THE IMPACT OF THREE DIFFERENT FOOTWEAR CONDITIONS ON INDIVIDUAL BIOMECHANICAL, PHYSIOLOGICAL AND PERCEPTUAL RESPONSES DURING RUNNING.

BY

JUSTIN JOHN MCDOUGALL

THESIS

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Department of Human Kinetics and Ergonomics

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ABSTRACT

Background: Despite the introduction of running footwear in the 1970's, running injury rates continue to be unacceptably high. The subsequent revival of barefoot running and the introduction of minimalist footwear occurred, in an attempt to reduce injury rates and increase performance. There is much contention in the literature around the effectiveness of these footwear conditions. Furthermore individual responses have recently been proposed to provide more accurate and reflective conclusions than the use of mean data. **Objectives:** Twofold: a) to compare the biomechanical, physiological and perceptual responses between the shod, minimalist and barefoot footwear conditions and b) to assess and compare individual responses under these footwear conditions. **Methods:** 26 well-trained, male, habitually shod endurance runners, aged between 18 - 30 years completed three experimental sessions on an indoor runway and motorized treadmill. Each session was completed in either the shod, minimalist or barefoot condition, running at 15km.h^{-1}. Variables assessed included stride rate, stride length, impact peak, vertical impact and average loading rate and strike time (biomechanical); heart rate, oxygen consumption and electromyography (physiological); and rating of perceived exertion and body discomfort (perceptual). **Results:** Biomechanics – Stride rate and stride length showed a significant ($p<0.001$) increase and decrease respectively when running in the minimalist or barefoot conditions versus shod. Running barefoot versus the minimalist and shod conditions resulted in a significantly ($p<0.001$) greater vertical impact loading rate. Strike time was significantly ($p=0.008$) reduced running in the minimalist and barefoot conditions versus shod. Physiology – Running barefoot versus shod resulted in a significantly ($p=0.02$) reduced heart rate and Tibialis Anterior activity ($p=0.005$). There was a large variability in individual responses for many variables, with responders and non-responders seen. **Conclusion:** The study suggests that there are significant differences between all three forms of running for some variables. It was further noted that there is support for the proposal that individual responses are highly variable and should be analysed accordingly.

Keywords: barefoot running, shod running, minimalist running, individual variability, biomechanics, physiology, perceptual responses, electromyography, responders, non-responders.

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INTRODUCTION

BACKGROUND TO THE STUDY

THE INTRODUCTION OF RUNNING FOOTWEAR

To ensure survival, humans are proposed to have evolved over many millennia to become successful endurance runners, a method to acquire foods rich in protein and provide protection from predators (Bramble and Lieberman, 2004). Over a relatively short period of time, the *contemporary* humans' way of life has altered considerably from the primitive beginnings of the early human. Current society is increasingly modernised and mechanised, which has seen endurance running transform from a necessary form of locomotion and proposed survival mechanism, into a popular recreational activity and highly competitive sport, associated with numerous health benefits (Rixe, Gallo and Silvis, 2012).

The recent introduction of modern running footwear, has seen runners shift away from traditional minimalist footwear (such as sandals, moccasins or racing flats) and barefoot running, the proposed method by which humans evolved to run (Bramble and Lieberman, 2004; Trinkaus and Shang, 2008; Fields, Sykes, Walker and Jackson, 2010; Lieberman, Venkadesan, Werbel, Daoud, D'Andrea, Davis, Mang'Eni and Pitsiladis, 2010; Noakes and Spedding, 2012 and Perl, Daoud and Lieberman, 2012). Modern running footwear was introduced in the 1970's, with the intention to reduce and prevent running related injuries, whilst providing stability to runners (Altman and Davis, 2012). Combined with a corresponding rapid growth in running participation (both recreationally and competitively as a form of exercise for health) over the last 40-50 years; a multi-billion dollar footwear industry developed, which entrepreneurs could exploit (Novacheck, 1998; Rixe *et al*., 2012).

Modern running footwear has advanced significantly since its introduction, with the incorporation of increased cushioning and motion control features (Warne and Warrington, 2014). Despite such features, the overall rate of injury in endurance runners has not decreased significantly in the last 30 years and in many instances is seen to have increased (Robbins and Gouw, 1991; Novacheck, 1998; Lieberman *et al*., 2010; Rixe *et al*., 2012). The current rate of running injuries experienced globally is undeniably high; however the assumption that running footwear has been ineffective in reducing running injuries is disputed. This is discussed below.

Since the introduction of footwear in the 1970's there has been an enormous increase in frequent (>100 times a year) running participation (Running USA). Modern runners display a far greater heterogeneity and potentially unfavourable characteristics to endurance running as a result of changes in biomechanics, anthropometrics and training characteristics (Tam, Wilson, Noakes and Tucker, 2014). Evidence shows a decline in runner performance. For example the average time taken to run a marathon in the USA was found to be 4:17:43 in 2012, while in the 80's this was in the 3.30's (Running USA). A similar argument is provided by Tam *et al*. (2014) who conclude that the labelling of modern running shoes is ineffective, as an inadequate and oversimplified argument.

THE RESURGENCE OF BAREFOOT RUNNING

Due to the labelling of modern running footwear as ineffective, barefoot running increased in popularity and gained international recognition. This was further supported by the release of Christopher McDougalls' book "*Born to Run: A Hidden Tribe, Super athletes, and the Greatest Race the World Has Never Seen" in 2009.* In this book he inferred that cushioned modern footwear was a major cause of running injury and responsible for the (alleged) increase in running-related injuries since the introduction of modern running shoes in 1972 (p.179). Subsequently, barefoot running or simulated barefoot running (through the use of minimalist footwear) has generated much interest in scientific publications and the lay-media due to the alleged benefits (both biomechanically and physiologically) to runners of all levels (Tam *et al*., 2014).

- *PROPOSED BENEFITS OF BAREFOOT RUNNING*

A number of benefits have been proposed to provide justification for barefoot running, these are discussed below.

Altered foot-strike pattern: A change in running foot-strike pattern, from a rear-foot strike (RFS) to a more anterior mid or fore-foot strike (MFS/FFS) pattern is a proposed benefit of barefoot running (Stacoff, Nigg, Reinschmidt, van den Bogert and Lundberg, 2000; Jungers, 2010; Lieberman *et al.,* 2010; Hamill, Russell, Gruber and Miller, 2011; Nigg and Enders, 2013). This shift has been associated with an increase in stride rate and a reduction in stride length and impact peak forces in selected individuals (Cheung and Rainbow, 2014). Hall, Barton, Jones and Morrissey (2013) suggest that these changes may be associated with positive biomechanical changes, with regards to injury prevention. In contradiction to the above findings, Larson, Higgins, Kaminski, Decker, Preble, Lyons, McIntyre, Normile (2011) contended that the strict characterization of barefoot running resulting in an anterior foot-strike (MF/FFS) and shod running resulting in a RFS is an oversimplification. This is evident when comparing the Lieberman *et al*. (2010) paper (based on runners from the Kalenjin tribe in Kenya) to Hatala, Dingwall, Wunderlich, and Richmond (2013) who used a different tribe (the Daasanach). Lieberman *et al*. (2010) found the majority of their participants ran with a FFS when barefoot, while the majority of participants in the Hatala *et al*. (2013) study used a RFS. These disparities clearly indicate the need for additional research into the foot-strike patterns employed by endurance runners, and the avoidance of broad generalizations for all populations.

Reduced impact peak: In 2010, Lieberman *et al.* compared the impact forces experienced when running shod versus barefoot. These authors found that barefoot runners experienced smaller impact forces than shod runners, when these participants switched to a FFS. The individuals who remained RFS experienced increased impact forces. Lieberman *et al.* (2010) advocated that running was most injurious the moment the foot strikes the ground, and therefore reduced impact forces shown in their study may result in a decreased overuse injury risk. Other studies however contend this issue. For example in an earlier study conducted by Nigg (2001) he suggests that it cannot be concluded that impact forces are important factors in the development of chronic and/or acute running-related injuries. A later systematic review by Zadpoor and Nikooyan (2011) supported this view, when they cited that impact forces are invalid indicators for running injuries (specifically stress fractures) and that impact forces are not any different when running shod compared to barefoot.

Energy cost: Barefoot running has been associated with a reduced energy cost of running. Numerous studies conducted by Burkett, Kohrt and Buchbinder (1985), Flaherty (1994), Divert, Mornieux, Freychat, Baly, Mayer and Belli (2008), Squadrone and Gallozzi (2009) and Hanson, Berg, Deka, Meendering and Ryan (2011) found decreased oxygen consumption rates when participants ran barefoot as opposed to shod. Contention is however widespread in the literature, for example Franz, Wierzbinski and Kram (2012) found (at equal mass) shod running had a 3-4% lower energy cost than running barefoot. Franz *et al*. (2012) therefore put forward that a decreased energy cost when running barefoot (seen in other studies) is due to the reduced foot mass when barefoot versus shod. Few of the above mentioned studies, however controlled or considered shoe mass, and therefore these findings should be interpreted with caution.

Decreased sensory feedback: Robbins and Hanna (1987) proposed that running footwear insulated the sensory feedback mechanism in the body, which leads to a decreased sensory feedback, associated with increased lower limb impact forces when running.

Literature is inconclusive surrounding barefoot running and its proposed benefits. While certain individuals may experience benefits running under this condition, more research needs to consider the option/s which provide benefits to the majority of runners and helps to understand why some individuals experience these responses while others do not.

MINIMALIST FOOTWEAR

Minimalist footwear was introduced in an attempt to mimic the suggested benefits of barefoot running, whilst providing some padding for hard surfaces and to negate the negative effects of environmental conditions (extreme hot or cold running surfaces) and puncture wounds (Squadrone and Gallozzi, 2009; Jenkins and Cauthon, 2011; Lorenz and Pontillo, 2012; Willson, Bjorhus, Williams, Butler, Porcari and Kernozek, 2014). Compared to research conducted on the shod and barefoot conditions, very few studies have investigated the various aspects associated with minimalist footwear. Studies conducted to date comparing minimalist footwear to the barefoot condition, have shown that the minimalist condition does not mimic barefoot running biomechanics as it was proposed to (Bootier, 2012; Bonacci, Saunders, Hicks, Rantalainen, Vicenzino and Spratford, 2013; Tung, Franz and Kram 2014). Willy and Davis (2014) found minimalist running resulted in no changes in step length or in step rate compared to the shod condition; however the vertical impact peak and average vertical loading rate were greater when shod versus the minimalist condition. Investigating physiological responses, Squadrone and Gallozzi (2009), Perl *et al*. (2012), Lussiana, Fabre, Hébert-Losier and Mourot (2013) and Warne and Warrington (2014) found running in minimalist footwear to be more economical than shod running, while Sobhani, Bredeweg, Dekker, Kluitenberg, van den Heuvel, Hijmans and Postema (2014) found no difference. Further studies investigating both the biomechanical and physiological responses are needed to provide additional information on the usefulness of minimalist footwear. The response of some individuals using this footwear condition is of particular interest, as it is anticipated some may respond positively under this condition.

