

# **TRAIL RUNNERS: NEUROMUSCULAR AND BIOMECHANICAL INSIGHTS**

By

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## LIST OF ABBREVIATIONS

<b>ANOVA</b>	:	Analysis of variance
<b>APGRF</b>	:	Anterior-posterior ground reaction force
<b>BF:</b>	:	<i>Biceps femoris</i>
<b>BW</b>	:	Body weight
<b>BMI</b>	:	Body Mass Index
<b>CRD</b>	:	Composite reach distance
<b>ES</b>	:	Effect size
<b>EMG</b>	:	Electromyography
<b>FFS</b>	:	Forefoot strike
<b>FSA</b>	:	Foot strike angle
<b>GAMED</b>	:	<i>Gastrocnemius medialis</i>
<b>GMAX</b>	:	<i>Gluteus maximus</i>
<b>GMED</b>	:	<i>Gluteus medius</i>
<b>GRF</b>	:	Ground reaction force
<b>INJURY</b>	:	Musculoskeletal symptom of the lower limb that requires a reduction or stoppage of normal training for at least a week (Lun et al., 2004)
<b>ILR</b>	:	Initial loading rate
<b>ML</b>	:	Medio-lateral ground reaction force
<b>PL</b>	:	<i>Peroneus longus</i>
<b>RF</b>	:	<i>Rectus femoris</i>
<b>RFS</b>	:	Rearfoot strike
<b>ROM</b>	:	Range of motion
<b>RMS</b>	:	Route mean squared
<b>RRI</b>	:	Running-related injury
<b>SD</b>	:	Standard deviation
<b>SEBT</b>	:	Star excursion balance test
<b>TA</b>	:	<i>Tibialis anterior</i>
<b>UBH</b>	:	Unilateral bridge hold
<b>VGRF</b>	:	Vertical ground reaction force
<b>VL</b>	:	<i>Vastus lateralis</i>

## ABSTRACT

Running is a popular recreational and competitive sport worldwide. Despite numerous proven health benefits associated with road running, the risk of sustaining a running-related injury (RRI) is extremely high. The cause of RRI is multifactorial and the result of running many kilometres on monotonous and mechanically stiff road surfaces has been suggested to increase the risk of sustaining an injury. Interestingly, this notion may be a key driving factor for the emergence and growing interest in, trail or 'off-road' running. Research investigating road running has been well-described, whereas the impact of regular running on natural, dynamic trail surfaces on the musculoskeletal system has yet to be fully considered.

Thus, this thesis sought to understand the trail running athlete, with particular focus on elucidating the clinical, biomechanical and neuromuscular consequences of habitual running training on off-road terrain. The present thesis begins with a comprehensive review of the literature. The aim of this chapter was to briefly describe the origins of trail running, explore the theoretical driving factors behind interest in trail running, and detail the current scientific understanding of trail running and the purported implications and benefits thereof. Gaps in the existing body of knowledge were highlighted, with recommendations for necessary future research.

The first study aimed to describe clinical measures of dynamic stability in well-trained trail runners and contrast this group with age- and performance-matched road runners. All runners performed three clinical assessments: the Star Excursion Balance Test (SEBT), Unilateral Bridge Hold (UBH) and Single Leg Squat (SLS). No differences were found in UBH and SEBT assessments. During the SLS task, trail runners exhibited less ankle varus and less ankle external rotation at peak knee flexion in comparison to road runners. These findings suggest that trail runners' performance in the SLS test may represent a kinematic adaptation to habitual terrain targeted at minimising ankle joint movement during weight-bearing.

Subsequently, we aimed to determine whether running biomechanics would differ between 20 habitually shod trail runners and 20 road running counterparts due to their preferred training terrain. A special focus of this chapter was to determine whether the groups of runners presented with disparate risk of sustaining a running-related injury (RRI). To evaluate this hypothesis, all runners performed barefoot and shod overground running trials on a synthetic track. Regardless of footwear condition, trail runners presented with greater step frequency, shorter ground

contact time and shorter step duration. Further group differences were observed, with trail runners exhibiting notably advantageous kinematics at the level of the ankle and the foot, presenting with: smaller foot strike angle, lower pronation magnitude and velocity, and lower ankle stiffness. Considering these biomechanical parameters, it was unexpected to find that trail runners experienced similar initial loading rates (ILRs) and higher ground reaction forces to road runners in response to the synthetic track.

The final experimental chapter explored the notion that preferred running terrain has an influence on neuromuscular regulation of running biomechanics. To examine this, electromyography and biomechanical variables were determined using previously described protocols. Regardless of footwear condition, trail runners exhibited greater *gluteus maximus*, *biceps femoris* and *peroneus longus* muscle activation during terminal swing in comparison to road runners. In addition, trail runners exhibited greater *tibialis anterior* activation during early swing. With regards to discrete biomechanics, trail runners presented with greater lower extremity joint stability in the sagittal plane, demonstrating lower pelvic, hip and knee flexion at initial ground contact. Interestingly, similar ground reaction forces were experienced by trail and road runners on the synthetic track, suggesting that the observed muscle ‘tuning’ responses to these impact forces may be managed by the differing neuromuscular responses.

The outcomes of this thesis suggest that there are numerous clinical, mechanical and neuromuscular implications of habitual running training on the trail and road. Although the present thesis is the first step to understanding the demands of regular trail running on the human body, future studies using portable motion capture and inertial systems are necessary to determine the precise influence of real-time trail running on the neuromuscular system and running biomechanics. Interestingly, trail runners demonstrated several purported ‘advantageous’ kinematic and spatiotemporal parameters, and exhibited differing muscle activity patterns in comparison to road runners in a controlled laboratory setting. However, trail and road runners experienced similar ILRs in response to the synthetic track. Considering the high incidence of road RRI, and that higher vertical load has been associated with chronic RRI, this finding suggests that trail and road runners could be at similar risk of developing a RRI.

However, due to the disparate nature of trail and road running terrains and the multifactorial nature of RRIs, further clarity on 1) the acute and long-term effects of off-road running and 2) the injury risk profile of a trail runner, is imperative for a holistic understanding of the risks and benefits associated with participation in this sport. We recommend that the influence of trail

running on the musculoskeletal system presented in this thesis be considered as a foundation for future large-scale epidemiological and prospective injury research.

**Key words:** trail running, biomechanics, muscle activity, dynamic stability

## **CHAPTER 1**

### **REVIEW OF LITERATURE AND SCOPE OF THESIS: QUESTIONING THE CONCEPT OF TRAIL RUNNING**

## 1.1 RATIONALE

### *Introduction*

Road running is a popular and accessible form of exercise with many proven health benefits. As a result, more people partake in running events around the globe each year (Scheerder et al., 2015, Foundation, 2013), undeterred by the fact that the risk of sustaining a running-related injury (RRI) in recreational and competitive running is high. Incidence rates vary greatly with research reporting a range of 2.5 to 59 injuries per 1000 hours of running exposure (Buist et al., 2010, van Gent et al., 2007, van Mechelen, 1992, Van Middelkoop et al., 2008, Lun et al., 2004, Videbaek et al., 2015, Hespanhol et al., 2013). The cause of RRI is multifactorial, with various intrinsic and extrinsic factors suggested to contribute to its high incidence (Meeuwisse, 1994).

Research regarding the mechanisms of RRI is ongoing and highly debated. To date, research on RRI has focused on ‘excessive forces or extreme movements during the gait cycle that expose the body to stresses that increase injury risk’ (Nigg and Wakeling, 2001). Subsequently, decades of scientific research and interventions have attempted to reduce the injury burden associated with running. Despite modern technological advances such as footwear, clinical intervention programmes and monitoring of training loads, RRI incidence remains high (Yeung, 2001). Even the most recent barefoot running trend in the early 2010’s, did little to reduce injury risk (Jenkins and Cauthon, 2011, Murphy et al., 2013).

Indeed, numerous studies have investigated the incidence and aetiology of road running injury, however the incidence and factors contributing to injury across other athletic sub-disciplines are unknown. A relatively new and under-researched sub-discipline of running, is trail or ‘off-road’ running. Trail running typically involves running in predominantly natural locations, e.g. forests, and mountains, or on plains and beaches. The primary discriminator between trail running and other competitive athletic disciplines is that most other disciplines take place predominantly on smooth and artificial surfaces, such as track athletics, road running and race walking. Cross-country could be considered similar, but unlike trail running, is still constrained to changes in gradient, distance and terrain.

The uniqueness of trail running is the mandatory setting that excludes the urban built environment. With this in mind, the primary motivator for involvement in trail running has been identified as for ‘pleasure’ or ‘enjoyment’, alongside other driving factors including exercise itself, a personal challenge, spending time outdoors, relaxation and stress relief (Foundation, 2010, Getz and McConnell, 2014). Exercising or spending time in the natural environment has

been shown to have restorative effects on psychological well-being and physical health (Barton and Pretty, 2010, Hartig et al., 1991). One can surmise that regular trail running may have similar salutogenic effects.

In addition, the high incidence of RRI in road runners may be contributing to the increase in trail running participation worldwide, as discontented road runners may become motivated to convert for the many reasons attributed to reduced injury susceptibility. There are numerous hypotheses regarding the musculoskeletal or physiological benefits of running on variable or compliant terrains (McMahon and Greene, 1979, Mann et al., 2015, Hamill et al., 1999), however the purported benefits of trail running remain anecdotal, and the effects of long-term running on off-road surfaces are unclear.

Trail running has not been well-documented in the scientific literature and the explanation for this is multifaceted. Possible reasons for this include: i.) Trail running is a relatively new sport; ii.) It is difficult to observe as a result of the varying terrain and locations; and iii.) There is no formalised definition of the sport.

This review therefore aims to discuss the origins of trail running as a sport; evaluate the merits of the theoretical factors driving the rise in interest of trail running; establish a current scientific understanding of trail runners and discuss the future research necessary to understand the risks and benefits of participation. In addition, due to the nature of the sport, certain theoretical factors have been proposed to be beneficial in reducing the risk of RRI. These factors include differing running biomechanics, neuromuscular control and certain clinical benefits to road runners. This review sought to critically evaluate these purported differences with consideration given to running performance and risk of injury.

### ***A Brief History of Trail Running***

The origins of trail running have been linked to that of the early hunter-gatherers, whereby running long distances over uneven, rough terrain was imperative for survival (Bramble and Lieberman, 2004, Lieberman and Bramble, 2007, Devine, 1985, Lieberman et al., 2009). In the modern era and specifically the early 1980's, mountain running was formalised with the inauguration of the International Committee of Mountain Running. Trail running on the other hand, was only acknowledged as a sport in 1995 by the British Athletic Association, who defined it as running "primarily along footpaths and bridle paths marked on Ordnance Survey maps as 'public rights of way'". They are "highways to which pedestrians have unrestricted access in English law. Towpaths, forest drives, farm cart tracks and paths in parks etc., from

which motorised traffic is excluded, are also trails when the owners' permission is obtained". (Association, 2001).

More recently, the International Association of Athletics Federation (IAAF) officially recognised trail running in 2015 as a discipline separate to that of road running, mountain running, and cross-country (Association, 2015). According to the IAAF's broad guidelines, a trail race should consist of at least 80% unpaved surfaces, and no limit should be set on distance or changes in altitude. Albeit that trail running is now a formalised discipline, the terrain where these races take place is not standardised by environment, gradient or distance as with road running.

Interestingly, the first trail world cup was held in 2007, organised by the International Association of Ultra Runners and hosted by different countries biannually until 2015. It is now held annually, and consists of a run with an average length of 70 km and roughly a 2500 m climb in elevation (Easthope, 2013). There are many popular trail races now that take place world-wide with races of a shorter length ranging between 5-50 km, and culminating in a 21 km trail world championship. With a rise in popularity and an increase in events and races worldwide, trail running is becoming a popular alternative to road running (Foundation, 2013, Foundation, 2010, Torbidoni et al., 2015, Hoffman and Wegelin, 2009, Foundation, 2017). There appear to be many reasons for this, but more interestingly for scientists and clinicians is its influence on running performance and the risk of injury.

### ***Profiling Running Injuries: Road vs. Trail***

Numerous intrinsic and extrinsic factors have been suggested to increase the risk of sustaining a RRI. A dearth of scientific support for intrinsic risk factors (e.g. biological traits) has compelled investigation into modifiable risk factors such as training errors, footwear and running biomechanics. Various interventions have been implemented by running coaches and clinicians to help mitigate the risk of sustaining a RRI (Yeung, 2001, Goss and Gross, 2012), but the incidence of RRI remains high.

Multiple training exposures have been linked to the high incidence of running and athletic injury. A training exposure that is pertinent to the present thesis is preferred running surface. The mechanical stiffness of artificial surfaces (i.e. paved roads, synthetic tracks) has been suggested to place concentrated strain on the lower extremity joints (Pine, 1991, Andreasson and Peterson, 1986, Torg et al., 1974, Nigg and Yeadon, 1987). Other key ingredients to consider when critically assessing a training regimen are weekly mileage, training intensity,



training frequency and running speed. Following an appropriate training programme designed by knowledgeable professionals may reduce excessive increases in running volume, frequency and intensity, and protect against the development of certain RRI (Malliaropoulos et al., 2015).

Running footwear and the specific constituents of a running shoe may play a role in the development of RRIs. There is some evidence to suggest that running shoes which are not replaced after four to six months of wear can increase the risk of sustaining a RRI, particularly in females (van der Worp et al., 2015). This may be as a result of the loss or deterioration in mid-sole cushioning that can occur after 300-800 km of running exposure (Cook et al., 1985). However, according to Nigg et al. (2015), the loss of mid-sole cushioning may not impact all runners equally. Indeed, Nigg et al. (2015) propose that runners have a higher risk of RRI when an individual's 'preferred comfort standards' are not met, and suggest that discomfort may have a greater influence on RRI than the components of the shoe itself. This notion warrants further research before the precise influence of running shoes on the risk of sustaining a RRI can be determined. However, isolating specific training exposures proves difficult, limiting research progress in this area, and thus the literature remains controversial (Nielsen et al., 2012).

The relationship between running biomechanics and RRIs have been extensively researched with conflicting results. For example, although 'typical' foot pronation mechanics have yet to be universally defined, both excessive (Willems et al., 2007) and reduced (Thijs et al., 2007) foot pronation during running has been suggested to be associated with RRI. With regards to running kinetics, the role of specific ground reaction force components experienced during running is also regularly debated. Greater vertical ground reaction forces (vGRFs) have long been associated with the development of RRI (Van der Worp et al., 2016, Zadpoor and Nikooyan, 2011, Hreljac et al., 2000, Bredeweg, Milner et al., 2006). However, a growing body of research suggests that average and instantaneous initial loading rates may have a greater influence on the development of RRI than vGRFs (Van der Worp et al., 2016, Zadpoor and Nikooyan, 2011).

Although the precise impact of both intrinsic and extrinsic risk factors on the incidence of RRI remains unclear, epidemiological studies show that most road running injuries are as a result of cumulative micro-trauma associated with regular and invariant movement (Stanish, 1983, Elliott, 1990). Most of these injuries occur at or around the knee (Kluitenberg et al., 2015, Lopes et al., 2012, Taunton et al., 2002), with common injuries including: exertional lower leg pain, calf pain, patellofemoral pain syndrome, iliotibial band syndrome, meniscal injuries and patellar tendinopathy (van Gent et al., 2007, Taunton et al., 2002, Wen, 2007).

Road RRI is well documented, but the literature pertaining to the epidemiology of injuries in trail runners is limited. In the Netherlands, a prospective injury study on 148 trail runners reported 242 injuries within a six month follow up period (Hespanhol Junior et al., 2017), with the lower leg and ankle documented as the most affected. 75.2% of the total injuries were reported as overuse injuries and almost half of the cohort reported multiple injuries. In a recent epidemiological study, 36 out of 40 Greek ultra-trail runners reported at least one previous injury (Malliaropoulos et al., 2015). Overuse injuries were most common (82.2% of total injuries), with lower back and knee being the most affected anatomical areas. Interestingly, these findings are mostly attributed to that of ultra-trail runners and may not truly reflect the injury profile of a typical trail runner. Ultra-runners are a specific niche of the running population, and the great mileage associated with ultra-marathons (race distances > 42.2 km) places an enormous physical demand on these runners during training and competition. As a consequence, the great mileage reported by ultra-runners (inclusive of road, trail and mountain runners) has been found to be a risk factor for RRI (James et al., 1978, Mann et al., 1981, van Gent et al., 2007), and high injury prevalence has previously been reported in these runners (Daoud et al., 2012, van Gent et al., 2007, Van Middelkoop et al., 2008).

In addition, these often described ‘trail running’ cohorts are reported to train on paved and unpaved surfaces. The stiffness of paved surfaces places strain on the lower extremity joints and surrounding tissue (muscles and ligature) (Nigg and Wakeling, 2001). In contrast, trail running terrain is erratic, requiring an interplay of significant gait and joint coordination variability and dynamic stability. Increased movement variability in combination with a more compliant surface during running may reduce the risk of overloading specific joints and musculature and thus the risk of sustaining a RRI (McMahon and Greene, 1979, Mann et al., 2015, Hamill et al., 1999). As the physical demand associated with trail and road running terrains fundamentally differ, it is plausible that these two running populations would be non-identical with regards to injury type and mechanisms of injury. Thus, future epidemiological studies are necessary to critically evaluate habitual road and trail running populations with regards to respective injury risk profiles.

