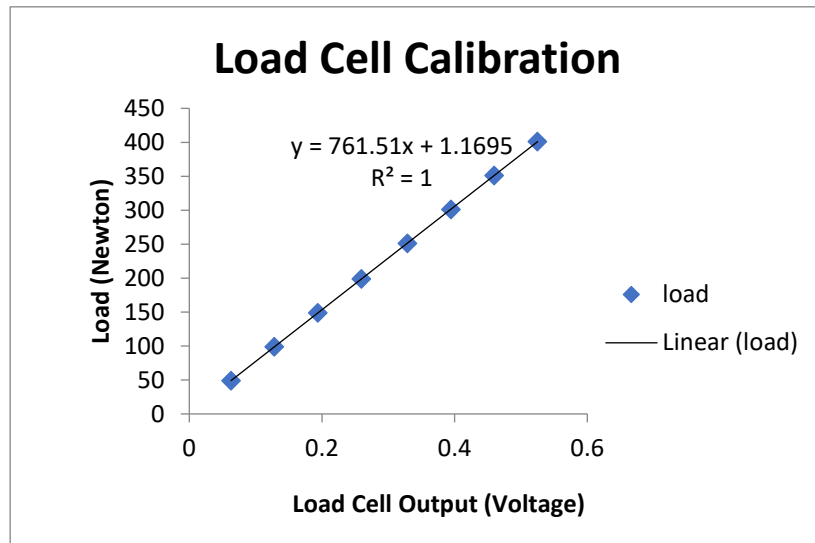


Figure 7.4. Calibration graph for Load Cell

At the time of testing, participants were seated in the custom-built isometric force chair with their hips and knees placed at 90° flexion. The load cell was attached to the participant's right leg at the superior malleoli via a noncompliant cuff. In order to aid with maximal effort during the MVC, the force trace was displayed on a computer screen in front of the participant (Baltzopoulos *et al.* 1991). Participants were also instructed to grasp the handles of the isometric force chair for further support.

7.2.9.2 Contractile Function

Stimulation of the motor nerve was used to provide measurement of contractile function, evaluated through twitch potentiation. Single and paired electrical stimulation (100 Hz) were delivered to the right knee extensor via a constant-current stimulator (DS7AH, Digitimer Ltd., Hertfordshire, UK). Circular self-adhesive surface electrodes (model number, Nidd Valley Medial Ltd., North Yorkshire, UK) were used. The electrodes were placed over the nerve high in the femoral triangle, with the anode placed between greater trochanter and iliac crest (Weavil *et al.* (2015). Once placement was identified the area of placement of the electrodes

were marked with inedible ink to ensure repeatable consistent placement for post and 24-h post measurements. Electrical stimulation was delivered at rest to the relaxed muscle beginning at 20 mA and increased incrementally in step wise fashion by 20 mA until a plateau occurred in quadriceps twitch amplitude (Q_{tw} , N). The resulting stimulation was increased by 30% to ensure a consistent, supra maximal stimulus. This was only performed prior to the start of each session testing day and therefore unnecessary to perform again before post measures, however necessary but required again at prior to 24-h post testing.

The evoked force and twitch characteristics are in response to a single pulse (100 Hz) electrical stimulation. Twitch potentiation was used in this chapter to assess contractile function following HIIT, identified through the amplitude of the evoked twitch at rest (Kufel *et al.* 2002). Twitch potentiation of force output of the knee extensors was measured through potentiated quadriceps twitch force ($Q_{tw,pot}$).

7.2.9.3 Voluntary Activation

Voluntary activation has been defined as the level of neural drive to the muscle during exercise (Gandevia *et al.* 1995). To examine the neural drive, the first step is to perform twitch interpolation technique to quantify the completeness of muscle activation during a voluntary contraction (Shield and Zhou, 2004). During an MVC, if motor units are not firing fast enough or not recruited, a supramaximal electrical stimulus delivered to the corresponding nerve will evoke a twitch like increment to force. The increment in force is called superimposed twitch (SIT) representing the inactive muscles during the MVC (Merton, 1954).

Paired electrical stimulation (100 Hz) of the femoral nerve were delivered during and 2 s after the MVC. This method of using paired stimulation is considered as the most valid when assessing voluntary activation while providing a high degree of certainty as motor units that

will be non-responsive to stimuli will be upon the second, therefore increasing the pool of motor unit stimulated (Place *et al.* 2007). Finally, voluntary activation was quantified by comparing the superimposed twitch force (SIT) during MVC, with the amplitude of the potentiated twitch force ($Q_{tw,pot}$) elicited 2 s after MVC at rest. Voluntary activation percentage was expressed as:

$$VA (\%) = [1 - \left(\frac{SIT}{Q_{tw,pot}} \right) \times 100]$$

These protocols to measure knee extensor MVC, $Q_{tw,pot}$, and %VA are standard operating procedures within the sports science labs at Northumbria University and have been shown to have good to excellent reliability (Brownstein, 2018). The reliability values from Brownstein (2018) was then used to extrapolate MDC for each measure.

7.2.10 Statistical analysis

The data were checked for normality using Q-Q plots; all variables were deemed normally distributed. Mean and standard deviation were calculated for all variables. Data were tested for sphericity using Mauchly's test. A one-way repeated measures ANOVA was used to assess changes in outcome measures for kinematics and joint coupling variability during SPR along with strength and neuromuscular function measures over time: pre, post, and 24-h post. Where appropriate, Tukey's LSD test was used post hoc. Effect sizes were calculated according to Cohen (1988) and interpreted as small (≥ 0.2), moderate (≥ 0.4), and large (≥ 0.8). The level of significance was set at $P < 0.05$. All statistical analysis was performed in SPSS v22.0 (SPSS Inc., Chicago, IL, USA).

On an individual level, fatigue effects were considered to have occurred when individual runners had changes either immediately post or 24 hours post HIIT that were greater than, or equal to, the minimum detectable change (MDC).

7.3. Results

7.3.1 Muscular strength

7.3.1.1 Group Assessment

All muscular strength measures decreased significantly with time following the HIIT (Table 7.2 and Figure 7.5) showing small to moderate effect sizes. Hip internal rotators had a significant effect with time ($F_{2,19} = 9.50$, $P = 0.001$) declined 10.8% in strength post HIIT, remaining unchanged at 24-h post (10.4%), post-hoc analysis revealed a significant reduction in strength both post ($P < 0.001$, $d = 0.39$) and 24-h post ($P = 0.009$, $d = 0.42$). In hip abduction strength, there was significant reduction in time ($F_{2,19} = 34.14$, $P < 0.001$). Runners exhibited an 11.2% reduction in hip abduction strength post HIIT ($P < 0.001$, $d = 0.41$) with minimal recovery the following day (9.5%), ($P < 0.001$, $d = 0.41$). Hip adduction strength as reduced significantly with time ($F_{2,19} = 18.5$, $P < 0.001$), at post ($P < 0.001$, $d = 0.37$) and 24-h post ($P = 0.002$, $d = 0.26$). A significant drop was found in hip external rotation with time ($F_{2,19} = 9.54$, $P < 0.001$), hip external rotators were reduced post HIIT ($P < 0.001$, $d = 0.47$; 12.8%), however this decline (5.8%) was no longer significant at 24-h post ($P = 0.267$, $d = 0.23$). Likewise, hip flexion strength showed a significant decline with time ($F_{2,19} = 25.94$, $P < 0.001$), hip flexion strength was significantly reduced post HIIT (11.3%) ($P < 0.001$, $d = 0.39$) but not at 24-h post (9.1%) ($P = 0.051$, $d = 0.34$).

Table 7.2. Hip body mass-normalised ($\text{kg} \cdot \text{kg}^{-1}$) represented as mean \pm standard dev (SD) and effect size (ES; Cohen's d) for pre, post, and 24-h post High Intensity Interval Training.

Strength Measures	Mean \pm SD (ES)			Time	Post MDC	24-h MDC
	Pre	Post	24-h post			
HABD	0.500 ± 0.16	$0.444 \pm 0.15^{***}$ (d = 0.36)	$0.452 \pm 0.15^{***}$ (d = 0.30)	†	2	3
HADD	0.314 ± 0.10	$0.277 \pm 0.10^{***}$ (d = 0.37)	$0.289 \pm 0.09^*$ (d = 0.26)	†	0	0
HF	0.438 ± 0.13	$0.388 \pm 0.12^{***}$ (d = 0.39)	0.398 ± 0.14 (d = 0.29)	†	0	0
HIR	0.195 ± 0.06	$0.174 \pm 0.06^{***}$ (d = 0.35)	$0.176 \pm 0.05^*$ (d = 0.34)	†	3	4
HER	0.219 ± 0.06	$0.191 \pm .05^{***}$ (d = 0.51)	0.208 ± 0.06 (d = 0.18)	†	2	2

Effect size is comparison with baseline

† denotes significant effect with time

Significant differences in comparison with baseline indicated by * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

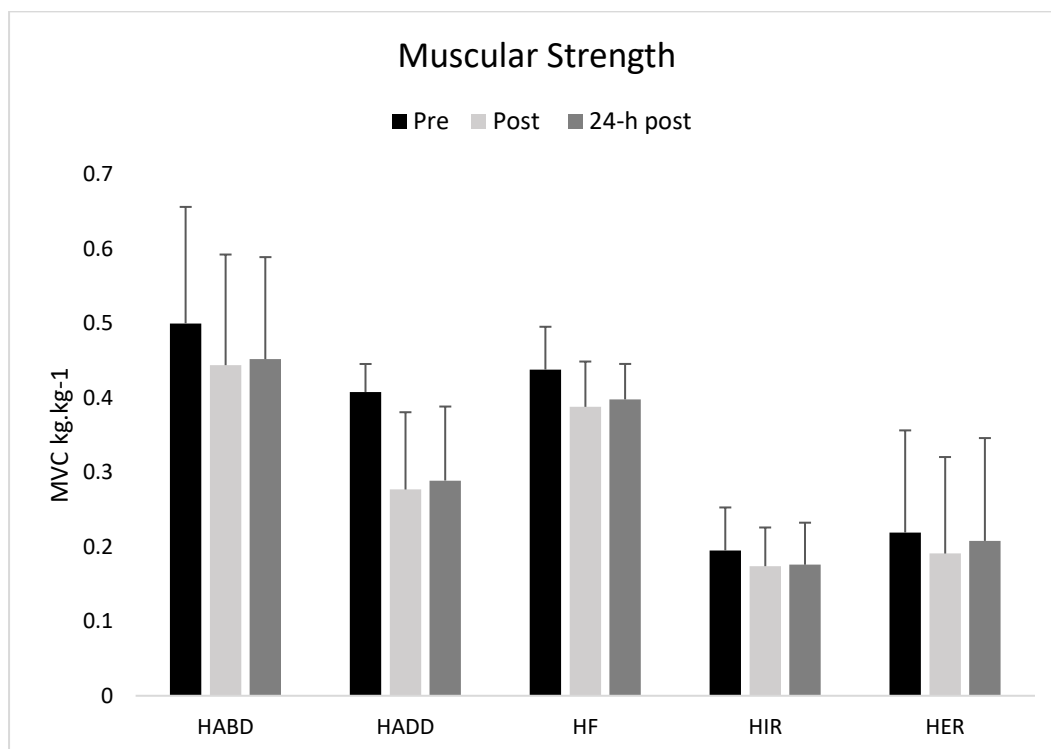


Figure 7.5. Muscular strength representation for hip abduction (HABD), hip adduction (HADD), hip flexion (HF), hip internal rotation (HIR), and hip external rotation (HER) at pre, post and 24-h post.

7.3.1.1 Individual Assessment

Number of runners that exceeded MDC is shown in figure 7.6. Two runners had reduced hip abduction strength beyond MDC after HIIT, while three runners experienced a drop greater than MDC at 24-h post. In hip internal rotation, three runners exceeded MDC post and all had recovered at 24-h post. Post HIIT, two runners experienced a drop in HER above MDC, of these, one runner experienced further drop at 24- post, while the other had recovered. For muscular strength of hip adduction and hip flexion, post, while the other had recovered. For muscular strength of hip adduction and hip flexion, no runner dropped force below MDC at any time point.

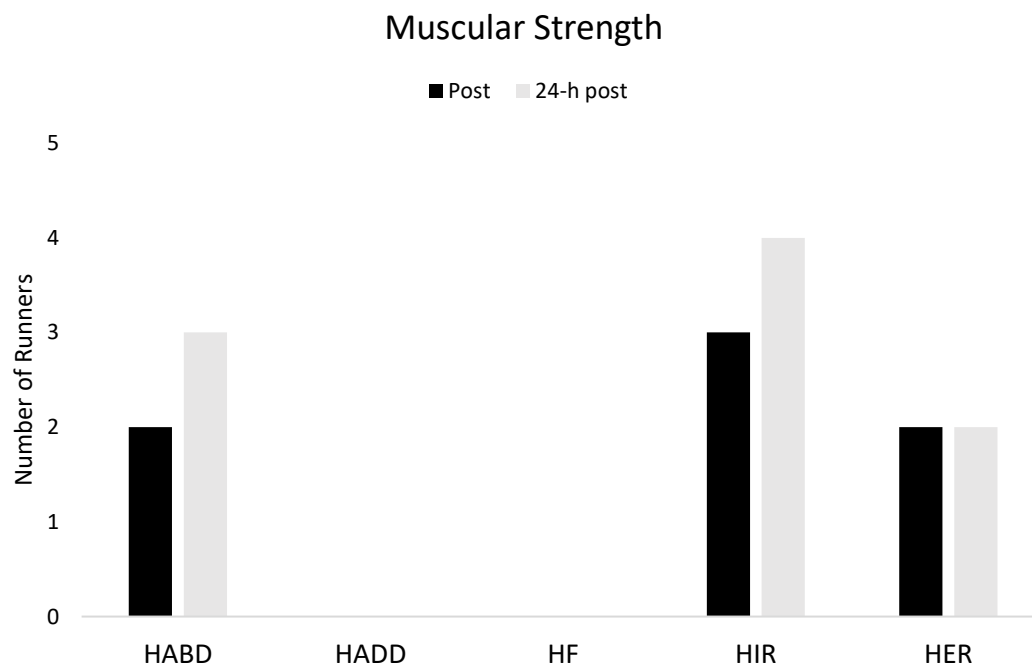


Figure 7.6. Number of runners that exceeded minimum detectable change (MDC count) in hip abduction (HABD), hip adduction (HADD), hip flexion (HF), Hip internal rotation (HIR), and hip external rotation (HER) muscular strength examination at post and 24-h post training run.

7.3.2 Kinematics

7.3.2.1 Group Assessment

There was a significant decrease in both hip maximum angle ($F_{2,19} = 11.05$, $P = 0.001$) and RoM ($F_{2,19} = 17.39$, $P < 0.001$) in the frontal plane. For maximum angle, post-hoc analysis revealed a large increase in hip adduction both post ($P < 0.001$, $d = 0.91$) and at 24-h post ($P < 0.001$, $d = 0.86$). Similarly, for RoM angle there was also a large increase in hip adduction during post SPR ($P < 0.001$, $d = 0.85$) which, although slightly reduced, remained elevated at 24-h post ($P < 0.001$, $d = 0.74$).

Knee kinematics showed a main effect for time in sagittal plane ROM angle ($F_{2,19} = 5.32$, $P = 0.015$, $d = 0.38$) and frontal plane maximum angle ($F_{2,19} = 3.65$, $P = 0.046$, $d = 0.74$). Post-hoc analysis failed to show a significant change either post or at 24-h post compared to baseline for either variable.

7.3.2.2 Individual Assessment

Individual assessment using MDC (Figure 7.7), showed that for hip frontal plane maximum angle 11 runners showing signs of fatigue post HIIT, with nine runners still affected 24-h post, more than any other variable. Seven runners experienced a change above MDC for hip frontal plane RoM angle post HIIT and three runners exceeded MDC at 24-h post. Two runners experienced a change greater than MDC for hip sagittal maximum angle post HIIT, however one runner had increased sagittal plane movement; the other decreased. The runner who experienced decreased sagittal plane movement exhibited a further decrease at 24-h post, while the other runner had recovered. For RoM angle, seven runners experienced an increase above MDC with two of them failing to recover at 24-h post.

Table 7.3. Kinematics represented as mean \pm standard deviation (SD) and effect size (ES; Cohen's d) for Standard Pace Runs performed at pre, post, and 24-h post High Intensity Training Run for maximum angles and range of motion (RoM) angles of the hip and knee joints in the sagittal and frontal plane movements.

		Mean \pm SD			Time	Post MDC	24-h MDC
		Pre	Post	24-h post			
Maximum Angles (deg)							
	Hip sagittal	38.8 \pm 6.2	38.2 \pm 7.2 (d = 0.09)	37.4° \pm 5.8 (d = 0.23)		2	3
	Hip frontal	9.6 \pm 3.9	13.3 \pm 4.2*** (d = 0.91)	12.7° \pm 3.3*** (d = 0.86)	†	11	9
	Knee sagittal	42.9 \pm 14.7	42.9 \pm 6.5 (d = 0.26)	43.7° \pm 4.7 (d = 0.20)		1	4
	Knee frontal	0.3 \pm 4.3	-0.1 \pm 3.3 (d = 0.08)	2.2° \pm 4.0 (d = 0.46)	†	0	1
ROM Angles (deg)							
	Hip sagittal	43.5 \pm 6.5	44.6 \pm 5.5 (d = 0.18)	43.8° \pm 4.8 (d = 0.05)		3	1
	Hip frontal	11.9 \pm 3.2	14.9 \pm 3.8*** (d = 0.85)	14.5° \pm 3.8*** (d = 0.74)	†	7	3
	Knee sagittal	31.3 \pm 13.4	27.6 \pm 4.3 (d = 0.38)	29.5° \pm 5.1 (d = 0.17)	†	4	6
	Knee frontal	5.5 \pm 2.6	4.8 \pm 1.7 (d = 0.32)	5.3° \pm 2.7 (d = 0.08)		1	1

Sagittal plane positive values represent flexion; negative values represent extension

Frontal plane positive values represent adduction angles; negative value represent abduction movement.