POLARIZATION AND INDIVIDUAL RESPONSES

A recent paper by Mann, Lamberts and Lambert (2014, p.1) discussing indivual repsonses to standardized training stated that "the response to an exercise intervention is often described in general terms, with the assumption that the group average represents a typical response for most individuals". In reality, however, it is more common for individuals to show a wide range of responses to an intervention rather than a similar response (Mann *et al*., 2014). A number of authors have shown this type of response in running based studies too. Logan, Hunter, Hopkins, Feland and Parcell (2010) found that a difference exists in loading rates between footwear conditions, however more importantly they found that the variability in responses between participants was large. A paper by Hatala *et al*. (2013) found that some individuals use different foot-strike patterns when running barefoot. These inter-individual differences have also been recognized in Nigg and Enders (2013), these authors state that inter-individual differences are substantial and it is not appropriate to associate barefoot running with fore-foot striking and shod running with a rear-foot strike. A review paper by Tam *et al*. (2014) notes how several studies have demonstrated an immediate adjustment in factors such as ankle and knee angle on impact, and resultant changes in foot-strike, however these changes do not occur equally for all runners. Lastly, Tung *et al*. (2014, p.326) stated: "we found considerable individual variation with respect to the effect of surface cushioning on metabolic demand". While the above mentioned studies are important and provide evidence that individuals respond differently (under various conditions), Tam *et al*.

(2014) is the first study (to the author's knowledge) to acknowledge the importance of individual responses in running specifically. No studies have however investigated this further.

It is anticipated that no single solution to running injuries or performance exists, yet previous literature has focussed predominately on determining the most effective condition (shod, minimalist or barefoot) to reduce running injuries and improve performance based on the premises of a one size fits all solution. These studies have fallen into the trap of comparing A vs. B (i.e. shod vs. barefoot), and considering no other option. This approach polarizes a complex issue and attempts to provide a simple explanation, when in reality no simple solution exists (Tam *et al*., 2014). Little is known about the variation in individual responses under each footwear condition, and therefore a better understanding of these responses may reveal how some individuals are more suited to certain footwear conditions than others. Assessing individual responses needs to be the approach going forward, and this may establish the factors which may provide the most effective running form for each individual and whether these factors are similar for all individuals or not.

STATEMENT OF THE PROBLEM

The problem addressed by this research project was twofold. In order to improve endurance running performance and reduce the risk of injury a clear and concise scientific understanding is imperative. Therefore the first problem was to investigate the contention surrounding the role of three different footwear conditions (shod, minimalist, and barefoot) on the biomechanical, physiological and perceptual responses in endurance runners. Secondly, the one size fits all approach to running injuries and performance appears to be an oversimplification, as a large variation in responses has been suggested, with responders and non-responders identified. Therefore individual responses were investigated further, in order to determine whether solutions/advice based on the individual is practical.

STATISTICAL HYPOTHESIS

1. Mean Hypothesis

There will be no change in biomechanical, physiological and perceptual responses between the three footwear conditions.

$\mathbf{H_O: \mu_{SHOD} = \mu_{MININMALIST} = \mu_{BAREFOOT}}$

There will be a change in biomechanical, physiological and perceptual responses between the three footwear conditions.

$\mathbf{H_A: \mu_{SHOD} \neq \mu_{MININMALIST} \neq \mu_{BAREFOOT}}$

2. Individual Hypotheses

There will be no change in individual biomechanical, physiological and perceptual responses between the footwear conditions.

$\mathbf{H_O: \mu_{SHOD} = \mu_{MINIMALIST} = \mu_{BAREFOOT}}$

There will be a change in individual biomechanical, physiological and perceptual responses between the footwear conditions.

$\mathbf{H_A: \mu_{SHOD} \neq \mu_{MINIMALIST} \neq \mu_{BAREFOOT}}$

Where:

- Biomechanical Responses = Stride Length, Stride Rate, Impact Peak and Vertical Impact and Vertical Average Loading Rate.
- Physiological Responses = Heart Rate, Oxygen Consumption, Energy Expenditure and Electromyography.
- Perceptual Responses = Rating of Perceived Exertion and Body Discomfort.

RESEARCH HYPOTHESIS

It is anticipated that physiological responses (HR, EE and $\dot{V}O_2$) between the three footwear conditions will not be significantly different, while biomechanical, perceptual and EMG responses will be significantly different between the barefoot and two shod conditions. It is expected that EMG activity will vary between the different conditions and individuals, with some muscles showing a reduction in activity while others an increase. It is expected that the foot-strike pattern employed under each condition will affect the EMG activity between muscles considerably. The expected biomechanical changes when running barefoot compared to minimalist or shod (based on mean data) will be an increased stride rate (SR), a decrease in stride length (SL), an increased impact force (foot-strike dependant) and a decreased loading rate (GRF). The secondary assessment of individual responses is however expected to display a large inter-individual variability between the elicited responses. It is anticipated that barefoot running will maximize variation in individual biomechanical, physiological and EMG responses, while running shod will minimize this variation, and minimalist footwear will fall somewhere in-between these two conditions.

DELIMITATIONS

The present study was delimited to 26 well-trained, male, habitually shod endurance runners, aged between 18 - 30 years. Some of the participants were students currently enrolled at Rhodes University, Grahamstown, South Africa. Each participant was required to attend three experimental sessions, each consisting of a set number of laps along a 20m indoor runway (with an embedded force plate), followed by a single 6 minute running protocol on a motorized treadmill. Each session was completed either shod, barefoot or in minimalist footwear at a pre-determined running speed.

LIMITATIONS

Although significant effort was made to meticulously control as many extraneous variables from affecting the reliability of measures, it was impossible to control all impinging influences. The following factors did pose limitations to the current study and should be taken into consideration when examining the implications and conclusions from the results obtained:

This study utilized participants with no minimalist or barefoot running experience, except for a short acclimatization trial prior to the experimentation sessions. Squadrone and Gallozzi (2009) state that runners not accustomed to running barefoot could have their natural foot structure weakened by long-term footwear use and a decreased proprioceptive sensitivity. As a result they could be less effective in adapting their running style when running with this condition. The participants used in this study were habitually shod runners; therefore the results obtained might not reflect the benefits of minimalist or barefoot running as well as if habitually shod runners were compared to habitually minimalist or barefoot runners. Habitually minimalist or barefoot runners were not accessible for experimentation.

Shoe sole-stiffness was not controlled, as this was not possible without purchasing standardized shoes for all participants, which was not an option available to the researcher. All participants therefore used their own shoes for all shod experimental sessions. Hanson *et al.* (2011) note a negative correlation between shoe stiffness and vertical impact forces, meaning that as the level of cushioning increases the harder one lands. The stiffer the sole, the more the natural motion of the foot is modified (Morio *et al*., 2009). This can have a negative influence on running economy (softer soles increase the cost of running). And the difference in sole-stiffness between participants could create some unwanted variance for the force variables.

Stride length and stride rate were measured in this study, but not controlled to a specific rate. This could affect the results, as running pace is determined by the spatial and temporal parameters of stride length and cadence (Lohman *et al*., 2011). Steudel-Numbers, Weaver and Wall-Scheffler (2007) have also shown that relatively longer lower limbs result in more efficient running. A shorter stride / increased stride rate can increase the cost of transport versus a longer stride / decreased stride rate which can result in a decreased cost of transport.

The conclusions and practical recommendations of the current study were based on responses measured in laboratory conditions over very short bouts of running. It is therefore recognized that while these conclusions and recommendations provide important insights into what is happening biomechanically, physiologically and perceptually when individuals run in these footwear conditions, these may not be robust enough to transfer to what happens in 'real life', where the training and racing mileage is high.

Participants completed experimental sessions on different days, and unfortunately the laboratory conditions could not be controlled to be identical for all experimental sessions. The laboratory conditions therefore depended on the external environment at the time of experimentation. The temperature was therefore noted prior to each session, but this was not controlled.

Participants were required to run a minimum of 30 $km.week^{-1}$ to participate in the study. The training status of the participants could however not be controlled stringently, as a number of participants ran a lot more than this and participated in other sports training regimes. Differences in training status thus may have had an impact on the results.

All participants were South African, well-trained male endurance runners. And although these runners possessed high levels of fitness and experience, extrapolation to the global running population is limited. Gender was an additional limitation, and recommendations of this study may not be applicable to female runners.

Participants were requested to follow the pre-experimental procedure; however the author was not able to control this and relied on participants being studious and truthful throughout. If participants admitted they had not followed the regulations prior to experimentation, the session was cancelled and re-scheduled.

Stature was not controlled and could have had an influence on individual limb length. The running economy of an individual could be influenced by this, as long limbs have been associated with a reduced energy cost (Steudel-Numbers *et al*., 2007).

Shoe mass was not controlled. All participants' shoes were weighed and this was noted during the analysis of the response data. Not controlling mass could have led to minor discrepancies due to the varied mass of utilized running shoes.

CHAPTER II

REVIEW OF RELATED LITERATURE

AN INTRODUCTION TO RUNNING

Humans are proposed to have adapted well into long distance runners, due to evolutionary adjustments (Bramble and Lieberman, 2004). Today running is second only to walking as the most important recreational activity undertaken by humans (De Wit, De Clercq and Aerts, 2000). The increased awareness, in the late 1960's, of the benefits accompanying aerobic exercise to maintain a healthy lifestyle, led to the exponential growth in endurance running participation (Fields *et al*., 2010; Hall *et al*., 2013). Despite direct improvements in cardiovascular fitness, a decreased risk of stroke and hypertension, an increased bone mass and psychological benefits such as decreased depression and a positive effect on mood state; running currently poses a high risk of injury (Hanson *et al*., 2011; Lohman *et al*., 2011; Hall *et al*., 2013).

Running is a complex movement to study where both mechanical and muscular characteristics interact with the external conditions (Divert, Mornieux, Baur, Mayer and Belli, 2005a). The addition of running footwear (shod, minimalist or barefoot), running surfaces, individual variation in runner characteristics, foot-strike patterns and running form complicate this further. A large body of research into endurance running has developed over the last four decades, some of which includes the investigation of ground reaction forces (Hamill, 1983; Nigg, 2001), the interaction between shod and barefoot running (Divert *et al*., 2005a), the impact of different running speeds, gradients (Gottschall and Kram, 2005) and the various landing patterns during a runners first attempt at barefoot running (Cheung and Rainbow, 2014). Despite this the understanding of running is insufficient and many questions remain unanswered. Further critical research is needed to increase the understanding of human locomotion, in order to improve running performance and make running less injurious. Limited studies have considered the impact of footwear on individual biomechanical, physiological and perceptual responses; which has recently been proposed as an important area for future research (Tam *et al*., 2014).