### ***The Biomechanics of a Trail Runner***

The literature describing the kinematics and kinetics associated with trail running is sparse. Research to date has simulated various features of off-road running surfaces under laboratory conditions, using high speed videography or motion capture systems to observe the acute response in running biomechanics (Kerdok et al., 2002, Hardin et al., 2004, Dixon et al., 2000,

Voloshina and Ferris, 2015). Other studies have compared the effects of short bouts of real-time running on different outdoor surfaces using videography, pressure-sensitive insoles and inertial systems (Schutte et al., 2016, Creagh et al., 1998, Tessutti et al., 2012, Tessutti et al., 2010). As a result, numerous working hypotheses exist regarding the biomechanical profile of a habitual trail runner.

In comparison to flat surfaces, running on uneven or perturbed terrain has been found to elicit differences in leg stiffness, joint angle positioning and spatiotemporal variables (Warren, 1986, Voloshina and Ferris, 2015, Sterzing et al., 2014, Grimmer et al., 2008, Ernst et al., 2014). Similarly, walking and running on surfaces of different stiffness can alter leg stiffness, ground reaction forces, and balance (Hardin et al., 2004, Tessutti et al., 2010, Tessutti et al., 2012, Dixon et al., 2000, Schutte et al., 2016). Considering this, it could be postulated that regular trail running on erratic, natural terrain with varying obstacles would influence and alter running biomechanics.

Optimal running form requires a precise interplay of lower extremity joint mobility and stability. When running on uneven ground, this relationship becomes more complex. To maintain dynamic stability on uneven ground, trail runners may require greater lower extremity joint integrity, alongside greater spatiotemporal gait and kinematic variability (Creagh et al., 1998, Schutte et al., 2016, Voloshina and Ferris, 2015). Spatiotemporal adaptations to ground irregularities may include changes in step length and width (Schutte et al., 2016, Voloshina and Ferris, 2015, Eckardt et al., 2017). Further, due to greater sensitivity to changes in ground properties, the ankle joint may contribute to overall global leg stiffness and dynamic stability to a greater extent than proximal knee and hip joints (Voloshina and Ferris, 2015, Muller et al., 2010). As a result of proprioceptive feedback or anticipatory feed-forward control, trail runners may minimise ankle joint movement, which may allow for greater variability or movement further up the kinematic chain.

In addition, trail runners must effectively manage natural obstacles and height perturbations during swing. Whether this response is subconscious (i.e. mechanical self-stability) or feed-forward controlled has been debated (Grimmer et al., 2008), but it could be hypothesised that trail runners may exhibit greater ankle, knee and hip displacement for effective ground clearance (Creagh et al., 1998). Furthermore, trail runners may adapt joint and leg stiffness in preparation for perturbations of different heights (Grimmer et al., 2008, Muller et al., 2010). It would be compelling to investigate the consequences of regular perturbed running on specific joint contributions to leg stiffness.

Biomechanical responses to surface stiffness should also be considered. Leg stiffness is suggested to adapt to surfaces of different stiffness (Ferris et al., 1999, Ferris et al., 1998). In addition, surface stiffness may affect ground contact parameters. For example, running on natural, ‘forgiving’ surfaces may increase ground contact time (McMahon and Greene, 1979, Tessutti et al., 2010). Furthermore, compliant terrain may have a dampening effect on ground contact forces experienced during running (Tessutti et al., 2010, Tessutti et al., 2012, Schutte et al., 2016). In this regard, trail runners may experience a reduction in dynamic loading on natural terrain. Although highly debated, running on compliant surfaces may reduce compressive joint forces and risk of injury (Zadpoor and Nikooyan, 2011).

Although these studies demonstrate the effects of isolated off-road exposures on running biomechanics, trail running surfaces are multifaceted. Moreover, these investigations do not account for surface habituation, and many participants in these studies were habitual road runners or merely ‘physically active’ individuals. Consequently, the running mechanics of habitual trail runners have yet to be fully described. For this reason, it would be compelling to investigate whether trail runners exhibit altered running biomechanics as result of habitually training on off-road terrain. The first step would be to study trail runners in a controlled laboratory setting. Later, to externally validate these findings, future work should employ the use of portable motion capture and inertial systems to observe real-time trail running.

### ***Neuromuscular Responses to Trail Running***

Walking and running on different surfaces have previously been shown to alter muscle activity patterns (Dolenec et al., 2015, Oliveira et al., 2016, MacLellan and Patla, 2006, Voloshina and Ferris, 2015). Although controversial, these changes may occur as passive responses (i.e. as a result of inherent muscle properties or reflex circuitries) or feed-forward responses to ground perturbations and surface stiffness (Nurse et al., 2005, Watanabe and Okubo, 1981, Grimmer et al., 2008, Muller et al., 2010). According to Nigg and Wakeling (2001), ground contact forces experienced with differing ground properties are input signals, and muscle activity would then be ‘tuned’ accordingly (Dixon et al., 2000). Considering this notion, it would be prudent for any new trail running research to understand the neuromuscular control of biomechanical adjustments that may occur with regular trail running. Muscle responses to off-road running could provide insight into the neuromuscular regulation of trail running biomechanics.

One could hypothesise that in response to exposure to disparate terrains, habitual trail and road runners may exhibit different pre-activation patterns. Specifically, pre-activation is defined as the muscle activation immediately prior to ground contact ( $\pm 100$  ms prior) that acts to prepare

the musculoskeletal system for impact shock. Pre-activation is a trained response, reacting and adapting to previous ground contact experiences (Kamibayashi and Muro, 2006). Changes in pre-activation play a prominent role in preparing for different ground properties by adjusting joint geometry and joint stiffness (Muller et al., 2010, Kamibayashi and Muro, 2006, Moritz and Farley, 2004). Although the demands of trail running terrain are more complex, studies have shown that running on asphalt *vs.* grass surfaces (Dolenec et al., 2015), or running on uneven *vs.* flat surfaces (Muller et al., 2010), can elicit changes in lower leg muscle pre-activation.

During pre-activation and subsequent ground contact, adequate coordination of muscle group activity is required to stabilise the lower extremity and optimise movement (Baratta et al., 1988, Di Nardo et al., 2015). Muscle co-activation is the simultaneous activation of agonist and antagonist muscles, and although debated, may be a mechanism of local joint and global leg stiffness regulation during dynamic locomotion (Hortobagyi and DeVita, 2000). Running on uneven ground, or in unstable shoes, has been shown to increase lower extremity muscle co-activity (Voloshina and Ferris, 2015, Apps et al., 2016). Whilst observing the mechanics and energetics of running on uneven ground, Voloshina and Ferris (2015) reported significant increases in co-contraction of *medial hamstring: vastus medialis* and *medial hamstring: vastus lateralis* muscle groups during early stance. This increase in lower extremity muscle activity may indicate a stabilising mechanism to counteract the greater demand of running on an irregular surface. It is likely that trail running surfaces would necessitate a similar response.

In addition, running on compliant or uneven surfaces can increase the variability of muscle activity patterns (Voloshina and Ferris, 2015). Uneven trail paths may warrant continuous leg stiffness and posture adjustments, which in turn could result in disrupted muscle recruitment patterns. Similar to previous responses in sand and uneven treadmill running, these irregular muscle activity patterns may increase the metabolic cost of trail running (Zamparo et al., 1992, Voloshina and Ferris, 2015, Pinnington and Dawson, 2001).

These studies provide sufficient evidence that habitual trail and road runner's muscle activity profiles may be non-identical. Future research is necessary to elucidate the implications of regular trail running on the neuromuscular system.

### ***Trail Running and Muscular Performance***

Regular changes in gradient are typical during trail running and require greater mechanical and muscular work than level surfaces (Vernillo et al., 2016). Downhill running is a large

component of trail running, and the increased negative work associated with downhill running can increase muscle damage (Eston et al., 1995). In addition, hostile and challenging trail running terrain has been shown to increase neuromuscular fatigue (i.e. decrease maximal voluntary contractions and muscle activity) (Easthope et al., 2010, Vercruyssen et al., 2016). For this reason, trail running has been used as a model for examining neuromuscular fatigue and muscle damage (Easthope et al., 2014).

Consideration should be given to investigating the neuromuscular consequences of downhill or negative gradient training in habitual trail runners. Downhill running places additional stress on the musculoskeletal system through eccentric loading of the muscle, and thus regular downhill training may have implications for RRI (Vernillo et al., 2016). On the other hand, a prior bout of downhill exercise can induce acute muscle adaptations that may be protective during subsequent downhill running (Byrnes et al., 1985, Pierrynowski et al., 1987). These adaptations have been shown to reduce muscle damage and delayed onset muscle soreness (DOMS) associated with negative training. The effects of downhill running warrant further research, which in turn will elucidate the implications of regular trail running on muscle activity patterns and determinants of running performance.

In addition to negative training, trail runners are regularly exposed to steep inclines. As the gradient increases, so does the energy cost of running (Vernillo et al., 2016). For this reason, incline or uphill training interventions have been shown to improve running economy in distance runners (Barnes et al., 2013, Ferley et al., 2014). Further, as previously mentioned, training on compliant and uneven surfaces may increase the metabolic cost of running (Zamparo et al., 1992, Voloshina and Ferris, 2015, Pinnington and Dawson, 2001). Following this, it is plausible that regular trail running may have a training effect on running economy. In this way, trail running may serve as an effective training intervention for improving running performance.

### ***Summary***

Although still in its infancy, preliminary research on the implications of trail running suggests that habitual trail runners may exhibit different muscle activity patterns and biomechanics in comparison to road running counterparts. In reality, trail runners are exposed to a complex coalescence of variable gradients, obstacles and surface stiffness. Regardless, extrapolating the findings of these studies provides insight into the adaptations that may manifest with long-term running in a dynamic environment. Future research is necessary to describe the demographical, clinical and biomechanical features of a ‘pure’ trail runner. In addition, the benefits and risks

associated with regular trail running should be described with respect to running economy, performance and injury.

This thesis endeavours to address the gaps in the current body of literature and identify the clinical, neuromuscular and biomechanical implications of trail running. As road running has been well-documented in scientific literature, special focus was placed on contrasting trail and road running athletes in this regard. Finally, this thesis aims to initiate a global conversation on trail running, whilst providing a foundation for further research into this field.

## 1.2 RESEARCH QUESTIONS

**Question 1.** *Do trail runners demonstrate greater lower extremity stability in dynamic weight-bearing activities in comparison to road runners?*

Trail runners run on uneven and unstable surfaces that would challenge and require greater whole body dynamic stability. Accordingly, we hypothesised that trail runners would exhibit greater dynamic lumbo-pelvic and lower extremity joint stability in comparison to road running counterparts.

**Question 2.** *Do trail runners exhibit differing running biomechanics to road runners?*

Road and trail running environments and training surfaces are considerably different. Acute exposure to running on different training surfaces can elicit changes in kinematics and spatiotemporal variables. Thus, we hypothesised that habitual running on a preferred surface would induce long-standing and diverse biomechanical adaptations in road and trail runners.

**Question 3.** *Do road runners demonstrate adverse kinematics and spatiotemporal parameters that increase the risk of sustaining a RRI?*

Road runners are predominantly exposed to monotonous and rigid surfaces during training. We hypothesised that unyielding road running surfaces may alter the habitual road runner's running biomechanics. We hypothesised that these changes may specifically predisposition road runners to chronic lower extremity running-related injuries (particularly those occurring at or around the knee).

**Question 4.** *Does running on road or trail terrain have an influence on the neuromuscular regulation of running biomechanics?*

It is possible to consider that neuromuscular differences exist when observing the habitual terrain that these groups train on. Acute changes in running mechanics that occur when running on different surfaces would logically require refined neuromuscular strategies. We hypothesised that as a result of long-term training on non-uniform running surfaces, experienced trail runners would exhibit different muscle activity patterns (increased activation in terminal swing and a balanced co-activation ratio) to road runners.



### **1.3 STRUCTURE OF THESIS**

This thesis comprises five sequential chapters, with the primary focus on examining and establishing an understanding of habitual trail running on the musculoskeletal system and running biomechanics of trail runners.

The second chapter, titled ‘Contrasting the trail and road running athlete: Clinical measures of dynamic stability’, clinically describes the influence of trail and road running surfaces on its participants, contrasting 21 well-trained trail runners (male and female) with 21 road running counterparts. More specifically, we assessed and subsequently compared these runners using three clinical measures of dynamic stability.

The following chapter, is titled ‘The biomechanics of trail runners & responses to barefoot running’ (Chapter Three). Preliminary findings from this study were presented at the International Society of Biomechanics in Sport (ISBS) conference in Cologne, Germany in 2017. We investigated and contrasted biomechanical and spatiotemporal gait parameters in 20 trail runners and 20 road running controls performing barefoot and shod overground running trials.

The fourth chapter, transpiring as a result of our findings detailed in Chapter Three, is titled ‘Neuromuscular contributions to trail running biomechanics’ and has been accepted for presentation at the European College of Sports Sciences (ECSS) congress in Dublin, Ireland in 2018. This chapter explores the notion that running on a preferred terrain has an influence on muscle activity patterns over the entire gait cycle (using a novel one-dimensional statistical parametric mapping method) and resultant biomechanics at discrete time points. Fifteen trail runners and 15 road runners performed overground running trials while synchronised marker trajectory, force plate and electromyographic data were collected.

The final chapter represents a holistic view of the outcomes of the present thesis. We recommend future work necessary to fully understand the implications of participating in trail running. Specifically, future research in this field should seek to augment and develop the current knowledge pertaining to the neuromuscular and biomechanical changes that occur with trail running, with special consideration given to running injury and performance.

## CHAPTER 2

### CONTRASTING THE TRAIL AND ROAD RUNNING ATHLETE: CLINICAL MEASURES OF DYNAMIC STABILITY

#### 2.1 ABSTRACT

**Introduction:** This study aimed to describe male and female trail (n = 21) and road (n = 21) runners located within the Cape Town region with regards to clinical measures of dynamic stability. Furthermore, as a secondary outcome, this study aimed to evaluate whether there were gender-related differences in clinical performance measures.

**Methods:** Three clinical assessments of dynamic stability were completed by all participants, namely: the Star Excursion Balance Test (SEBT), the Unilateral Bridge Hold (UBH) and Single Leg Squat (SLS). Marker trajectory data were collected using an eight camera motion capture system during the SLS assessment.

**Results:** No differences were found in SEBT reach distances (% leg length), SEBT composite reach distance (% leg length) and UBH times (s) between trail and road runners. When assessing the SLS task, trail runners exhibited significantly greater knee external rotation (-10.66 (22.70) vs. (11.00 (21.28) °), less ankle varus (-0.02 (4.44) vs. 4.96 (5.75) °) and less ankle external rotation (-1.55 (15.12) vs. -18.22 (20.60) °) at peak knee flexion in comparison to road runners. No gender-related effects on clinical performance outcomes were observed.

**Conclusion:** Trail runners' performance in the SLS may represent a kinematic adaptation to habitual terrain targeted at minimising ankle joint movement during weight-bearing. Future work is recommended to confirm the validity of the SLS, SEBT and UBH in the comparison of dynamic stability between different running populations and gender.

## 2.2 INTRODUCTION

Road running remains a popular recreational and competitive sport for men and women worldwide, despite the high incidence of running-related injury (RRI) (Buist et al., 2010, Fields et al., 2010, van Gent et al., 2007, van Mechelen, 1992, Van Middelkoop et al., 2008, Lun et al., 2004, Taunton et al., 2003). Numerous training exposures (e.g. weekly mileage, footwear, running surface) have been investigated in relation to running injury (Nielsen et al., 2012, Hespanhol et al., 2013). Isolating specific training factors is challenging, limiting research progress in this area, thus the risk of sustaining a RRI remains high. Although RRI's are multifactorial, the relationship between preferred running surface and RRI has been subjected to significant debate and this discussion will be central to the present thesis.

Road running terrain predominantly consists of flat, rigid surfaces such as asphalt or concrete, commonly believed to exacerbate musculoskeletal stress during exercise (Torg et al., 1974, Tessutti et al., 2012, Schutte et al., 2016, Andreasson and Peterson, 1986). Over the past decade, running 'off-road' has gained increasing appeal in the running world, with trail running becoming a popular alternative to running on the road (Foundation, 2013, Foundation, 2010, Torbidoni et al., 2015, Hoffman and Wegelin, 2009, Foundation, 2017). While road surfaces may allow for monotonous and 'mechanical' running, trail paths are variable that require anticipation of obstacles, changes in surface stiffness and steep gradients. Although research into running on unpredictable, variable terrains is in its infancy, it is plausible that off-road running may have implications for dynamic loading and stability (Schutte et al., 2016). As deficits in dynamic stability have previously been associated with RRI, the comparison of dynamic stability between road and trail runners would be of interest to clinicians (Willson et al., 2005, Williardson, 2007).

Trail runners may require greater core (lumbopelvic region) stability to maintain balance and postural control whilst running on challenging terrain. 'Core stability' is imperative for effectively producing, changing and controlling movement of the upper and lower extremities and requires a combination of neuromuscular control, muscle strength and muscle endurance (Willson et al., 2005). Running on unstable, challenging trail surfaces may amplify the engagement of local and global core musculature. Regular training may subsequently increase lower extremity and core muscle strength, which in turn may reduce aberrant joint motions during running (Williardson, 2007). Accordingly, it could be hypothesised that habitual trail runners may demonstrate superior dynamic core stability and postural control to road runners.

Furthermore, the trail running environment typically consists of fluctuating, steep slopes that may require greater work from proximal leg muscles (Biewener and Daley, 2007). Considering this, it is hypothesised that habitual trail runners may have increased hip and knee flexor muscle strength (due to greater work required during uphill running) (Roberts and Belliveau, 2005), as well as greater hip and knee extensor strength (due to greater eccentric (negative) work required during downhill running) (Vernillo et al., 2016, Eston et al., 1995). Although downhill running places significant strain on the musculoskeletal system (Giandolini et al., 2015a), the often associated acute muscle damage (delayed onset muscle soreness), fatigue and strength loss after downhill running may be reduced with training. Regular downhill training has been suggested to elicit soft tissue adaptations that act to reduce these unfavourable muscle responses (Eston et al., 1995). As a result of frequent gradient training, trail runners may exhibit significant lower extremity muscle strength, allowing for enhanced dynamic stability.