Effect size is comparison with baseline

† denotes significant effect with time

Significant differences in comparison with baseline indicated by * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

For the knee, one runner decreased knee sagittal plane maximum angle beyond MDC post HIIT. At 24-h post, four runners experienced a change beyond MDC, one runner exhibiting a reduction in angle however the remaining three increased knee flexion. Four runners displayed a reduced sagittal plane knee RoM post HIIT that exceeded. At 24-h post, six runners exceeded MDC with two of the runners changing from a decrease to increase RoM above MDC, while the others still exhibited a decreased RoM. No runner experienced a change above MDC for maximum angle of the knee in the frontal plane post HIIT and only one runner changed above MDC at 24-h post. This runner altered their gait strategy from running in abduction at post HIIT to adduction at 24-h post. For knee RoM angle, only one runner exceeded MDC at post with an increased RoM angle that was still present 24-h later.

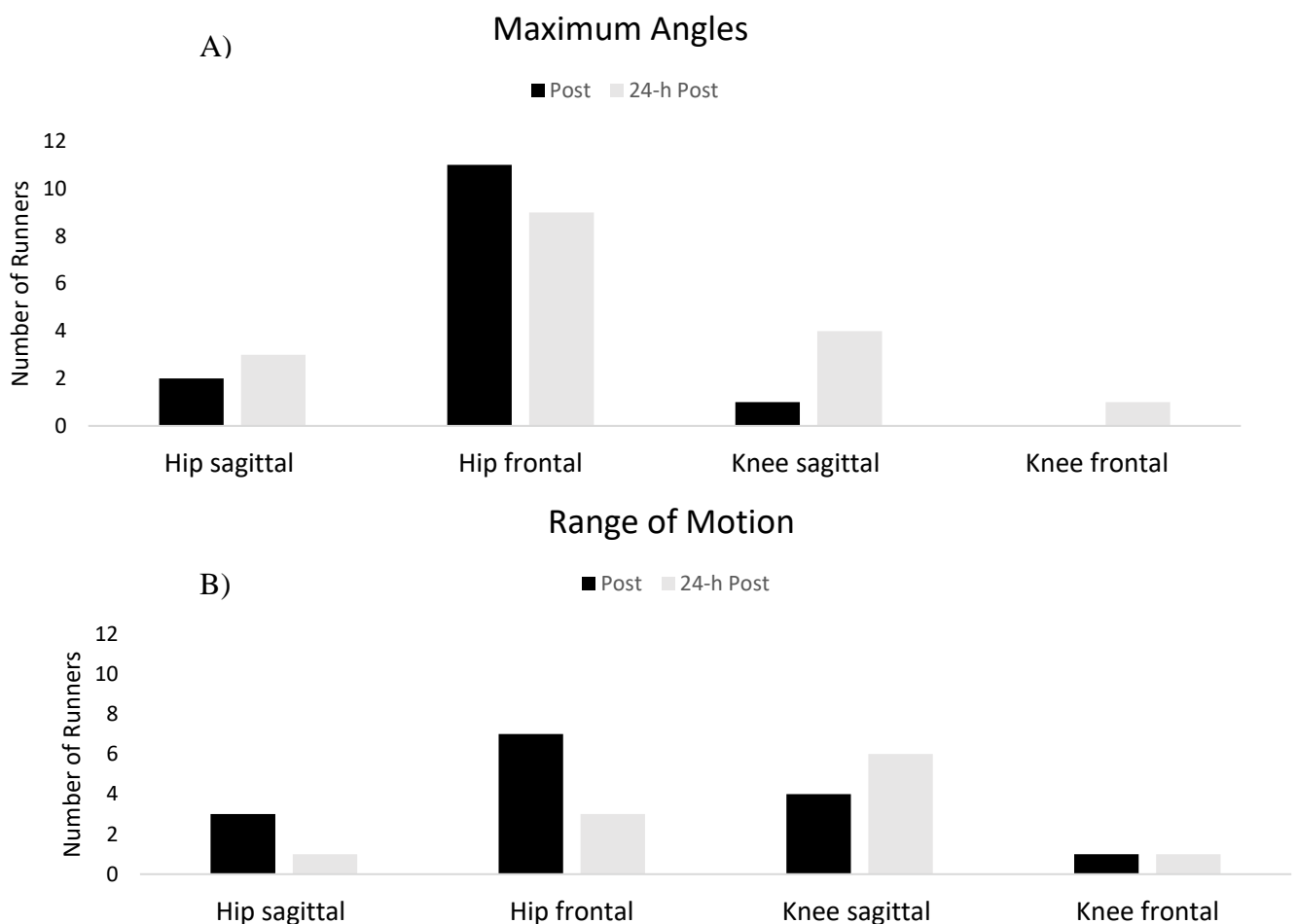


Figure 7.7. Number of runners that exceeded minimum detectable change (MDC count) in A) maximum angle and B) Range of Motion for hip and knee sagittal and frontal planes of motion at post and 24-h post training run.

7.3.3 Coordination Variability

7.3.3.1 Group Assessment

Running coordination variability, assessed by vector coding coupling angle, revealed no significant change with time (Table 7.4). In contrast, individual assessment showed that in $\text{Hip}_{\text{flex/ext}} - \text{Knee}_{\text{abd/add}}$ 16 runners exhibited a change above MDC post HIIT. Of those 16 runners, seven had increased variability immediately post HIIT, but this had changed to decreased variability at 24-h post. The remaining runners exhibited decreased variability both at post and 24-h post, with one runner recovering. Two runners exhibited a change in variability above MDC in both post and 24-h post for $\text{Hip}_{\text{flex/ext}} - \text{Knee}_{\text{flex/ext}}$ coupling. Seven runners experienced above MDC change for coupling of $\text{Hip}_{\text{abd/add}} - \text{Knee}_{\text{flex/ext}}$ at post and 24-h post; three showed increased variability at post and two remained affected at 24-h post. Post HIIT, 14 runners had altered variability above MDC in $\text{Hip}_{\text{abd/add}} - \text{Knee}_{\text{abd/add}}$ coupling, eight of whom remained altered at 24-h post.

Continuous relative phase variability revealed a significant change in time for all coupling interactions. Post hoc examination showed that the increased variability observed at both post and 24-h post after the training session was significant for all examined interactions (Table 7.4).

7.3.3.2 Individual Assessment

Individual assessment (Figure 7.8) of $\text{Hip}_{\text{flex/ext}} - \text{Knee}_{\text{flex/ext}}$ showed that three runners experienced a change above MDC at post and while the three remained increased, an additionally three runners exhibited increased variability at 24-h. In $\text{Hip}_{\text{flex/ext}} - \text{Knee}_{\text{abd/add}}$

Table 7.4. Joint coupling interactions of standard pace runs at pre, post, and 24-h post High Intensity Interval Training run represented as mean \pm standard deviation (SD) and effect size (ES; Cohen's d) for joint coupling interactions of sagittal (flex/ext) and frontal plane (abd/add) movements of the hip and knee measured through continuous relative phase (CRPV) and vector coding coupling angle (CAV).

		Mean \pm SD (ES)			Time	Post MDC	24-h MDC
		Pre	Post	24-h			
CAV (deg)							
	Hip _{flex/ext} - Knee _{flex/ext}	66.7 \pm 5.3	67.3 \pm 4.9 (d = 0.12)	66.2 \pm 4.5 (d = 0.10)		2	2
	Hip _{flex/ext} - Knee _{abd/add}	66.8 \pm 6.3	67.3 \pm 5.2 (d = 0.09)	68.0 \pm 4.6 (d = 0.22)		16	15
	Hip _{abd/add} - Knee _{flex/ext}	71.7 \pm 1.8	71.4 \pm 2.5 (d = 0.14)	71.6 \pm 2.2 (d = 0.05)		7	7
	Hip _{abd/add} - Knee _{abd/add}	68.4 \pm 4.8	68.6 \pm 4.2 (d = 0.44)	69.8 \pm 3.3 (d = 0.34)		14	8
CRPV (deg)							
	Hip _{flex/ext} - Knee _{flex/ext}	12.9 \pm 3.9	17.8 \pm 10.1* (d = 0.64)	19.7 \pm 13.0* (d = 0.74)	†	3	6
	Hip _{flex/ext} - Knee _{abd/add}	9.1 \pm 4.8	15.2 \pm 14.1* (d = 0.56)	20.3 \pm 16.5* (d = 0.90)	†	3	7
	Hip _{abd/add} - Knee _{flex/ext}	16.2 \pm 4.1	23.5 \pm 13.9* (d = 0.73)	26.0 \pm 12.6** (d = 1.05)	†	5	4
	Hip _{abd/add} - Knee _{abd/add}	11.0 \pm 4.9	21.3 \pm 14.3** (d = 0.93)	23.3 \pm 14.7** (d = 1.10)	†	6	9

Effect size is comparison with baseline

† denotes significant effect with time

Significant differences in comparison with baseline indicated by

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

three runners exceeded MDC post HIIT, at 24-h post, the same three runners still exhibited increased running coordination variability with additional four runners. For $\text{Hip}_{\text{abd/add}} - \text{Knee}_{\text{abd/add}}$, five runners that exceeded MDC and all but one exceeded MDC at 24-h post. For $\text{Hip}_{\text{abd/add}} - \text{Knee}_{\text{flex/ext}}$ coupling, five runners exceeded MDC at post, while four remained altered at 24-h post. In all CRPV interactions, the runners had increased variability apart for one runner who reduced variability in all couplings except $\text{Hip}_{\text{abd/add}} - \text{Knee}_{\text{flex/ext}}$.

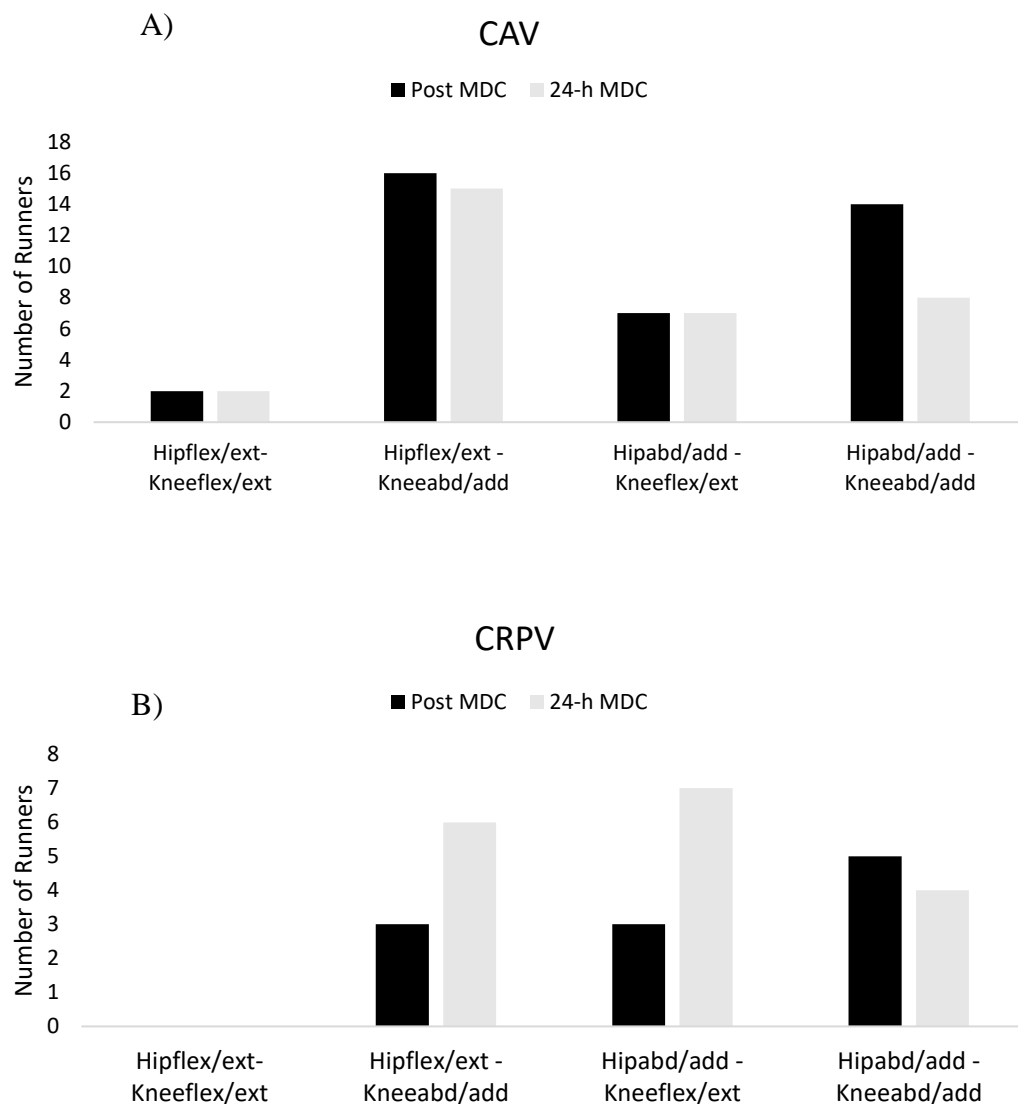


Figure 7.8. Number of runners that exceeded minimum detectable change (MDC count) in A) Coupling Angle variability and B) Continuous Relative Phase Variability (B) for hip and knee couplings at post and 24-h post training run.

7.3.4 Neuromuscular function

7.3.4.1 Group Assessment

Fatigue was present post exercise as KE MVC showed a reduction in strength with a significant for time ($F_{2,13} = 19.74$, $P < 0.001$) (Gandevia, 2001). Maximal voluntary contraction was reduced by 8.1% ($P < 0.001$, $d = 0.31$) pre to post HIIT and remained 3.2% lower ($P = 0.022$, $d = 0.30$) at 24-h post (Table 7.5). Similarly, $Q_{tw,pot}$ exhibited a significant decrement in time ($F_{2,14} = 4.08$, $P = 0.017$). Quadriceps potentiated twitch force was reduced from pre to post training run ($P = 0.013$, $d = 0.56$), but had recovered by 24-h post ($P = 0.393$, $d = 0.12$; Table 7-5). There was also a significant impairment to the central nervous system, showing central fatigue assessed by VA with time ($F_{2,14} = 17.25$, $P < 0.001$). Voluntary activation showed a large signification drop of 7.3% from pre to post ($P < 0.001$, $d = 1.07$) and recovered to 2.0% at 24-h post, which was still significantly lower than pre ($P = 0.013$, $d = 0.37$).

Table 7.5. Measures of neuromuscular function represented as mean standard \pm deviation (SD) and effect size (ES; Cohen's d) for Voluntary activation percentage (VA%), Quadriceps resting twitch potential ($Q_{tw,pot}$, N) and maximum voluntary contraction (MVC) of the knee extensors at pre, post and 24-h post training run.