The following chapter provides a critical review of current literature (related to this study), an appraisal and critical reflection of the current state of knowledge surrounding endurance running.

THE EVOLUTION OF HUMANS AS ENDURANCE RUNNERS

THE SIGNIFICANCE OF EVOLUTION

Up until the 1970's walking was extensively studied, with comparatively little research into running, as running was not considered to have played a major role in human evolution, because humans, like apes, are poor sprinters compared to most quadrupeds (Bramble and Lieberman, 2004). Humans are also less manoeuvrable, have a greater energy cost than most other mammals and lack many structural modifications characteristic of most quadrupedal cursors, such as elongate digitigrade feet and short proximal limb segments (Bramble and Lieberman, 2004).

While comparatively poor sprinters, as endurance runners humans have an impressive ability to perform at relatively high speeds and in extremely hot conditions (Lieberman *et al*., 2006). Noakes and Spedding (2012: p295) provide support of this, when they recently wrote "s*imply put we (humans) evolved to run"*. Humans are thought to have evolved as tree-dwelling apes to become specialized endurance runners and this is what makes the genus *Homo* unique from other primates (Bramble and Lieberman, 2004; Mattson, 2012). The increased size of the human brain relative to other primates, and its' resultant cognitive capabilities, may have played an important role in the endurance runner phenotype (Mattson, 2012). This links well to Bramble and Lieberman's (2004) proposed hypothesis that human's developed into specialized endurance runners in order to compete in pursuit hunting or scavenging; which helped early hominids exploit protein-rich resources such as meat, bone-marrow and brain.

Pickering and Bunn (2007) agree that obtaining a high-quality diet (with a substantial meat component) was critical to the evolutionary success of the genus *Homo* lineage. They contend however that from an ethnographic point of view, due to the landscape encountered and the cognitive capabilities of early humans, endurance running (as a technique in pursuit hunting or scavenging) was not employed regularly or successfully. They argue further that these techniques contributed minimally, if at all. They contend instead that meat could have been obtained via pursuit hunting when walking or via pursuit foraging. For a more complete understanding on this debate please refer to the following journals: Bramble and Lieberman (2004); Lieberman *et al.* (2006); Pickering and Bunn (2007) and Lieberman *et al.* (2007).

For the purpose of this thesis it is sufficient to be able to understand that humans are proposed to have engaged in endurance running for millions of years (Bramble and Lieberman, 2004) and this was accomplished without footwear during most of this time (Altman and Davis, 2012). Throughout the development of endurance runners, running was performed barefoot 99% of the time or in minimal footwear (such as sandals or moccasins) with smaller heels and little cushioning relative to modern footwear (Jungers, 2010).

EVOLUTIONARY-MODIFICATIONS FOR RUNNING

A shift to bipedalism played a significant role in influencing the human gait and performance (Bramble and Lieberman, 2004). Walking and running on two legs distinguishes humans from apes, and has long been the defining adaptation of the genus *Homo* (Bramble and Lieberman, 2004; Lieberman *et al*., 2006). The human foot and lower extremity is uniquely specialised for bipedalism which has important biomechanical implications.

Structural and physiological underpinnings of endurance running ability among mammals has revealed several novel features of the genus *Homo* that evolved within the past 2 million years, to provide humans with a superior long distance running capability (Bramble and Lieberman, 2004; Perl *et al*., 2012). The majority of these modifications are specifically for running and have little benefit for walking, lending support to Bramble and Lieberman (2004) and Noakes and Spedding (2012). Bipedal endurance running imposes four main demands on the body’s structure: energetics, strength, stabilization and thermoregulation. The ideas illustrated overleaf (Table I) stems primarily from research by Bramble and Lieberman (2004) due to their seminal paper in this area of research.

Table I: Evolutionary Modifications for Running

ENERGETICS	Long tendons (i.e. Achilles), short muscles = economical force + save 50% COT	Elastic structure (plantar arch) returns ±17% of energy per stance	Effective springs and long legs allow speed ↑ by ↑ stride length rather than rate = favour oxidative, fatigue resistant muscle fibres	↓ distal limb mass = substantial metabolic savings	
SKELETAL STRENGTH	Running produces a ground reaction force, which is ↓ by limb compliance via modifications such as ↑ joint surface area, enlarge iliac pillar of pelvis, shortened femoral neck and ↓ inter-acetabular hip-breadth				
STABILIZATION	Expanded area on sacrum and posterior iliac spine for erector spinae muscles to attach	Greatly enlarged gluteus maximus muscle - strongly recruited in running	Forwardly inclined trunk and neck		
THERMOREGULATION & RESPIRATION	Unmatched ability to dissipate heat - elaboration and multiplication of eccrine sweat glands and reduced body hair	Narrow and elongated body form, and elaborate cranial venous circulation	Mouth breathing - ↑ airflow rates and ↓ resistance and muscular effort		

These modifications enabled humans to run upright on two limbs, a gait which is different to that of the walking gait. A review of this unique running gait is discussed below.

A REVIEW OF THE RUNNING GAIT

The analysis of the human running gait is necessary to understand the mechanics of human locomotion (Kövecses and Kovács, 2011). During running, the major leg joints undergo substantial flexion and extension during stance as the legs behave in a spring-like manner (Cappellini *et al.*, 2006). The mass-spring model is commonly used to describe the running gait (Bullimore and Burn, 2007), discussed below.

THE MASS-SPRING MODEL OF RUNNING

During running, once a limb strikes the ground, the kinetic and gravitational potential energy is temporarily stored (absorption) as elastic strain energy via a complex system of springs composed of muscles, tendons, and ligaments and various connective tissues of the lower extremity (Bramble and Lieberman, 2004; Bishop *et al.*, 2006; Cappellini *et al.*, 2006). This energy is then nearly all recovered during the propulsive (propulsion) second half of the stance phase. The running gait cycle consists of a stance phase, swing phase and a float phase. The first half of stance phase is concerned with force absorption, whereas the second half is responsible for propulsion (Figure 1). The body's centre of mass is lowered and raised in the process of absorption and propulsion respectively. The limbs play an important role in ensuring that forces are minimalized during running and minimal energy is utilized throughout this process, thereby reducing the risk of injuries and increasing efficiency.

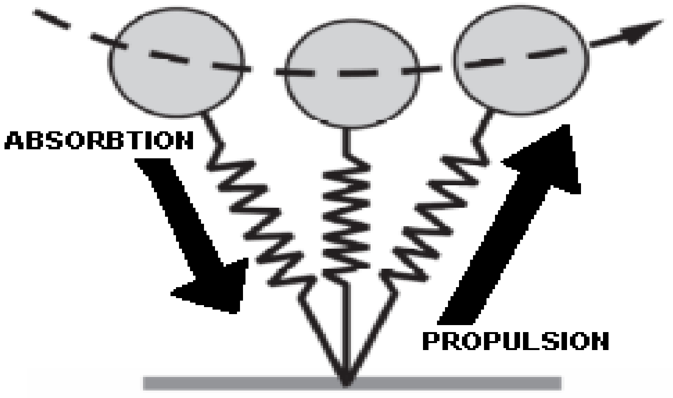

Figure 1: The stance phase of the running gait, illustrating absorption and propulsion supported by the lower extremity and the movement of the body's centre of mass (Adapted from Kerdok, Biewener, McMahon, Weyand and Herr (2002)).

RUNNING RELATED INJURY RATES

According to Taunton *et al*. (2002) and Lohman *et al*. (2011) running is associated with numerous injury risks due to the combination of extrinsic factors (training errors, old footwear, incorrect shoe choice, running surface) and intrinsic factors (flexibility, mal-alignment, anthropometry, previous injury, running experience). Running injuries have been documented since the running boom in the 1970's (Rixe *et al*., 2012) and it is generally accepted that the regularity with which they occur is unacceptably high, with no significant decline in the past 30 years, despite considerable efforts to reduce them (Daoud *et al*., 2012).

Technological advances such as increased cushioning and motion control features in modern footwear, have not been able to reduce the overall rate of injury in distance runners, and in many instances injuries are seen to have increased (Robbins and

Gouw, 1991; Novacheck, 1998; Lieberman *et al*., 2010; Lohman *et al*., 2011; Perl *et al*., 2012; Rixe *et al*., 2012). The percentage of runners injured each year ranges from 25% up to 79% (Novacheck, 1998; Taunton *et al*., 2002; Fields *et al*., 2010; Lieberman *et al*., 2010; Lohman *et al*., 2011; Hanson *et al*., 2011 and Altman and Davis, 2012). Even at the lowest rate of injury, 25%, a quarter of the running population is injured in a given year. Despite the introduction of modern running shoes (of all nature - minimalist to cushioned) there is no conclusive evidence on their effectiveness in preventing injury (Jenkins and Cauthon, 2011).

The following section will cover the introduction of footwear to running, and the impact that footwear has had on running injuries. This will be followed by various injury prevention strategies utilized by runners (including various forms of footwear) in an attempt to reduce injuries.

INTRODUCTION OF RUNNING FOOTWEAR

Prior to the 1970s, individuals either ran barefoot or in minimal footwear which were modified sandals or moccasins (Fields, Sykes, Walker and Jackson, 2010; Lieberman *et al*., 2010; Rixe *et al*., 2012). Sandals or moccasins were invented less than 50 000 years ago, with the earliest example of footwear being discovered over 10 000 years ago (Altman and Davis, 2012; Perl *et al*., 2012). This early running footwear was constructed on a flat surface of woven sagebrush, with strapping to keep them on the feet, worn to protect the bottom surface of the foot (Altman and Davis, 2012). Modern running footwear has had a profound impact on human running biomechanics, not solely due to the effect of footwear, but also the proposed association of such footwear and a shift in foot-strike patterns (Perl *et al.,* 2012). Modern running footwear now incorporates a significant amount of cushioning and stabilization materials; marketed for comfort, injury protection and the correction of movement patterns (Nigg, 1986; Robbins and Gouw, 1991; Altman and Davis, 2012; Bonacci *et al*., 2013).

INJURY AND INJURY PREVENTION

Repetitive stress / overuse injuries have been found to be amongst the most prevalent in endurance runners (Lieberman, 2012). The most common of these are patella femoral pain syndrome, ilio-tibial band friction syndrome, plantar fasciitis, and meniscal damage (Taunton *et al*., 2002; Hreljac, 2004; Daoud *et al*., 2012). According to Taunton *et al*. (2002) and van Gent *et al*. (2007) the most commonly injured site is the knee.

In an attempt to reduce the high injury rates experienced, runners have adopted numerous strategies, which includes: adapting ones foot-strike pattern, the use of footwear (shod and minimalist) or running without footwear (barefoot).