Finally, moving further down the kinematic chain, Voloshina and Ferris (2015) propose that running on uneven surfaces, alters the work done at the ankle joint to a greater extent to that of proximal hip and knee joints. In response to greater proprioceptive feedback, it has been suggested that the muscles surrounding the ankle joint act to minimise joint motion, in order to effectively and rapidly manage ground disturbances (Voloshina and Ferris, 2015, Biewener and Daley, 2007). In contrast, muscles acting at the hip and knee joint may not be as sensitive to changes in ground properties, and may instead act to manage anticipated perturbations through feed-forward control. Trail runners may therefore demonstrate greater ankle joint stability, further contributing to dynamic stability during running.

To our knowledge, habitual trail and road runners have not been compared with regards to clinical measures of dynamic stability. This study aimed to describe these two running populations using three functional assessments, namely: the Single Leg Squat (SLS), Unilateral Bridge Hold (UBH) and the Star Excursion Balance Test (SEBT). It was hypothesised that as a result of training in complex, unpredictable environments, trail runners would exhibit superior dynamic stability to road running counterparts. Specifically, it was hypothesised that trail runners would present with greater lumbo-pelvic, hip and ankle joint stability. Further, due to known anatomical differences between male and female runners (Horton and Hall, 1989, Gribble et al., 2013), it would be prudent to consider clinical performance outcomes in relation to gender. It was hypothesised that common musculoskeletal differences between males and females would influence measures of dynamic stability.

## **2.3 MATERIALS AND METHODS**

### **2.3.1 PARTICIPANTS**

Twenty-one male and female trail runners (80% of running training completed on off-road terrain for the past year) and 21 age- and performance-matched road running controls (80% of training completed on road surfaces (asphalt/pavement) volunteered to participate in this study. Participants were experienced and habitually shod runners, training at least four hours a week for two years prior to the study, and could complete a 10 km road run in  $\leq 50$  minutes. Participants had been injury free for six months prior to enrolment in the study, and had no current or previous history of orthopaedic abnormalities, neurological disorders, or previous lower limb surgeries.

Participants were recruited via a media release to local running clubs, to which recruitment posters & flyers were distributed. Participants were fully aware of the risks and benefits associated with the study and provided written informed consent prior to participation in the study. The study was granted ethical approval from the University of Cape Town Human Research Ethics Committee (HREC #371/2016).

### **2.3.2 TESTING PROCEDURE**

Participants were requested to visit the laboratory on a single occasion. Participants completed a questionnaire to establish previous and current training status and injury history. Basic anthropometric measurements were recorded. Participants subsequently completed three clinical function tests: the Star Excursion Balance Test (SEBT), Unilateral Bridge Hold (UBH) and Single Leg Squat (SLS). Reflective markers were placed on participants for biomechanical analysis during the SLS test.

### **2.3.3 PERSONAL DETAILS AND MEDICAL HISTORY**

#### **QUESTIONNAIRE**

A standard research unit questionnaire regarding personal details, medical history, running injuries, performance and experience was completed by all participants.

### **2.3.4 ANTHROPOMETRIC MEASUREMENTS**

Participants were instructed to remove their footwear and socks. Various anthropometric measurements (height (cm), body mass (kg), leg length (cm), medio-lateral knee (across knee

axis) and medio-lateral ankle (inter-malleolar) width (cm)) were recorded with the participant in standing position. Bilateral leg length was measured from the anterior superior iliac spine to the medial malleolus using a standard tape measure. Bilateral knee and ankle width were measured using a small anthropometer. Body mass index (BMI) was calculated ( $\text{BMI} = \text{body mass (kg)} / \text{height (m)}^2$ ).

### **2.3.5 CLINICAL ASSESSMENTS**

Participants remained barefoot for the entire clinical test battery. Leg dominance was determined as the preferred leg the participant would use to kick a ball. The SEBT was repeated for dominant and non-dominant limbs, while the UBH and SLS were performed with the dominant limb as stance limb (Non-dominant leg was suspended). Each test was described (with criteria for termination of tests detailed) and demonstrated by the investigators.

#### ***Star Excursion Balance Test (SEBT)***

The SEBT is considered a reliable and validated measure of dynamic lumbo-pelvic stability, and a valuable clinical tool in predicting the likelihood of a lower extremity injury in physically active individuals (Gribble et al., 2012). The test utilises a star-shaped grid, consisting of three standard tape measure lines (in 5 mm increments) securely fixed to the floor. The start position is in the centre of the grid, where all three lines of the grid begin at 0 mm and extend out from each other in different directions. As recommended by Hertel et al. (2006) only three reach directions were utilised, namely: anterior, posteromedial and posterolateral. Participants chose a stance limb at random, placing the foot in the centre of the grid with the heel aligned with the anterior direction, and the distal aspect of the big toe placed at the intersection of all three lines. Participants were verbally informed that the goal of the test was to reach as far as possible in all three directions with the reach limb and instructed to lightly touch the directional tape with the reach limb whilst maintaining balance on their stance limb. Participants were instructed to complete four practice trials prior to the test to eliminate a possible learning curve (Munro and Herrington, 2010), after which the test was initiated. The participants attempted each reach direction three times, returning to the start position between test attempts (Hertel et al., 2000). A test attempt was considered invalid if the participant was unable to maintain balance on the stance limb, lifted or moved the stance limb from the start position during the trial, rested their reach limb on the tape (instead of a light touch), or failed to return the reach limb to the starting position. In the case of an invalid trial, reach distance was not recorded, and the participant was instructed to repeat the trial. For all three 'good' directional attempts, the stance limb and the

maximum reach distance (in centimetres) was recorded by the investigator. The test was subsequently repeated with the opposite limb as the reach limb.

### ***Unilateral Bridge Hold (UBH)***

Lumbo-pelvic stability and endurance was assessed using a timed supine unilateral leg bridge hold (McGill et al., 2003, Sato and Mokha, 2009, Butowicz et al., 2016). Participants were instructed to lie supine on the floor with hands by their sides, knees bent and feet flat on the floor. Feet were placed under the knees, creating a 90 degree angle (confirmed with a goniometer). From this position, participants raised their hips off the floor, creating a straight line from the knees through to their shoulders. Participants slowly raised and extended their non-dominant leg, with knees parallel and pelvis raised and level. Participants were instructed prior to the start of the test to hold this final position for as long as possible, with a 120 second period being both the maximum allotment of time given for the test and the best possible score. During the test, the investigator encouraged the participant by verbally communicating the time elapsed in 30 second intervals. The test was terminated if: the 120 second time limit was reached, the pelvis dropped a total of 2 cm from starting height position, or the correct single leg bridge hold position could no longer be maintained (as observed by investigator). Maximum holding time (seconds) and supporting leg (i.e. dominant leg) were recorded.

### ***Single Leg Squat (SLS)***

The SLS is a reliable clinical tool used to observe dynamic lower extremity alignment and stability during weight-bearing (Zeller et al., 2003, Alenezi et al., 2014). Participants were instructed to stand on their dominant leg with arms folded across the chest and opposite leg extended in front of the body. From this position, the participant was instructed to squat down as far as possible, and then back to the start position, keeping the non-supported leg from touching the ground. To most closely resemble clinical practice, squat depth was not standardised (Crossley et al., 2011). Participants were allowed up to three practice attempts, and then performed five consecutive SLS trials (Crossley et al., 2011). A trial was deemed invalid if participant lost balance or fell, or if the non-supporting leg touched the ground (Dingenen et al., 2014).

Three-dimensional (3D) marker trajectories were recorded during SLS protocol using an eight camera VICON MX motion capture system (Oxford Metrics Ltd, Oxford, UK) sampling at 250 Hz. Marker trajectories were reconstructed and gaps filled using VICON Nexus 1.8.2 software. Passive reflective markers were attached bi-laterally on the lower body with double-sided tape. A modified Helen-Hayes marker set as described by Kadaba et al. (1990) was used (Marker 15

was replaced with two posterior superior iliac crest markers, wand markers 4, 6, 11 & 13 were replaced with asymmetrically placed normal marker placements). This marker set was used to define anatomical co-ordinate systems in each of the three segments (hip, knee and ankle).

## **2.4 DATA ANALYSIS**

With regards to the SEBT, average reach distances for all three directions were used for analysis. In addition, the average reach distance for each direction was summed to yield a composite reach distance (CRD) for each limb. Each averaged reach distance was normalised to leg length and reported as a percentage of leg length (MAXD) (Gribble and Hertel, 2003).

$$\% \text{ MAXD} = \text{reach distance/leg length (cm)} \times 100.$$

In the same way, CRD (cm) was normalised by dividing the sum of all three averaged reach distances (cm) by 3 times leg length (cm) and multiplying by 100.

The difference between average anterior reach distances (cm) for dominant and non-dominant limbs was normalised to the average of left and right leg length (cm) and multiplied by 100. Participants were classified as either at risk of injury (> 4.5% of limb length) or normal ( $\leq$  4.5% of limb length) (Stiffler et al., 2017).

During the SLS, marker trajectory data were collected from the motion capture cameras and filtered using a low-pass fourth order Butterworth filter with a cut-off frequency at 8 Hz. The second valid squat in a sequence of five was used for analysis. The PlugInGait Model (VICON, Oxford Metrics, Oxford, UK) was used to determine 3D joint angles at the lower extremity joints in sagittal, frontal and transverse planes. Three-dimensional (3D) joint angles of the ankle, knee and hip joints were calculated according to the joint coordinate system (Grood and Suntay, 1983). Kinematic variables were exported to .csv files and imported into a customised MATLAB (R2014a, 8.3.0.532, Mathworks Inc., Natick, USA) programme for data analysis. Discrete kinematics were extracted at peak knee flexion (PKF) of the dominant limb. At this point, two participants (one from each running group) were removed due to incomplete data. The SLS data reported here represents the results from 40 participants.

## **2.5 STATISTICAL ANALYSIS**

Statistical analysis was performed using IBM SPSS (Statistical Package for the Social Sciences) (IBM, New York, USA). Data were screened for normality and homogeneity of variance using Shapiro-Wilk's and Levene's test, respectively. A two-way analysis of variance (ANOVA) or



non-parametric equivalent Mann-Whitney U test (for non-normally distributed data) tested for differences between groups (Trail *vs.* Road) and gender (Male *vs.* Female) in: age (years), height (cm), mass (kg), BMI (kg.m<sup>2</sup>), 10 km and 21 km performance time (s), peak hip, knee and ankle angles at PKF (degrees) during the SLS assessment, UBH time (s), SEBT excursion distances (% leg length), CRD (% leg length) and anterior direction asymmetry (% leg length). In addition, four separate two-way ANOVAs tested for differences between groups (Trail *vs.* Road) and tested leg (Dominant *vs.* Non-Dominant) in SEBT excursion distances (% leg length) and CRD (% leg length). Chi-squared tests of independence were applied to test the relationship between excessive anterior direction asymmetry (% leg length) and 1) running group, and 2) gender. Effect sizes (ES) were calculated according to Cohen (1988), with ES magnitudes defined as small (0.2), medium (0.5) or large (0.8). Statistical significance was set at  $p < 0.05$ . Data are presented as means (standard deviations) unless otherwise stated.

## 2.6 RESULTS

### 2.6.1 GROUP DESCRIPTIVE CHARACTERISTICS

The descriptive characteristics of the trail and road runners are presented in Table 2.1. Of the 21 participants in the trail group, 13 were male and eight were female. The road running group comprised 11 male and 10 female participants. Male runners presented with greater body mass (73.89 (8.20) vs. 54.84 (6.94) kg,  $p < 0.001$ , ES = 2.51, very large effect), height (176.55 (6.20) vs. 166.92 (7.56) cm,  $p < 0.001$ , ES = 1.39, very large effect) and body mass index (BMI) (23.67 (1.96) vs. 19.65 (1.76) kg.m<sup>2</sup>,  $p < 0.001$ , ES = 2.16, very large effect) in comparison to female runners.

**TABLE 2.1.** Descriptive characteristics of trail and road runners

	Trail (n = 21)		Road (n = 21)	
	Female (n = 8)	Male (n = 13)	Female (n = 10)	Male (n = 11)
<b>Age (years)</b>	31 (7.20)	32 (6.14)	27 (6.04)	33 (12.17)
<b>Body mass (kg)</b>	53.51 (6.47)	75.05 (4.40)	55.90 (7.46)	72.52 (11.30)**
<b>Height (cm)</b>	166.40 (9.11)	176.58 (3.94)	167.34 (6.56)	176.50 (8.36)**
<b>BMI (kg.m<sup>2</sup>)</b>	19.28 (1.16)	24.09 (1.53)	19.94 (2.14)	23.17 (2.35)**
<b>10 km personal best (min)</b>	46 (5.58)	42 (5.81)	43 (6.76)	40 (5.78)
<b>21 km personal best (min)</b>	104 (12.54)	98 (14.61)	100 (20.70)	92 (12.08)

\*\* significant gender difference ( $p < 0.01$ )

### 2.6.2 CLINICAL TESTS

The dominant and non-dominant limb SEBT reach distances and CRD (% leg length) for trail and road runners are presented in Table 2.2.

No differences were found in normalised SEBT distances (cm) in all 3 reach directions (% leg length), composite reach distance (% leg length), anterior direction asymmetry (% leg length) and unilateral bridge hold time (s) between running groups (Trail vs. Road) and gender (Male vs. Female) (Table 2.3).

When assessing the SLS test task, various group kinematic differences were found (Table 2.3). At PKF, trail runners exhibited greater knee external rotation ( $p = 0.006$ , ES = 0.98, large effect), less ankle varus ( $p = 0.008$ , ES = 0.97, large effect) and less ankle external rotation ( $p$

= 0.017, ES = 0.86, large effect) in comparison to the road runners. No significant gender differences were found.

**TABLE 2.2.** Star excursion balance test reach distance (% of leg length) in trail and road runners

	Trail (n = 21)		Road (n = 21)	
	Dominant	Non-Dominant	Dominant	Non-Dominant
<b>Anterior Reach</b>	73.58 (11.97)	74.03 (13.1)	77.05 (12.25)	76.05 (11.33)
<b>Posteromedial Reach</b>	100.34 (14.45)	100.5 (15.95)	98.7 (13.63)	97.46 (12.61)
<b>Posterolateral Reach</b>	107.15 (15.92)	107.23 (17.3)	109.09 (14.06)	108.25 (10.89)
<b>CRD<sup>†</sup></b>	93.69 (13.34)	93.92 (14.49)	94.95 (12.12)	93.92 (10.21)

CRD: Composite Reach Distance. <sup>†</sup>Normalised to 3 times leg length (cm).

**TABLE 2.3.** Clinical test battery results in female and male trail and road runners (dominant-limb only)

	Trail		Road	
	Female	Male	Female	Male
<b>UBH Time (s)<sup>a</sup></b>	107 (78.75-120)	110 (87 - 120)	120 (120-120)	120 (64 - 120)
<b>SEBT Reach (% of leg length)</b>				
Anterior	70.03 (11.44)	75.76 (12.2)	78.25 (13.52)	75.96 (11.53)
Posteromedial	96.16 (10.36)	102.91 (16.32)	101.15 (13.31)	96.48 (14.17)
Posterolateral	103.89 (12.56)	109.15 (17.85)	108.43 (15.84)	109.69 (13.00)
CRD <sup>b</sup>	90.03 (10.89)	95.94 (14.59)	95.94 (13.84)	94.05 (10.94)
Anterior side-to-side asymmetry <sup>†</sup>	3.19 (1.98)	3.31 (3.03)	4.27 (4.97)	4.75 (3.01)
<b>Single Leg Squat (PKF °)</b>				
Hip Flexion	61.24 (16.53)	61.82 (30.41)	51.54 (22.89)	71.48 (18.93)
Hip Adduction <sup>a</sup>	12.21 (5.23 - 15.00)	9.78 (6.46 - 10.95)	10.05 (6.94 - 19.73)	12.08 (4.56 - 14.22)
Hip Rotation <sup>§</sup>	16.41 (22.79)	19.09 (25.25)	1.41 (13.45)	6.73 (21.18)
Knee Flexion <sup>a</sup>	77.20 (72.76 - 83.00)	72.13 (57.13 - 112.98)	73.99 (61.09 - 85.13)	74.59 (63.27 - 88.10)
Knee Varus	16.98 (19.82)	17.61 (24.43)	3.77 (14.23)	10.17 (17.39)
Knee Rotation <sup>§</sup>	-5.18 (24.23)	-14.31 (21.92)	7.64 (16.65)	14.37 (25.56) ##
Ankle Dorsiflexion <sup>a</sup>	33.48 (29.61 - 39.64)	38.49 (25.61 - 42.46)	31.46 (21.61 - 33.64)	32.67 (28.05 - 42.19)
Ankle Varus	2.38 (3.92)	-1.59 (4.16)	4.76 (5.15)	5.17 (6.56) ##
Ankle Rotation <sup>§</sup>	-9.82 (19.16)	3.96 (15.84)	-14.84 (16.13)	-21.59 (24.72) #

UBH: Unilateral Bridge Hold; SEBT: Star Excursion Balance Test; CRD: Composite Reach Distance; PKF: Peak Knee Flexion. <sup>a</sup>Median and interpercentile range presented. <sup>b</sup>Normalised to 3 times dominant

leg length (cm). †Normalised to average of right & left limb length (cm). §Positive values – internal rotation; negative values – external rotation. #significant group difference ( $p < 0.05$ ). ##significant group difference ( $p < 0.01$ ).