	Mean \pm SD (ES)			Time	Post MDC	24-h MDC
	Pre	Post	24-h post			
MVC (N)	495.4 \pm 153.8	448.7 \pm 142.7*** ($d = 0.31$)	451.8 \pm 127.9* ($d = 0.30$)	†	6	5
$Q_{tw,pot}$ (N)	188.6 \pm 43.9	162.9 \pm 48.5* ($d = 0.56$)	183.1 \pm 49.3 ($d = 0.11$)	†	8	2
VA%	93.2 \pm 4.4	86.4 \pm 7.8*** ($d = 1.07$)	91.3 \pm 5.8* ($d = 0.37$)	†	15	4

Effect size is comparison with baseline

† denotes significant effect with time

Significant differences in comparison with baseline indicated by * $P < 0.05$, ** $P < 0.01$,

*** $P < 0.001$

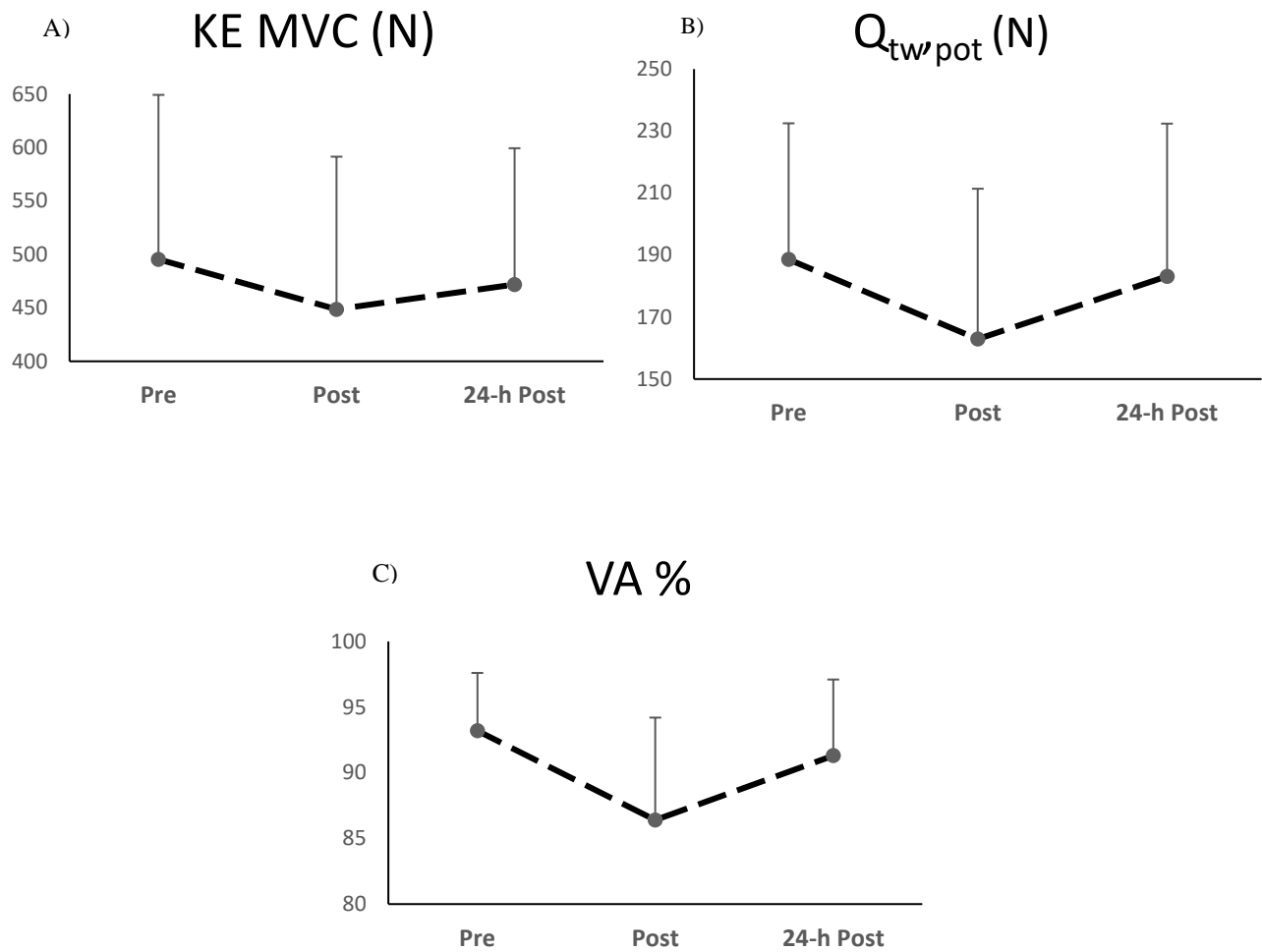


Figure 7.9. Graphs representing A) knee extension maximal voluntary contraction (KE MVC), B) quadriceps resting twitch potentiation ($Q_{tw,pot}$) and C) Voluntary activation (VA%) at pre, post, and 24-h post high intensity interval training run.

7.3.4.2 Individual Assessment

Individual assessment of knee extensor MVC assessment revealed that six runners reduced strength above MDC, with only one runner recovering at 24-h post. For $Q_{tw,pot}$, eight runners exhibited a reduction beyond MDC immediately post, two of them failed to recover 24-h later. Furthermore, VA% dropped beyond MDC for 15 runners, with four runners still remaining impaired at 24-h. Two runners exceeded MDC for all measures at post and 24-h post.

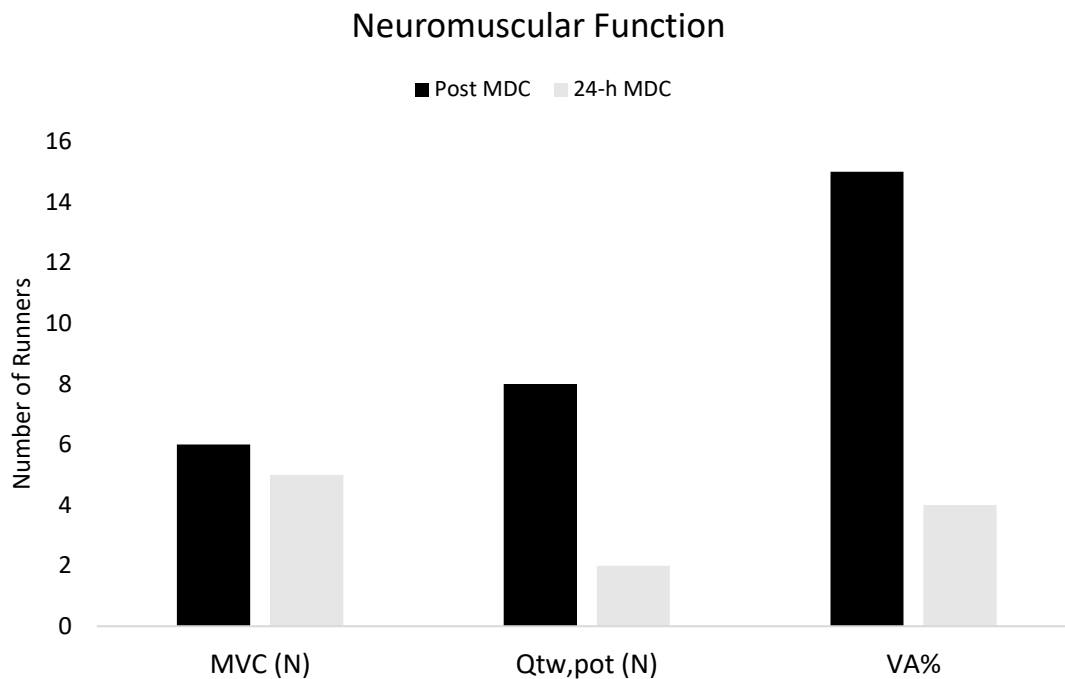


Figure 7.10. Number of runners that exceeded minimum detectable change (MDC count) for knee extension maximal voluntary contraction (MVC), quadriceps twitch potentiation ($Q_{tw,pot}$), and voluntary activation percentage at post and 24-h post training run. .

7.4. Discussion

This chapter was able to corroborate, and thereby reinforced, the previous chapter's findings of reduced hip and knee strength, increased frontal plan hip kinematics, and increased coordination variability following a HIIT session. In addition, this chapter was able to extend those findings by being the first to report impairments to central and peripheral drive following a HIIT session alongside changes to risk factors. The time course of recovery following a HIIT session had not been examined prior to this thesis. This chapter is the first to report that decrements to neuromuscular function, reduced muscular strength, and altered mechanics persisted in some runners 24-h post a HIIT session.

The most prominent interpretation between grouped and individual assessment is that not all runners were at risk of injury, with the majority having recovered from changes to RROI risk factors at 24-h post. Eleven of the runners displayed a similar pattern of increased maximum angle of hip adduction immediately after HIIT. Of these 11 runners, nine still exhibited an increase in hip adduction angle 24-h later. Closer inspection showed that immediately post HIIT, three runners experienced a reduction in evoked electrical stimulation measures along with a loss of muscular strength at the hip, altered kinematics and increased variability post HIIT. One of these runners did not recover in any of these variables at 24-h post. The runners that had impaired scores, in any variable, at 24-h post were considered to be individuals with a potential risk of injury development, as they require longer recovery times to avoid running in a compromised state.

The two runners that exhibited a loss of hip abduction strength beyond MDC immediately post HIIT, also exhibit increased maximum hip adduction angle above MDC. At 24-h post, the three runners that exceeded MDC in hip abduction strength also showed increased maximum hip frontal angle and RoM. These findings are also supported by previous studies examining hip abductor strength pre and post prolonged runs (Bazett-Jones *et al.* 2013; Dierks *et al.* 2008), where hip abductor strength was lower following a run along with increased hip adduction angle. The findings of this chapter further supports the suggestion of chapter 6 that examination of risk of developing running related overuse injuries are better suited to be performed on an individual basis.

The causality of these alterations in running gait e.g. the observed increase in hip adduction angle, have been mostly attributed to muscular decrements (Dierks *et al.* 2008; Noehren *et al.* 2014). Runners suffering from PFP or ITBS exhibit dysfunction at the gluteus medius muscle, which can result in a poor frontal plane movement control (Semciw *et al.* 2016). While EMG activity was not measured, the reduction in gluteus medius strength observed

through decreased hip abduction strength, is the likely cause for the increased hip adduction angles observed. The inability to control hip frontal movement can also contribute to increased strain on the IT band and stress on the patellofemoral joint (Dierks *et al.* 2010; Noehren *et al.* 2007; Powers, 2010). The findings of this chapter are able to further support previous the body of evidence suggesting reduced strength to be the cause of altered kinematics (Brown *et al.* 2016; Dierks *et al.* 2010; Powers, 2010; Willwacher *et al.* 2020).

The observed impairments in neuromuscular function as a group immediately post are lower than to those found in previous studies. Following maximal repeated sprints Goodall *et al.* (2014) reported a drop of 12% in KE MVC and 23% in $Q_{tw,pot}$ compared to the 8.1% in MVC and 14% in $Q_{tw,pot}$ of this chapter. The $Q_{tw,pot}$ however is slightly higher than runs of 1 hour (13%) or 30 km (8%) (Davies and White., 1982; Millet *et al.* 2003). The HIIT induced a 6.8% drop in voluntary activation, however this drop was lower than previously reported reductions in VA following an ultramarathon (13%), 24-h treadmill running (33%), and repeated sprints (9%) (Millet *et al.* 2002; Martin *et al.* 2010; Goodall *et al.* 2014). This observation, as a group, was however not unexpected as the extent of fatigue is dependent on exercise intensity. Martin *et al.* (2010) reported the largest of the decrement in VA following a 24-hr treadmill run, however this was performed at lower intensity than the HIIT of this chapter. Fatigue resulting from lower intensity activities has been shown to be mostly of central origin (Burnley and Jones, 2016) while the HIIT induced both central and peripheral decrement.

This chapter is the first to report individual impairments in neuromuscular function immediately and 24-h post HIIT. Nearly all runners experienced impairments in at least one variable of neuromuscular function immediately post, while only two exhibited signs in all three variables. One runner exhibited a 24% reduction in VA that was accompanied with a reduction of 50% in $Q_{tw,pot}$ and 12% in KE MVC. Five runners exhibited a reduction in VA

between 10 – 15%, four of these runners exhibited a decrement in $Q_{tw,pot}$ ranging between 2 – 61%. At 24-h, in all but four runners, both VA and $Q_{tw,pot}$ had recovered, this is not surprising as the vast majority of runners do not experience an injury after each training run. Individual variations in the extent and origin of fatigue along with recovery further support the use of the alternative statistical approach used throughout this thesis.

The HIIT also induced decrements in the contractile function of the knee extensors, as there was an impaired force output measured through $Q_{tw,pot}$ immediately post HIIT that persisted for 24-h. Such a decrement in force output can be due to both metabolic and / or mechanical factors that influence excitation-contraction coupling along with action potential transmission at the sarcolemma (Allen *et al.* 2008). The reduced $Q_{tw,pot}$ implies a negative effect on the excitation-contraction coupling process. This could be at the cross-bridge level resulting from metabolic and mechanical disturbances, as well as impairments to neuromuscular transmission at the sarcolemma (Goodall *et al.* 2014; Allen *et al.* 2008). Moreover, it could be due to mechanical stresses e.g. a disorganisation of sarcomeres and Ca^{2+} handling interference (Skurvydas *et al.* 2016). Interestingly studies that have reported $Q_{tw,pot}$ reduction following cycling exercises have shown faster recovery compared to running tasks (Blain *et al.* 2016), this may be due to lack of impact force experienced with each ground contact in running.

The results within this chapter show that healthy runners can exhibit instability during running, measured through coordination variability (Hamill *et al.* 1999). Schöner (1995) suggested that muscles and joints can be organized by the central nervous system to stabilise different task specific performances. Decrements to central nervous system function could play a role in gait stability with neurological patients exhibiting atypical, multi-joint coordination movement patterns. This can lead to compensatory changes in muscle activation strategies such an increase in co-activation of agonist-antagonist muscle to impact gait

deviation, thereby increasing or decreasing variability to improve stabilization (Latash and Huang, 2015). At the end of the HIIT, most runners were unable to maintain a stable running form. This was probably caused by the impaired central drive, along with the reduced capability of the gluteus medius muscle, working eccentrically, to act as a brake, resulting in increased variability.

The increased coordination variability observed is an indicator of fatigue. Alterations in coordination variability in injured runners have been hypothesised to be caused by muscle dysfunction (Miller *et al.* 2008). The suggestion however was made without any measurement of muscle function. This chapter showed increased variability alongside a reduction in strength in the hip and knee musculature, corroborating the finding of chapter 6. In addition, this chapter was able to show the presence of both peripheral and central decrement at the end of the run that coincided with the increase in variability. An increase in coordination variability as result of fatigue, might be a protective mechanism to reduce the impact of decreased muscular strength. This concurs with Bartlett, (2004), who suggested that little or no variation in a movement, would result in the same tissue being loaded each time, with potentially damaging consequences. Ferber and Pohl (2011) observed increased variability, albeit in walking, following locally induced fatigue in healthy participants. They attributed this to the diminished ability of the posterior tibialis to produce force, therefore requiring greater assistance from other muscles that contribute to the same joint movement. The possible dysfunction of gluteus medius (Neal *et al.* 2016; Willson *et al.* 2011), could have required a compensatory increase in activation of other muscles contributing to this movement e.g. gluteus minimus and tensor fascia lata (Flack *et al.* 2014). Additionally, the decrease in muscle force could suggest a longer braking action and therefore increase hip adduction RoM. This requires further examination through direct measurement of muscle

activity using electromyography. Increased coordination variability, therefore, can be considered as a mechanism to distribute impact loading as the muscle becomes fatigued.

The four runners who experienced an impairment to either central or peripheral drive at 24-h post concurrently had increased coordination variability in at least one coupling for either CAV or CRPV. The persistence of increased coordination variability at 24-h post would suggest that the contractile and neural decrements might not have recovered from fatigue. As runners train on consecutive days, the lack of adequate recovery could lead to potential overuse injury development. The pathway to injury can be created by a pattern of moving from optimal variability to high variability, which acutely could help protect fatiguing muscles. In this scenario, if runners recover from the fatigue, which most in this chapter did, then there is no risk of injury development. Of greater concern is a failure to recover, this could cause a move from high variability to low variability, which Hamill *et al.* (2012) considered a precursor to overuse injury. Such high to low changes in variability were only observed in one runner.

It is possible that if reduced variability can be used as a tool to discriminate between injured and none injured (Seay *et al.* 2011), increased variability could provide a means to detect fatigue. Increased variability could be the result of decrements in strength and / or impairments in neuromuscular control, as observed in this chapter. The detection of fatigue through variability could signal decrements in contractile or neural function of the muscles when not examined directly. Future studies using wearable technology could enable this to be tested outside of a lab where more ecological testing can be performed on large sample sizes.

Limitations

This chapter was not without limitations. Neuromuscular function was measured in the quadriceps, in running however hip abductors take a more important role in controlling

movements that contribute to both PFP and ITBS. Performing evoked electrical stimulation in these muscle groups is however very complex and therefore not routinely performed. Furthermore, this chapter did not examine the time it takes to fully recover from impairments to neuromuscular function, reduction in muscle strength, altered running kinematics or variability. There is a need for future studies to examine the complete time course of recovery from a fatigue inducing training run with a focus on the few runners that had not recovered at 24-h post.

Conclusion

The HIIT session induced impairments to both central and peripheral drive in the majority of runners immediately post session, with more runners showing decrements in central drive. Most runners were able to recover within 24-h post and therefore would presumably be able to train again with no discernible increase in injury risk. By contrast, a small number of runners experienced decrements in neuromuscular function and muscle strength, along with altered kinematics and coordination variability that persisted at 24-h post. These runners therefore showed limited signs of recovery and did not return to a stable running gait. The lack of recovery prior to the subsequent running session likely placed these runners at an elevated risk of RROI development. Finally, this chapter suggests that increased coordination variability can be used as a tool for the detection of fatigue.

CHAPTER 8 GENREAL DISCUSSION

8.1 Introduction

The main aim of this thesis was to examine changes in running related overuse injury risk factors following typical training runs through examining the risk factors of loss in muscular strength, altered frontal plane hip kinematics and running variability. This thesis was the first to examine the effects of fatigue arising from a HIIT session and the recovery kinetics over the subsequent 24 hours.

Chapter 4 assessed the reliability of the tools and protocols used to examine the risk factors of running related overuse injury used in this thesis. In it, acceptable relative and absolute reliability were found for hip and knee strength, treadmill running kinematics and running coordination variability using dynamical system theory. Reliability was also established at multiple time points during the run and various speeds for kinematics and coordination variability applications, which were used in the subsequent chapters.

Previous studies have used a range of stride counts when investigating treadmill running kinematics with no identified guideline or gold standard for the required number of strides for data analysis. Chapter 5 examined the number of strides required to achieve stable kinematic values during treadmill running. The finding that a minimum of 20 strides would be required to achieve stable and reliable motion analysis during treadmill running provided a guideline for data analysis in kinematic assessment.