- *Adapting Foot-strike Patterns*

The adjustment from a rear-foot strike (RFS) to a mid-foot or fore-foot strike (MFS/FFS) has been found to limit certain lower extremity injuries experienced by a large percentage of runners; however remaining with a RFS is suggested to be an important predictor for development of running related injuries (Lieberman *et al*., 2010 and Daoud *et al*., 2012). Daoud *et al*. (2012) found that approximately 74% of cross-country runners experienced some form of moderate-to-severe injury annually, however RFS had twice (2.6 times for mild injuries and 2.4 times greater for severe injuries) the rate of repetitive stress injuries than those utilizing a FFS, while traumatic injury rates were not significantly different.

Kulmala, Avela, Pasanen and Parkkari (2013) found a FFS exhibits lower patella-femoral stress and knee frontal plane moment than a RFS, which may reduce the risk of running related knee injuries. However a parallel increase in ankle plantar-flexor and Achilles tendon loading was evident, which may increase risk for ankle and foot injuries. A FFS may reduce injuries at the knee and contribute to fewer injuries overall, however it has been shown to cause injuries elsewhere, such as Achilles tendinopathies, injuries of the foot and stress fractures of the metatarsals (Perl *et al*., 2012). A similar argument is put forward by Stearne, Alderson, Green, Donnelly and Rubenson (2014), who found there appears to be no clear mechanical advantage of habitual RFS or FFS running. These foot-strike patterns just shift the injury mechanisms. If this is the case, it begins to explain findings by studies such as

Diebal, Gregory, Alitz and Gerber (2012) who found that six weeks of running with a FFS decreased lower leg intra-compartmental pressure for Chronic Exertional Compartment Syndrome sufferers. There is insufficient evidence to support the use of a single foot-strike pattern to reduce injury risk in all areas of the limb, however adapting ones foot-strike pattern appears to shift injury mechanisms within the kinetic-chain.

- *Running Barefoot*

Lieberman *et al*. (2010) contend that running without the assistance of modern running footwear, barefoot, may lead to a reduction in the incidence of running injuries. Barefoot running is the condition in which external protection and shock reduction is minimal / non-existent (Divert *et al*., 2005a). Barefoot runners are proposed to gain increased sensory feedback during each foot contact compared to shod runners, and are therefore better able to adjust leg stiffness (Hanson *et al*., 2011; Lieberman, 2012; Rixe *et al*., 2012). Increased sensory feedback enables runners to sense high rates of loading and thus adjust their gait or contract muscle appropriately to find a preferred level of impact (Hanson *et al*., 2011; Lieberman, 2012).

Jenkins and Cauthon (2011) found no evidence which sufficiently demonstrated a reduced prevalence of running injuries in barefoot runners; however studies exist that demonstrate reduced injury factors in laboratory situations. Such as a reduced stride length which may protect runners from impact-related injuries (Edwards, Taylor and Rudolphi, 2009; Heiderscheit, Chumanov and Michalski, 2011 and Hobara, Sato and Sakaguchi, 2012). Running barefoot is proposed to reduce injuries in one segment of the kinetic chain, but cause injuries elsewhere; such as puncture wounds on the soles and stress fractures in the metatarsals (Collier, 2011). Salzler *et al.* (2012) found runners experienced stress fractures primarily on the second and third metatarsal when transitioning from the shod to barefoot condition.

The injury prevention potential of barefoot running is complicated by the complexity of injury aetiology, with no single factor having been identified as causative for the most common running injuries (Tam *et al*., 2014). Due to the potential link between mechanics and risk factors for injury, and the documented changes occurring to various joints during barefoot running, it is interesting to consider whether barefoot running may be prescribed as a treatment modality for certain individuals (Tam *et al*., 2014). Tam *et al.* (2014) recently suggested that future research needs to answer the question of whether biomechanical changes in the barefoot condition are learned responses, thus all runners can achieve these adjustments equally, or not, in which case some individuals are potentially better off shod. Since habitually barefoot runners present with markedly different kinematic and kinetic characteristics than novice barefoot runners, it is reasonable to propose that a substantial learning component exists (Tam *et al*., 2014). Tam *et al*. (2014) concluded that too little is known about barefoot running and its role in injury prevention and performance. Currently, barefoot running therefore raises more questions about injuries than there are answers available (Lieberman, 2012) and the link between barefoot running and injury or performance remains tenuous and speculative at best (Tam *et al*., 2014).

- *Running in Minimalist Footwear*

Minimalist footwear is defined as a shoe with a lower profile and thus a thin, flexible midsole and outsole with a light, basic upper, with little or no heel counter and a lack of motion control features (Hamill *et al*., 2011 and Bonacci *et al*., 2013). Minimalist footwear has been developed in an attempt to mimic the proposed benefits of barefoot running, while removing the associated negative aspects, such as puncture wounds, extremely hot or cold running surfaces and hard running surfaces (Squadrone and Gallozzi, 2009; Jenkins and Cauthon, 2011; Lorenz and Pontillo, 2012; Willson *et al*., 2014) and have been extensively marketed as such, leading to the popularity of this footwear.

Although it has been suggested that minimalist footwear may replicate barefoot running mechanics, there are numerous studies that contradict this (Bootier, 2012; Bonacci *et al*., 2013 and Tung *et al*., 2014). Minimalist footwear may lead to an increased risk of injury, due to the added stress of running without the benefit of cushioning under the foot (Ryan, Elashi, Newsham-West and Taunton, 2013). Many runners are switching to minimalist footwear, but there is a lack of agreement on the advantages or disadvantages of this change (Ridge *et al*., 2013).

Salzler *et al.* (2012), in a retrospective case study, investigated participants who developed injuries within the first year of converting from standard running footwear to minimalist footwear. These authors found the list of injuries included metatarsal stress fractures, calcaneal stress fractures and plantar fascia ruptures. These injuries occurred in individuals who converted abruptly and those who followed the shoe manufacturer's instructions. This study is limited and only mentions injuries reported by individuals who were injured when switching to minimalist footwear. It did not include a comparison to individuals who transitioned successfully or list the total percentage of "converts" injured out of all the individuals transitioning to minimalist footwear. Ridge *et al*. (2013) found increases in bone marrow edema are more common in participants transitioning to minimalist footwear, which is indicative of the added stress (due to a lesser amount of cushioning and stabilization materials). This study did not consider a proper habituation and slow transition before individuals set out running in minimalist footwear. The progression from grass to trail to road may also allow sufficient time to adapt to the hardness of modern day surfaces. The fact that these participants continued with their normal training programmes also would not have allowed the slow adaptation to occur. The interpretation of such results, without habituation, should be done with caution. Lastly, a study by Ryan, Elashi, Newsham-West and Taunton (2013) concluded that minimalist footwear appears to increase the likelihood of an injury occurring and full minimalist design increase pain specifically at the shin and calf regions.

IMPACT FORCES AND INJURY

Work emanating from the department of human evolutionary biology at Harvard University (Lieberman *et al.,* 2010 and Lieberman, 2012) proposed that running is potentially most injurious when the foot makes contact with the ground due to the striking impact of the foot, and the associated impact peaks. This contention is based on modelling, and to date there has been no clinical study which has demonstrated its superiority in reducing injury and therefore no evidence to support this. Early research hypothesized that minimising impact forces may reduce injury risk, however this has been viewed as an oversimplification (Nigg and Wakeling, 2001). Impact forces may only be part of, or completely unrelated to, the development of injury (Nigg, 2001). There are an increasing number of studies, such as Divert *et al*. (2005a) and van Gent *et al*. (2007) which have found impact forces may be associated with tibial stress fractures and plantar fasciitis injuries. Based on the current literature, the role of impact forces on injury causation warrants further investigation, however the general consensus appears to support that an increase in impact forces leads to an increase in injury risk.

BIOMECHANICAL AND PHYSIOLOGICAL CONSIDERATIONS OF RUNNING

ANKLE, KNEE AND HIP BIOMECHANICS

Proper running biomechanics involves the synchronous movements of all the components of the kinetic chain. The foot serves as the link between the ambulatory surface and the remainder of this chain and its functions include adaptation to uneven terrain, proprioception for proper position and balance and leverage for propulsion (Dugan and Bhat, 2005). During the gait cycle, foot motion facilitates, and can be affected by, compensatory movement of the other bones and joints in the lower extremity. Improper alignment from the lumbar spine and lower limb below can alter mechanics and lead to injury (Dugan and Bhat, 2005). It is essential to understand the biomechanics of running gait along the entire kinetic chain.

- *Hip and Knee*

Barefoot runners have been shown to create lower sagittal moments in the knee and hip, which is partially explained by footwear with wide and elevated soles that increase joint moments acting around the ankle, knee and hip (Kerrigan *et al*., 2009; Lieberman, 2012). Hamill *et al.* (2011) found that knee stiffness did not differ between the shod and barefoot condition. Bonacci *et al.* (2013) found that barefoot running demonstrated less knee flexion during mid-stance, an 11% decrease for both peak internal knee extension and abduction moments as well as a 24% decrease in negative work done at the knee compared to shod conditions. On the contrary, Willy and Davis (2014) found participants ran with increased knee flexion and foot dorsiflexion in minimalist footwear (which is proposed to replicate barefoot mechanics) as opposed to shod. The particular moments or movements in the knee which make it prone to injury need to be established; therefore more research investigating the effect of footwear on these responses is required.

- *Ankle*

Hamill *et al.* (2011) found ankle stiffness to differ between shod and barefoot running; running shod, the ankle was dorsi-flexed (±11^{o}) versus barefoot where it was plantar flexed (±7^{o}). A later study by Williams, Green, Wurzinger and Allen (2012) investigated foot-strike patterns under these same conditions, and found that when participants ran shod or barefoot with a RFS, the ankle was dorsi-flexed (14.85°) and (0.03°) respectively, while running with a FFS when shod led to a more plantar-flexed ankle at (-12.46°). Bonacci *et al*. (2013) also found less dorsiflexion, at initial contact, when running barefoot as opposed to shod. These authors also found a 14% increase in peak power generation and a 19% increase in the positive work done.

Comparing minimalist footwear to the shod condition, Willy and Davis (2014) found participants ran with increased dorsiflexion in the minimalist footwear. This is contradictory to expected responses, as minimalist footwear has been promoted as replicating barefoot running mechanics; however this appears to be untrue. It is evident from the above findings that the footwear condition and foot-strike pattern employed appears to influence the elicited responses considerably. It is unclear how individual responses differ under these conditions, and therefore more research is needed investigating the influence of individual responses.