## 2.7 DISCUSSION

The purpose of this study was to describe the trail running athlete in comparison to the road running athlete, with the supposition that they both possess differing preferred training surfaces. Specifically, this study aimed to compare clinical measures of dynamic stability in male and female trail and road runners. The main finding of this study was that the battery of three common clinical tests employed revealed few differences between the two running populations. Furthermore, secondary analysis revealed that gender had no effect on clinical performance outcomes.

Interestingly, clinically meaningful differences between trail and road runners were observed only in the SLS assessment. By recording the SLS with a 3D motion capture system, the specific hip, knee and ankle joint contributions to lower extremity stability could be investigated (Nakagawa et al., 2012, Alenezi et al., 2014, Weeks et al., 2012). Peak knee flexion (PKF), purported to be the strongest predictor of performance in a SLS (Weeks et al., 2012), was similar between the groups. However, at PKF, trail runners presented with greater knee joint movement in the transverse plane, with less movement in the ankle joint in frontal and transverse planes, in comparison to road runners. These findings imply that during weight-bearing in the SLS, trail runners stabilised the lower extremity to a greater extent at the level of the ankle, allowing for greater joint movement further up the kinematic chain.

These results support this study's hypothesis, and are consistent with previous research into the biomechanical differences of even vs. uneven treadmill running (Voloshina and Ferris, 2015). Voloshina and Ferris (2015) reported notably less range of motion and work done at the ankle joint on an uneven treadmill surface in comparison to a standard treadmill. Due to its distal location, the ankle is more sensitive to load and changes in surface properties, and these adjustments may represent a lower extremity control strategy. In the present study, it is plausible that the irregular nature of trail surfaces may require trail runners to have significant running gait and kinematic variability, while the ankle joint, the first point of contact with surface, is more stable. Running on surfaces of different stiffness and height perturbations has been shown to alter joint kinematics (Hardin et al., 2004, Tessutti et al., 2010, Tessutti et al., 2012, Dixon

et al., 2000, Schutte et al., 2016), and thus the observed differences in kinematics between the groups may be an adaptation to preferred running terrain.

Contrary to this study's hypothesis, UBH time to fatigue and SEBT performance were similar in trail and road runners. This finding suggests that despite disparate training exposures, trail and road runners may have similar lumbo-pelvic stability and endurance. The current literature with regards to the utilisation of UBH as a clinical assessment for runners is sparse, with methodological differences making comparisons to the literature challenging. However, using a similar protocol, Sato and Mokha (2009) reported an average UBH time to fatigue (or a degree of pelvic instability) of 23.0 (6.5) seconds in 43 healthy participants. Although these UBH times are notably lower than those reported for the runners in the current study, greater UBH scores are to be expected in well-trained runners.

Moreover, Sato and Mokha (2009) used a digital inclinometer to monitor a predetermined degree of pelvic instability. This may be a more sensitive method of terminating the test in comparison to the 2 cm pelvic drop used in the present study. Regardless, both running groups in the present study completed the same UBH testing protocol. Despite similar performances, it is plausible that as a result of training on different surfaces, trail and road runners may have different muscle recruitment strategies to maintain lumbo-pelvic control (Magee et al., 2015). Further research is required to determine the specific muscle contributions to UBH performance and dynamic stability in trail and road runners.

Trail and road runners' SEBT reach and composite reach distances are comparable to those previously reported in healthy & athletic participants (Coughlan et al., 2012, Plisky et al., 2006, Stiffler et al., 2015). To the best of our knowledge, this is the first study to report SEBT performance in trail runners. Although caution should be exercised when interpreting SEBT performance outside of the context of running (Stiffler et al., 2017), Stiffler et al. (2015) reported anterior direction asymmetry of >4.5% to be associated with the likelihood of sustaining a non-contact ankle or knee injury in various collegiate athletes, regardless of sport. In this case, 13.1% of the participants in the present study (7 road and 4 trail runners) would be at risk of sustaining an injury. However, future research is imperative before SEBT outcomes can be adequately considered in association with running performance and injury.

In summary, these findings suggest that preferred training surface may not have a notable effect on the clinical measures of dynamic stability utilised in the present study. Interestingly, a recent study by Yang and King (2016) observed that young, healthy adults demonstrated similar

dynamic stability whilst walking on different surfaces. Further exploration revealed that these participants exhibited significantly different gait parameters between the two surfaces. Considering this, it is possible that trail and road runners may adjust for changes in surface properties through changes in spatiotemporal and biomechanical gait characteristics. Further investigation with comprehensive running analyses will be necessary to understand the long-term effects of habitual training surfaces in different running disciplines.

The second finding was that gender had a negligible effect on clinical outcomes measures. The differences observed in height, mass and body mass index (BMI) between male and female participants were anticipated. However, despite established anatomical differences (Horton and Hall, 1989, Gribble et al., 2013) and previous research reporting gender-related differences in lower extremity function and kinematics observed during running and various clinical tests (Chumanov et al., 2008, Ferber et al., 2003, Graci et al., 2012), gender had no effect on the outcomes for all three clinical assessments. Future studies will be necessary to confirm these findings.

In summary, although similar performances in the SEBT and UBH test may be attributed to the well-matched demographics of the participants, it is possible that these two clinical tests may not be sensitive enough to reveal differences between different running populations or genders. In addition, as testing procedures and data analysis in the SLS, SEBT and UBH have not been standardised, nor normative data for performance in these tests exist for road or trail runners, it makes comparisons to the literature challenging. However, this investigation is the first step towards describing and reporting normative data for these three tests in road and trail runners. Future research should look to supplement the test battery with other functional screening tools to describe these two running populations.

## **2.8 CONCLUSION**

Although recent research suggest that running on challenging, erratic terrain influences dynamic stability (Schutte et al., 2016), the scientific understanding of the potential musculoskeletal consequences of running on natural, trail surfaces is limited. The present study adds to the literature by clinically assessing and describing habitual male and female trail and road runners. The major finding from the present study was that trail runners exhibited significantly greater knee external rotation, with decreased ankle varus and external rotation during weight bearing in the SLS in comparison to road runners. These kinematics may represent an adaptation to regular trail running, and suggest that the ankle joint is a major

contributor to dynamic stability when running on uneven ground. However, whether trail runners demonstrate superior dynamic stability to road runners warrants further inquiry. Interestingly, gender was observed to have a trivial effect on all clinical performance outcomes. Future work is necessary to confirm the validity of the SLS, SEBT and UBH clinical tests in running populations.

## CHAPTER 3

# THE BIOMECHANICS OF TRAIL RUNNERS & RESPONSES TO BAREFOOT RUNNING

### 3.1 ABSTRACT

**Introduction:** This study aimed to investigate the biomechanical differences between 20 well-trained trail runners and 20 performance-matched road runners during barefoot and shod running trials. In addition, the study aimed to determine whether trail runners possess characteristics that are favourable in reducing the risk of running-related injury (RRI) when compared to their road running counterparts.

**Methods:** Three-dimensional motion capture marker trajectory and synchronised force platform kinetic data were collected during randomised barefoot and shod overground running on a synthetic track. Kinematic (lower extremity joint angles, joint stiffness and spatiotemporal parameters) and kinetic (ground reaction forces and initial loading rate (ILR)) data were captured for subsequent analysis.

**Results:** Trail runners demonstrated lower peak knee flexion (34.71 (6.77) vs. 42.86 (7.25) °) and pronation variables (magnitude (15.99 (6.97) vs. 21.30 (9.56) °) and velocity (68.40 (31.22) vs. 84.86 (40.25) °.s<sup>-1</sup>) during stance, and lower ankle stiffness (7.0 (4.0) vs. 9.27 (4.59) Nm/°) during initial ground contact compared to road runners. Spatiotemporal parameter analysis revealed shorter step duration (0.34 (0.02) vs. 0.35 (0.02) s), shorter ground contact time (0.24 (0.02) vs. 0.25 (0.03) s) and higher step frequency (2.91 (0.20) vs. 2.83 (0.18) Hz) in the trail runners. When assessed barefoot, both running groups presented with significantly greater ILR (136.72 (83.29) vs. 79.76 (41.61) BW.s<sup>-1</sup>) and foot pronation components (magnitude (21.74 (7.77) vs. 15.55 (8.62) °) and velocity (91.35 (33.61) vs. 61.92 (34.07) °.s<sup>-1</sup>), compared to shod conditions.

**Conclusion:** These findings suggest that a runner's habitual terrain can have biomechanical implications that may determine the relative risk of sustaining a RRI. Given that trail runners demonstrated purported superior running gait characteristics for injury and performance, it was unexpected to find that the trail runners exhibited similar knee stiffness and ILR to road runners. In this regard, trail and road runners may be at a similar risk of chronic RRI. Additionally,



consistent with current evidence, habitually shod runners who engage in barefoot running may be at greater risk of developing a RRI.

## **3.2 INTRODUCTION**

Road running (a sport characterised by running primarily on asphalt or concrete terrain) is a popular form of exercise, with multiple physiological and psychological benefits (Hassmén et al., 2000, Penedo and Dahn, 2005). However, despite technological advances in running footwear and medical sciences, incidence for RRI remain high, with 40-50% of distance road runners reporting an injury every year (Fields et al., 2010). The majority of these injuries are categorised as overuse injuries (cumulative micro-trauma occurring as a result of repetitive movement) (Elliott, 1990), with the soft tissue structures at, or around the knee joint being the most common points of injury (van Gent et al., 2007).

To date, research on RRI has largely been limited to the road running population, and little is known about the incidence or aetiology of RRI in other disciplines or forms of running. The causes of RRI in road runners are universally debated, with multiple intrinsic (i.e. personal characteristics) and extrinsic factors suggested to increase the risk of sustaining a RRI. The association between intrinsic factors and RRI is unclear, thus the monitoring and assessment of extrinsic factors, or a combination of both, is believed to be useful in providing insight into RRIs. Two extrinsic factors relevant to this investigation are: atypical running biomechanics (e.g. lower limb joint angular excursions, joint stiffness and dynamic foot function) (Gijon-Nogueron and Fernandez-Villarejo, 2015, Willems et al., 2007, Dowling et al., 2014, Hamill et al., 2009), and training-related errors (e.g. training surface, weekly mileage and footwear) (Daoud et al., 2012, van Gent et al., 2007, van der Worp et al., 2015).

A recent development in recreational and competitive running has been the emergence of trail (off-road) running. Trail running is characterised by exposure to compliant surfaces, steep gradients, uneven terrain and unexpected obstacles. Although research on trail running is still in its infancy, running on surfaces with varying stiffness has been shown to alter lower limb kinematics and/or result in compensatory changes in leg stiffness (Hardin et al., 2004, Dixon et al., 2000, Kerdok et al., 2002, Ferris et al., 1998). In the same way, acute exposure to uphill/downhill running and running on uneven terrains can result in adaptive changes in joint mechanics, ground reaction forces (GRFs) and dynamic stability (Schutte et al., 2016, Vernillo et al., 2016). Furthermore, an epidemiological study on RRI in ultra-trail runners reported that training on mountainous paths may be protective against the development of RRI when

compared to training on asphalt surfaces (Malliaropoulos et al., 2015). By extrapolating the findings of this research, it is plausible to suggest that habitual trail runners may present with differing biomechanical and spatiotemporal gait patterns and injury profiles relative to their road running counterparts. However, current insight into the demands of regular off-road running and the relationship between trail running and injury remains speculative.

Another growing running collective is that of barefoot running. Some researchers suggest that running barefoot minimizes impact at ground contact, improves muscle strength and running efficiency (Lieberman et al., 2010, Gillinov et al., 2015, Robbins and Hanna, 1987, Divert et al., 2005). Subsequently, over the last decade, barefoot running gained widespread interest in the global running community (Jenkins and Cauthon, 2011). However, similar to that of trail running, the available literature with regards to the mechanical, clinical and performance-related implications of barefoot running, is still emerging. Limited evidence supports these claims, and the purported benefits of barefoot running may only occur with an adaptive foot strike pattern change from a rearfoot strike (RFS) pattern (typical in 75% of habitually shod road runners) to a forefoot strike (FFS) position (Hall et al., 2013, Larson et al., 2011, Hasegawa et al., 2007, De Wit et al., 2000). A more flat-footed, FFS landing position has been shown to eliminate the initial impact peak on ground contact as observed with heel striking. In addition, FFS patterns may favourably change spatiotemporal parameters to reduce loading and moments around the knee and hip, and may reduce the risk of sustaining a RRI (Heiderscheit et al., 2011, Lieberman et al., 2010, Daoud et al., 2012).

However, whether a FFS pattern is synonymous with barefoot running is still unclear, with recent research reporting significantly increased impact and ILRs in habitually shod runners engaging in acute barefoot running (Tam et al., 2016a, Lieberman, 2012). In this case, barefoot running may pose a greater risk of RRI to individuals that typically run in traditional, cushioned running shoes. Furthermore, recent research identifies great inter-individual variability in responses to barefoot running (Tam et al., 2016b), highlighting that from a clinical perspective, the encouragement of barefoot running for protection from RRI and improving performance may be imprudent. Although the recommendation of barefoot running may be unsubstantiated, running in the absence of shoes (variable in technology and wear, amongst other confounding factors) acts as a controlled and unfamiliar condition in the laboratory. In this regard, exposure to acute barefoot running remains a valuable research tool, allowing for the effective comparison of motor control strategies and biomechanics between habitually shod populations.

With widespread growth in participation of trail and barefoot running disciplines, investigation into the biomechanical implications on RRI is imperative. Accordingly, the present study aimed to describe the differences in lower limb biomechanics in experienced habitually shod trail and road runners. In addition, this study aimed to examine whether these two running populations would respond differently to barefoot running. It was hypothesised that experienced trail and road running populations would present with altered biomechanical profiles due to training on different running terrains, with habitual road runners presenting with kinetics & kinematics that may predispose them to lower limb RRI (particularly RRI occurring at or around the knee). Furthermore, it was hypothesised that biomechanical adaptations that may occur with habitual trail running would result in a favourable response to acute barefoot running in the laboratory. The supposition was that the response would appear in the form of lower ILR and ground reaction forces during exposure to acute barefoot running.

### **3.3 MATERIALS AND METHODS**

#### **3.3.1 PARTICIPANTS**

20 male and female trail runners (80% of running training completed on off-road terrain for the past year) and 20 age- and performance-matched road running controls (80% of training completed on road (asphalt/pavement) volunteered to participate in this study. Participants were experienced and habitually shod runners, training at least four hours a week for two years prior to the study, and could complete a 10 km road run in  $\leq 45$  minutes. Participants had been injury free for six months prior to enrolment in the study, and had no current or previous history of orthopaedic abnormalities, neurological disorders, or previous lower limb surgeries.

Participants were recruited via a media release to local running clubs, to which recruitment posters & flyers were distributed. Participants were fully aware of the risks and benefits associated with the study and provided written informed consent prior to participation in the study. The study was granted ethical approval from the University of Cape Town Human Research Ethics Committee (HREC #371/2016).

#### **3.3.2 TESTING PROCEDURE**

Participants were requested to visit the laboratory on a single occasion. Reflective markers were placed on each participant for biomechanical analysis. Participants were provided with a familiarisation period on the running track. They were requested to complete at least ten running bouts at a speed best matching that which they would currently use for a 21 km training run. An individualised target velocity was created using the average speed from the final three familiarisation runs.

Participants subsequently completed six clean overground running trials along the 40 m runway in both barefoot and shod conditions. A trial was accepted if the velocity of the run was within 5% of the target speed. A participant landing directly on the force plate, striking first with their dominant leg and with no evidence of targeting defined a successful trial. Leg dominance was determined as the preferred leg the participant would use to kick a ball.

### **3.3.3 EXPERIMENTAL CONDITIONS**

Biomechanical testing for both trail and road running groups was performed in two randomised conditions, barefoot and shod. Shod trials were performed in the shoe in which the participant was currently completing the most mileage. Shoes were not controlled for wear or mileage.

### **3.3.4 INSTRUMENTATION**

Running trials were completed on a 40 m indoor synthetic track. Passive reflective markers were attached bi-laterally on the lower body with double-sided tape. A modified Helen-Hayes marker set (described in Chapter Two, Section 2.3.5) was used (Kadaba et al., 1990). Three-dimensional (3D) marker trajectories forces were recorded using an eight camera VICON MX motion capture system (Oxford Metrics Ltd, Oxford, UK) sampling at 250 Hz. Ground reaction force data was collected with a 900 x 600 mm embedded force platform (AMTI, Watertown, MA, USA) sampling at 2000 Hz and synchronised with the motion capture system. Kinetic and kinematic data were captured for all participants over 9 m of the track. Marker trajectories were reconstructed and gaps filled using VICON Nexus 1.8.2 software.

### **3.3.5 DATA ANALYSIS**

Marker trajectory data collected from the motion capture cameras and kinetic data collected from the force plates were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency at 8 and 60 Hz, respectively. The PlugInGait Model (VICON, Oxford Metrics, Oxford, UK) was used to determine 3D joint angles and net resultant joint moments at the lower extremity joints in sagittal, frontal and transverse planes. 3D joint angles of the ankle, knee and hip joints were calculated according to the joint coordinate system (Grood and Suntay, 1983) and net external resultant moments were calculated using an inverse dynamics procedure (Davis et al., 1991). External moments were normalised to body mass ( $\text{Nm.kg}^{-1}$ ). Sagittal plane quasi-joint stiffness for the ankle and knee joint were calculated according to Hamill et al. (2009) at the point at which the joint reached maximum flexion during ground contact (from initial contact to mid-stance).