Chapter 6 examined whether there was a change to potential RROI risk factors during the two energy expenditure matched training runs. That study found fatigue to be present in both HIIT and MICR, with a greater incidence following HIIT. Fatigue was evident as there were reductions, above MDC, in the hip and knee muscle strength along with altered mechanics and joint coordination variability. The combination of effect size and individual assessment in chapter 6 indicated that the changes were greater, and therefore posed a greater risk of injury development post HIIT than MICR. HIIT became the sole focus of the subsequent

study where it was fatigue induced changes would only constitute an increased risk of RROI if they were still present at the start of the next training session.

Chapter 7 therefore examined the time-course of recovery from the fatigue effects observed in chapter 6 to see if the gait related changes were still present 24-h post HIIT. Both chapters 6 and 7 observed consistent findings immediately post HIIT, confirming the pattern of reduced hip muscular strength and increased hip adduction angles and running variability. Chapter 7 also included measures of neuromuscular function, through electrical stimulation, to try and provide a more mechanistic explanation. The neuromuscular function measurements showed that several runners experienced both central and peripheral impairments following HIIT. Impairments to neuromuscular function were observed immediately post HIIT. Arguably, the most novel finding of Chapter 7 was the lack of recovery 24 hours after the HIIT session in some runners. The inability to recover from decrements to neuromuscular function, global fatigue, and altered mechanics provided support for the assertion that some runners are at an increased risk of developing an overuse injury following a HIIT session.

8.2 Aetiology of RROI

Recently Bertelsen *et al.* (2017) proposed a framework providing a possible sequence of events leading to the development of RROI. The central tenet of their model is the inability of specific structures to tolerate the cumulative load experienced during a training session and that overuse injuries occur when the cumulative load exceeds the tolerance capacity of specific tissues. They outlined that the cumulative load during a run, determined by the magnitude of the load experienced per stride, distributed over tissue structures per stride and multiplied by the cumulative stride count, progressively reduces the ability of the tissue to tolerate further loading. Hrlejac (2004) purposed a similar, more simplistic model but

suggested biomechanical factors have a large role in RROI development. Changes in mechanics could alter which tissues, or the specific location within them, that absorbs the load or the magnitude of the load experienced, both potentially increasing the cumulative load and likelihood of developing a RROI.

Bertelsen's model provides a strong framework, however it lacks explanatory power on the possible outcomes after a runner exceeds the specific tissue load capacity. This thesis had several novel findings that addressed this. On the basis of these findings a new framework outlining a pathway of development in RROIs is proposed (Figure 8-1). The findings of chapter 6 and 7 observed mechanisms of peripheral and central fatigue that contributed to the alterations in running gait. Based on the findings of this thesis, a new model, which is an extension of Bertelsen's, (2017) is proposed. This new model eliminates the gap between the loss of structure specific load tolerance and accumulated load with the occurrence of injury (Figure 8.1, section 3). The model is split into three sections, each section (presented below) is affected by mechanisms that contribute to the chain of events potentially leading to the development of RROI. Outside of the three sections, the framework also incorporates components of recovery and RROI risk status.

Below, sections 1-3 from Figure 8.1 are detailed in turn.

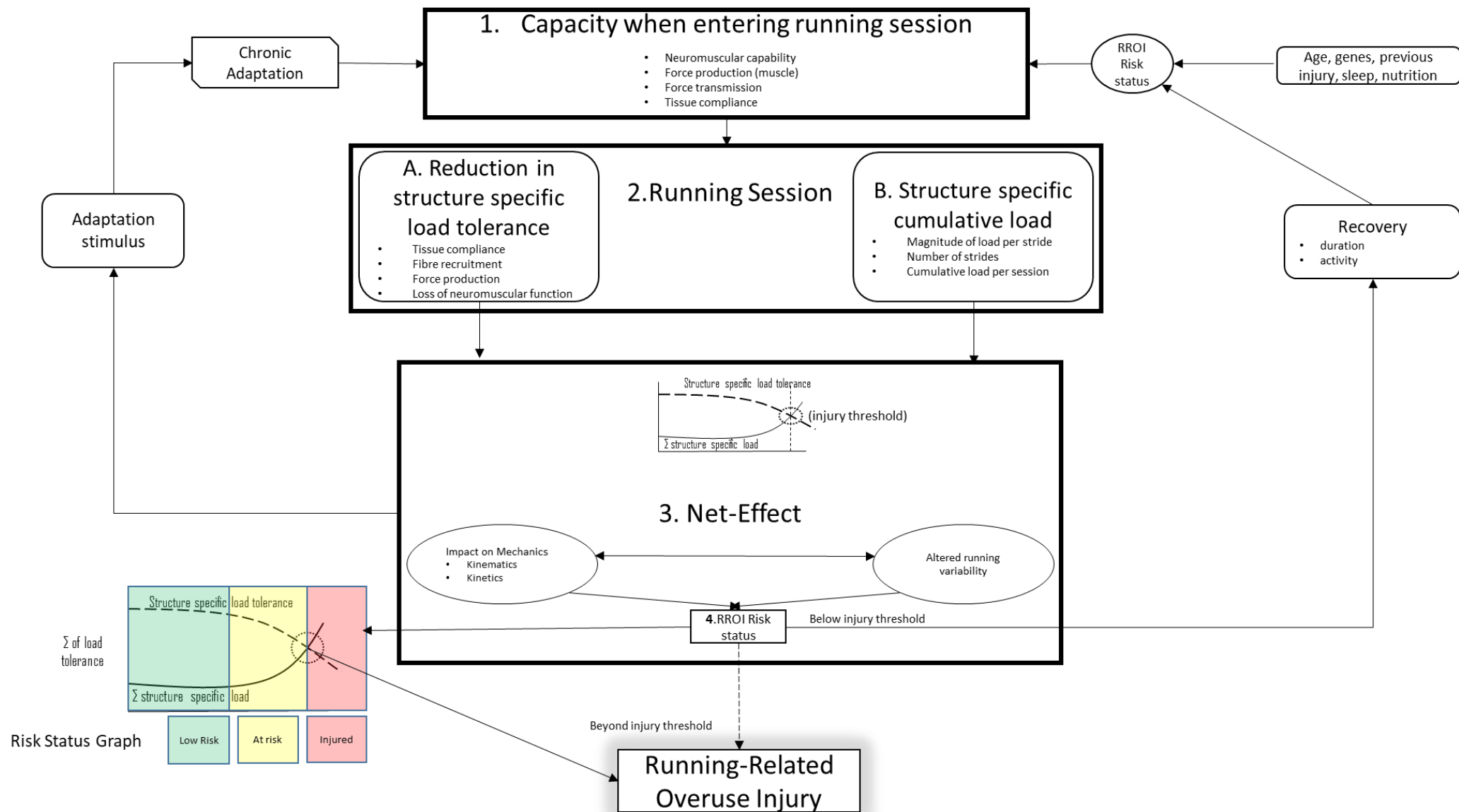


Figure 8.1. Schematic outlining pathway to Running Related Overuse Injury

Capacity when entering a running session.

The first section of the model is the initial status of a runner at the start of a given training session. The model presented in this thesis outlines that load tolerance capacity is determined by factors that are either transient, modifiable or fixed. Fixed factors include genetics and age, along with other transient factors that can be altered both acutely, by lifestyle (sleep, nutrition, recovery); and finally, previous injury. These transient factors were not examined in this thesis. The model however outlines that the initial capacity of a runner is influenced by neuromuscular capability, muscle strength, force transmission and tissue compliance. The focus for this thesis was placed on strength of the hip and knee musculature along with neuromuscular capability of the knee extensors following a running session as the likely means of controlling gait mechanics and variability. The proceeding section is the running session itself.

Running session

This section is addressing the running session and is split into two parts: a) reduction in musculoskeletal system ability to produce force; b) cumulative load experienced in a run.

Section A

Of the factors that make up load tolerance, this thesis was able to examine muscular strength and neuromuscular function. Previous studies have hypothesised that a reduction in the strength of the muscles that control movement at the hip and knee joints alters running mechanics (Powers, 2010; Willwacher *et al.* 2020). Prior to this thesis no work had been done to examine strength pre and post a typical running session. This thesis is the first to i) report reduced strength in the muscles controlling the hip and knee joints immediately after a medium intensity continuous run

and high intensity interval training, rather than a prolonged run to exhaustion ii) examine recovery from the training runs.

Both group and individual assessment showed a reduction in strength of hip and knee musculature after MICR and HIIT. The reduction in hip and knee musculature strength along with the loss of neuromuscular function following a typical training run may be suggestive of an inability to tolerate load.

As fatigue accumulated, the muscles were unable to produce the same force as at the start. In chapter 7, the HIIT induced failures at both central nervous system and contractile function level, contributing to the drop in MVC. The increase in variability at the end of the HIIT alongside reduced strength, provided further evidence of neural and peripheral impairments. Coordination patterns between the hip and knee experienced instability due to the musculature being under stress. The increase in coordination variability could then be an indicator of a distribution of stress across the muscle tissue to alleviate the strain. The decrement in voluntary activation in chapter 7 provided evidence that there is a reduction in recruitment of motor neurons for the knee extensors, this then may require aid from the surrounding structures of the muscle to compensate for the loss in order to maintain performance. This however is not well understood as to whether the distribution of stress is to increase strain on ligaments or surrounding muscles that provide the same movement. The lack of understanding regarding the distribution of tissue stress as fatigue accumulates is part of the complexities of the aetiology of RROI.

In chapter 6, runners experienced fatigue following both HIIT and MICR identified through a loss of hip muscle strength during hip abduction. Reduced muscle strength has been identified as the primary mechanism that contributes to altered gait in injured runners. This thesis was able to show that in healthy runners, a similar pattern exists i.e. increased maximum hip adduction angle

when fatigued. These findings provide support for studies that have suggested the link between muscle strength and gait, this endorses the incorporation of section 2A of the model. To increase ecological validity, the runs used in this thesis were more in line with the common practices of recreational runners rather than a run to exhaustion.

Section B

Chapter 6 reported an estimation of the total number of strides performed during the HIIT (1782) and MICR (2279). More runners however, experienced fatigue effects in kinematics and coordination variability following the HIIT session. While kinetics were not examined in this thesis, faster running speeds require increased force production (Kyröläinen *et al.* 1999). To achieve faster running, runners increase extremity velocity prior to foot contact, runners also elevate collisional impulse and total amount of forces applied to the ground (Clark *et al.* 2014). This suggests that the runners likely experienced higher rates of loading during HIIT. Joint loading and forces have been identified to play a key role in a chain of events that contribute to the development of PFP (Powers *et al.* 2017). Part B of section 2 was not examined within this thesis and requires further investigation.

Net-Effects

This section of the framework addressed the gap in Bertelsen *et al.*'s (2017) model between the occurrence of injury and a reduced ability to tolerate load during a running session. Bertelsen *et al.* (2017) did not identify how a reduced tolerance to load could lead to injury. The core findings of this thesis have resulted in the insertion of the net-effects component of the model based on the effects on gait from the fatigue experienced during the training runs.

At the end of the run, the decrements in muscle strength and neuromuscular function of the runners were manifest as changes to gait, or a net-effect. By the end of the running session, in study 7, 75% of the runners exhibited impaired voluntary activation and all of those runners experienced an alteration in at least one kinematic variable. All of the runners that exhibited a loss of hip abduction strength also experienced increased RoM or maximum angle during hip abduction. The observed alterations in hip abduction were in line with gait signatures of runners presenting symptoms of overuse running injuries such as PFP and ITBS. Previous studies have suggested that increased hip adduction angle may occur when the gluteus medius muscle, the primary hip abductor, is fatigued or showing signs of dysfunction. (Powers, 2010; Noehren *et al.* 2007). This thesis also identified a potential loss of motor control due to an inability to maintain muscle strength and /or the loss of central drive. Both chapters 6 and 7 observed an increased variability of coordination between the hip and knee at the end of a typical training run. The observed changes potentially place a runner at an increased risk of RROI development.

To address the multifactorial nature of RROI, measures of coordination variability via CRPV and CAV were included. Coordination variability provided a more detailed understanding of the fatigue effects during a run. In both chapters 6 and 7, runners experienced increased coordination variability in conjunction with altered kinematics.

For the majority of runners there was a loss of motor control as result of either fatigue within the central nervous system or an inability of fatigued muscles, at the hip and knee, to produce force and control movement. The runners likely needed to recruit more coordination patterns as a mechanism to prevent injury (Bartlett *et al.* 2007) signalled by the increase in variability. This increase in coordination variability could indicate that the tolerance to load is near its capacity, and this was an attempt to ease the stress on the structures to prevent exceeding of load capacity (Bartlett *et al.* 2007). Potentially, this is an important mechanisms of injury prevention during

SSC activities, where structures experience impact forces with each ground contact (Nicol and Komi, 2010). Neither these ground reaction forces, or their cumulative effect, were examined within this thesis but warrant further investigation. The resultant net-effects on the tissues ability to tolerate load, could push the runners to a point where injury occurs. Where injury does not occur, if the runner has had insufficient recovery, they will start of the next training session with a reduced capacity to load tolerance and therefore increased risk of injury. In the runners that still exhibited signs of fatigue 24 hours after the HIIT, the level of risk of injury is higher than those that had recovered.

Risk Status and Recovery

Risk status changes as the runner recovers. It is therefore presented twice within the model; firstly, immediately after the session, at the point of greatest fatigue and then later, immediately prior to the next run, when the athlete would be at their most recovered. A runner is at risk of a RROI at any given time, the level of risk however is determined on how close the runners is to exceeding the threshold of summation of load tolerance. If the damage brought on by exceeding tissue load tolerance is unrepaired prior to the next session, the runner is unlikely to perform the run due to occurrence of injury. The severity of the potential injury risk is indicated in the risk status graph by the associated colour and based on the magnitude of net-effects during or following the training run and recovery. Some of the runners in studies 6 and 7 exhibited changes in kinematics and reduced muscle strength. Study 7 showed that some runners had limited recovery following the HIIT session and were the still at an elevated risk when they started the run at 24-h. These runners were identified to have the biggest risk following a training run.

The question of recovery from a HIIT had not been previously addressed. While there is no systematic attempt being made to document the aetiology of recovery in the literature (Carroll *et al.* 2017), the findings of this thesis show that the impairments in central nervous system and running mechanics can persist for 24-h following a HIIT. The evoked electrical stimulation showed that muscular mechanical properties remained impaired the following day in several runners. In turn, this can lower the capacity to tolerate load where some runners that exhibited impaired central drive at 24-h post, still exhibited altered mechanics and increased variability. Insufficient recovery can contribute to a gradual reduction in the capacity of various tissues to tolerate load (Bertelsen *et al.* 2017). The runners could become increasingly susceptible to being pushed beyond the threshold where the accumulated load and load tolerance meet. This assessment is in line with Hrlejac's (2005) hypothesis, linking the capacity to tolerate load with injury. The lack of recovery from the impaired neuromuscular function and subsequent altered running mechanics prior to the next session observed in chapter 7, suggests a lower initial capacity for the next run.

Finally, the use of this model is to not just to identify the pathway to injury but also show how to potentially reduce injury risk. Intervention studies strengthening hip musculature have produced outcomes that are beneficial to runners in minimising kinematic alterations and in turn pain in runners experiencing PFP (Ferber *et al.* 2011; Ramskov *et al.* 2015). Reducing the loss of muscle strength to combat the accumulated structure load during a running session may alleviate the net-effects and in turn stronger tissues (muscle and connective) for an increase in load tolerance. This element of the model can also be tested through acute intervention studies such as foam rolling. This area however requires much further investigation and should be a focus of future research.

8.3 Individual assessment

While not abandoning P value group assessments, it was the stance of this thesis to rely more on individual findings by way of using MDC to detect a ‘real change’ (Charter, 1996; Weir, 2005) and therefore a possible precursor of risk in injury development at an individual level. The application of MDC in studies 6 and 7 enabled the examination of individual change. The magnitude of the net-effects from the runs identified the risk of injury on the runners following the running sessions.

Group examination is unlikely to be a true reflection of how many runners are actually at risk of injury. Individual runners exhibit varying changes that make it difficult to group together. The implementation of individual assessment revealed that only a handful of runners exhibited a profile of injury risk, matching the review of epidemiology studies identifying 7.7 injuries every 1000 hours of running in recreational runners (Videbaek *et al.* 2015). This finding highlights the need to clearly identify the few runners who are at risk of injury. Using MDC allowed for a close examination of fatigue effects on each runner’s neuromuscular function, gait, and variability. In chapter 7, while the majority (15 out of 20) of runners exhibited decrements in central drive immediately post HIIT, not all exhibited the same gait changes and patterns of coordination variability. Similarly, runner’s recovery patterns showed considerable inter-individual variation, particularly with coordination variability. An interesting observation was the identification that three runners shifted from increased coordination variability post HIIT to decreased at 24-h post in at least one coupling interaction, with one of three exhibiting this pattern in two couplings. According to the model provided by Hamill *et al.* (2012), these runners can be identified as having the highest risk of injury as, they exhibit signs of injury development due to inability to match similar patterns of coordination as at the start of the previous session. Throughout this

thesis, it became evident that the risk of injury is individual and that not only did each runner differ in risk at the end of the session, but also with recovery pattern.