FOOT-STRIKE PATTERNS

Runners typically make contact with the ground using one of three foot-striking patterns. A RFS, where the heel lands first, a MFS, where the heel and the ball of the foot land simultaneously or a FFS, where the ball of the foot lands before the heel comes down (Lieberman *et al*., 2010). This classification has come under scrutiny by Tam *et al*. (2014) who suggest that the categorization of foot-strike patterns into three clusters may be somewhat reductionist, as foot-striking has been shown to exist as a spectrum by Altman and Davis (2012). Generally, running with a RFS leads to the foot landing in front of the knee and hip, with a relatively extended knee, and with a dorsi-flexed, slightly inverted and abducted ankle; the runner then plantar-flexes rapidly as the ankle everts just after impact (Perl *et al*., 2012). FFS runners have been found to land with a more flexed knee and plantar-flexed ankle, making ground contact below the fourth or fifth metatarsal heads; the runner then simultaneously everts and dorsi-flexes the foot during the brief period of impact, usually with more ankle and knee compliance (Perl *et al*., 2012). A FFS landing is found to cause a higher net moment around the ankle in the sagittal plane and lower net moment around the knee and hip in both the sagittal and transverse planes (Perl *et al*., 2012). Williams *et al*. (2012) found similar with a FFS associated with the most plantar-flexion, which demonstrated the most peak ankle power absorption and lowest knee power absorption. Jungers (2010) proposed that a FFS serves to blunt impact forces, resulting in a smoother ride.

Landing with altered foot-strike patterns has shown to lead to variations in ground reaction forces between individuals, which is proposed to have important biomechanical implications for injury causality (Hamill *et al*., 2011). Foot-strike patterns depend to some extent on speed, running surface, footwear and fatigue; but a FFS is more common at higher speeds, and amongst barefoot or minimally shod runners, especially on hard surfaces (Perl *et al.,* 2012).

- *Foot-strike Distribution between various ranks of runners*

Hasegawa, Yamauchi, and Kraemer (2007) and Larson *et al*. (2011) looked at the distribution of foot-strike patterns between elite, sub-elite and recreational athletes during a half-marathon/marathon. They found disparities between the percentages of foot-strike patterns between the different ranks of runners (Table II).

Table II: The percentage of different foot-strike patterns employed in elite, sub-elite and recreational athletes.

	% of population		
	RFS	MFS	FFS
Elite Athletes	74.9	23.7	1.4
Elite (top 50 @15km)	62	36.6	2
Sub-Elite and Recreational Athletes	94.4	3.6	1.9

A major difference was evident between the percentages of runners utilizing a MFS or RFS amongst the elite and sub-elite / recreational runners. From these findings, it appears that the more elite an athlete is, the greater the likelihood of employing a foot-strike pattern towards the anterior of the foot. Of the elite athletes, the top 50 runners (who run faster) showed an even greater tendency to run towards the anterior of the foot (Hasegawa *et al*., 2007). The overall percentage of runners utilizing a FFS is extremely low; suggesting only a small percentage of the running population is suited to the biomechanics of this running pattern.

- *Influence of Footwear*

Footwear has been shown to influence the foot-strike patterns employed by individuals, with Lieberman *et al.,* (2010) stating the main difference between barefoot and shod runners appears to be in the way which the foot strikes the ground. Numerous studies (Stacoff *et al*., 2000; Jungers, 2010; Lieberman *et al.,* 2010; Lohman *et al.,* 2011; Hamill *et al*., 2011 and Altman and Davis, 2012) have found that barefoot running encourages runners to land on the anterior of the foot, with a MFS or FFS pattern (associated with a reduction in impact loading and stride length), while the majority of shod runners with a RFS pattern. Recently, a number of studies have begun questioning this transition and mounting evidence has shown that substantial inter-individual differences are found in foot-strike selection, and therefore it is not appropriate to associate barefoot running with an anterior landing (MFS/FFS) or shod running with a RFS only (Nigg and Enders, 2013).

Individual variation: Hasegawa *et al.* (2007) found that in modern running footwear; at least 75% of distance runners used a RFS. Jungers (2010); Lieberman *et al.* (2010) and Perl *et al.* (2012) found supporting evidence. Lieberman *et al*. (2010) found that runners from the Kalenjin tribe in Kenya, who grew up barefoot or switched to barefoot running, ran predominantly FFS at a wide range of speeds. Williams *et al*. (2012) however found that not all participants converted to a MFS or FFS, when switching to barefoot running. While Hatala *et al*. (2013) found that not all habitually barefoot individuals from a north-western Kenyan tribe, "*The Daasanach*", preferred to use a FFS at a self-selected running speed and the majority instead used a RFS at endurance running speeds. These findings create uncertainty with regards to the popular theory that all habitually barefoot people run by landing on their forefoot, to avoid the high impact forces typically associated with a RFS. Hatala *et al*. (2013) suggest that running speed, alongside other factors such as the firmness of the running surface, may have similarly influenced variation in the running gaits of early man, rather than one gait being preferred in all circumstances.

When switching to minimalist footwear, Willson *et al*. (2014) found that after two weeks of exposure to minimalist footwear, only three out of 19 runners switched away from a RFS. The majority of participants continued to use an RFS pattern after training in minimalistic footwear. Warne and Warrington (2014) conducted four weeks of habituation to minimalist footwear, and found no significant difference in foot-strike patterns between the shod and minimalist groups. During and post the four weeks, however a FFS was significantly favoured.

STRIDE LENGTH AND STRIDE RATE

An individual's stride length is a function of the runners height and leg length (Lohman *et al*., 2011). Stride length was defined as the length the treadmill belt moves from toe off to initial ground contact in successive steps, while stride rate was defined as the number of ground contact events per minute (Lohman *et al*., 2011). The typical stride length in endurance running is greater than 2m, and can even exceed 3.5m in elite runners (Bramble and Lieberman, 2004). Stride length and stride rate are dependent on one another, when stride rate increases stride length decreases to maintain speed. Stride rates range from 93 to 100 strides (185 to 200 steps) per minute across events and sexes (Lohman *et al*., 2011).

The influence of footwear on stride length and stride rate has been investigated in numerous studies, such as De Wit *et al*. (2000), Divert *et al*. (2005a), Squadrone and Gallozzi (2009); Bonacci *et al*. (2013) and Moore, Jones and Dixon (2014). These studies found significant increases in stride rate and decreases in stride length when running barefoot versus shod. Shod runners have been found to have between a 3.3 to 6% greater stride length than barefoot runners (Kerrigan *et al*., 2009 and Franz *et al*., 2012). De Wit *et al*. (2000), Squadrone and Gallozzi (2009) and Braunstein, Arampatzis, Eysel and Brüggemann (2010) found significantly shorter ground contact times were present when running barefoot versus shod with an associated increased in stride rate.

Comparing minimalist footwear to the shod condition, Bonacci *et al*. (2013) found that barefoot running to have a greater stride rate and shorter stride length than both the minimalist and shod conditions. No change in step length or rate were observed by Willy and Davis (2014) when comparing shod to minimalist running. While Warne and Warrington (2014) found minimalist running to have a significant 2.7% higher stride rate than running shod. Minimalist footwear is shown to have an intermediate stride rate, which is greater than running shod and lower than barefoot (Squadrone and Gallozzi, 2009). The same is evident for stride length between these conditions. The biomechanical adjustment of a reduced stride length and increased stride rate, has been proposed to reduce the impact forces which need to be absorbed by the muscular-skeletal system, which is significant as impact forces are associated with tibial stress fractures and plantar fasciitis injuries (Divert *et al*., 2005a; van Gent *et al*., 2007). Chumanov, Wille, Michalski and Heiderscheit (2012) found an increased stride rate may have benefits to individuals with anterior knee pain. While a shorter stride length reduces the moment arm of the ground reaction force to the hip and knee joints, reducing the joint moments that are generated (Altman and Davis, 2012). While biomechanically an increase in stride rate is desired, a study by Anderson (1996) found an association between longer strides and more economical runners. This tends to suggest that a trade-off occurs between the biomechanical and physiological responses.

GROUND REACTION FORCES

Running generates a set of complex and dynamic forces with every step, which are then repeated millions of times per year for most runners (Lieberman, 2012). The consequence of these forces on the musculoskeletal system is evaluated through a comparison of ground reaction forces (GRF). GRFs are often used as the primary descriptive component in the analysis of the support phase of running (Hamill, 1983). GRF data may be used to quantify impacts, understand propulsion and braking, compute muscle forces and calculate mechanical energy fluctuations (Gottschall and Kram, 2005). The magnitude of GRFs is affected by a number of variables including running form, foot-strike pattern (RFS, MFS, FFS), speed, stride length, footwear, ground surface and the inclination of the running surface (Lohman *et al*., 2011). The forces analysed in this research project were: impact peak (IP), vertical impact loading rate (VILR), vertical average loading rate (VALR) and strike time (ST).

- *Impact Peak Forces*

It is established that footwear with greater cushioning provokes a sharp reduction in the shock-moderating behaviour of the limbs, thus potentially increasing the impact forces experienced (Robbins and Hanna, 1987). The type of footwear utilized whilst running therefore has significant implications on the forces experienced by runners (Lohman *et al*., 2011). The introduction of running footwear is proposed to have made RF striking (associated with a high impact transient) on a hard surface comfortable, by dampening the magnitude of the impact peak by 10%. However, footwear does not eliminate the impact peak entirely (Lieberman *et al*., 2010; Lieberman, 2012; Perl *et al*., 2012). The impact peak has been found to approach 3-4 times body weight at higher endurance running speeds (Lieberman *et al*., 2010; Hatala *et al.*, 2013). Running with a RFS when shod or barefoot produces a double-peaked impact transient (Figure 3) (Lieberman *et al*., 2010).