Discrete kinetic measurements extracted were peak vertical ground reaction force (vGRF) (BW), medio-lateral GRF (BW), anterior-posterior GRF (BW), initial loading rate (ILR) ( $\text{BW.s}^{-1}$ ) and vertical impulse ( $\text{N.s}^{-1}$ ). Discrete kinematics extracted included self-selected speed ( $\text{m.s}^{-1}$ ), foot strike angle ( $^{\circ}$ ), peak knee flexion angle during stance ( $^{\circ}$ ), foot pronation magnitude during stance ( $^{\circ}$ ) and foot pronation velocity during stance ( $^{\circ}.\text{s}^{-1}$ ). Discrete spatiotemporal

parameters extracted were swing time (s), stride duration (s), frequency (Hz) and ground contact time (s). Foot pronation magnitude (rearfoot eversion) was inversely calculated as the difference between total inversion at ‘foot-strike’ and ‘toe-off’ phases during stance. Foot pronation velocity was subsequently calculated as the quotient of foot pronation magnitude divided by total ground contact time. Ankle angle at initial ground contact in the sagittal plane was used to elucidate rudimentary foot strike patterns, with the investigators assigning a value above 0° to represent ‘Rearfoot strike (RFS)’, and a value below 0° to represent ‘Forefoot strike (FFS)’ (Altman and Davis, 2012).

Biomechanical variables were exported to .csv files and imported into a customised MATLAB (R2014a, 8.3.0.532, Mathworks Inc., Natick, USA) programme for data analysis. The data for each participant’s dominant limb for the complete gait cycle was averaged over three trials for each condition (barefoot and shod) and normalised to stance phase. Stance phase was defined as the period over which a vertical force exceeded one standard deviation (SD) above baseline force platform noise and continued to elevate until toe-off (Tam et al., 2017).

### **3.3.6 STATISTICAL ANALYSIS**

Statistical analysis was performed using IBM SPSS (Statistical Package for the Social Sciences) (IBM, New York, USA). Data were screened for normality and homogeneity of variance using Shapiro-Wilk’s and Levene’s test, respectively. A t-test was applied for age- and performance-matching of the groups. A two-way analysis of variance (ANOVA) or non-parametric equivalent Mann-Whitney U test (for non-normally distributed data) tested for differences between groups (Trail vs. Road) and conditions (Barefoot vs. Shod) in all other biomechanical variables. A chi-squared test of independence was applied to test the relationship between running groups and foot strike pattern in different running conditions. Effect size (ES) was calculated according to Cohen (1988), with ES magnitudes defined as small (0.2), medium (0.5) or large (0.8). Statistical significance was set at  $p < 0.05$ . Data are presented as means (standard deviations) unless otherwise stated.

### 3.4 RESULTS

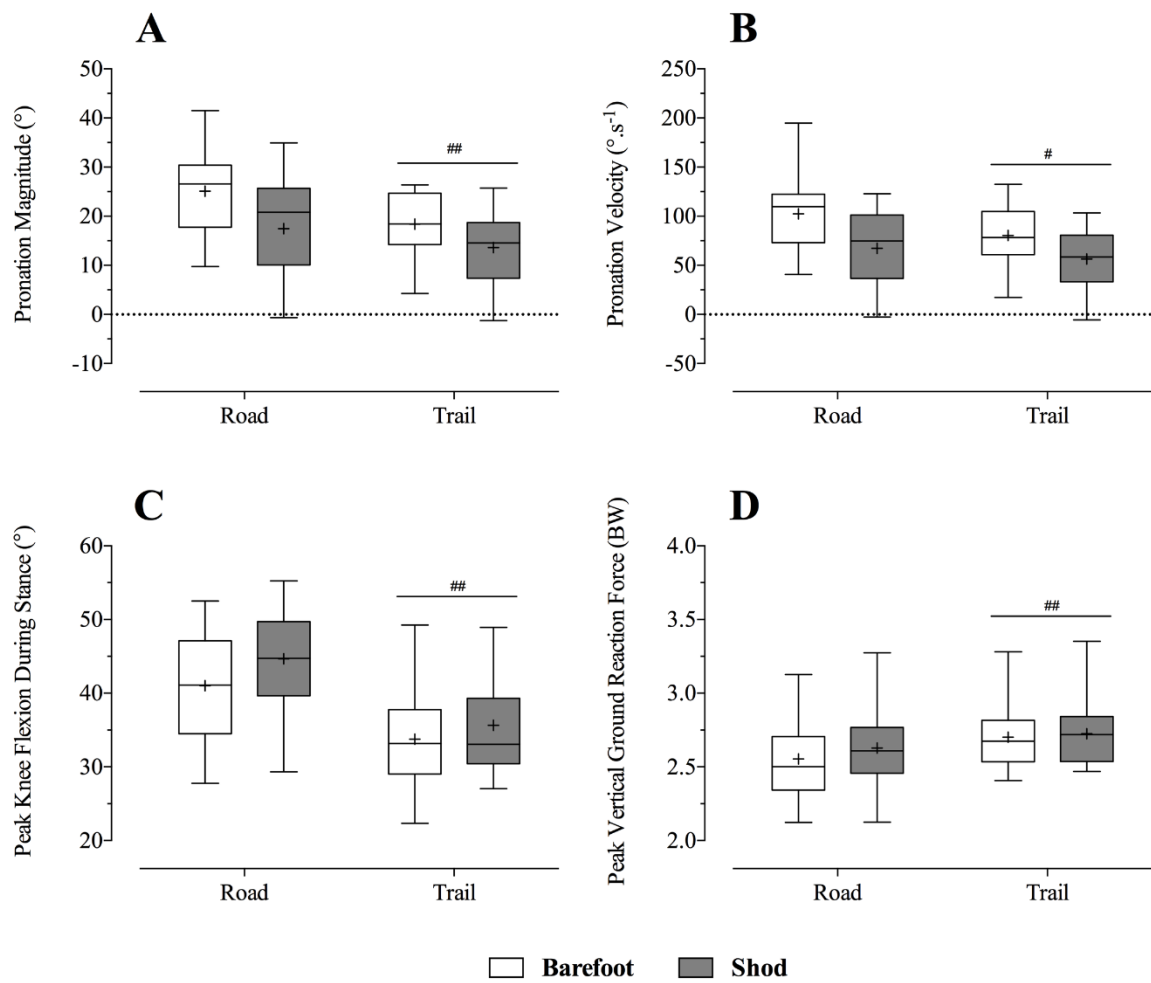
The descriptive characteristics of the trail and road running groups are presented in Table 3.1. Of the 20 participants in the trail group, 13 were male, 7 were female. Similarly, there were 11 male and 9 female participants in the road running group. The average self-selected running speed during overground running trials was similar between the groups ( $p = 0.502$ ,  $ES = 0.35$ , small effect)

**TABLE 3.1.** Descriptive characteristics of trail and road runners

	<b>Trail (n=20)</b>	<b>Road (n=20)</b>
<b>Age (years)</b>	32 (6.58)	31 (10.24)
<b>Body mass (kg)</b>	66.97 (12.17)	65.22 (12.71)
<b>Height (cm)</b>	172.34 (8.03)	172.47 (8.83)
<b>10 km personal best (min)</b>	43 (6)	41 (5.50)
<b>21 km personal best (min)</b>	100 (14)	93 (13.77)
<b>Preferred testing speed (m.s<sup>-1</sup>)</b>	3.54 (0.27)	3.40 (0.49)

With regards to group differences (independent of footwear condition), the trail running group exhibited lower pronation magnitude (15.99 (6.97) *vs.* 21.30 (9.56) °,  $p = 0.029$ ,  $ES = 0.63$ , medium effect) (Figure 3.1A), pronation velocity (68.40 (31.22) *vs.* 84.86 (40.25) °.s<sup>-1</sup>,  $p = 0.003$ ,  $ES = 0.46$ , small effect) (Figure 3.1B) and peak knee flexion during stance (34.71 (6.77) *vs.* 42.86 (7.25) °,  $p < 0.001$ ,  $ES = 1.16$ , large effect) (Figure 3.1C) than road runners. Peak vertical GRFs were significantly greater in the trail running group (2.71 (0.21) *vs.* 2.59 (0.28) BW,  $p = 0.030$ ,  $ES = 0.48$ , small effect) (Figure 3.1D). Trail and road runners experienced similar anterior-posterior GRFs, medio-lateral GRFs, vertical impulse and ILR.

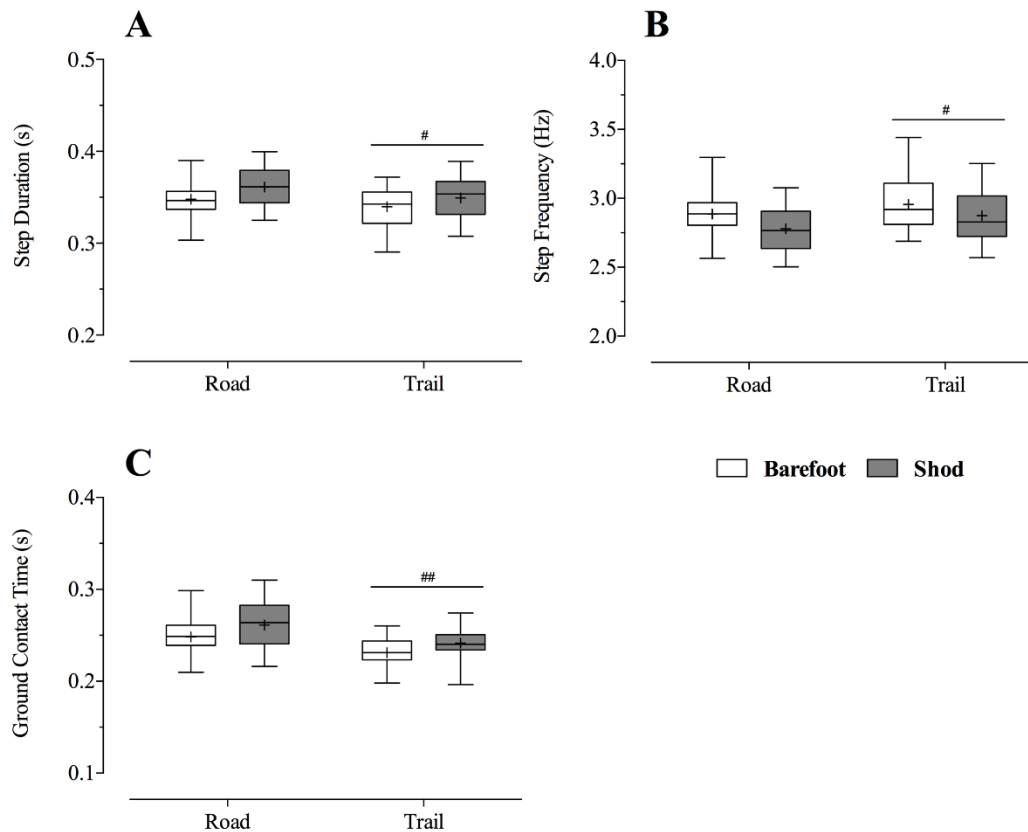
Greater ankle stiffness was found in the road running group (7.0 (4.0) *vs.* 9.27 (4.59) Nm/°,  $p = 0.044$ ,  $ES = 0.52$ , medium effect), but not in knee stiffness ((8.59 (4.32) *vs.* 7.55 (2.91) Nm/°,  $p = 0.264$ ,  $ES = 0.28$ , small effect). Ankle angle in the sagittal plane during initial ground contact was different between groups (-5.95 (14.85) *vs.* 3.16 (11.6) °, Trail *vs.* Road respectively,  $p = 0.004$ ,  $ES = 0.68$ , medium effect), and the trail group exhibited a greater percentage of FFS pattern landings (68.3% of trail runners *vs.* 31.7% of road runners) (( $X^2$ , (1,  $n = 80$ ) = 9.78 (1),  $p = 0.002$ ,  $ES = 0.75$ , medium effect).



**FIGURE 3.1** Kinematic and kinetic running group differences in A) pronation magnitude, B) pronation velocity, C) peak knee flexion during stance, and D) peak vertical ground reaction force in barefoot and shod conditions. # - significant group difference ( $p < 0.05$ ), ## - significant group difference ( $p < 0.01$ )



The trail runners exhibited differing spatiotemporal parameters to road runners. Specifically, a shorter step duration (0.34 (0.02) vs. (0.35 (0.02) s,  $p = 0.043$ , ES = 0.50, medium effect) (Figure 3.2A), paired with a higher step frequency (2.91 (0.20) vs 2.83 (0.18) Hz,  $p = 0.046$ , ES = 0.42, small effect) (Figure 3.2B) and shorter ground contact time (0.24 (0.02) vs. 0.25 (0.02) s,  $p < 0.001$ , ES = 0.50, medium effect) (Figure 3.2C).



**FIGURE 3.2** Spatiotemporal parameter running group differences in A) step duration, B) step frequency, and (C) ground contact time in barefoot and shod conditions. # - significant group difference ( $p < 0.05$ ), ## - significant group difference ( $p < 0.01$ )

A sole interaction effect was observed between running groups and foot strike patterns in the barefoot condition. Barefoot trail runners were more associated with a FFS landing than barefoot road runners (85% of trail runners vs. 40% of road runners) ( $X^2$ , (1, N = 40) = 8.64 (1),  $p = 0.003$ , ES = 1.0, large effect).

Combined group (n = 40) footwear condition differences are presented in Table 3.2. When comparing barefoot and shod conditions, greater ILR ( $p = 0.004$ , ES = 0.87, large effect), foot pronation magnitude ( $p = 0.001$ , ES = 0.75, medium effect) and velocity ( $p < 0.001$ , ES = 0.87, large effect) was observed in the barefoot compared to shod condition. Foot strike angle (sagittal plane) was greater in the shod condition ( $p = 0.004$ , ES = 0.54, medium effect). In

addition, 40% of all runners were observed to land with a FFS in the shod condition, increasing to 62.5% when barefoot ( $X^2, (1, N = 80) = 4.05, p = 0.044, ES = 0.46$ , small effect).

Spatiotemporal differences included greater ground contact time ( $p = 0.018, ES = 0.06$ , trivial effect) and step duration ( $p = 0.020, ES = 1$ , large effect) in the shod condition. In contrast, step frequency was higher in the barefoot condition ( $p = 0.023, ES = 0.49$ , small effect).

**TABLE 3.2.** Discrete kinematic and kinetic parameters in barefoot and shod conditions

	<b>Barefoot (n = 40)</b>	<b>Shod (n = 40)</b>
<b>Spatiotemporal</b>		
Ground Contact Time (s)	0.24 (0.22)	0.25 (0.02)*
Swing Time (s)	0.45 (0.04)	0.46 (0.04)
Step Duration (s)	0.34 (0.02)	0.36 (0.02)*
Step Frequency (Hz)	2.92 (0.19)	2.83 (0.18)*
<b>Kinematics</b>		
FSA (°) <sup>a</sup>	-4.58 (-12.24 – 4.14)	5.53 (-5.91 – 13.67)**
Peak Knee Flexion (°)	37.40 (8.06)	40.17 (7.97)
Pronation Magnitude (°)	21.74 (7.77)	15.55 (8.62)**
Pronation Velocity (°·s <sup>-1</sup> )	91.35 (33.61)	61.92 (34.07)**
<b>Ground Reaction Forces</b>		
ILR (BW·s <sup>-1</sup> ) <sup>a</sup>	112.23 (66.31 – 212.43)	76.32 (45.45 – 93.28)**
Peak apGRF (BW)	0.40 (0.07)	0.39 (0.08)
Peak mlGRF (BW) <sup>a</sup>	0.07 (0.04 – 0.08)	0.08 (0.04 – 0.12)
Peak vGRF (BW)	2.62 (0.26)	2.68 (0.25)
Vertical Impulse (N·s <sup>-1</sup> ) <sup>a</sup>	237.61 (184.35 – 264.52)	245.74 (188.41 – 269.88)
<b>Joint Stiffness</b>		
Ankle Stiffness (Nm/°) <sup>a</sup>	6.23 (4.05 – 8.55)	9.45 (5.00 – 13.47)*
Knee Stiffness (Nm/°) <sup>a</sup>	7.54 (5.44 – 8.55)	7.69 (5.20 – 10.29)

FSA- Foot Strike Angle; ILR- Initial loading rate; Peak apGRF- Peak anterior-posterior ground reaction force; Peak mlGRF – Peak medio-lateral ground reaction force; Peak vGRF – Peak vertical ground reaction force. \*significant footwear condition difference (\*p < 0.05, \*\*p < 0.01). <sup>a</sup>Median and interpercentile range presented.

### 3.5 DISCUSSION

This study explored the biomechanical differences between well-trained trail and road runners. Additionally, this study investigated whether training on different surfaces could influence a habitually shod runner's acute response to barefoot running.

The primary finding of this investigation was that trail runners exhibited different spatiotemporal and biomechanical gait patterns to road runners. Specifically, greater step frequency, shorter step duration and ground contact times were observed in the trail runners despite both groups running at similar speeds and having reported similar running performance times (Figure 3.2). Considering this, the trail runners exhibited spatiotemporal parameters that may be more metabolically efficient and that are associated with reduced peak vertical ground reaction forces (vGRFs) (Heiderscheit et al., 2011, Schubert et al., 2014). Edwards et al. (2009) proposed that a 10% increase in an individual's stride frequency could decrease the probability of developing a stress fracture by 3-6%. However, the trail runners in this study presented with greater peak vGRF with comparable initial loading rates (ILR) to the road runners. Whether or not these higher peak vGRFs would expose trail runners to greater risk of RRIs is ambiguous (Zadpoor and Nikooyan, 2011), and clarity may be found by considering further biomechanical findings alongside the groups' differing vGRFs.