8.4 Limitations

Both Berthelsen *et al.* (2017) and Powers *et al.* (2017) identified that the load experienced per stride and the change in load, are part of a chain of events that contribute to RROI. The accumulated load per stride during a training session was highlighted in section 2B of the framework (Figure 8.1) as a reflection of the demands placed upon both the load bearing joints and active muscles. It was not possible to measure ground reaction force, joint moments, or the rate of loading, moreover the total number of strides was not recorded. In chapter 6 the two runs were considered to be metabolically equivalent, however it is unknown if they were mechanically equivalent. Further research is required to determine how to equate the accumulated load from ground reaction force, or rate of loading, for HIIT and MICR sessions. To be able to measure this during running without the need to cease running however, requires a force treadmill.

A limitation of the thesis was the lack of knowledge of the participants training programme. Knowing the training background of the runners would have enabled further insight into why some runners were placed at risk of potential injury development while others were not. In addition, knowing their training programme could have provided an insight into how often runners perform HIIT sessions and possible links with recovery kinetics i.e. do those who regularly perform HIIT recover faster?

8.5 Recommendations for future research

The validity of the proposed model can only be achieved by testing it; this can be done through a number of different studies detailed below:

- By examining cumulative load experienced in a run, box 2B, which was not examined in this thesis, can be addressed. Loading and stiffness during each stride and their cumulative totals that each runner experienced during the session, were identified as factors that would influence the ability to maintain a stable running style. In chapter 6, it was observed that fatigue was more prevalent following HIIT, however it was estimated that runners performed fewer strides in comparison to MICR. The ability to measure load tolerance is central to the model. To measure load tolerance requires new approaches to find a valid and acceptable measurement tool. Muscle stiffness could be a potential measure of load tolerance but this needs to be investigated.
- The measurement of EMG activity during a typical training run in healthy runners could provide further information on section 2A. The ability to identify the activity of gluteus medius and surrounding muscles with the progression of fatigue would provide further information on possible muscle recruitment patterns and the distribution of stress strategies during a run. Furthermore, changes in EMG activity with fatigue could be correlated with the changes in muscle strength.
- Athletes use a variety of acute interventions such as stretching and foam rolling to enhance recovery. Their use immediately post training run would allow further assessment of the recovery path within the model. There is however no consensus on benefits of applying foam rolling to enhance recovery where only a few studies have

looked at its effectiveness (Wiewelhove *et al.* 2019). While the prescription of stretching has also gone under criticism (Sands *et al.* 2013), its use has been suggested as a method to enhance recovery from exercise induced muscle damage (Howatson and Van Someren, 2008) and is widely practised by runners. The model presented in this thesis provides an opportunity to examine their effectiveness on acute recovery when examined with proper management and prescription.

- Similarly, chronic intervention studies such as strength training can also be viewed as a method for prevention of RROI incidence while also providing more insight in the role of neuromuscular capability during a running session, section 2 of the model. In chapter 7, when fatigued, 75% of the runners exhibited impaired neuromuscular function and altered gait signature. While all had some form of altered kinematics due to fatigue, post HIIT 55% of the runners exhibited a gait that was similar those of PFP and ITBS runners. Strength training has shown to improve neuromuscular capability by delaying fatigue (Damasceno *et al.* 2015; Paavolainen *et al.* 1999) and therefore may lessen the impact on mechanical changes observed in this thesis.
- The effect of fatigue accumulated during a run on patellofemoral joint stress has yet to be examined. This would provide a greater mechanistic understanding of the aetiology of PFP and possible prevention strategies. This knowledge would also add to the net-effects section of the model. The fatigue induced changes to hip adduction and knee flexion angles in some runners suggests a possible decrease in the contact area between patella and trochlear groove of the patella giving way to elevated patellofemoral joint stress (Almonroeder and Benson, 2016).

- To strengthen the findings of this thesis, the runners that participated in studies 6 and 7, that were identified to be at risk of injury, could have been tracked for a period of time to assess if these runners experienced injury or not. A prospective study could be undertaken tracking all runners to see if there is a link between either the extent of fatigue or ability to recover and incidence of injury. Noehren *et al.* (2013) performed a similar study where they followed runners for a two year period and found that the runners that exhibited greater hip adduction angle were more likely to develop PFP.
- Finally, the majority of runners perform sessions outdoors and to be able to examine gait in this environment would be more ecologically valid. The use of accelerometry and inertial measurement units could enable the detection of changes in gait during running (Lee *et al.* 2010; Sheerin *et al.* 2019; Wundersitz *et al.* 2015, 2013). Wearable technologies could offer valuable information from outside of a lab. This approach can offer longitudinal tracking of kinematic and kinetic data (Mundt *et al.* 2020). In addition, accelerometers facilitate the use of larger sample sizes and track multiple runners at the same time and for longer duration. Their use can aide real time tracking throughout a training session or race to discern the point in time which fatigue begins to develop and is altering change in gait.

8.6 Conclusion

The main finding from this thesis was the concurrent mechanical changes and loss of strength along with time course of recovery from these changes following typical training run, placing runners at potential risk of RROI development. This thesis was able to demonstrate between-day reliability for hip and knee muscular strength, kinematics and coordination variability. Using

different statistical approaches, group *P* value examination and individual examination through minimum detectable change, this thesis reported fatigue induced changes to kinematics and coordination variability following two energy expenditure matched training runs. Healthy runners gait became akin to gait signatures commonly observed with PFP and ITBS runners. Lastly, while employing a similar statistical approach this thesis was the first to investigate the time course of recovery following a HIIT session. Recovery from fatigue induced changes to muscle strength and gait were examined alongside the presence of central and peripheral fatigue via evoked electrical stimulation. Using a different statistical approach, there were decrements in central and peripheral drive post HIIT, the fatigue also induced changes in gait. At 24-h, most runners had recovered, however a few still displayed impairments to central and peripheral drive along with gait changes matching the signatures of PFP and ITBS runners. Based on the findings, a new framework for the aetiology of running related overuse injuries was proposed. This framework outlined the progression of events that could lead to the development of running related overuse injuries.

REFERENCES

- 2019 Running USA U.S. Running Trends Report [WWW Document], n.d. URL https://runningusa.org/RUSA/News/2019/Running_USA_Releases_2019_U.S._Running_Trends_Report.aspx (accessed 11.9.19).
- Abt, J.P., Sell, T.C., Chu, Y., Lovalekar, M., Burdett, R.G., Lephart, S.M., 2011. Running kinematics and shock absorption do not change after brief exhaustive running. *J. Strength Cond. Res.* 25, 1479–1485.
- Allen, D.G., Lamb, G.D., Westerblad, H., 2008. Skeletal muscle fatigue: Cellular mechanisms. *Physiol. Rev.* 88, 287–332.
- Almonroeder, T.G., Benson, L.C., 2016. Sex differences in lower extremity kinematics and patellofemoral kinetics during running. *J Sport. Sci* 1–7.
- Amann, M., Dempsey, J.A., 2008. Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *J. Physiol.* 586, 161–173.
- Amann, M., Venturelli, M., Ives, S.J., McDaniel, J., Layec, G., Rossman, M.J., Richardson, R.S., 2013. Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *J. Appl. Physiol.* 115, 355–364.
- Anderson, T., 1996. Biomechanics and running economy. *Sport. Med.*
- Arnold, C.M., Warkentin, K.D., Chilibeck, P.D., Magnus, C.R.A., 2010. The Reliability and Validity of Handheld Dynamometry for the Measurement of Lower-Extremity Muscle Strength in Older Adults. *J. Strength Cond. Res.* 24, 815–824.
- Asmussen, E., 1979. Muscle Fatigue. *Med. Sci. Sports Exerc.* 11, 313–321.
- Avela, J., 1996. Effects of differently induced stretch loads on neuromuscular control in drop jump exercise. *Eur. J. Appl. Physiol. Occup. Physiol.* 72, 553–562.
- Avela, J., Kyröläinen, H., Komi, P. V., Rama, D., 1999. Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. *J. Appl. Physiol.* 86, 1292–1300.
- Bacon, A.P., Carter, R.E., Ogle, E.A., Joyner, M.J., 2013. VO₂max Trainability and High Intensity Interval Training in Humans: A Meta-Analysis. *PLoS One* 8.
- Baker, R., 2007. The history of gait analysis before the advent of modern computers. *Gait Posture* 26, 331–342.
- Baltzopoulos, V., Williams, J.G., Brodie, D.A., 1991. Sources of error in isokinetic dynamometry: Effects of visual feedback on maximum torque measurements. *J. Orthop. Sports Phys. Ther.* 13, 138–142.
- Bartlett, R., 2004. Is Movement Variability Important for Sports Biomechanists? In: Paper Presented at the International Society of Biomechanics in Sports Conference, Ottawa, Canada. pp. 521–524.
- Bartlett, R., Wheat, J., Robins, M., 2007. Is movement variability important for sports

- biomechanists? *Sport. Biomech* 6, 224–243.
- Bassett, David R., Howley, E.T., 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med. Sci. Sports Exerc.* 32, 70–84.
- Bates, B.T., Osternig, L.R., Sawhill, J.A., James, S.L., 1983. An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. *J. Biomech.* 16, 181–191.
- Batschelet, E., 1981. Circular statistics in biology BT - Mathematics in biology. Academic Press, London.
- Bazett-Jones, D.M., Cobb, S.C., Huddleston, W.E., O'Connor, K.M., Armstrong, B.S., Earl-Boehm, J.E., 2013. Effect of patellofemoral pain on strength and mechanics after an exhaustive run. *Med Sci Sport. Exerc* 45, 1331–1339.
- Bazett-Jones, D.M., Cobb, S.C., Joshi, M.N., Cashin, S.E., Earl, J.E., 2011. Normalizing hip muscle strength: Establishing body-size-independent measurements. *Arch. Phys. Med. Rehabil.* 92, 76–82.
- Bernstein N, 1967. The co-ordination and regulation of movements. Co-ord. Regul. movements.
- Bertelsen, M.L., Hulme, A., Petersen, J., Brund, R.K., Sørensen, H., Finch, C.F., Parner, E.T., Nielsen, R.O., 2017. A framework for the etiology of running-related injuries. *Scand. J. Med. Sci. Sport.*
- Bigland-Ritchie, B., Woods, J.J., 1984. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve* 7, 691–699.
- Billat, V.L., Flechet, B., Petit, B., Muriaux, G., Koralsztejn, J.P., 1999. Interval training at $\dot{V}O_{2max}$: Effects on aerobic performance and overtraining markers. *Med. Sci. Sports Exerc.* 31, 156–163.
- Birnbaum, K., Siebert, C.H., Pandorf, T., Schopphoff, E., Prescher, A., Niethard, F.U., 2004. Anatomical and biomechanical investigations of the iliotibial tract. *Surg. Radiol. Anat.* 26, 433–446.
- Blain, G.M., Mangum, T.S., Sidhu, S.K., Weavil, J.C., Hureau, T.J., Jessop, J.E., Bledsoe, A.D., Richardson, R.S., Amann, M., 2016. Group III/IV muscle afferents limit the intramuscular metabolic perturbation during whole body exercise in humans. *J. Physiol.* 594, 5303–5315.
- Bosco, C., Montanari, G., Ribacchi, R., Giovenali, P., Latteri, F., Iachelli, G., Faina, M., Colli, R., Dal Monte, A., La Rosa, M., Cortili, G., Saibene, F., 1987. Relationship between the efficiency of muscular work during jumping and the energetics of running. *Eur. J. Appl. Physiol. Occup. Physiol.* 56, 138–143.
- Brown, A M, Zifchock, R.A., Hillstrom, H.J., 2014. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture* 39, 915–919.
- Brown, A M, Zifchock, R.A., Hillstrom, H.J., Song, J., Tucker, C.A., 2016. The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clin. Biomech.* 39, 84–90.
- Brownstein, C.G., Dent, J.P., Parker, P., Hicks, K.M., Howatson, G., Goodall, S., Thomas, K., 2017. Etiology and recovery of neuromuscular fatigue following competitive soccer match-

- play. *Front. Physiol.* 8.
- Buist, I., Bredeweg, S.W., Lemmink, K., van Mechelen, W., Diercks, R.L., 2010. Predictors of Running-Related Injuries in Novice Runners Enrolled in a Systematic Training Program A Prospective Cohort Study. *Am. J. Sports Med.* 38, 273–280.
- Buist, I., Bredeweg, S.W., van Mechelen, W., Lemmink, K.A.P.M., Pepping, G.-J., Diercks, R.L., 2008. No Effect of a Graded Training Program on the Number of Running-Related Injuries in Novice Runners: A Randomized Controlled Trial. *Am. J. Sports Med.* 36, 33–39.
- Burnley, M., Jones, A.M., 2016. Power–duration relationship: Physiology, fatigue, and the limits of human performance. *Eur. J. Sport Sci.* 18, 1–12.
- Butler, R.J., Crowell, H.P., Davis, I.M.C., 2003. Lower extremity stiffness: Implications for performance and injury. *Clin. Biomech.* 18, 511–517.
- Cady, E.B., Jones, D.A., Lynn, J., Newham, D.J., 1989. Changes in force and intracellular metabolites during fatigue of human skeletal muscle. *J. Physiol.* 418, 311–325.
- Carroll, T.J., Taylor, J.L., Gandevia, S.C., 2017. Recovery of central and peripheral neuromuscular fatigue after exercise. *J. Appl. Physiol.*
- Cavagna, G.A., Saibene, F.P., Margaria, R., 1965. Effect of negative work on the amount of positive work performed by an isolated muscle. *J. Appl. Physiol.* 20, 157–158.
- Cavanagh, P.R., Lafortune, M.A., 1980. REACTION FORCES IN DISTANCE RUNNING *. *J. Biomech.* 13, 397–406.
- Cavanagh, P.R., Williams, K.R., 1982. The effect of stride length variation on oxygen uptake during distance running. *Med. Sci. Sports Exerc.* 14, 30–35.
- Chamorro, C., Armijo-Olivo, S., De la Fuente, C., Fuentes, J., Javier Chiroso, L., 2017. Absolute Reliability and Concurrent Validity of Hand Held Dynamometry and Isokinetic Dynamometry in the Hip, Knee and Ankle Joint: Systematic Review and Meta-analysis. *Open Med.* 12, 359–375.
- Chang, R., Emmerik, R. Van, Hamill, J., 2008. Quantifying rearfoot – forefoot coordination in human walking 41, 3101–3105.
- Chapman, R.F., Laymon, A.S., Wilhite, D.P., McKenzie, J.M., Tanner, D.A., Stager, J.M., 2012. Ground contact time as an indicator of metabolic cost in elite distance runners. *Med. Sci. Sports Exerc.* 44, 917–925.
- Charter, R.A., 1996. Revisiting the Standard Errors of Measurement, Estimate, and Prediction and Their Application to Test Scores. *Percept. Mot. Skills* 82, 1139–1144.
- Chumanov, E.S., Schache, A.G., Heiderscheit, B.C., Thelen, D.G., 2012. Hamstrings are most susceptible to injury during the late swing phase of sprinting. *Br J Sport. Med* 46, 90.
- Clansey, A.C., Hanlon, M., Wallace, E.S., Lake, M.J., 2012. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med. Sci. Sports Exerc.* 44, 1917–1923.
- Cohen, J., n.d. *Statistical Power Analysis For The Behavioral Sciences* By Jacob Cohen.
- Coupland, M.E., Puchert, E., Ranatunga, K.W., 2001. Temperature dependance of active tension

- in mammalian (rabbit psoas) muscle fibres: Effect of inorganic phosphate. *J. Physiol.* 536, 879–891.
- Crowell, H.P., Davis, I.S., 2011. Gait retraining to reduce lower extremity loading in runners. *Clin. Biomech.* 26, 78–83.
- Cunningham, T.J., Mullineaux, D.R., Noehren, B., Shapiro, R., Uhl, T.L., 2014. Coupling angle variability in healthy and patellofemoral pain runners. *Clin. Biomech.* 29, 317–322.
- Damasceno, M. V., Lima-Silva, A.E., Pasqua, L.A., Tricoli, V., Duarte, M., Bishop, D.J., Bertuzzi, R., 2015. Effects of resistance training on neuromuscular characteristics and pacing during 10-km running time trial. *Eur. J. Appl. Physiol.* 115, 1513–1522.
- Davids, K., Glazier, P., Araújo, D., Bartlett, R., 2003. Movement Systems as Dynamical Systems. *Sport. Med.* 33, 245–260.
- Davies, C.T., White, M.J., 1982. Muscle weakness following dynamic exercise in humans. *J. Appl. Physiol.* 53, 236–41.
- Davis, R.B., Öunpuu, S., Tyburski, D., Gage, J.R., 1991. A gait analysis data collection and reduction technique. *Hum. Mov. Sci.* 10, 575–587.
- Derrick, T., Dereu, D., McLean, S., 2002. Impacts and kinematic adjustments during an exhaustive run.
- Derrick, T.R., Dereu, D., Mclean, S.P., 2002. Impacts and kinematic adjustments during an exhaustive run. *Med. Sci. Sport. Exerc* 34, 998–1002.
- Derrick, T.R., Hamill, J., Caldwell, G.E., 1998. Energy absorption of impacts during running at various stride lengths. *Med. Sci. Sports Exerc.* 30, 128–135.
- di Prampero, P.E., 2003. Factors limiting maximal performance in humans. *Eur. J. Appl. Physiol.*
- Diedrich, F.J., Warren, W.H., 1995. Why change gaits? Dynamics of the walkun transition. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 183–202.
- Dierks, T.A., Davis, I., 2007. Discrete and continuous joint coupling relationships in uninjured recreational runners. *Clin. Biomech.* 22, 581–591.
- Dierks, Tracy A., Davis, I.S., Hamill, J., 2010. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J. Biomech.* 43, 2993–2998.
- Dierks, T.A., Manal, K.T., Hamill, J., Davis, I., 2011. Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Med. Sci. Sports Exerc.* 43, 693–700.
- Dierks, T.A., Manal, K.T., Hamill, J., Davis, I.S., 2008. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J. Orthop. Sport. Phys. Ther.* 38, 448–456.
- Dorn, T.W., Schache, A.G., Pandy, M.G., 2012. Muscular strategy shift in human running: Dependence of running speed on hip and ankle muscle performance. *J. Exp. Biol.* 215, 1944–1956.
- Dostal, W.F., Soderberg, G.L., Andrews, J.G., 1986. Actions of Hip Muscles. *Phys. Ther.* 66, 351–359.