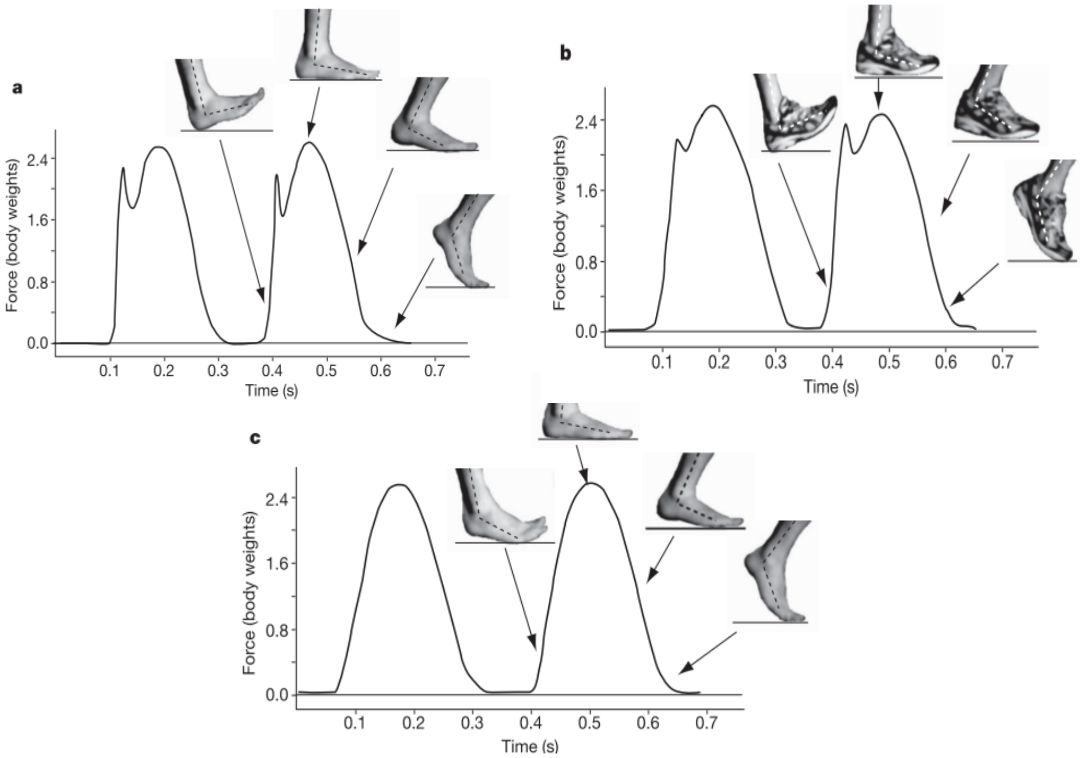

Figure 2: Running barefoot (a) and shod (b) with a RFS produces a double-peaked impact transient, while running barefoot (c) using a FFS generates no impact transient (Lieberman *et al*., 2010).

Shod vs. barefoot: Barefoot running has gained popularity due to its proposed ability to decrease overall GRFs and the amount of force received by the heel upon each foot-strike (Freychat *et al*., 1996; De Wit *et al*., 2000; Divert *et al*., 2005a). Consequently, a number of studies have found significantly smaller impact forces when running barefoot compared to shod (Squadrone and Gallozzi, 2009; Lieberman *et al*., 2010; Hamill *et al.* 2011). As mentioned earlier, barefoot running has been associated with a switch to a more anterior foot-strike pattern, as shown in Perl *et al.*

(2012) who found barefoot runners tend to FFS on rough or hard surfaces, a foot-strike pattern which has been associated with no impact peak (Figure 2). Similarly Kurz and Stergiou (2004), Lieberman *et al*. (2010) and Hatala *et al*. (2013) found barefoot runners with a FFS generate smaller collision forces than shod RF strikers. Kurz and Stergiou (2004) proposed that these forces are reduced due to runners utilizing a coordination strategy, which starts at the ankle and helps distribute the force of impact over a greater surface area than the heel alone.

Individual variability: While certain individuals, who switch to the anterior of the foot may experience reduced impact forces, there is mounting evidence that no uniform foot-strike pattern exists in all individuals when switching from shod to barefoot or minimalist footwear (as highlighted in the foot-strike section). The establishment of recommendations based on the idea of a uniform foot-strike pattern, is prone to undesirable consequences, as it has been found that individuals who continue to RFS when barefoot (Figure 3) experience impact forces which are 8.6% greater than shod (Lieberman *et al*., 2010). Similarly these individuals experience a rate of loading approximately 700% greater than the shod condition (Lieberman *et al*., 2010). Thus, the acute response of a majority of runners to barefoot running exposes them to impact forces and loading rates that are significantly higher than when shod (Tam *et al*., 2014). Further research is needed to provide recommendations which are based on individuals rather than mean data. The use of a 'one-size-fits-all' solution appears to be an over-simplification.

- *Loading rates*

Shod vs. barefoot: The continued exposure to increased loading rates over time, is proposed to have detrimental effects to runners (Willson *et al*., 2014). Shih, Lin and Shiang (2013) found the average loading rates were similar between barefoot and shod running conditions; however running with a RFS had a significantly higher loading rate compared to running with a FFS. Cheung and Rainbow (2014) on the contrary found that (most) habitual shod runners when switching to barefoot experience a decrease in VALR and VILR, which was associated with a switch away from a RFS. A lack of consistency between studies along with Cheung and Rainbow (2014) indicating that not all individuals experience this decrease provides further justification for the need of additional research into loading rates, as well as individual responses.

Shod vs. minimalist: Willy and Davis (2014) investigated minimalist footwear and found increased loading of the lower extremity, in the short term, compared to running shod. Similarly Willson *et al*. (2014) found the majority of participants continued to use an RFS pattern after training in minimalistic footwear, which has been associated with higher loading rates. These participants experienced vertical loading rates that were three times greater than those who chose to run with a non-RFS pattern.

- *Strike time*

Strike time (otherwise referred to as contact time) refers to the duration of contact between the foot and running surface during each foot-strike, measured from ground contact until toe off. A longer ground contact time was found to correlate with a higher $\dot{V}O_2$ by Nummela, Keränen and Mikkelsson (2007) and Saunders, Pyne, Telford and Hawley (2004). A significantly reduced strike time was found by Squadrone and Gallozzi (2009) when participants ran barefoot or in minimalist footwear opposed to shod. This same study found the minimalist condition to have the shortest strike time; however this was not significantly smaller than the barefoot condition. A prospective cohort study by Bredeweg, Kluitenberg, Bessem and Buist (2013) found runners with higher loading rates and shorter strikes times were associated with a higher risk of injury. Di Michele and Merni (2014) found a significantly shorter ground contact time in MF strikers compared to RF strikers (6% longer). These same authors compared strike time and oxygen consumption and found no significant difference between the groups; however they did find that a 1 ms^{-1} longer contact time resulted in an approximately 0.51 $mL.min.kg^{-1}$ lower oxygen uptake. One study is insufficient to state that shorter strike times will result in an increased injury risk, however based on the above studies it does appear that a trade-off may appear between the physiological and biomechanical responses. If this is the case, it seems unlikely that individuals can increase performance for this variable without increasing injury risk. Alternate techniques may however enable increased performance and decreased injury risk.

ELECTROMYOGRAPHY

The muscular pattern during running is influenced by a number of factors, such as running speed, foot-strike patterns and footwear worn (Novacheck, 1998). Generally muscles are most active in anticipation of and just after initial contact, and muscle contraction is more important at that time than it is for the preparation for and the act of leaving the ground (Novacheck, 1998).

Only a few studies have considered different footwear conditions, and Nigg and Wakeling (2001), von Tscharner, Goepfert and Nigg (2003) and Olin and Gutierrez (2013) found an increase in muscle activity for the Tibialis Anterior when participants ran shod or with a RFS as opposed to barefoot or with a FFS. These same authors along with Divert *et al.* (2005a) and Shih, Lin and Shiang (2013) found an increase in muscle activity for the Gastrocnemius when participants ran barefoot or with a FFS versus shod or with a RFS. A FFS therefore appears to elicit a higher pre-activation of the plantar flexor muscles, when running barefoot compared to shod, before the braking phase (Komi, Gollhofer, Schmidtbleicher, and Frick, 1987 and Divert *et al*., 2005a). This demonstrates how a reduction in heel impact forces are observed when switching to a forefoot technique, as the EMG activity before heel-strike appears to be pre-programmed, based on the expected impact shock *(Divert et al*., 2005a).

OXYGEN CONSUMPTION

The metabolic cost of running is commonly assessed during endurance running through the measurement of oxygen consumption ($\dot{V}O_2$). $\dot{V}O_2$ is the amount of oxygen (in millilitres) which an individual inhales per minute, relative to body weight (McArdle, Katch and Katch, 2007). This has been compared in many studies to date (Table III).

Table III: Oxygen consumption studies to date.

OXYGEN CONSUMPTION ($\dot{V}O_2$) SHOD VS BAREFOOT			
AUTHOR/S	COMPARED	FINDINGS	
Burkett, Kohrt and Buchbinder, 1985	BF vs. Shod / Shod (orthotics)	BF = 1.3-2.4% lower $\dot{V}O_2$	↓
Flaherty, 1994	BF vs. Shod (700g)	BF = 4.7% lower $\dot{V}O_2$	↓
Divert *et al*. 2008	BF vs. Shod (350g socks/shoes)	BF = 1.3-2.8% lower $\dot{V}O_2$	↓
Squadrone and Gallozzi, 2009	BF vs. Shod	** BF = 1.3% lower $\dot{V}O_2$	↓
Hanson *et al.* 2011	BF vs. Shod (over-ground / treadmill)	BF = 2 & 5.7% lower $\dot{V}O_2$ respectively	↓
Perl *et al*. 2012	BF vs. Shod	BF = lower COT	↓
Franz *et al.* 2012	BF vs. Shod (controlled mass)	BF = 3-4% higher $\dot{V}O_2$	↑
Tung *et al*. 2014	Cushioning	Cushioning decreases the metabolic cost of running (to a point)	↓
Moore *et al*. 2014	BF vs. Shod	BF = Significantly Lower	↓
OXYGEN CONSUMPTION ($\dot{V}O_2$) SHOD VS MINIMALIST			
AUTHOR/S	COMPARED	FINDINGS	
Squadrone and Gallozzi, 2009	Shod vs. MF	Lower oxygen consumption in MF	↓
Perl *et al*. 2012	Shod vs. MF	MF was more economical than shod (controlled mass, strike pattern and stride frequency)	↓
Lussiana, Fabre, Hébert-Losier and Mourot, 2013	Shod vs. MF	MF had a 1.3% lower energy cost of running	↓
Warne and Warrington, 2014	Shod vs. MF	MF had a 6.9% improved running economy (size of improvement = other factors than mass of shoes)	↓
Sobhani *et al*. 2014	Shod vs. MF	**No significant difference	↔
Moore *et al*. 2014	Shod vs. MF	MF was lower	↓

BF = Barefoot / MS = Minimalist Footwear / ** = no statistical significance

Shod vs. barefoot: It is evident, from Table III, the majority of studies have found a reduced $\dot{V}O_2$ when running barefoot as opposed to shod, with differences ranging from 1.3 to 5.7%. A ~4% difference in $\dot{V}O_2$ is significant, and endurance runners are experiencing such an increase or decrease in $\dot{V}O_2$ would notice a significant effect on running speed and therefore performance (Warburton, 2001). Perl *et al.* (2012) disagreed and found that shod running was more economical. Importantly, most of these studies were conducted without accounting for shoe mass, barring Divert *et al.* (2008) and Perl *et al.* (2012). This is important to note, as for example, the decrease seen by Divert *et al.* (2008), could be directly linked to the increased mass of the footwear when running shod. Without controlling or noting shoe mass, it becomes difficult to determine whether a lower oxygen cost is caused directly due to a lighter distal mass when barefoot or if other factors such as foot-strike patterns, leg length, shoe construction or barefoot running experience contribute. It is generally accepted that for every 100g of added shoe mass, $\dot{V}O_2$ increases by 1% (Frederick, 1984). The counter argument is that a lighter distal mass is an advantage of running barefoot, and by controlling this during experimentation, other potential benefits may be concealed. Therefore shoe mass needs to be controlled in order to establish the real factors eliciting the changes seen between shod, minimalist and barefoot running. It is essential that more studies investigate this limitation, by both comparing responses (biomechanical, physiological and perceptual) when running with controlled mass and uncontrolled mass.