Kinematic and joint stiffness differences were found between trail and road runners. Specifically, trail runners exhibited smaller foot strike angles, lower pronation magnitude and velocity, and lower peak knee flexion during stance (Figure 3.1). Despite finding differences in peak knee flexion between the groups, knee stiffness was similar. This implies that knee flexion range of motion (ROM) and moments between initial ground contact and mid-stance were not disparate between trail and road runners. In contrast, ankle stiffness was lower in the trail runners. A greater proportion of trail runners exhibited a FFS landing pattern, which could have resulted in a greater dorsiflexion ROM around the ankle (Almeida et al., 2015), leading to lower ankle stiffness. These discussed kinematics and kinetic differences may be as a result of exposure to an unfamiliar running surface during biomechanical testing, or as compensation to the vGRF experienced. The synthetic track, more rigid than typically found in a natural environment, may require subconscious kinematic or leg stiffness adjustments in order for the trail runners to maintain preferred gait characteristics (Ferris et al., 1998, Dixon et al., 2000).

To expand on this, 85% of the trail runners landed with a FFS when barefoot, compared to 50% when shod. In contrast, 30% of the road runners landed with a FFS during shod running, with

only a 10% increase in FFS in the barefoot running condition. Landing on the heel pad when barefoot running can be painful and uncomfortable (Chi and Schmitt, 2005), and it is well known that barefoot running encourages the transition to a more flat-footed, plantarflexed foot strike, most likely to attenuate impact shock on the exposed fatty heel tissue (De Wit et al., 2000). Although highly debated, FFS running has been suggested to reduce impact peaks and risk of RRI (Daoud et al., 2012). Of significance in this investigation is that the trail runners acutely adapted to barefoot running through a change in foot strike. These results are in accordance with the findings from a 2015 case study, where an elite ultra-trail runner continuously adapted his foot strike pattern throughout a 45 km trail race (Giandolini et al., 2015b). It is plausible that regular training on irregular terrains and uneven ground results in a learned and subconscious response to unfamiliar conditions. This response may be a protective mechanism acting to reduce the likelihood of sustaining a RRI, or a way in which to reduce metabolic cost during running.

Regardless of disparities in foot strike pattern landings and ankle stiffness, similar knee stiffness values may indicate a similar level of shock absorption further up the kinetic chain in both groups of runners. Joint stiffness is an indirect measure of the ability of a joint to attenuate and absorb load during running, and has been suggested to be associated with the development of overuse injuries (Hamill et al., 2009). Although, peak knee flexion was different between the groups, optimal peak knee flexion during stance is debated. A reduced degree of knee flexion could potentially limit the shock absorption capabilities of the knee joint. In contrast, excessive knee flexion under force could overload the patellofemoral joint (Prentice, 2015). However, the association between these two purported biomechanical risk factors and RRI remains controversial and it is important to highlight that most recreational road running injuries occur at or around the knee (Kluitenberg et al., 2015). Following this, it is plausible that the observed kinematic adjustments may predispose trail runners to knee injury in the same way. The differences observed in these two groups should be considered prospectively to any RRIs that may occur and could lay the foundation for future research on the topic.

Our final finding was contrary to our initial hypothesis. Despite differences in foot strike patterns, both groups demonstrated similar biomechanical responses to barefoot running. Specifically, barefoot runners exhibited greater ILR, foot pronation velocity and magnitude in comparison to the shod condition (Table 3.2). The presence of a greater ILR during barefoot running is consistent with the findings of Lieberman et al. (2010) and Tam et al. (2016b) who found that most habitually shod runners experience higher collision forces when engaging in

barefoot running, compared to that of habitual barefoot runners. This increase in ILR while barefoot is attributed to a habitually shod runner's tendency to continue to heel strike when transitioning to the barefoot condition (Tam et al., 2014). However, it is important to note the large range in ILR (66.31 – 212.43 BW.s<sup>-1</sup>) for the combined road and trail running group when running barefoot, suggesting a highly variable response in the entire cohort to this unfamiliar condition (Tam et al., 2016a).

Greater foot pronation velocity and magnitude found during barefoot running may be due to a lack of arch strength and neuromuscular control required to tolerate barefoot running. Although considerably researched, the relationship between atypical foot motion and injury remains unclear, with authors reporting reduced or excessive pronation to be injurious (especially at or around the knee) (Thijs et al., 2007, Willems et al., 2007), with others reporting no link to injury (Ferber et al., 2009). Regardless, when exposed to significantly greater ILR and eccentric load on the ankle during acute barefoot running, habitually shod trail and road runners had insufficient muscle strength to prevent pronation, and in this regard, could be at higher risk of bones stress injuries (Ridge et al., 2013, Tam et al., 2016a).

Running barefoot has been shown to increase stride frequency, reduce stride duration and length and reduce ground contact time, all of which can be verified with our current findings (Divert et al., 2005, Divert et al., 2008). Although spatiotemporal parameter adjustments with acute barefoot running are not a new paradigm, these subconscious modifications to gait appeared to be very similar to those found in the trail runners. These changes would naturally reduce time spent in contact with the ground, and in combination with the transition to a significantly more plantarflexed ankle position at impact, could allow for greater cushioning and surface area distribution of impact forces. Ground reaction force peaks were not significantly different between barefoot and shod conditions, but despite these purported favourable gait characteristics, runners experienced greater ILR when barefoot. It is recommended that the RRI and ground reaction force relationship receive greater attention before clinicians can apply biomechanical and spatiotemporal data to advise runners on 'appropriate' gait mechanics and footwear. Regardless, the biomechanical differences observed between barefoot and shod running in this investigation, highlight the fact that habitually shod runners wishing to transition to barefoot running activities, should be duly cautioned.

The findings of this study caution the advocating of barefoot running for habitually shod trail and road runners. Notably, this study is limited to the acute responses to barefoot running and may not be applicable to habituated barefoot runners. Regardless, the application of a

progressive barefoot running training programme yields controversial results, with some researchers reporting habitually shod runners to show a preference for mid-to-FFS landing patterns post-intervention (Latorre-Román et al., 2016), with others reporting no kinematic or kinetic changes with training (Tam et al., 2016b). It is plausible that a progressively applied training programme, with the guidance of a clinician, may yield contrasting results to those reported in this study. However, conflicting literature calls attention to the large inter-individual responses seen with barefoot running, and adaptations to trained, or long-term barefoot running should be prospectively studied with respect to both performance and injury risk.

To our knowledge, this is the first study to analyse the biomechanical implications of habitual trail running. Most of our scientific understanding of trail running to date has been extrapolated from kinematic changes associated with acute bouts of running on compliant (e.g. rubber-modified surfaces or tracks) or outdoor surfaces (e.g. grass), or running on uneven surfaces or surfaces with height variations (Voloshina and Ferris, 2015, Sterzing et al., 2014, Creagh et al., 1998, Schutte et al., 2016). Long-term exposure to these elements may result in distinctly altered running biomechanics, and the study of acute exposures may not adequately reflect these potential changes. Thus, the assessment of biomechanical differences between these two groups is the first step to understanding the mechanical effects of habitual running on ‘off-road’ surfaces, and may act as a platform for future prospective injury and randomised control trial studies.

Despite the novelty of this research, it is important to consider that there were limitations in this study. Particularly, both road and trail runners were removed from their natural environment and terrain, and tested on a synthetic track. Additionally, trail runners are regularly exposed to varying elevation profiles and unexpected obstacles, and the variable and spontaneous mechanics required would not be adequately represented with testing on our flat laboratory track. Nonetheless, to maintain a degree of external validity, runners were guided to select a preferred, comfortable testing speed (Queen et al., 2005). Running speeds were not significantly different between the groups, and both groups were unfamiliar with the synthetic track. Future research should make use of portable motion capture systems to fully understand the biomechanical differences between these two running populations.

Another limitation would be that the shoes utilised in this study were not standardised, nor controlled for wear or midsole stiffness. Research shows that lower extremity kinematics and kinetics can be altered with varying midsole stiffness (Hardin et al., 2004, Baltich et al., 2015). Trail running shoes tend to be more minimalistic and less cushioned than conventional road

running shoes, marketed to allow for greater proprioceptive feedback on the unstable and uneven terrain. Nonetheless, no biomechanical differences were found in shod conditions between the running groups.

### **3.6 CONCLUSION**

In summary, the findings from the present study indicate that trail and road runners exhibit disparate running biomechanics, and as a result, may duly present with different injury risk profiles. For road runners, greater peak knee flexion and pronation variables during stance may predispose these runners to RRIs. In contrast, it would appear the trail running-injury relationship cannot be oversimplified. The results from this study suggest that trail runners may be more adept at acclimatising to unfamiliar conditions through instinctual foot strike pattern modifications. However, it was unexpected to find that the trail runners exhibited similar knee stiffness and ILR to road runners, given that trail runners demonstrated purported superior running gait characteristics for injury and performance. Specifically, trail runners exhibited greater step frequency, shorter ground contact time and shorter step duration. In addition, habitually shod trail runners exhibited greater foot pronation components and ILR when barefoot, suggesting a similar risk of RRI when compared to their road running counterparts. Future epidemiological and prospective injury studies are imperative to adequately compare these two running populations with respect to injury.



## CHAPTER 4

# NEUROMUSCULAR CONTRIBUTIONS TO TRAIL RUNNING BIOMECHANICS

### 4.1 ABSTRACT

**Introduction:** This study aimed to compare muscle activity patterns and biomechanics in 15 habitual trail runners and 15 age- and performance-matched road runners during overground running. This study aimed to determine whether a preferred running surface has a long-standing effect on the neuromuscular regulation of running biomechanics.

**Methods:** Specific kinematic gait, ground reaction force and lower extremity muscle activity pattern data were captured during barefoot and shod overground running trials on a synthetic track. One-dimensional statistical parametric mapping was employed to detect differences between muscle activity waveforms in trail and road runners over the entire gait cycle.

**Results:** Distinct differences in muscle activity waveforms and kinematics were found between trail and road runners, regardless of the footwear condition. During stance and swing phase of the gait cycle, trail runners exhibited greater muscle activation in comparison to road runners in: *gluteus maximus* at early stance (0-3% of the gait cycle) and late swing (98-100% of gait cycle), *biceps femoris* at early stance (0-5%) and late swing (95-100%), and *peroneus longus* at late swing (94-100%). In addition, trail runners exhibited greater *tibialis anterior* activation during early swing (45-55%). With regards to discrete kinematics, trail runners presented with lower pelvic, hip and knee flexion in the sagittal plane at initial ground contact.

**Conclusion:** These findings suggest that a runner's preferred training terrain may have a long-standing effect on muscle activity patterns and discrete lower extremity joint kinematics. In trail runners, neuromuscular adaptations to training surface may be aimed at stabilising the lower extremity during stance and to allow for greater ground clearance during swing.

## 4.2 INTRODUCTION

The analysis of running biomechanics improves our understanding of running-related injury (RRI) and performance in individual runners and the running population at large (Novacheck, 1998). We have previously shown in Chapter Three that biomechanical differences exist between trail and road runners when running in a controlled environment. It is important to expand on this prior research and consider the influence of neuromuscular control on the running biomechanics of these runners.

It is possible to consider that neuromuscular differences exist when observing the habitual terrain that these groups train on. Road running terrain is monotonous and stiff, whereas off-road running surfaces are irregular and may vary in stiffness. Indeed, the trail runner must adapt to the fluctuating demands whilst running on off-road surfaces, whilst concurrently attempting to maintain consistent running biomechanics (Voloshina and Ferris, 2015, Nigg et al., 2015). These acute changes in running mechanics would logically require refined neuromuscular strategies.

In addition, we have previously shown that trail runners experienced greater vertical ground reaction forces (vGRFs) when running on a synthetic running track in comparison to road runners (Chapter Three). Adequate acceptance of these differing impact forces rely on specific lower extremity muscle recruitment and contraction patterns (Christina et al., 2001). According to Boyer and Nigg (2004), muscle activity is ‘tuned’ in response to different impact forces (i.e. input signals). Small mechanical changes that directly affect impact conditions, i.e. joint displacement or leg stiffness, therefore require specific muscle adaptations to control or minimise soft tissue vibrations (Boyer and Nigg, 2007). Considering the different terrain and varying biomechanical responses in these two groups of runners, it is plausible that muscle activity patterns would differ too.

Skeletal muscle contraction requires the recruitment of the muscle’s functional units called ‘motor units’. Each motor unit consists of a motor neuron (extending from the spinal cord) and the collection of muscle fibres that it innervates. Neuromuscular adaptation to different training exposures may include changes in the regulation of the timing, synchronisation and number of motor-units recruited to produce the desired movement and optimal metabolic efficiency (Bonacci et al., 2009, Sale, 1987). Interestingly, Nigg and Wakeling (2001) suggest that feedback information from previous ground contact experiences during running may adjust the timing and rate of motor recruitment. For example, muscle pre-activation, occurring in

anticipation of ground contact during terminal swing, is suggested to be a learned response to adequately prepare the musculoskeletal system for impact shock (Nigg and Wakeling, 2001). Certain training variables may alter pre-activation, with faster running performance times associated with greater muscle activation during this period (Paavolainen et al., 1999). Accordingly, it could be hypothesised that muscle activation during terminal swing may differ between trail and road runners.

It would be of further interest to investigate muscle activity synergies that regulate joint stiffness, movement and control (Kellis et al., 2011). This can be achieved through the study of muscle co-activation patterns (Butler et al., 2003). Muscle co-activation describes the simultaneous activation of agonist and antagonist muscle groups either over time or the activation intensity at set events (Solomonow et al., 1988, Heise et al., 1996). Although under-researched, regular running may adapt or refine muscle co-activation patterns (Bonacci et al., 2009). Optimal lower extremity muscle co-activation is required throughout the gait cycle to execute movement, attenuate load (internal and external) and reduce the metabolic cost of running (Heise et al., 1996, Kellis et al., 2011). In Chapter Three, we suggest that changes in biomechanics and spatiotemporal gait can manifest with different running surfaces. These findings imply that the muscle co-activation patterns responsible for these biomechanical differences would be similarly disparate.

To improve our understanding of trail runners and the influence of training terrain on neuromuscular responses, this study was designed to compare lower extremity muscle activity patterns and resultant joint biomechanics in trail and road runners. Surface electromyography (EMG) is a research tool that can provide insight into the complex neuromuscular regulation of human movement. EMG is used to measure and record superficial skeletal muscle electrical activity. Until recently, the processing and analysis of the EMG signal has been limited to the extraction and comparison of muscle activity patterns during discrete phases of the gait cycle. A new technique, one-dimensional statistical parametric mapping (1DSPM), now allows for the observation and analysis of EMG data throughout the entire gait cycle (Pataky et al., 2015b, Pataky et al., 2015a). The careful examination of the entire muscle activity waveform may assist in advancing the understanding of the neuromuscular regulation of running biomechanics.

It was hypothesised that as a result of long-term training on non-uniform running surfaces, trail runners would exhibit differences in muscle activity patterns (increased activation in terminal swing and a balanced co-activation ratio) and resultant biomechanics compared to road runners. In addition, the present study aimed to compare muscle responses to acute barefoot running in

trail and road runners. We have previously shown that habitually shod trail and road runners exhibit similar spatiotemporal and biomechanical gait when exposed to barefoot running. It was therefore hypothesised that lower extremity muscle patterns during barefoot running would also be similar.

## **4.3 MATERIALS AND METHODS**

### **4.3.1 PARTICIPANTS**

Fifteen male and female trail runners (80% of running training completed on off-road terrain for the past year) and 15 age- and performance-matched road runners (80% of their training completed on road (asphalt/pavement) volunteered to participate in this study. Participants were experienced and habitually shod runners, training at least four hours a week for two years prior to the study, and were able to complete a 10 km road run in  $\leq 45$  minutes. Participants had been injury free for six months prior to enrolment in the study, and had no current or previous history of orthopaedic abnormalities, neurological disorders, diabetes mellitus or previous lower limb surgeries.

Participants were recruited via a media release to local running clubs, to which recruitment posters & flyers were distributed. Participants were fully aware of the risks and benefits associated with the study and provided written informed consent prior to participation in the study. The study was granted ethical approval from the University of Cape Town Human Research Ethics Committee (HREC #371/2016).

### **4.3.2 TESTING PROCEDURE**

Participants were requested to visit the laboratory on a single occasion. Participants completed six clean overground running trials at a self-selected speed in barefoot and shod conditions as previously described in Chapter Three, Section 3.3.2. After completion of running trials, participants performed a maximal sprint whilst shod. Synchronised biomechanical and EMG data were collected during all running trials and maximal sprints.

### **4.3.3 EXPERIMENTAL CONDITIONS**

Biomechanical testing for both trail and road running groups was performed in two randomised conditions, barefoot and shod. Shod trials were performed in the shoe in which the participant was currently completing the most mileage. Shoes were not controlled for wear or mileage.

### **4.3.4 INSTRUMENTATION AND PREPARATION**

Running trials were completed on a 40 m indoor synthetic track. Passive reflective markers were attached bi-laterally on the lower body with double-sided tape. A modified Helen-Hayes marker set (described in Chapter Two, Section 2.3.5) was used (Kadaba et al., 1990). Three-dimensional marker trajectories were recorded using an eight camera VICON MX motion

capture system (Oxford Metrics Ltd, Oxford, UK) sampling at 250 Hz. Ground reaction force data was collected with a 900 x 600 mm embedded force platform (AMTI, Watertown, MA, USA) sampling at 2000 Hz and synchronized with the motion capture system. Kinetic and kinematic data were captured for all participants on nine metres of the total track. Marker trajectories were reconstructed and gaps filled using VICON Nexus 1.8.2 software.