- Dugan, S.A., Bhat, K.P., 2005. Biomechanics and analysis of running gait. *Phys. Med. Rehabil. Clin. N. Am.* 16, 603–621.
- Edwards, W.B., Derrick, T.R., Hamill, J., 2012. Musculoskeletal attenuation of impact shock in response to knee angle manipulation. *J. Appl. Biomech.* 28, 502–510.
- Enoksen, E., Tjelta, A.R., Tjelta, L.I., 2011. Distribution of training volume and intensity of elite male and female track and marathon runners. *Int. J. Sport. Sci. Coach.* 6, 273–293.
- Esculier, J.-F., Roy, J.-S., Bouyer, L.J., 2015. Lower limb control and strength in runners with and without patellofemoral pain syndrome. *Gait Posture* 41, 813–819.
- Esculier, J.F., Roy, J.S., Bouyer, L.J., 2015. Lower limb control and strength in runners with and without patellofemoral pain syndrome. *Gait Posture* 41, 813–819.
- Ferber, R., Davis, I., S Williams, D., Laughton, C., 2002. A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners.
- Ferber, R., Davis, I.M., Williams, D.S., 2005. Effect of foot orthotics on rearfoot and tibia joint coupling patterns and variability. *J. Biomech.* 38, 477–483.
- Ferber, Reed, Kendall, K.D., Farr, L., 2011. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. *J. Athl. Train.* 46, 142–149.
- Fitch, H.L., Tuller, B., Turvey, M.T., 1982. The Bernstein perspective: III. Tuning of coordinative structures with special reference to perception. In: Kelso, J.A.S. (Ed.), *Human Motor Behavior: An Introduction*. Lawrence Erlbaum Associates, Hillsdale, NJ., pp. 271–287.
- Flack, N.A.M.S., Nicholson, H.D., Woodley, S.J., 2014. The anatomy of the hip abductor muscles. *Clin. Anat.* 27, 241–253.
- Flanagan, E.P., Comyns, T.M., 2008. The Use of Contact Time and the Reactive Strength Index to Optimize Fast Stretch-Shortening Cycle Training. *Strength Cond. J.* 30, 32–38.
- Ford, K.R., Taylor-Haas, J.A., Genthe, K., Hugentobler, J., 2013. Relationship between Hip Strength and Trunk Motion in College Cross-Country Runners. *Med. Sci. Sports Exerc.* 45, 1125–1130.
- Fredericson, M., Cookingham, C.L., Chaudhari, a M., Dowdell, B.C., Oestreicher, N., Sahrmann, S. a, 2000. Hip abductor weakness in distance runners with iliotibial band syndrome. *Clin. J. Sport Med.* 10, 169–175.
- Froyd, C., Millet, G.Y., Noakes, T.D., 2013. The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *J. Physiol.* 591, 1339–1346.
- Fuchs, A., Jirsa, V.K., Haken, H., Kelso, J.A., 1996. Extending the HKB model of coordinated movement to oscillators with different eigenfrequencies. *Biol. Cybern.* 74, 21–30.
- Fulkerson, J.P., 2002. Current concepts. Diagnosis and treatment of patients with patellofemoral pain. *Am. J. Sports Med.* 30, 447–456.
- Gandevia, S.C., 2001. Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.*
- Garland, S.J., Kaufman, M.P., 1995. Role of muscle afferents in the inhibition of motoneurons

- during fatigue. *Adv. Exp. Med. Biol.*
- Gazeau, F., Koralsztein, J.P., Billat, V., 1997. Biomechanical events in the time to exhaust-
ArchPhysBiochem.pdf. *Arch. Physiol. Biochem.*
- Gent, R.N. Van, Siem, D., Middelkoop, M. Van, Os, A.G. Van, Koes, B.W., 2007. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br. J. Sports Med.* 469–480.
- Gerlach, K.E., White, S.C., Burton, H.W., Dorn, J.M., Leddy, J.J., Horvath, P.J., 2005. Kinetic changes with fatigue and relationship to injury in female runners. *Med. Sci. Sports Exerc.* 37, 657–663.
- Goodall, S., Charlton, K., Howatson, G., Thomas, K., 2014. Neuromuscular fatigability during repeated-sprint exercise in male athletes. *Med. Sci. Sports Exerc.* 47, 528–536.
- Greenland, S., Senn, S.J., Rothman, K.J., Carlin, J.B., Poole, C., Goodman, S.N., Altman, D.G., 2016. Statistical tests, P values, confidence intervals, and power: a guide to misinterpretations. *Eur. J. Epidemiol.* 31, 337–350.
- Hamill, J., Derrick, T.R., Holt, K.G., 1995. Shock attenuation and stride frequency during running. *Hum. Mov. Sci.* 14, 45–60.
- Hamill, J., Haddad, J.M., McDermott, W.J., 2000. Issues in quantifying variability from a dynamical systems perspective. In: *Journal of Applied Biomechanics*. Human Kinetics Publishers Inc., pp. 407–418.
- Hamill, J., McNiven, S.L., 1990. Reliability of selected ground reaction force parameters during walking. *Hum. Mov. Sci.* 9, 117–131.
- Hamill, J., Palmer, C., Van Emmerik, R.E.A., 2012. Coordinative variability and overuse injury. *Sport. Med. Arthrosc. Rehabil. Ther. Technol.* SMARTT 4, 45.
- Hamill, J., van Emmerik, R.E.A., Heiderscheit, B.C., Li, L., 1999. A dynamical systems approach to lower extremity running injuries. *Clin. Biomech.* 14, 297–308.
- Hanley, B., Mohan, A.K., 2014. Changes in gait during constant pace treadmill running. *J. Strength Cond. Res.* 28, 1219–1225.
- Hanley, B., Smith, L.C., Bissas, A., 2011. Kinematic variations due to changes in pace during men's and women's 5 km road running. *Int. J. Sports Sci. Coach.* 6, 243–252.
- Hanon, C., Thépaut-Mathieu, C., Vandewalle, H., 2005. Determination of muscular fatigue in elite runners. *Eur. J. Appl. Physiol.* 94, 118–125.
- Hasegawa, H., Yamauchi, T., Kraemew, W.J., 2007. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J. Strength Cond. Res.* 21, 888–893.
- Hawley, J., 2002. Adaptations to endurance training in muscle. *Clin. Exp. Pharmacol. Physiol.* 29, 218–222.
- Hayes, P., Caplan, N., 2012. Foot strike patterns and ground contact times during high-calibre middle-distance races. *J. Sports Sci.* 30, 1275–1283.
- Hayes, P.R., Caplan, N., 2014. Leg stiffness decreases during a run to exhaustion at the speed at [Formula: see text] O₂max. *Eur. J. Sport Sci.* 14, 556–62.

- Heglund, N.C., Cavagna, G.A., 1985. Efficiency of vertebrate locomotory muscles. *J. Exp. Biol.* VOL. 115, 283–292.
- Heiderscheit, B.C., 2000. Movement variability as a clinical measure for locomotion. In: *Journal of Applied Biomechanics*. Human Kinetics Publishers Inc., pp. 419–427.
- Heiderscheit, B.C., Hamill, J., van Emmerik, R.E.A., 2002. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *J. Appl. Biomech.* 18, 110–121.
- Hennessey, L., Kilty, J., 2001. Relationship of the Stretch-Shortening Cycle to Sprint Performance in Trained Female Athletes. *J. Strength Cond. Res.* 15, 326–331.
- Herrington, L., Law, J., 2012. The effect of hip adduction angle on patellar position measured using real time ultrasound scanning. *Knee* 19, 709–712.
- Hespanhol Junior, L.C., Mechelen, W., Postuma, E., Verhagen, E., 2016. Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study. *Scand. J. Med. Sci. Sports* 26, 1091–1099.
- Hespanhol Junior, L.C., Pena Costa, L.O., Lopes, A.D., 2013. Previous injuries and some training characteristics predict running-related injuries in recreational runners: A prospective cohort study. *J. Physiother.* 59, 263–269.
- Hodgson, M., Docherty, D., Robbins, D., 2005. Post-activation potentiation: Underlying physiology and implications for motor performance. *Sport. Med.* 35, 585–595.
- Horita, T., Komi, P. V, Nicol, C., Kyrolainen, H., 1996. Stretch shortening cycle fatigue: interactions among joint stiffness, reflex, and muscle mechanical performance in the drop jump [corrected][erratum appears in *Eur J Appl Physiol* 1996;74(6):575]. *Eur. J. Appl. Physiol. Occup. Physiol.* 73, 393–403.
- Howatson, G., Van Someren, K.A., 2008. The prevention and treatment of exercise-induced muscle damage. *Sport. Med.*
- Hreljac, A., 2005. Etiology, Prevention, and Early Intervention of Overuse Injuries in Runners: a Biomechanical Perspective. *Phys. Med. Rehabil. Clin. N. Am.* 16, 651–667.
- Huberti, H.H., Hayes, W.C., 1984. Patellofemoral Contact Pressures - The Influence of Q-angle and Tendofemoral Contact. *J. Bone Jt. Surgery-American Vol.* 66A, 715–724.
- Hulteen, R.M., Smith, J.J., Morgan, P.J., Barnett, L.M., Hallal, P.C., Colyvas, K., Lubans, D.R., 2017. Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis. *Prev. Med. (Baltim).*
- James, C.R., Herman, J.A., Dufek, J.S., Bates, B.T., 2007. Number of trials necessary to achieve performance stability of selected ground reaction force variables during landing 20, 126–134.
- James, D.V.B., Doust, J.H., 2000. Time to exhaustion during severe intensity running: response following a single bout of interval training. *Eur. J. Appl. Physiol.* 81, 337–345.
- Jones, A.M., 2006. The Physiology of the World Record Holder for the Women's Marathon. *Int. J. Sports Sci. Coach.* 1, 101–116.

- Jones, A.M., Carter, H., 2000. The effect of endurance training on parameters of aerobic fitness. *Sport. Med.* 29, 373–386.
- Jones, A.M., Doust, J.H., 1996. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J. Sports Sci.* 14, 321–327.
- Jordan, K., Challis, J., Newell, K., 2006. Long range correlations in the stride interval of running.
- Joyner, M.J., 1991. Modeling: Optimal marathon performance on the basis of physiological factors. *J. Appl. Physiol.* 70, 683–687.
- Joyner, M.J., Coyle, E.F., 2008. Endurance exercise performance: The physiology of champions. *J. Physiol.*
- Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., Gaine, J., Gorton, G., Cochran, G.V.B., 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J. Orthop. Res.* 7, 849–860.
- Katoh, M., Yamasaki, H., 2009. Comparison of Reliability of Isometric Leg Muscle Strength Measurements Made Using a Hand-Held Dynamometer with and without a Restraining Belt. *J. Phys. Ther. Sci.*
- Kellis, E., Liassou, C., 2009. The effect of selective muscle fatigue on sagittal lower limb kinematics and muscle activity during level running. *J. Orthop. Sports Phys. Ther.* 39, 210–20.
- Kelln, B.M., Mckee, P.O., Gontkof, L.M., Hertel, J., 2008. Hand-Held Dynamometry : Reliability of Lower Extremity Muscle Testing in Healthy , Physically Active , Young Adults. *J. Sport Rehabil.* 17, 160–170.
- Kelso, J.A.S., 1995. *Dynamic Patterns: The Self-Organization of Brain and Behavior (Complex Adaptive Systems)*.
- Kelso, S., 1984. Phase transitions and critical behavior in human bimanual coordination.
- Kelso, S., Buchanan, J., Wallace, S.A., 1991. Order parameters for the neural organization of single, multijoint limb movement patterns.
- Kelso, S., L. Southard, D., Goodman, D., 1979. On the coordination of two-handed movements.
- Koblbauer, I.F., Schooten, K.S. Van, Verhagen, E.A., Dieën, J.H. Van, 2013. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J. Sci. Med. Sport.*
- Komi, P.V., 1984. Physiological and Biomechanical Correlates of Muscle Function: Effects of muscle structure and stretch-shortening cycle on Force and Speed. *Exerc. Sport Sci. Rev.* 12, 81–122.
- Komi, P. V., 2000. Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. In: *Journal of Biomechanics*. Elsevier Science Ltd, pp. 1197–1206.
- Komi, P. V., 2003. Stretch-Shortening Cycle. In: *Strength and Power in Sport*. Blackwell Science Ltd, Oxford, UK, pp. 184–202.
- Koo, T.K., Li, M.Y., 2016. A Guideline of Selecting and Reporting Intraclass Correlation

- Coefficients for Reliability Research. *J. Chiropr. Med.* 15, 155–163.
- Kufel, T.J., Pineda, L.A., Jeffery Mador, M., 2002. Comparison of potentiated and unpotentiated twitches as an index of muscle fatigue. *Muscle and Nerve* 25, 438–444.
- Kuitunen, S., Avela, J., Kyöläinen, H., Komi, P. V., 2004. Voluntary activation and mechanical performance of human triceps surae muscle after exhaustive stretch-shortening cycle jumping exercise. *Eur. J. Appl. Physiol.* 91, 538–544.
- Kuitunen, S., Avela, J., Kyröläinen, H., Nicol, C., Komi, P. V., 2002. Acute and prolonged reduction in joint stiffness in humans after exhausting stretch-shortening cycle exercise. *Eur. J. Appl. Physiol.* 88, 107–116.
- Kurz, M.J., Stergiou, N., 2002. Effect of normalization and phase angle calculations on continuous relative phase. *J. Biomech.* 35, 369–74.
- Kyröläinen, H., Belli, A., Komi, P. V., 2001. Biomechanical factors affecting running economy. *Med. Sci. Sports Exerc.* 1330–1337.
- Kyröläinen, H., Komi, P. V., Belli, A., 1999. Changes in Muscle Activity Patterns and Kinetics With Increasing Running Speed, National Strength & Conditioning Association J. Strength Cond. Res.
- Lamb, P., Stöckl, M., 2014. On the use of continuous relative phase: Review of current approaches and outline for a new standard.
- Latash, M.L., Huang, X., 2015. Neural control of movement stability: Lessons from studies of neurological patients. *Neuroscience* 29–48.
- Lattier, G., Millet, G.Y., Martin, A., Martin, V., 2004. Fatigue and recovery after high-intensity exercise. Part II: Recovery interventions. *Int. J. Sports Med.* 25, 509–515.
- Laursen, P.B., 2010. Training for intense exercise performance: High-intensity or high-volume training? *Scand. J. Med. Sci. Sport.* 20, 1–10.
- Lee, J.B., Sutter, K.J., Askew, C.D., Burkett, B.J., 2010. Identifying symmetry in running gait using a single inertial sensor. *J. Sci. Med. Sport* 13, 559–563.
- Lepers, R., Pousson, M.L., Maffiuletti, N.A., Martin, A., Van Hoecke, J., 2000. The effects of a prolonged running exercise on strength characteristics. *Int. J. Sports Med.* 21, 275–280.
- Linton, L., Valentin, S., 2018. Running with injury: A study of UK novice and recreational runners and factors associated with running related injury. *J. Sci. Med. Sport.*
- Lu, T.W., Hsu, H.C., Chang, L.Y., Chen, H.L., 2007. Enhancing the examiner's resisting force improves the reliability of manual muscle strength measurements: Comparison of a new device with hand-held dynamometry. *J. Rehabil. Med.* 39, 679–684.
- Lun, V., Meeuwisse, W.H., Stergiou, P., Stefanyshyn, D., 2004. Relation between running injury and static lower limb alignment in recreational runners. *Br. J. Sports Med.* 38, 576–580.
- Lysholm, J., Wiklander, J., 1987. Injuries in runners. *Am. J. Sports Med.* 15, 168–171.
- Malisoux, L., Nielsen, R.O., Urhausen, A., Theisen, D., 2015. A step towards understanding the mechanisms of running-related injuries. *J. Sci. Med. Sport* 18, 523–528.