Minimalist vs. Shod: There is comparatively less research into minimalist footwear than into barefoot and shod running, which is expected as minimalist footwear is a recent introduction to running footwear. The current body of literature is however growing rapidly as the interest into the usefulness of such footwear develops. An early study Squadrone and Gallozzi (2009) found a 2.8% decrease in $\dot{V}O_2$ when running in minimalist versus standard running footwear, which is a greater decrease than the 1.3% observed when barefoot versus shod. Perl *et al.* (2012) found that running in minimalist footwear on average decreased $\dot{V}O_2$ by 2.41- 3.32% after accounting for the effects of shoe mass, strike type, habitual footwear and stride frequency. On the whole the majority of studies have found minimalist footwear to be more economical than running shod. Possible reasons for a decrease in $\dot{V}O_2$ when wearing minimalist footwear tends to be mostly speculative and as yet no definite factors have been established.

- *Foot-strike patterns*

Alternative factors, other than an added shoe mass, have been investigated in a bid to establish potential causes for the observed decrease in $\dot{V}O_2$ when barefoot or minimalist footwear when compared to shod. Variation in foot-strike patterns have been identified as a potential cause of the observed decreases in $\dot{V}O_2$. Ardigò, Saibene and Minetti (2003) compared RF and FF strikers at a range of running speeds and found no significant differences in $\dot{V}O_2$ between the different foot-strikes, while Cunningham, Schilling, Anders and Carrier (2010) found no significant difference in the cost of transport when participants ran with a RFS versus a FFS. Perl *et al.* (2012) found similarly, with no significant difference evident in the costs between a RFS and FFS gait (in the same footwear), however running in minimalist footwear with a FFS was 0.74% less costly than running in standard footwear with an RFS. Perl *et al*. (2012) concluded from these findings that a FFS was not more economical than a RFS, and that the foot-strike pattern employed by individuals does not provide a metabolic advantage as previously thought.

Gruber, Umberger, Braun and Hamill (2013) criticized the above studies due to the low number of participants tested and because the participants utilized were not habitually RF or FF strikers. Therefore, Gruber *et al.* (2013) performed this same study, comparing RF and FF strikers at three different speeds, with a large number of participants and participants who were habitually RF or FF strikers. These authors also found no significant differences in $\dot{V}O_2$ as well as the percentage of carbohydrate utilization (Gruber *et al*., 2013). It is apparent that insufficient research paired with methodological inconsistencies when investigating the role of foot-strike pattern, makes conclusive findings and recommendations hard to formulate.

- *Further proposed mechanisms for a decrease in energy consumption*

Some studies have found a decrease in $\dot{V}O_2$ when running barefoot or minimalist compared to shod, however a number of these decreases found were not significant. An increase in energy costs, as found by Franz *et al.* (2012) creates contention in the literature. Some authors have assessed a few plausible explanations as to why running barefoot or in minimalist footwear may be more efficient. The first explanation by Bramble and Lieberman (2004) suggests that running barefoot allows increased elastic energy storage through the depression of the plantar arch, which supplies around 17% of the energy for each stance phase. It is this elastic energy which may be reduced when running shod (due to the sole stiffness and reduced range of motion that footwear imposes). Secondly, Divert *et al.* (2005a) proposed the higher energy cost of shod running is potentially due to the simple additional mass effect associated with shoes combined with the worse elastic energy storage and restitution associated with shod running. Thirdly, a difference may be observed due to the continual acceleration and deceleration of the effective mass of the foot during each stride, which is greater when shod (Bramble and Lieberman, 2004 and Warburton, 2001). A fourth proposed explanation is the additional external work done to compress and flex the sole of shoes and rotating the sole against the ground (Warburton, 2001). Linked with this, footwear may compromise the ability of the lower limb to act like a spring, as it should naturally by utilizing the mass-spring mechanism (Warburton, 2001). Lastly, Perl *et al.* (2012) suggested that the tendons, ligaments and muscles in the lower extremity may be used more effectively when running barefoot or with a FFS via several mechanisms. For example the Achilles tendon stores and releases more energy in a FFS versus a RFS and even more when FF striking when barefoot versus standard running footwear.

Barefoot running may be less efficient than shod running due to: the increased triceps-surae muscle force required when FF striking, which has the opposite effect on running economy (Perl *et al*., 2012). This theory could potentially explain why a larger decrease in cost is not seen when barefoot, or even why barefoot running is more costly than shod running. However not all barefoot runners utilize a FFS as previously thought (Hatala *et al*., 2013), so the validity of this statement is problematic.

HEART RATE

Squadrone and Gallozzi (2009) and Sobhani *et al*. (2014) found no significant differences in heart rate (HR) responses when running shod versus barefoot or in minimalist footwear. While Hanson *et al.* (2011) measured HR responses in individuals running shod and barefoot on both a treadmill and over-ground surface, it was found that HR responses were greater when running shod over both surfaces. Recently, Warne and Warrington (2014) found no difference at pre-test between shod and minimalist footwear. However following 4 week of habituation to these, they found a significantly reduced HR for the minimalist condition. The authors concluded that some degree of adaptation took place, which cannot only be explained by changes in shoe weight or design.

RATING OF PERCEIVED EXERTION

Very few studies have compared the perceptual responses in running based studies, specifically with reference to different footwear conditions. Those published to date, have found no significant differences in rating of perceived exertion (RPE) responses when running shod, barefoot or in minimalist footwear (Squadrone and Gallozzi, 2009) or when shod versus minimalist footwear (Sobhani *et al*., 2014; Warne and Warrington, 2014). Hanson *et al.* (2011) is the only study (to the author's knowledge) which found increased RPE responses when running shod (on a treadmill and over-ground).

THE FUTURE OF RUNNING BASED RESEARCH

In comparison to biomechanical responses, little research has been conducted comparing the physiological and perceptual responses when running shod or in minimalist footwear and the barefoot condition. Studies which have been conducted are contradictory, making accurate recommendations difficult to provide. No studies (to the author's knowledge) have considered the variation in individual responses under these different footwear conditions. More dependable and accurate research, which asks the right questions, is needed to increase our understanding of running. A better understanding will allow more accurate recommendations to be provided to the running public, which could ultimately lead to a reduction in running injuries and increased running performance.

CHAPTER III

METHODOLOGY

INTRODUCTION

A great deal of research has concentrated on biomechanical, physiological or perceptual responses in endurance runners under various conditions. Differences in study design and methodology, such as over-ground and treadmill running or minimalist, shod and barefoot conditions, have however made accurate comparison and conclusions difficult (Tam *et al*., 2014). Achieving reliable and accurate scientific-based evidence requires a sound study design and methodology, which outlines the risks and benefits associated with conducting such research, establishes areas of research which are currently lacking or insufficiently understood and provides new information in the specific field of research. This study incorporated a holistic approach to its laboratory based research protocols. The three running conditions in this study were not designed to simulate outdoor running conditions, however impinging variables that may have had an impact on the experimentation procedure and results were eliminated or controlled. A complete description and justification of the experimental design is provided below.

PILOT TEST PROTOCOL

Prior to experimental procedures, pilot investigations were performed in the Department of Human Kinetics and Ergonomics, Rhodes University, Grahamstown. These were performed to determine the feasibility of the proposed experimentation protocols, and included selecting the number of runway trials required to obtain adequate ground reaction forces data, selecting the appropriate muscles for electromyography analysis, determining the feasibility of the pre-selected running speed and the effect of off-centre landing on the embedded force plate. Pilot testing also allowed further familiarization with the experimental protocol and laboratory equipment for the principal researcher and assistant. All sessions were conducted using the same equipment and laboratory setup as used for the final experimentation. Extreme care was taken to ensure the runners' safety throughout the proceedings. Any inaccuracies, concerns or glitches regarding the experimentation procedure were noted and resolved during this stage. All individuals used for the pilot tests were volunteers; and were required to fill out a consent form (describing the risks of conducting such research) prior to completing these sessions.

EXPERIMENTAL DESIGN

DESIGN MATRIX

The current study was comprised of a 3 by 1 experimental design (Table IV), with three experimental conditions: running in a standard running shoe, a minimalist running shoe and barefoot. The justification for the selection of these conditions is provided below.

Table IV: The 3x1 design matrix utilized for the current research project.

Shod (Standard Shoe)	Minimalist	Barefoot

SELECTION OF RUNNING FOOTWEAR CONDITIONS

Humans are proposed to have evolved over many millennia to become successful endurance runners, to ensure survival by providing a method to acquire foods rich in protein as well as protection from predators (Bramble and Lieberman, 2004). For the most part, individuals ran barefoot or with modified sandals or moccasins (within the last 50 000 years) (Fields, Sykes, Walker and Jackson, 2010; Lieberman *et al*., 2010; Rixe *et al*., 2012; Altman and Davis, 2012; Perl *et al*., 2012). Running footwear was introduced in the 1970's, and now incorporates a significant amount of cushioning and stabilization materials; marketed for comfort, injury protection and the correction of movement patterns (Nigg, 1986; Robbins and Gouw, 1991; Altman and Davis, 2012; Bonacci *et al*., 2013).

In 2010, Lieberman *et al*. proposed that barefoot running introduces a better running form compared to shod running. This (coupled with other factors) has seen a shift back towards minimalist running footwear in recent years. Minimalist footwear manufacturers claim that minimalist running mimics the proposed benefits of barefoot running, while removing the associated negative aspects, such as puncture wounds, extremely hot or cold running surfaces and hard running surfaces (Squadrone and Gallozzi, 2009; Jenkins and Cauthon, 2011; Lorenz and Pontillo, 2012; Willson *et al*., 2014). Barefoot and minimalist running has since generated much interest in scientific publications and the lay media as a result of its alleged benefits for runners at all levels (Tam *et al*., 2014).

The independent variable of interest in this study was running footwear. Three footwear conditions were compared, a standard running shoe, a minimalist running shoe and the barefoot condition. These conditions were selected, as these are the conditions most commonly available to modern runners (increasingly or decreasingly) and more studies need to establish their impact on running injuries and running performance. Numerous studies have investigated the biomechanical and physiological responses comparing these conditions including (but not limited to) Squadrone and Gallozzi, 2009; Hanson *et al*. 2011 and Perl *et al*. 2012. A lack of consensus in literature is evident when examining which footwear condition (if any) provides the most effective solution from an injury protection and/or running performance perspective. The current understanding of these footwear conditions is provided below.