Bipolar surface EMG (Noraxon 2400T G2, Noraxon, USA), which was synchronised with the Vicon motion capture system, recorded eight muscles of the dominant leg during running gait trials. Muscles of interest were; *gluteus maximus* (Gmax), *gluteus medius* (Gmed), *rectus femoris* (RF), *vastus lateralis* (VL), *biceps femoris* (BF), *tibialis anterior* (TA), *peroneus longus* (PL) and *gastrocnemius medialis* (GaMed). Electrode sites were determined according to standard Surface Electromyography for the Non-Invasive Assessment of Muscles guidelines (Hermens et al., 2000).

EMG preparation procedures were conducted as previously described by Albertus-Kajee et al. (2010). To reduce electrical impedance from skin, the area where electrodes were to be placed was shaved and rubbed with ethanol swabs. Two circular surface electrodes (Blue Sensor, Medicotest, Denmark) were placed on the muscle belly, parallel to the direction of the muscle fibres, at an inter-electrode distance of 20 mm. One reference electrode was placed on adipose tissue (the abdomen), and on a bony landmark (the anterior superior iliac crest). A telemetric signal was relayed to an online computer and data were sampled at a rate of 2000 Hz (Myoresearch, Noraxon USA, Inc., Arizona, USA).

The wire-leads and pre-amplifiers connected to the electrodes were well secured with medical grade tape to prevent signal artefact from lower limb movement during running. The transmitter unit was placed in a halter strapped to the participant's back to minimise the movement artefact. The mass of the halter and transmitter unit ( $\pm 300$  g) is assumed to have a negligible effect on running technique. Before recording muscle activity signals during the trials, each participant was lead through a variety of movements by the investigators to isolate and contract all eight muscles. These exercises are important to verify the absence of crosstalk in the EMG signal and for the appropriate placement of the EMG electrodes.

### 4.3.5 DATA ANALYSIS

Marker trajectory and kinetic data were filtered as previously described in Chapter Three, Section 3.3.5. Joint angles of the ankle, knee and hip joints were calculated according to the joint coordinate system (Groot and Suntay, 1983) and net external resultant moments were calculated using an inverse dynamics procedure (Davis et al., 1991). External moments were normalised to body mass ( $\text{Nm.kg}^{-1}$ ). Sagittal plane quasi-joint stiffness for the ankle and knee joint were calculated according to Hamill et al. (2009).

Biomechanical variables were exported as .csv files and imported into a customised Matlab (R2014a, 8.3.0.532, Mathworks Inc., Natick, USA) programme for data analysis. The data for each participant's dominant limb for the complete gait cycle was averaged over three trials for each condition (barefoot and shod) and normalised to stance phase. Stance phase was defined as the period over which a vertical force exceeded one standard deviation (SD) above baseline force platform noise and continued to elevate until toe-off (Tam et al., 2017).

Sagittal plane ankle, knee, hip and pelvic angles (degrees) were reported. Discrete kinematics extracted were: self-selected speed ( $\text{m.s}^{-1}$ ); ankle, knee, hip and pelvic flexion at ground contact ( $^{\circ}$ ); peak ankle, knee, hip and pelvic flexion during stance ( $^{\circ}$ ); ankle, knee, hip and pelvic range of motion (ROM) ( $^{\circ}$ ); foot pronation magnitude ( $^{\circ}$ ) and foot pronation velocity ( $^{\circ}.\text{s}^{-1}$ ). Discrete kinetics extracted were peak vertical ground reaction force (vGRF) (BW), medio-lateral GRF (BW), anterior posterior GRF (BW), and initial loading rate (ILR) ( $\text{BW}.\text{s}^{-1}$ ).

The raw digital EMG signal was processed using Noraxon's Myoresearch software (Version 2.2). The data were rectified and filtered using a 50 Hz notch filter to remove any electrical interference from external sources. A 15-500 Hz band pass filter was applied to remove noise or movement interference below 15 Hz and other non-physiological signals above 500 Hz. The data were smoothed using root mean squared analysis (RMS), with a 50 ms moving window.

Processed EMG data were exported from Noraxon Myoresearch to .mat files and synchronised with time-matched kinematic and kinetic data using a customised Matlab programme. EMG data for each participant's dominant limb was averaged over the three trials for each condition (barefoot and shod). Average EMG for the entire gait cycle was then normalised to peak activity obtained during the maximal sprint. Muscle activity data over the gait cycle were normalised over 101 data points from ground contact to ground contact, and represented as waveforms that change throughout the gait cycle (one for each percentage of the cycle).

In addition, averaged EMG amplitude was extracted for pre-activation (defined as 100 milliseconds prior to ground contact) and during stance (ground contact to toe-off). Co-activation ratios during pre-activation and stance were calculated for four agonist: antagonist muscle combinations, namely; RF:BF, GaMed:TA, RF:GMed and VL:BF. A co-activation ratio of 1 indicates equal activation of both muscles, with a ratio of greater or less than 1 indicating an agonist or antagonist muscle activity dominance, respectively (Kellis et al., 2011, Kellis and Kouvelioti, 2009).

#### **4.3.6 STATISTICAL ANALYSIS**

Statistical analysis of discrete variables was performed using IBM SPSS (Statistical Package for the Social Sciences) (IBM, New York, USA). Data were screened for normality and homogeneity of variance using Shapiro-Wilk's and Levene's test, respectively. An independent sample T-test was applied to determine differences in age and performance between the running groups. A two-by-two mixed model analysis of variance (ANOVA) or non-parametric equivalent Mann-Whitney U test (for non-normally distributed data) was applied to discrete biomechanical variables and muscle co-activation ratios to determine differences between footwear conditions (Barefoot *vs.* Shod) and groups (Trail *vs.* Road). Pearson's and Spearman's rank-order correlation tests were applied to test for associations between co-activation ratios and joint stiffness between the groups. Effect size (ES) were calculated according to Cohen (1988), with ES magnitudes defined as small (0.2), medium (0.5) or large (0.8).

To detect differences between muscle activity waveforms in an objective way, 1DSPM was employed. Differences between groups and conditions were compared using a two-way ANOVA. All 1DSPM analyses were implemented using the open-source 1DSPM code (v.MO.1, [www.spm1d.org](http://www.spm1d.org)) in Matlab (R2014a, 8.3.0.532, Mathworks Inc., Natick, USA) (Pataky et al., 2015a). Data are presented as means (standard deviations) unless otherwise stated. Significance was set at  $p < 0.05$ .



## 4.4 RESULTS

### 4.4.1 GROUP DESCRIPTIVE CHARACTERISTICS

The descriptive characteristics of the trail and road runners are presented in Table 4.1. Of the 15 participants in the trail group, nine were male and six were female. Similarly, eight male and seven female participants were in the road running group. No differences were found for age and personal best race times between road and trail runners. Overall self-selected speed was different between the groups, regardless of footwear condition. This difference exhibited a moderate effect size ( $p = 0.017$ ,  $ES = 0.67$ ).

**TABLE 4.1.** Descriptive characteristics of trail and road runners

	Trail (n = 15)	Road (n = 15)
Age (years)	31 (6.96)	31 (9.24)
Body mass (kg)	65.35 (13.06)	63.61 (12.56)
Height (cm)	171.51 (8.91)	171.55 (9.47)
10 km personal best (min)	43 (5.65)	40 (3.84)
21 km personal best (min)	99 (14.11)	92 (9.18)
Self-Selected Testing Speed ( $m.s^{-1}$ )	3.55 (0.29)	3.31 (0.42) #

# significant group difference ( $p < 0.05$ ).

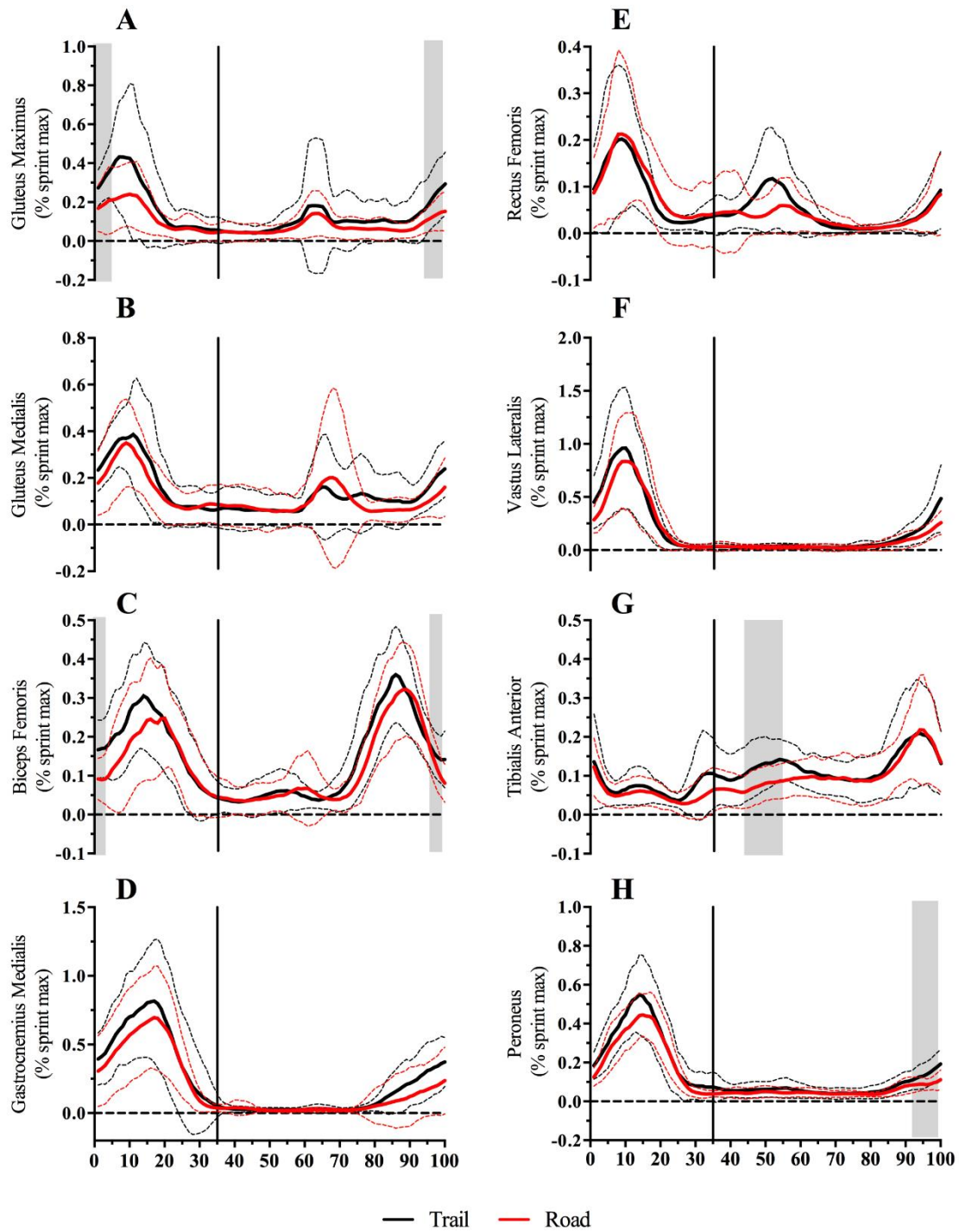
### 4.4.2 MUSCLE ACTIVITY

Specific group differences in muscle activity waveforms over the entire gait cycle were found (Table 4.2 and Figure 4.1). Trail runners showed greater muscle activity waveforms in *gluteus maximus* (Figure 4.1A) and *biceps femoris* (Figure 4.1C) during late swing and early stance in comparison to road runners. In addition, trail runners demonstrated greater muscle activity in *tibialis anterior* muscles during early swing (Figure 4.1G) and *peroneus longus* (Figure 4.1H) muscles during late swing. No condition differences were found in waveform data.

**TABLE 4.2.** SPM Analysis Summary

<b>Muscle of Interest</b>	<b>Critical Threshold Exceeded (% of gait cycle)</b>	<b>Super-threshold p-value</b>	<b>Critical threshold (*f)</b>
<i>Biceps Femoris</i>	Early Stance (0-3%)	p = 0.027	F = 10.7479
	Late Swing (98-100%)	p = 0.044	
<i>Gluteus Maximus</i>	Early Stance (0-5%)	p = 0.019	F = 10.209
	Late Swing (95-100%)	p = 0.026	
<i>Peroneus Longus</i>	Late Swing (94-100%)	p = 0.011	F = 10.5947
<i>Tibialis Anterior</i>	Early Swing (45- 55%)	p = 0.001	F = 10.2999

Presented differences in muscle activity waveforms over the entire gait cycle in trail and road runners.



**FIGURE 4.1** Muscle activity waveforms over the entire gait cycle for posterior (A-D), anterior (E-G) and lateral (H) muscle groups in trail and road runners. Presented means (SD) for trail runners (black lines) and road runners (red lines). Significant differences between groups highlighted in grey ( $p < 0.05$ ). ‘Toe off’ observed at 35.04% of gait cycle.

No differences were found in co-activation ratios between trail and road runners during pre-activation and stance phase of the gait cycle. Similarly, no correlations were found between agonist: antagonist muscle co-activation ratios and joint stiffness (ankle and knee) in trail and road runners.

Muscle co-activation ratios for barefoot and shod conditions are presented in Table 4.3. In the barefoot condition, dominant GaMed activity was found during GaMed:TA pre-activation ( $p = 0.001$ ), and a lower activation during stance ( $p < 0.001$ ).

**TABLE 4.3** Muscle co-activation ratios in barefoot and shod conditions in pre-activation and stance for all runners

Agonist: Antagonist Ratio	Barefoot (n = 30)	Shod (n= 30)
<b>RF:BF</b>		
Pre-activation	0.35 (0.08 – 0.60)	0.20 (0.09 – 0.81)
Stance	0.63 (0.43 – 0.78)	0.68 (0.44 – 0.96)
<b>RF:GMed</b>		
Pre-activation	0.29 (0.10 – 0.70)	0.27 (0.07 – 0.45)
Stance	0.57 (0.37 – 0.86)	0.69 (0.51 – 0.97)
<b>VL:BF</b>		
Pre-activation	0.11 (0.06 – 0.42)	0.10 (0.06- 0.33)
Stance	0.78 (0.66 – 1.12)	0.85 (0.71 – 1.12)
<b>GaMed:TA</b>		
Pre-activation	0.35 (0.07 – 1.11)	0.07 (0.05 – 0.11) **
Stance	1.22 (0.72 – 1.64)	2.31 (1.90 – 3.18) **

Median and interpercentile range reported. RF:BF – *Rectus Femoris: Biceps Femoris*; RF:GMed – *Rectus Femoris: Gluteus Medius*; VL:BF- *Vastus Lateralis: Biceps Femoris*; GaMed:TA- *Gastrocnemius Medialis: Tibialis Anterior*. \*\*significant footwear condition difference ( $p < 0.01$ ).

## 4.5 KINEMATICS AND KINETICS

Specific running group differences (independent of footwear condition) were found in discrete biomechanical variables (Table 4.4). Peak ground reaction forces and ILR were similar between the groups. However, at initial ground contact, ankle ( $p = 0.004$ , ES = 0.45, small effect), knee ( $p = 0.014$ , ES = 0.66, medium effect), hip ( $p = 0.001$ , ES = 0.81, large effect) and pelvic ( $p = 0.023$ , ES = 0.52, medium effect) flexion angles were significantly lower in the trail running group in comparison to road runners. Similarly, peak knee flexion ( $p < 0.001$ , ES = 1.37, large

effect), hip flexion ( $p < 0.001$ ,  $ES = 0.90$ , large effect) and pelvic ( $p = 0.031$ ,  $ES = 0.50$ , medium effect) flexion during stance were significantly lower in the trail group.

Knee range of motion (ROM) ( $p = 0.02$ ,  $ES = 0.59$ , medium effect) was significantly different between the running groups, with trail runners exhibiting less knee ROM throughout stance. Pronation magnitude ( $p = 0.002$ ,  $ES = 0.75$ , medium effect), pronation velocity ( $p = 0.02$ ,  $ES = 0.56$ , medium effect) and ankle stiffness ( $p = 0.015$ ,  $ES = 0.56$ , medium effect) were all lower in the trail running group. In addition, the trail runners were associated with a greater likelihood of FFS pattern landings (10/15 (66.7%) trail runners *vs.* 4/15 (26.7%) road runners,  $p = 0.002$ ,  $ES = 0.88$ , large effect). Barefoot trail runners were more likely to land on their forefoot compared to barefoot road runners (13/15 (86.7%) trail runners *vs.* 4/15 (26.7%) road runners,  $p = 0.001$ ,  $ES = 1.52$ , large effect).

When comparing differences between footwear conditions, pronation magnitude (22.53 (8.36) *vs.* 15.41(8.09) °,  $p = 0.001$ ,  $ES = 0.87$ , large effect), pronation velocity (95.05 (36.30) *vs.* 62.25 (33.05) °.s<sup>-1</sup>,  $p < 0.001$ ,  $ES = 0.94$ , large effect) and ILR (153.39 (86.91) *vs.* 86.78 (41.71) BW.s<sup>-1</sup>,  $p = 0.003$ ,  $ES = 0.98$ , large effect) were greater in the barefoot condition for all runners ( $p < 0.01$ ). In contrast, knee range of motion (30.28 (5.77) *vs.* 33.89 (5.90) °,  $p = 0.016$ ,  $ES = 0.62$ , medium effect), foot strike angle (-3.40 (11.66) *vs.* 2.88 (16.13) °,  $p = 0.019$ ,  $ES = 0.45$ , small effect) and ankle stiffness (6.97 (2.93) *vs.* 9.80 (4.88) (Nm/°),  $p = 0.016$ ,  $ES = 0.70$ , medium effect) were significantly greater in the shod condition ( $p < 0.05$ ).