- Martin, V., Kerhervé, H., Messonnier, L.A., Banfi, J.C., Geyssant, A., Bonnefoy, R., Féasson, L., Millet, G.Y., 2010. Central and peripheral contributions to neuromuscular fatigue induced by a 24-h treadmill run. *J. Appl. Physiol.* 108, 1224–1233.
- Maughan, R.J., Leiper, J.B., 1983. Aerobic capacity and fractional utilisation of aerobic capacity in elite and non-elite male and female marathon runners. *Eur. J. Appl. Physiol. Occup. Physiol.* 52, 80–87.
- McGinley, J.L., Baker, R., Wolfe, R., Morris, M.E., 2009. The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait Posture* 29, 360–369.
- McMahon, L.M., Burdett, R.G., Whitney, S.L., 1992. Effects of muscle group and placement site on reliability of hand-held dynamometry strength measurements. *J. Orthop. Sports Phys. Ther.* 15, 236–242.
- McMahon, T.A., Valiant, G., Frederick, E.C., 1987. Groucho running. *J. Appl. Physiol.* 62, 2326–2337.
- Mercer, J.A., Bates, B.T., Dufek, J.S., Hreljac, A., 2003. Characteristics of shock attenuation during fatigued running. *J. Sports Sci.* 21, 911–919.
- Merican, A.M., Amis, A.A., 2009. Iliotibial band tension affects patellofemoral and tibiofemoral kinematics. *J. Biomech.* 42, 1539–1546.
- Merton, P.A., 1954. Voluntary strenght and fatigue. *J. Physiol* 123, 553–564.
- Midgley, Adrian W., McNaughton, L.R., Carroll, S., 2006. Verification phase as a useful tool in the determination of the maximal oxygen uptake of distance runners. *Appl. Physiol. Nutr. Metab.* 31, 541–548.
- Midgley, A.W., McNaughton, L.R., Jones, A.M., 2007. Training to enhance the physiological determinants of long-distance running performance: Can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sport. Med.* 37, 857–880.
- Midgley, Adrian W, Mcnaughton, L.R., Wilkinson, M., 2006. Is there an Optimal Training Intensity for Enhancing the Maximal Oxygen Uptake of Distance Runners ? *Sport. Med.* 36, 117–132.
- Miller, R.H., Lowry, J.L., Meardon, S.A., Gillette, J.C., 2007. Lower extremity mechanics of iliotibial band syndrome during an exhaustive run. *Gait Posture* 26, 407–413.
- Miller, R.H., Meardon, S.A., Derrick, T.R., Gillette, J.C., 2008. Continuous Relative Phase Variability During an Exhaustive Run in Runners With a History of Iliotibial Band Syndrome. *J. Appl. Biomech.* 24, 262–270.
- Millet, G.Y., Lepers, R., Maffiuletti, N.A., Babault, N., Martin, V., Lattier, G., 2002. Alterations of neuromuscular function after an ultramarathon. *J. Appl. Physiol.* 92, 486–492.
- Millet, G.Y., Martin, V., Lattier, G., Ballay, Y., 2003. Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J. Appl. Physiol.* 94, 193–198.
- Millet, G.Y., Martin, V., Martin, A., Vergès, S., 2011. Electrical stimulation for testing neuromuscular function: From sport to pathology. *Eur. J. Appl. Physiol.*
- Mizrahi, J, Verbitsky, O., Isakov, E., 2000. Fatigue-related loading imbalance on the shank in

- running: a possible factor in stress fractures. *Ann. Biomed. Eng.* 28, 463–469.
- Mizrahi, Joseph, Verbitsky, O., Isakov, E., Daily, D., 2000. Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Hum. Mov. Sci.* 19, 139–151.
- Morin, J.B., Samozino, P., Zameziati, K., Belli, A., 2007. Effects of altered stride frequency and contact time on leg-spring behavior in human running. *J. Biomech.* 40, 3341–3348.
- Muhle, C., Ahn, J.M., Yeh, L., Bergman, G.A., Boutin, R.D., Schweitzer, M., Jacobson, J.A., Haghighi, P., Trudell, D.J., Resnick, D., 1999. Iliotibial band friction syndrome: MR imaging findings in 16 patients and MR arthrographic study of six cadaveric knees. *Radiology* 212, 103–110.
- Mundt, M., Koeppe, A., David, S., Witter, T., Bamer, F., Potthast, W., Markert, B., 2020. IMU-based estimation of joint kinematics and kinetics during gait. *Front. Bioeng. Biotechnol.* 8, 41.
- Neal, B.S., Barton, C.J., Gallie, R., O'Halloran, P., Morrissey, D., 2016. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: A systematic review and meta-analysis. *Gait Posture* 45, 69–82.
- Needham, R., Naemi, R., Chockalingam, N., 2014. Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique. *J. Biomech.* 47, 1020–1026.
- Nicol, C., Avela, J., Komi, P. V., 2006. The stretch-shortening cycle: A model to study naturally occurring neuromuscular fatigue. *Sport. Med.*
- Nicol, C., Komi, P. V., 2010. Stretch-Shortening Cycle Fatigue. In: *Neuromuscular Aspects of Sport Performance*. Wiley-Blackwell, Oxford, UK, pp. 183–215.
- Nicol, C., Komi, P. V., Marconnet, P., 1991a. Effects of marathon fatigue on running kinematics and economy. *Scand. J. Med. Sci. Sports* 1, 195–204.
- Nicol, C., Komi, P. V., Marconnet, P., 1991b. Fatigue effects of marathon running on neuromuscular performance: I. Changes in muscle force and stiffness characteristics. *Scand. J. Med. Sci. Sports* 1, 10–17.
- Niemuth, Paul E, Johnson, R.J., Myers, M.J., Thieman, T.J., 2005. Hip Muscle Weakness and Overuse Injuries in Recreational Runners. *Clin. J. Sport Med.* 15, 14–21.
- Noehren, B, Davis, I., Hamill, J., 2007. ASB Clinical Biomechanics Award Winner 2006 Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin. Biomech.* 22, 951–956.
- Noehren, B., Hamill, J., Davis, I., 2013. Prospective evidence for a hip etiology in patellofemoral pain. *Med. Sci. Sports Exerc.* 45, 1120–1124.
- Noehren, B., Manal, K., Davis, I., 2010. Improving between-day kinematic reliability using a marker placement device. *J. Orthop. Res.* 28, 1405–1410.
- Noehren, B., Schmitz, A., Hempel, R., Westlake, C., Black, W., 2014. Assessment of Strength, Flexibility, and Running Mechanics in Men With Iliotibial Band Syndrome. *J. Orthop. Sport. Phys. Ther.* 44, 217–222.
- Noehren, B., Scholz, J., Davis, I., 2011. The effect of real-time gait retraining on hip kinematics,

- pain and function in subjects with patellofemoral pain syndrome. *Br. J. Sports Med.* 45, 691–6.
- Noehren, B.W., Davis, I., Hamill, J., Ferber, R., 2006. Secondary Plane Biomechanics of Iliotibial Band Syndrome in Competitive Female Runners. *Med. Sci. Sports Exerc.* 38, S393–S393.
- Norman, R.W., Komi, P. V, 1979. Electromechanical delay in skeletal muscle under normal movement conditions. *Acta Physiol. Scand.* 106, 241–248.
- Novacheck, T.F., 1998. The biomechanics of running. *Gait Posture.*
- Nummela, A., Keränen, T., Mikkelsen, L.O., 2007. Factors related to top running speed and economy. *Int. J. Sports Med.* 28, 655–661.
- O'Donoghue, P., 2012. Statistics for sport and exercise studies : an introduction. Routledge.
- Orendurff, M.S., Kobayashi, T., Tulchin-Francis, K., Tullock, A.M.H., Villarosa, C., Chan, C., Kraus, E., Strike, S., 2018. A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds. *J. Biomech.* 71, 167–175.
- Osis, S.T., Hettinga, B.A., Macdonald, S., Ferber, R., 2016. Effects of Simulated Marker Placement Deviations on Running Kinematics and Evaluation of a Morphometric-Based Placement Feedback Method 1–13.
- Ounpuu, S., 1994. The biomechanics of walking and running. *Clin. Sports Med.*
- Paavolainen, L., Nummela, A., Rusko, H., Häkkinen, K., 1999. Neuromuscular characteristics and fatigue during 10 km running. *Int. J. Sports Med.* 20, 516–521.
- Parkrun 2019 [WWW Document], n.d. URL <https://www.parkrun.com/> (accessed 11.9.19).
- Peters, B.T., Haddad, J.M., Heiderscheit, B.C., Van Emmerik, R.E.A., Hamill, J., 2003. Limitations in the use and interpretation of continuous relative phase. *J. Biomech.* 36, 271–274.
- Petersen, J., Sorensen, H., Nielsen, R.O., 2015. Cumulative Loads Increase at the Knee Joint With Slow-Speed Running Compared to Faster Running: A Biomechanical Study. *J. Orthop. Sport. Phys. Ther.* 45, 316–322.
- Place, N., Lepers, R., Deley, G., Millet, G.Y., 2004. Time course of neuromuscular alterations during a prolonged running exercise. *Med. Sci. Sports Exerc.* 36, 1347–1356.
- Place, N., Maffiuletti, N.A., Martin, A., Lepers, R., 2007. Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. *Muscle and Nerve* 35, 486–495.
- Powers, C.M., 1998. Rehabilitation of patellofemoral joint disorders: A critical review. *J. Orthop. Sport. Phys. Ther.* 28, 345–354.
- Powers, C.M., 2003. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J. Orthop. Sport. Phys. Ther.* 33, 639–646.
- Powers, Christopher M, 2010. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J. Orthop. Sports Phys. Ther.* 40, 42–51.

- Powers, C.M., Shellock, F.G., Beering, T. V, Garrido, D.E., Goldbach, R.M., Molnar, T., 1999. Effect of bracing on patellar kinematics in patients with patellofemoral joint pain. / Effet du port de genouilleres sur la cinématique rotulienne chez des patients souffrant de douleurs au niveau de l'articulation femoro-rotulienne. *Med. Sci. Sport. Exerc.* 31, 1714–1720.
- Powers, Christopher M, Witvrouw, E., Davis, I.S., Crossley, K.M., 2017. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *Br. J. Sports Med.* bjsports-2017-098717.
- Ton van den Bogert, Practical Guide To Data Smoothing and Filtering, 1996.
- Raastad, T., Hallén, J., 2000. Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise. *Eur. J. Appl. Physiol.* 82, 206–214.
- Ramskov, D., Barton, C., Nielsen, R.O., Rasmussen, S., 2015. High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: a 1-year observational study. *J. Orthop. Sports Phys. Ther.* 45, 153–61.
- Reilly, T., Garrett, R., 1998. Investigation of diurnal variation in sustained exercise performance. *Ergonomics* 41, 1085–1094.
- Richards, J., Thewlis, D., Hobbs, S.J., 2008. Methods of analysis of movement. In: Richards, J. (Ed.), *Biomechanics in Clinic and Research*. Churchill Livingstone Elsevier, pp. 103–116.
- Riley, P.O., Dicharry, J., Franz, J., Croce, U. Della, Wilder, R.P., Kerrigan, D.C., 2008. A kinematics and kinetic comparison of overground and treadmill running. *Med. Sci. Sports Exerc.* 40, 1093–1100.
- Riley, P.O., Paolini, G., Della Croce, U., Paylo, K.W., Kerrigan, D.C., 2007. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait Posture* 26, 17–24.
- Rolf, C., 1995. Overuse injuries of the lower extremity in runners. *Scand. J. Med. Sci. Sports.*
- Ryan, M.B., MacLean, C.L., Taunton, J.E., 2006. A review of anthropometric, biomechanical, neuromuscular and training related factors associated with injury in runners. *Int. Sport. J.* 7, 120-137 18p.
- Sands, W.A., McNeal, J.R., Murray, S.R., Ramsey, M.W., Sato, K., Mizuguchi, S., Stone, M.H., 2013. Stretching and its effects on recovery: A review. *Strength Cond. J.* 35, 30–36.
- Satterthwaite, P., Norton, R., Larmer, P., Robinson, E., 1999. Risk Factors for Injuries and Other Health Problems Sustained in a Marathon. *Br. J. Sports Med.* 33, 22–26.
- Saunders, P.U., Pyne, D.B., Telford, R.D., Hawley, J.A., 2004. Factors affecting running economy in trained distance runners. *Sport. Med.*
- Schache, A.G., Blanch, P.D., Dorn, T.W., Brown, N.A.T., Rosemond, D., Pandy, M.G., 2011. Effect of Running Speed on Lower Limb Joint Kinetics. *Med. Sci. Sports Exerc.* 43, 1260–1271.
- Schache, A.G., Blanch, P.D., Rath, D.A., Wrigley, T. V., Starr, R., Bennell, K.L., 2001. A comparison of overground and treadmill running for measuring the three-dimensional

- kinematics of the lumbo-pelvic-hip complex. *Clin. Biomech.* 16, 667–680.
- Scheerder, J., Breedveld, K., Borgers, J., 2015a. Running across Europe: The rise and size of one of the largest sport markets.
- Scheerder, J., Breedveld, K., Borgers, J., 2015b. Who is Doing a Run with the Running Boom?: The Growth and Governance of one of Europe's Most Popular Sport Activities. In: *Running across Europe: The Rise and Size of One of the Largest Sport Markets*. Palgrave Macmillan, pp. 1–27.
- Schöner, G., 1995. "Recent developments and problems in human movement science and their conceptual implications": Comments on Schöner. *Ecol. Psychol.* 7, 315–319 ST-"Recent developments and problems in.
- Seay, J.F., Van Emmerik, R.E., Hamill, J., 2011. Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clin Biomech (Bristol, Avon)* 26, 572–578.
- Semciw, A., Neate, R., Pizzari, T., 2016. Running related gluteus medius function in health and injury: A systematic review with meta-analysis. *J. Electromyogr. Kinesiol.* 30, 98–110.
- Shaw, A.J., Ingham, S.A., Fudge, B.W., Folland, J.P., 2013. The reliability of running economy expressed as oxygen cost and energy cost in trained distance runners. *Appl. Physiol. Nutr. Metab.* 38, 1268–1272.
- Sheerin, K.R., Reid, D., Besier, T.F., 2019. The measurement of tibial acceleration in runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. *Gait Posture*.
- Shield, A., Zhou, S., 2004. Assessing Voluntary Muscle Activation with the Twitch Interpolation Technique. *Sport. me* 34, 253–267.
- Sinclair, J., Edmundson, C.J., Brooks, D., Hobbs, S.J., Taylor, P.J., 2013. The influence of footwear kinetic, kinematic and electromyographical parameters on the energy requirements of steady state running. *Mov. Sport. Sci. - Sci. Mot.* 80, 39–49.
- Sjodin, B., Svedenhag, J., 1985. *Applied Physiology of Marathon Running*. Sport. Med. An Int. J. Appl. Med. Sci. Sport Exerc.
- Škof, B., Strojnik, V., 2006. Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. *Br. J. Sports Med.* 40, 219–222.
- Skurvydas, A., Jascaninas, J., Zachovajevs, P., 2000. Changes in height of jump, maximal voluntary contraction force and low-frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiol. Scand.* 169, 55–62.
- Skurvydas, A., Mamkus, G., Kamandulis, S., Dudoniene, V., Valanciene, D., Westerblad, H., 2016. Mechanisms of force depression caused by different types of physical exercise studied by direct electrical stimulation of human quadriceps muscle. *Eur. J. Appl. Physiol.* 116, 2215–2224.
- Smith, C.G.M., Jones, A.M., 2001. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *Eur. J. Appl. Physiol.* 85, 19–26.

- Sparrow, W.A., Donovan, E., Van Emmerik, R., Barry, E.B., 1987. Using relative motion plots to measure changes in intra-limb and inter-limb coordination. *J. Mot. Behav.* 19, 115–129.
- Stergiou, N., Harbourne, R.T., Cavanaugh, J.T., 2006. Optimal Movement Variability. *J. Neurol. Phys. Ther.* 30, 120–129.
- Stief, F., Böhm, H., Michel, K., Schwirtz, A., Döderlein, L., 2013. Reliability and Accuracy in Three-Dimensional Gait Analysis : A Comparison of Two Lower Body Protocols 105–111.
- Stratford, P.W., Binkley, J.M., Riddle, D.L., Guyatt, G.H., 1998. Sensitivity to Change of the Roland-Morris Back Pain Questionnaire: Part 1. *Phys. Ther.* 78, 1186–1196.
- Switaj, T.L., O'Connor, F.G., 2008. Gait Analysis. In: *The Sports Medicine Resource Manual*. Elsevier Inc., pp. 536–542.
- Taunton, J., Ryan, M.B., Clement, D., McKenzie, D., Lloyd-Smith, D., Zumbo, 2002. A retrospective case-control analysis of 2002 running injuries. *Br. J. Sports Med.* 36, 95–101.
- Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R., Zumbo, B.D., 2003. A prospective study of running injuries: the Vancouver Sun Run “In Training” clinics. *Br. J. Sports Med.* 37, 239.
- Taylor-haas, J.A., Lucas, K.C.H., Bates, N.A., Myer, G.D., Cscs, D., Ford, K.R., 2014. Reduced hip strength is associated with increased hip motion during running in young adult and adolescent male. *Int. J. Sports Phys. Ther.* 9, 456–467.
- Taylor, J., Komi, P. V., Nicol, C., 2008. Central and Neuromuscular Fatigue. In: *Physiological Bases of Human Performance during Work and Exercise*. Churchill Livingstone, pp. 91–113.
- Taylor, J.L., Todd, G., Gandevia, S.C., 2006. Evidence for a supraspinal contribution to human muscle fatigue. In: *Clinical and Experimental Pharmacology and Physiology*. pp. 400–405.
- Terry, G.C., Hughston, J.C., Norwood, L.A., 1986. The anatomy of the iliopatellar band and iliotibial tract. *Am. J. Sports Med.* 14, 39–45.
- Thomeé, R., Augustsson, J., Karlsson, J., 1999. Patellofemoral Pain Syndrome: A Review of Current Issues. *Sport. Med.* 28, 245–262.
- Thorborg, K., Bandholm, T., Schick, M., Jensen, J., Hölmich, P., 2011. Hip strength assessment using handheld dynamometry is subject to intertester bias when testers are of different sex and strength. *Scand. J. Med. Sci. Sports* 23, 487–493.
- Trafimow, D., Marks, M., 2015. Editorial on Null Hypothesis testing. *Basic Appl. Soc. Psych.* 37, 1–2.
- Trimble, M.H., Kukulka, C.G., Thomas, R.S., 2000. Reflex facilitation during the stretch-shortening cycle. *J. Electromyogr. Kinesiol.* 10, 179–87.
- Tuller, B., Turvey, M.T., Fitch, H.L., 1982. The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. In: Kelso, J.A.S. (Ed.), *Human Motor Behavior: An Introduction*. Lawrence Erlbaum Associates, Hillsdale, NJ., pp. 253–270.
- Van Emmerik, R.E., Wagenaar, R.C., Winogrodzka, A., Wolters, E.C., 1999. Identification of axial rigidity during locomotion in Parkinson disease. *Arch. Phys. Med. Rehabil.* 80, 186–

- Van Gent, R.N., Siem, D., Van Middelkoop, M., Van Os, A.G., Bierma-Zeinstra, S.M.A., Koes, B.W., 2007. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Sport en Geneesk.* 40, 16–29.
- Van Hooren, B., Fuller, J.T., Buckley, J.D., Miller, J.R., Sewell, K., Rao, G., Christian Barton, ., Bishop, C., Willy, R.W., 2019. Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies. *Sport. Med.* 1–29.
- Van Middelkoop, M, Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S.M., Koes, B.W., 2008. Risk factors for lower extremity injuries among male marathon runners. *Scand J Med Sci Sport.* 18, 691–697.
- Van Middelkoop, M., 2009. Lower Extremity Injuries in Non-Elite Runners: A Review. *Clin. J. Sport Med.* 19, 77.
- Vicon, 2018. Attach Plug-in Gait markers to a patient - Nexus 2.5 Documentation - Documentation | VICON [WWW Document]. URL <https://docs.vicon.com/display/Nexus25/Attach+Plug-in+Gait+markers+to+a+patient> (accessed 1.22.20).
- Weavil, J.C., Sidhu, S.K., Mangum, T.S., Richardson, R.S., Amann, M., 2015. Intensity-dependent alterations in the excitability of cortical and spinal projections to the knee extensors during isometric and locomotor exercise. *Am. J. Physiol. - Regul. Integr. Comp. Physiol.* 308, R998–R1007.
- Weir, J., 2005. Quantifying Test-Retest Reliability Using The Intraclass Correlation Coefficient and the SEM. *Journal of Strength and Conditioning.*
- Wen, D., Utesch, T., Wu, J., Robertson, S., Liu, J., Hu, G., Chen, H., 2019. Effects of different protocols of high intensity interval training for VO₂max improvements in adults: A meta-analysis of randomised controlled trials. *J. Sci. Med. Sport* 22, 941–947.
- Weyand, P.G., Sternlight, D.B., Bellizzi, M.J., Wright, S., Peter, G., Sternlight, D.B., Matthew, J., Wright, S., 2000. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J. Appl. Physiol.* 89, 1991–1999.
- Wiewelhove, T., Döweling, A., Schneider, C., Hottenrott, L., Meyer, T., Kellmann, M., Pfeiffer, M., Ferrauti, A., 2019. A Meta-Analysis of the Effects of Foam Rolling on Performance and Recovery. *Front. Physiol.* 10, 376.
- Wikholm, J.B., Bohannon, R.W., 1991. Hand-held Dynamometer Measurements : Tester Strength. *J. Orthop. Sport. Phys. Ther.* 191–198.
- Williams, K.R., Cavanagh, P.R., 1987. Relationship between distance running mechanics, running economy, and performance. *J. Appl. Physiol.* 63, 1236–1245.
- Willson, J.D., Kernozek, T.W., Arndt, R.L., Reznichuk, D.A., Scott Straker, J., 2011. Gluteal muscle activation during running in females with and without patellofemoral pain syndrome. *Clin. Biomech.* 26, 735–740.
- Willson, J.D., Loss, J.R., Willy, R.W., Meardon, S.A., 2015. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J. Biomech.* 48,

4155–4159.

- Willson, J.D., Petrowitz, I., Butler, R.J., Kernozek, T.W., 2012. Male and female gluteal muscle activity and lower extremity kinematics during running. *Clin. Biomech.* 27, 1052–1057.
- Willwacher, S., Sanno, M., Brüggemann, G.P., 2020. Fatigue matters: An intense 10 km run alters frontal and transverse plane joint kinematics in competitive and recreational adult runners. *Gait Posture* 76, 277–283.
- Willy, R.W., Paquette, M.R., 2019. The physiology and biomechanics of the master runner. *Sports Med. Arthrosc.* 27, 15–21.
- Wiltshire, G.R., Fullagar, S., Stevinson, C., 2017. Exploring parkrun as a social context for collective health practices: Running with and against the moral imperatives of health responsabilisation. *Sociol. Heal. Illn.*
- Wirtz, A.D., Willson, J.D., Kernozek, T.W., Hong, D.-A., 2012. Patellofemoral joint stress during running in females with and without patellofemoral pain. *Knee* 19, 703–708.
- Wundersitz, D.W.T., Gastin, P.B., Richter, C., Robertson, S.J., Netto, K.J., 2015. Validity of a trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running. *Eur. J. Sport Sci.* 15, 382–390.
- Wundersitz, D.W.T., Netto, K.J., Aisbett, B., Gastin, P.B., 2013. Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. *Sport. Biomech.* 12, 403–412.
- Yamato, T.P., Saragiotto, B.T., Lopes, A.D., 2015. A Consensus Definition of Running-Related Injury in Recreational Runners: A Modified Delphi Approach. *J. Orthop. Sport. Phys. Ther.* 45, 375–380.
- Zinner, C., Schäfer Olstad, D., Sperlich, B., 2018. Mesocycles with different training intensity distribution in recreational runners. *Med. Sci. Sports Exerc.* 50, 1641–1648.

APPENDICES

Appendix 1 – Examples of participant information sheet and health questionnaire

Faculty of Health & Life Sciences

Project Title: Recovery from high intensity interval training in trained, masters age group, runners

Investigator: Sherveen Riazati

Participant Information Sheet

You are being invited to take part in this research study. Before you decide it is important for you to read this leaflet so you understand why the study is being carried out and what it will involve.

Reading this leaflet, discussing it with others or asking any questions you might have will help you decide whether or not you would like to take part.

What is the Purpose of the Study?

The main purpose of H will be to observe how trained runners recovery from a high intensity interval training session over the following 24 and 48-hours post run. This will inform the investigators of possible residual effects of such training and potential risks towards RROI.

Why have I been invited?

It is important that we assess as many people as possible and you have indicated that you are interested in taking part in this study.

Also, you are a person between ages of 35 to 50 that is actively running at least 20 km per week. Free from any lower extremity injury for at least 6 months, and free from any cardiovascular or neurological condition that would preclude safe treadmill running. You will be asked to complete a health questionnaire that will disclose your current health status to ensure your eligibility to take part in the study.

Do I have to take part?

No, participation in the study is voluntary. This information sheet is provided to help you make that decision. If you do decide to take part, you can withdraw from the study whenever you choose, without giving the reason for doing so. You are also free to leave the study before its completion. Not participating or leaving the study before its completion will not affect you in any way.

What will happen if I take part?

If you decide to take part in this study, you will be asked to visit the University Gait laboratory on 3 days in total. First visit will last 2.5 hours with a purpose to measure sub-

maximal steady state (lactate levels) and maximal oxygen consumption ($\dot{V}O_2$ max) – which will determine the running speeds in the other tests. Also, the first session will familiarise you with the procedures of peripheral nerve stimulation and strength measures.

Your 2nd visit will last up to 2 hours and you will be performing a 6-minute low intensity run and measures of muscle function before and after the interval training. The high intensity interval training (HIIT) session will consist of 6 repetitions of 800 meters with a recovery equal to the time spent running. Upon arrival, you will be asked to perform neuromuscular measures and lower body strength tests for the hip and knee joints. Neuromuscular measure will involve you sitting in a chair with your ankle attached to a cuff, you will be asked to contract against this cuff while electrical stimulation is delivered to the nerve that activates your quadriceps. These measurements will allow us to measure the degree of fatigue in response to the exercise, and the recovery of the peripheral nervous system and muscle.

Following Neuromuscular measures, you will be asked to push against a handheld device that measures the force you exert against it. You will be familiarised for these tests on your first visit, and be asked to perform the same tests after completion of the HIIT session. Following the strength and neuromuscular measures, the investigator will place 6 sensors on your skin, these sensors are designed to give readings of muscle activity when you run. The investigator will also place 16 reflective markers at various points of your lower body by using double sided adhesive tape. Once the sensors and markers are secured you will be asked to complete a 6-min standard run at a low intensity designed to assess baseline measures and used as a warm up. Followed the 6-min run, you will then perform the HIIT session. Once completed, you will then be asked to perform neuromuscular function measure followed by another 6-min moderate intensity run and strength measures.

Day 3 will take place 24-hours after HIIT session. It will last up to 1 hour, where the neuromuscular function and strength tests will be taken measured again, and you will complete the 6-min run.

All runs will be recorded through a 14-camera 3-Dimensional motion analysis system that will be used to assess your running gait. You will also be asked to wear a vest equipped with an accelerometer that is used to assess your gait, during all runs.

You will also be asked to refrain from training 24 hours prior to your training run session until the completion of the study.

What are the possible disadvantages of taking part?

The training runs can be very fatiguing with the possibility of experiencing muscle soreness with a small injury risk. If the procedure causes muscle soreness, it should subside within a few days. There is some mild discomfort with electrical nerve stimulation and lactate level testing, which requires pricking at the tip a finger on multiple occasions to draw out a very small sample of blood. Either procedures may cause discomfort, in case of excessive discomfort, you will be able to withdraw your participation in the study at any time.

What are the possible benefits of taking part?

By taking part in this study you will help us assess if runners have a greater risk of injury 24-hours after performing a high intensity interval training run.

Will my taking part in this study be kept confidential and anonymous?

Yes. The research team has put into place a number of procedures to protect your confidentiality. You will be allocated a participant code that will always be used to identify any data that you provide as this will ensure your name or other personal details will not be associated with your data, for example the consent form will be kept separate from your data.

All paper records will be stored in a locked filing cabinet, accessible only to the research team, and all electronic information will be stored on a password-protected computer.

In general, all of the information you provide will be treated in accordance with the General Data Protection Regulations as you will not be identifiable from any academic publications that may arise from this study. The only exception to this confidentiality is if the researcher feels that you or others may be harmed if information is not shared.

How will my data be stored?

Your information will be stored on a password-protected computer or in a locked filing cabinet. All information is only used for the purpose of this study. Written consent will be obtained from you for any other purpose than use in this study. All data will be stored in accordance with University guidelines and General Data Protection Regulations. Any personal information will be destroyed after 3 years.

What will happen to the results of the study?

Data may be published in peer review journals or presented at science conferences. However, your information will remain fully confidential and not referred to at any time unless we have asked for your specific consent for this beforehand. We can provide you with a summary of the findings from the study if you email the researcher at the address below.

Who is Organizing and Funding the Study?

The study is organized and funded by Northumbria University.

Who has reviewed this study?

The Faculty of Health and Life Sciences Research Ethics Committee at Northumbria University has reviewed the study in order to safeguard your interest and have granted approval to conduct the study. If you require confirmation of this please contact the chair of the ethics committee using the details below stating the full title and principal investigator of the study:

Chair of the Faculty of Health and Life Sciences Ethics Committee,
Northumberland Building,
Northumbria University,
Newcastle upon Tyne,
NE1 8ST

Contact for further information:

Any further information required for this study can be obtained through the Principal Investigator:

Sherveen Riazati

Faculty of Health and Life Sciences

Northumbria University

Newcastle Upon Tyne

NE1 8ST

Email: sherveen.riazati@northumbria.ac.uk

Phone: 0191 243 7018

Alternatively, you can seek information from the Principal Investigator's Supervisor:

Dr. Phil Hayes

Email: phil.hayes@northumbria.ac.uk

If you would like to discuss the study, withdraw your data or register a complaint, please contact the chair of the ethics committee listed in the debrief.

Participant Health Screening

Name _____ Phone number: _____ Date _____

Date of Birth (dd/mm/yy) ____/____/____ Weight _____kg Height _____m

1. How often do you take part in structured physical activity?

For example: Jogging, team sports, aerobics etc.

Please tick one:

How many hours?

a. Once a week

☐

b. Twice a week

☐

c. Three times a week

☐

d. Four times a week

☐

e. More than 5 times a week

☐

f. Never

☐

2. Do you run more than 20 kilometres per week?

Yes ☐

No ☐

If you answer yes to any of the following questions you are not eligible to take part in the study.

3. Do you suffer from any medical conditions?

For example: Arthritis, Myositis, Fibromyalgia, Myopathy, Diabetes Mellitus, or Hypothyroidism

Yes ☐

No ☐

If yes, please elaborate: _____

4. Are you currently taking any medication?

Yes ☐

No ☐

5. Are you currently suffering from any musculoskeletal or tendon injury in your lower body?

For example: Sore muscles, broken bones or sore tendons

Yes ☐

No ☐

If yes, please describe information regarding the type of injury, injury location, and when it occurred (dd/mm/yy): *For example: knee pain during stair ascent and decent, running, and walking.*

6. Have you suffered any from any musculoskeletal or tendon injury to your lower body within the last 6 months?

For example: Sore muscles, broken bones or sore tendons

Yes ☐

No ☐

If yes, please describe information regarding the type of injury, injury location, and when it occurred (dd/mm/yy):

7. Are you currently experiencing any cardiovascular conditions?

Yes ☐

No ☐

8. Are you currently experiencing any neurological conditions?

Yes ☐

No ☐

9. Are you allergic to adhesive material?

Yes ☐

No ☐

If yes, please describe information regarding the type of allergy:

Contact Details:

Sherveen Riazati (Lead Researcher)

Sherveen.riazati@northumbria.ac.uk

The information I have given is correct to the best of my knowledge at the time of completion.

Signature of

Participant.....Date.....

Appendix 2 - Consent Form

Recovery from high intensity interval training in trained masters age group runners

Principal Investigator: **Sherveen Riazati**

*please tick or initial
where applicable*

I have carefully read and understood the Participant Information Sheet.	<input type="checkbox"/>
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	<input type="checkbox"/>
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	<input type="checkbox"/>
I agree to take part in this study.	<input type="checkbox"/>

Signature of participant.....
Date.....

(NAME IN BLOCK
LETTERS).....

Signature of Parent / Guardian in the case of a minor

Signature of researcher.....
Date.....

(NAME IN BLOCK
LETTERS).....

Appendix 3 – Recruitment Poster



Runners needed to take part in research looking at the effect of fatigue on running related injuries



Purpose of the study

- The main purpose of this study will be to identify whether running style changes during 2 different types of training session and if changes in running style increase your injury risk. One training session is a steady run, the other an interval training session.
- Running style changes with fatigue and this has been linked to muscle strength and flexibility. Certain characteristics of running style have been identified as running related injury risk factors. We aim to investigate the relationships between these factors, fatigue, flexibility and strength. A secondary aim of this study is to see how reproducible the measures are.

Why do we need you?

We want to do research on 'typical' club / recreational runners. Our long term goal is to be able to suggest activities that reduce your injury risk. To do this we want to recruit male and female runners aged between 30 and 50, who run at 20+ km per week. You must have been free from any major lower extremity injury for at least 3 months, any minor injuries for 1 month, and free from any condition that would preclude safe treadmill running.

Purpose of the study

If you decide to take part in this study, you will be asked to visit the laboratory on 5 days in total.

- The first visit will last 2.5 hours with a purpose to familiarize with procedures of strength, flexibility, and running assessments to measure lactate threshold and VO2 max.
- Visits on days 2, 3, 4, and 5 will last 2 hours, on these days you will be performing a training session.
- You will be performing two types of training sessions, a high intensity interval session consisting of 6 repetitions of 800 meters and a matched steady continuous run.
- Prior to the training session, you will perform strength and flexibility tests, then a 6-minute moderate intensity control run
- Immediately after you training run, you will undergo the same strength and flexibility examination followed by a 6-minute control run.
- During all the treadmill running your running style will be recorded using a 3D filming system



Location:

The research will take place at the Gait Lab located in the Newcastle city campus of Northumbria University.

Contact information

Any further information required for this study can be obtained through the Principal Investigator or my supervisor

Sherveen Riazati (PhD student)
Department of Sport, Exercise and Rehabilitation,
Northumbria University,
Newcastle Upon Tyne.
NE1 8ST

Email: sherveen.riazati@northumbria.ac.uk
Phone: 0191 243 7018

Supervisor:
Dr Phil Hayes
Email: phil.hayes@northumbria.ac.uk
Phone: 0191 227 4690