**TABLE 4.4:** Discrete biomechanical variables in trail and road runners

	Trail (n = 15)	Road (n= 15)
<i>Sagittal Plane (°)</i>		
<b>Ankle</b>		
Initial Ground Contact (FSA) <sup>a</sup>	-3.79 (-13.30 – 4.02)	7.92 (-2.09 – 13.04) <sup>##</sup>
Peak during Stance	27.26 (6.55)	27.05 (6.18)
ROM during Stance <sup>a</sup>	57.07 (50.60 – 64.81)	56.49 (46.63 – 62.72)
<b>Knee</b>		
Initial Ground Contact	10.23 (5.94)	14.84 (7.88) <sup>#</sup>
Peak during Stance <sup>a</sup>	31.44 (28.59 – 37.74)	44.88 (38.62 – 47.82) <sup>##</sup>
ROM during Stance	30.35 (6.16)	33.83 (5.54) <sup>#</sup>
<b>Hip</b>		
Initial Ground Contact <sup>a</sup>	32.85 (27.50 – 39.76)	39.86 (35.16 – 45.71) <sup>##</sup>
Peak during Stance	32.47 (12.03)	41.30 (6.76) <sup>##</sup>
ROM during Stance	48.30 (4.30)	47.70 (4.72)
<b>Pelvis</b>		
Initial Ground Contact <sup>a</sup>	14.98 (12.23 – 17.99)	17.15 (14.90 – 20.27) <sup>#</sup>
Peak during Stance <sup>a</sup>	17.35 (15.39 – 22.57)	20.20 (17.42 – 23.65) <sup>#</sup>
ROM during Stance <sup>a</sup>	5.89 (5.17 – 8.01)	6.46 (5.27 – 7.76)
<b>Foot Pronation</b>		
Pronation Magnitude (°)	15.83 (7.16)	22.11 (9.48) <sup>##</sup>
Pronation Velocity (°·s <sup>-1</sup> )	68.34 (33.01)	88.96 (40.69) <sup>#</sup>
<b>Ground Reaction Forces</b>		
ILR (BW·s <sup>-1</sup> ) <sup>a</sup>	90.96 (57.48 – 167.69)	109.37 (66.98 – 173.73)
Peak apGRF (BW)	0.39 (0.07)	0.39 (0.07)
Peak mlGRF (BW) <sup>a</sup>	0.05 (0.03 – 0.10)	0.07 (0.04 – 0.10)
Peak vGRF (BW)	2.70 (0.17)	2.62 (0.30)
<b>Joint Stiffness (Nm/°)<sup>a</sup></b>		
Ankle Stiffness	5.99 (3.82 – 9.61)	8.80 (6.18 – 11.30) <sup>#</sup>
Knee Stiffness	7.55 (3.69 – 11.65)	7.13 (5.38 – 9.51)

FSA- Foot Strike Angle; ROM- Range of Motion; ILR- Initial loading rate; Peak apGRF- Peak anterior-posterior ground reaction force; Peak mlGRF – Peak medio-lateral ground reaction force; Peak vGRF- Peak vertical ground reaction force. Significant group difference (<sup>#</sup>p<0.05, <sup>##</sup>p<0.01) <sup>a</sup>median and interpercentile range presented.

## 4.6 DISCUSSION

We have previously shown that trail runners exhibit differing running gait and ground reaction forces during overground running in comparison to road running counterparts (Chapter Three). To expand on these findings, this study aimed to describe the neuromuscular regulation of trail and road running biomechanics. The uniqueness of this study is that trail and road runners exhibited differences in muscle activity patterns throughout the gait cycle. Furthermore, the SPM analysis of muscle activity over the entire gait cycle provided a temporal assessment of amplitude difference in neuromuscular activation.

The first finding was that trail runners presented with greater activation in *gluteus maximus* and *biceps femoris* during terminal swing through to early stance in comparison to road runners (Figure 4.1A and 4.1C). This finding illustrates the heightened activity of the posterior lower limb musculature in trail runners prior to and at early ground contact. Notably, muscle activity during late stance has been suggested to be ‘tuned’ according to previous ground contact experiences (Boyer and Nigg, 2007). The bi-articular *gluteus maximus* and *biceps femoris* muscles cross the pelvis and hip, and the hip and knee joint, respectively, allowing these muscles to influence movement at both joints (Montgomery et al., 1994). During late swing into early stance, these two posterior muscles act together to eccentrically control and extend the knee and hip. Greater activation of these muscles would minimize joint displacement and may have translated into greater knee and hip joint stability in the trail runners. This suggests both refined anticipation of ground contact and differing means of ground reaction attenuation in the lower limb of the trail runners in comparison to road runners.

In support of these findings, trail runners exhibited lower peak knee, hip and pelvic flexion at initial ground contact and throughout stance. Facilitated by greater posterior muscle activity, reduced peak joint flexion may be a stabilizing mechanism to counteract regular surface perturbations found on off-road terrain. In addition, reduced joint flexion may be an adaptive strategy to minimize muscle strength and volume required to support body weight during running (Kerdok et al., 2002). As uneven, compliant terrain has been suggested to increase the energetic cost of running, compared to that of stiffer, level terrain (Zamparo et al., 1992, Lejeune and Willems, 1998, Voloshina and Ferris, 2015), we suggest that the observed kinematics in trail runners may be a mechanical indication of an energy conservation strategy. Further consideration of this notion is encouraged.

In the shank, trail runners exhibited greater activation of the *peroneus longus* during late swing when compared to road runners (Figure 4.1H). Acting to evert and plantarflex the ankle, activation of the *peroneus longus* is necessary during this phase of gait to prepare and stabilise the ankle prior to ground contact. Reduced pre-activation of the *peroneus longus* has previously been associated with Achilles tendinopathy and lateral ankle instability (Azevedo et al., 2009). On the contrary, the trail runners exhibited greater activation during late swing, suggesting greater eccentric control of the ankle. This finding is further supported by lower foot pronation magnitude and velocity during stance in the trail runners. In combination, these findings suggest that trail runners may have a pre-emptive ability to stabilize the ankle and the shank prior to and during ground contact to accommodate for the variable surface terrain. This is in line with our previous findings in Chapter Two, whereby trail runners demonstrated greater ankle joint stability during a single leg squat assessment in comparison to road runners.

Despite reduced foot pronation variables in the trail runners, lower ankle joint stiffness was observed. Greater activation of the *peroneus longus* muscle during late swing may therefore have facilitated increased ankle joint compliance in response to the load experienced at impact in the sagittal plane, while still maintaining ankle joint stability in the frontal plane (Nigg and Wakeling, 2001, Boyer and Nigg, 2004). Although it is possible that superior dampening strategies were applied at the ankle in trail runners, both road and trail runners did not experience significantly different ground reaction forces in response to running on the synthetic track. This is in contrast to our previous findings in Chapter Three. The observed differences in ground contact kinematics and muscle activity in these two groups could instead be as a result of trained neuromuscular responses.

Our third finding was that *tibialis anterior* activation was greater during early swing (Figure 4.1G). This finding suggests a ground clearance mechanism, as trail runners are regularly exposed to natural obstacles (e.g. fallen branches, rocks and foliage). The *tibialis anterior* muscle, situated in the anterior compartment of the lower leg, concentrically contracts to dorsiflex the ankle during swing to ensure ground clearance and prevent falling (Novacheck, 1998). Greater *tibialis anterior* muscle activity would therefore ensure ankle dorsiflexion and foot clearance to prevent falls. Interestingly, auxiliary clearance would have been unnecessary during testing on our laboratory's flat, synthetic track. This finding suggests that greater *tibialis anterior* activation in trail runners may be a result of a training adaptation to habitual running on irregular, perturbed natural paths.



Finally, and in support of our previous findings in Chapter Three, trail and road runners responded similarly to acute barefoot running. Both groups exhibited greater *gastrocnemius medialis* (GaMed) co-activity during pre-activation, with lower GaMed co-activity during stance. Both groups also presented with a decreased foot strike angle (FSA) and ankle stiffness when barefoot. These findings are in accordance with previous research (Divert et al., 2005, De Wit et al., 2000), and suggests that increased GaMed co-activity prior to ground contact acts to dampen the heel impact experienced with barefoot running (Boyer and Nigg, 2007). However, despite a flatter foot placement at ground contact, greater initial loading rate (ILR) and greater pronation variables were observed during barefoot running. Greater ILR and pronation variables have previously been associated with RRI (Thijs et al., 2007, Willems et al., 2007) (Zadpoor and Nikooyan, 2011), and thus caution should be exercised when advocating barefoot running for habitually shod runners.

To our knowledge, this is the first study to observe and compare muscle activity patterns and kinematics between experienced trail and road runners. It is important to highlight that trail and road runners were not tested in their natural running environment, and the findings of this study may represent acute responses to running on a synthetic track. The track was however an unfamiliar surface for both groups, and thus the observed group differences may represent trained responses. Future research should employ the use of portable motion capture systems or inertial sensors in order to ecologically compare these two running groups in their preferred environment.

A limitation to consider in this study was that both trail and road runners exhibited significantly different self-selected speeds during overground running in the laboratory (3.55 (0.29) vs. 3.31 (0.42) m.s<sup>-1</sup>, Trail vs. Road, respectively). However, the effect size of this difference was found to be moderate (ES = 0.63) suggesting this difference is not practically significant. We acknowledge that different running speeds have an effect on neuromuscular strategies and control (Kyrolainen et al., 2005, Montgomery et al., 1994). Running at greater velocities should increase the rate and magnitude of impact force, and according to Boyer and Nigg (2007), greater muscle activity would be required to attenuate these forces (Boyer and Nigg, 2004, Wakeling and Nigg, 2001). In contrast, although trail runners exhibited greater average running speeds in the laboratory, ILR and impact peaks were similar to that of road runners. This suggests the negligible difference in average velocity between these groups (0.24 m.s<sup>-1</sup>) did not practically impose a different workload. The observed differences in muscle activity in these two groups may instead be as a result of inherent mechanisms of motor control.

## 4.7 CONCLUSION

In conclusion, this study found that trail runners exhibited greater *gluteus maximus*, *biceps femoris* and *peroneus longus* muscle activation in late swing in comparison to road runners. Furthermore, trail runners exhibited greater *tibialis anterior* activation during early swing. These muscle activation patterns may be targeted towards stabilisation of the lower limb and auxiliary ground clearance. Collectively, these results suggest that regular running on off-road surfaces may translate into trained alterations in neuromuscular pathways, evident in patterns of muscle activation and biomechanical parameters. However, despite these suggested neuromuscular differences, shod trail and road runners responded similarly to barefoot running. Specifically, all runners presented with greater pronation variables and ILR whilst barefoot, in comparison to shod running. Future research should consider the role of these adaptations in running performance and injury.

## CHAPTER 5

### SUMMARY AND PERSPECTIVES: CONTEMPORARY UNDERSTANDING OF THE TRAIL RUNNER

#### 5.1 INTRODUCTION

Road running is one of the most popular sports world-wide. Key driving factors are the associated health benefits of cardiovascular exercise, the accessibility of the sport and the minimal equipment requirements (Scheerder et al., 2015). However, the likelihood of sustaining a chronic running-related injury (RRI) remains concerning for sports medicine practitioners and runners alike (Buist et al., 2010, van Gent et al., 2007, van Mechelen, 1992, Van Middelkoop et al., 2008, Lun et al., 2004, Videbaek et al., 2015, Hespanhol et al., 2013). Hypothesised contributors to the increased incidence of RRI include the repetitive and monotonous running terrain and running surface medium. Many attempts to reduce the prevalence of RRI include novel footwear technology and training load modification (Yeung, 2001), however these figures remain high. Consequently, many recreational and competitive runners are searching for an alternative to road running. One such alternative is an ‘off-road’ sub-discipline of running, known as ‘trail running’.

The trail running environment is unique in that it customarily comprises natural terrains such as sand or grass. This natural topography allows an individual to vary their running gait and possibly provides other psychosocial benefits (Barton and Pretty, 2010, Hartig et al., 1991). In addition, the variable and ‘forgiving’ surfaces have been suggested to reduce the risk of sustaining a chronic RRI (McMahon and Greene, 1979, Mann et al., 2015, Hamill et al., 1999). However, despite the emergence of this new sub-discipline over the last decade, the body of scientific literature on trail running and its participants remains in its infancy.

Accordingly, this thesis was borne out of a need to understand the implications of trail running on the musculoskeletal system and on running mechanics. We hypothesised that running on natural, irregular surfaces would have a long-standing and positive influence on neuromuscular patterns and running biomechanics in well-trained trail runners. Further, we hypothesised that due to regular training on sporadic, uneven trail surfaces, trail runners would demonstrate considerable dynamic stability.

The purpose of this thesis was therefore to describe the trail running athlete with regards to dynamic stability, muscle activity patterns and running biomechanics. Furthermore, to elucidate whether there are long-term effects of running on a preferred terrain, we sought to examine and compare these parameters between trail and road runners.

## 5.2 SUMMARY AND OUTLOOK

This thesis advances the current understanding of trail running and its participants by demonstrating that:

- i. Specific clinical assessments revealed no differences between trail and road runners with regards to lower extremity muscle endurance and balance. However, trail runners demonstrate greater ankle stability during dynamic weight-bearing in comparison to road runners. Minimal ankle displacement during weight bearing in trail runners may be a mechanical response to exposure to running on uneven terrain.
- ii. Experienced trail runners exhibit differing biomechanical and spatiotemporal running gait to road runners in controlled laboratory conditions. This finding warrants further external validation within trail running environments, but suggests that regular trail running can inherently alter or adapt running biomechanics.
- iii. Trail runners demonstrate several kinematic (decreased pronation magnitude and velocity, smaller foot strike angles) and spatiotemporal (greater stride frequency, shorter ground contact time and shorter stride duration) parameters that are purported to be 'favourable' in reducing the risk of sustaining a running-related injury (RRI) in comparison to road running counterparts.
- iv. Road runners present with greater peak knee flexion and pronation components (magnitude and velocity) during stance in comparison to trail runners, which may predispose them to lower extremity RRI.
- v. Interestingly, despite several differing kinematic parameters, trail and road runners experience similar initial loading rates (ILR) in response to a short bout of running on a synthetic track. ILR is one of many risk factors that have been associated with RRI, which suggests that these two running populations could be at a similar risk of sustaining a RRI. This complex trail running-injury relationship warrants further scientific consideration.
- vi. Trail runners exhibit greater *gluteus maximus*, *biceps femoris* and *peroneus longus* muscle activation during terminal swing phase of the gait cycle in controlled laboratory

conditions. Muscle activity during this period has been suggested to be adjusted according to previous ground contact experiences to prepare the musculoskeletal system for landing. Greater lower extremity muscle activation during terminal swing in trail runners may be a neuromuscular adaptation that serves to minimise unnecessary joint displacement during ground contact and contributes to whole body dynamic stability.

- vii. Trail runners exhibit greater *tibialis anterior* activation during early swing in a laboratory setting. The *tibialis anterior* acts to dorsiflex the foot, pulling the foot towards the shin. Greater activation during this phase of the gait cycle would allow for greater ground clearance, which suggests that trail runners may be well-adapted to running over various height perturbations.
- viii. Regular trail running on natural, irregular terrain appears to have positive, long-lasting effects on the neuromuscular regulation of running biomechanics.

Recommendations for future work include:

- i. Large-scale epidemiological studies to observe and report on the prevalence and incidence of injury rates in ‘pure’ trail runners. We recommend that the risks and benefits associated with trail running be examined and compared across all trail running populations (e.g. forest running *vs.* mountain running, ultra-runners *vs.* long-distance runners).
- ii. Further development and critical consideration of the notion that habitual running on a preferred terrain has long-standing effects on neuromuscular and biomechanical patterns.
- iii. Comprehensive investigation into the influence of trail running on the human body, including the physiological and metabolic responses to trail running.
- iv. Isokinetic muscle testing to examine the influence of running on steep inclines and declines on muscle strength and endurance in experienced trail runners. As trail running is used as a scientific model of muscle fatigue, it would be of further interest to elucidate the specific muscle adaptations or mal-adaptations that may occur with regular trail running.
- v. Research that compares biomechanical and spatiotemporal gait symmetry and variability between road and trail runners in different environments.
- vi. Research that employs the use of portable motion capture and inertial systems to observe real-time trail running.

- vii. Randomised control trial and prospective injury studies that examine the utilisation and efficacy of trail running as a clinical intervention for road runners with chronic running-related injuries. Trail runners are exposed to variable and ‘forgiving’ terrain that may reduce repetitive loading of the musculoskeletal system. In this regard, trail running may serve as a promising alternative to road running.
- viii. Research into the efficacy of trail running as training tool for other running disciplines. Trail running may have the potential to optimise one’s running biomechanics, improve muscle endurance and strength, and improve overall running performance.

The outcomes of this thesis suggest that there are numerous clinical, mechanical and muscular implications of trail running. Although there may be no distinct advantage of trail running over road running, trail running continues to grow in popularity and provide an alternative to running on the road. For this reason, it is imperative that the risks and benefits associated with participating in this sport be critically considered and examined.

The present thesis thus serves as the first step in holistically understanding the long-term effects of habitual trail running. It is our hope that the work presented in this thesis will be utilised as a springboard for the necessary scientific research to fill the gaps in the current understanding of the trail running athlete.

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