Biomechanical Comparison: A consistent reduction in stride length and corresponding increase in stride rate has been found when running barefoot versus shod or in minimalist footwear versus shod (De Wit *et al*., 2000; Divert *et al*., 2005a; Divert, Baur, Mornieux, Mayer and Belli, 2005b; Squadrone and Gallozzi, 2009; Franz *et al*., 2012; Bonacci *et al*., 2013; Moore *et al*., 2014).

Foot-strike patterns are contentiously debated in the literature. Originally Squadrone and Gallozzi (2009) and Lieberman *et al*. (2010) found significant differences in ground reaction forces between the different foot-strike patterns. A more anterior placed foot-strike has been shown by Lieberman *et al*. (2010) to generate smaller collision forces than runners who rear-foot strike (RFS). This has significant implications for the reduction of injury risk, if this is the case. Currently however the literature is inconclusive as to the percentage of runners utilizing each foot-strike pattern under each condition. Hamill *et al*. (2011) found that participants predominantly switched to a mid-foot strike (MFS) when running barefoot, while

Hatala *et al*. (2013) found that only a small percentage of runners switch to a fore-foot strike (FFS) when barefoot, while Willson *et al*. (2014) found that a small number of participants switched away from a RFS when running in minimalist footwear. Contentious findings warrant further evaluation of these footwear conditions, to determine the percentage of runners switching to the anterior when barefoot or in minimalist footwear. Furthermore do all individuals who FF strike (or MF and RF strike) have similar ground reaction forces? Should recommendations be based on individuals or the 'one-size-fits-all' approach?

Physiological Comparison: There is a lack of consistency between studies comparing physiological responses between footwear conditions. Few studies have considered heart rate responses, with Squadrone and Gallozzi (2009) finding no difference between the three footwear conditions and Hanson *et al*. (2011) finding an increased heart rate when shod compared to barefoot. Similarly Warne and Warrington (2014) found a significantly lower heart rate after four weeks training in minimalist footwear versus shod.

Divert *et al*. (2008), Squadrone and Gallozzi (2009), Hanson *et al*. (2011), Perl *et al*. (2012), Moore *et al.* (2014) and Tung *et al*. (2014) all found lower energy costs when running barefoot versus shod. On the contrary, Franz *et al*. (2012) found (at equal foot-mass) running shod to have a lower energy cost than barefoot running. Methodological inconsistencies such as different participant characteristics, lack of consistency in footwear used and contrasting experimental setups need to be acknowledged. These discrepancies make accurate comparisons and deductions difficult (Tam *et al*., 2014). Comparatively fewer studies into minimalist footwear have been conducted, with little comparison to the shod or barefoot conditions. Squadrone and Gallozzi (2009), Warne and Warrington (2014), Lussiana, Fabre, Hébert-Losier and Mourot (2013) and Moore *et al*. (2014) found minimalist footwear to have a lower energy consumption than shod, while Sobhani *et al*. (2014) found no difference in oxygen consumption between minimalist and the shod condition. A lack of comparable studies due to both methodological inconsistencies and few studies into the minimalist condition, further studies comparing these conditions are required.

Perceptual Comparison: There are no studies (to the author's knowledge) which have compared the perceptual responses between these footwear conditions. Warne and Warrington (2014) and Sobhani *et al*. (2014) compared the rating of perceived exertion (RPE) between a minimalist shoe and a standard running shoe and found no statistical difference. It is evident that perceptual measures such as RPE and body discomfort are under-researched and further studies determining the usefulness of these measures is necessary.

In conclusion, it is evident that further research is required comparing the standard running shoe, minimalist shoe and barefoot conditions due to a) the significant amount of contention in the literature when comparing various biomechanical, physiological and perceptual responses; b) a lack of studies comparing perceptual responses between these footwear conditions; and c) a lack of studies comparing the minimalist condition to the standard running shoe and barefoot conditions.

MEAN DATA VERSUS INDIVIDUAL DATA

Running has been investigated in numerous studies, with recommendations and conclusions primarily based on mean response data. Although mean data is useful, and should not be disregarded, it does not provide a comprehensive and complete analysis. Neither does it display variation (if evident) between individuals when exposed to various interventions. The use of mean data, therefore may lead to an inadequate interpretation of the results obtained, specifically in the situation that positive and negative responders (described below) were found in response to a condition. A recent (non-running related) paper by Mann *et al*. (2014) highlighted this issue, and noted that many studies to date assume the average response to an intervention, represents a typical response for most individuals. In reality, it is however more common for individuals to show a wide range of responses (Mann *et al*., 2014). A mean based analysis often displays that no changes have been observed, however considering individual responses, this may not be the case and in fact positive and negative responders are likely to be found. An unrelated example is used to demonstrate this. Considering the aerobic capacity of humans, it is well established that some individuals experience large increases in aerobic capacity due to training, while others experience minor or no increases at all in aerobic capacity, as shown by Medbø and Burgers (1990). The same is expected to occur in response to running footwear conditions. Tam *et al*. (2014) highlight this by using the study by Lieberman *et al*. (2010) as an example. This study found that barefoot running leads to reduced impact peaks and rates of loading in habitually shod individuals that switched to an anterior foot-strike pattern. However some of these individuals experienced greater impact peaks and rates of loading running barefoot than when shod. These individuals, as noted in Lieberman *et al*. (2010), were as a result exposed to loading rates sevenfold greater than when in shoes. Recommendations on mean data in this instance can cause serious ramifications, and therefore research into individual responses is imperative to improve the understanding of the role of footwear in endurance running. The current study incorporates the analysis of both mean data, as well as the analysis of individual responses under the various conditions.

POSITIVE, NEGATIVE AND NON RESPONDERS

It was expected that assessing individual responses would reveal a large variation in responses between participants under the footwear conditions. The standard running shoe was selected as a reference condition, as the participants were habitually shod and therefore trained and competed in these shoes. Using the shod condition as a reference condition, allowed the author to classify participant responses as positive, negative or neutral to the unfamiliar barefoot and minimalist conditions. Furthermore this enabled the comparison of individual responses during a runner's first attempt at barefoot or minimalist running. Participants could therefore experience increased, equal or decreased biomechanical, physiological and perceptual responses in the barefoot or minimalist conditions, compared to the standard shoe. It was necessary to define the expected differences in responses between individuals.

A positive-responder (in the current study) referred to an individual who experienced a) an increase in stride rate, a decrease in stride length, impact forces and loading rate, b) a decrease in all physiological measures and c) a decrease in perceptions when switching from shod to minimalist or barefoot running. A negative-responder referred to an individual who experienced a) a decreased in stride rate, an increase in stride length, impact forces and loading rates, b) an increase in all physiological measures and c) an increase in perceptions when switching from shod to minimalist or barefoot running. A non-responder (neutral) referred to an individual who experienced no changes for the respective variables. EMG responses were analysed differently, as it was expected that participants would experience varied responses related to the foot-strike pattern they adopted, as it was anticipated that not all individuals would use the same foot-strike pattern under each of the conditions. It was anticipated that a RFS would elicit the greatest muscle activity for the Tibialis Anterior and the lowest activity for the Gastrocnemius, Vastus Medialis and Biceps Femoris muscles. A FFS was anticipated to elicit the greatest muscle activity for the Gastrocnemius, Vastus Medialis and Biceps Femoris; and the lowest activity for the Tibialis Anterior muscle.

It must be noted that the use of this classification for the various responders is simplified, and as a result the reader should acknowledge that a wide range of negative or positive responses may occur. Therefore all positive responses should not be assumed to be equal. Range of responses and individual responses were used in order to demonstrate this variability in the current study.

SELECTION OF DEPENDANT VARIABLES

To thoroughly assess the biomechanical, physiological and perceptual variables, the appropriate measures were recorded to assess the role of running footwear on individual responses.

- *Biomechanical Responses*

The following biomechanical variables were selected for investigation in the current study: stride rate (SR), stride length (SL) and ground reaction forces (impact peak and loading rate). The justification for the selection of these variables is provided below.

Stride rate and stride length provide a valuable biomechanical assessment of individual responses and running form. These responses have been investigated by numerous studies (De Wit *et al*., 2000; Divert *et al*., 2005a; Lieberman *et al*., 2010; Bonacci *et al*., 2013) which found these variables to be altered under the different footwear conditions. A runner’s kinematics affects how external and internal forces are generated and withstood by the body (Daoud *et al*., 2012). These measures are therefore important as they may illustrate crucial kinematic changes in running form under each footwear condition, which may be key determinants in the causation of various injuries.

Ground reaction forces were recorded to illustrate the loading of the musculoskeletal system at contact with the ground (Zadpoor and Nikooyan, 2011). The impact peak has been associated with musculoskeletal injuries (Nigg, 2001; Daoud *et al*., 2012). The magnitude of ground reaction forces may be between 2 and 11 times the body weight during various activities such as running and the human body needs to actively manage the collision with the ground to minimize its proposed adverse effects (Zadpoor and Nikooyan, 2011). Numerous studies have investigated these responses under various conditions. Nilsson and Thorstensson (2008) found impact peaks increased with increasing running speed. Logan *et al.* (2010) found significantly greater loading rates, peak vertical impact forces and peak braking forces in running flats (similar to minimalist footwear) compared to shod running. Looking at the ground reaction forces between different foot-strike patterns whilst shod, Boyer, Rooney and Derrick (2013) found peak resultant and vertical loading rates were not ubiquitously lower when using a FFS compared to a RFS. The findings of this study did not provide evidence that a FFS is more beneficial than using a RFS. While studies have investigated ground reaction forces, there is a lack of conclusive evidence of these responses, specifically comparing first time transitioning from shod to barefoot or minimalist running. It was anticipated, for the current study that impact forces and loading rates would vary between individuals under the experimental footwear conditions.

The foot-strike pattern employed by runners often depends on the footwear worn. Lieberman *et al.* (2010) notes that 75% of habitually shod runners RFS, while barefoot runners tend to land on the anterior of the foot with a MFS or a FFS. There is much conflict over the percentage of foot-strikers under each footwear condition and that all individuals respond the same under these conditions (refer to review for in-depth comparison). Different foot-strike patterns have been found to alter the kinetics and kinematics of individuals when running (Daoud *et al*., 2012; Goss and Gross, 2012). Foot-strike patterns were not controlled in this study, for both the runway and treadmill protocols, and all participants ran the experimental conditions using the foot-strike pattern which came most naturally to them under that footwear condition. An individual's foot-strike pattern might vary between conditions, however the author wanted to analyse this, in an attempt to examine if any individuals remain RFS when barefoot or in minimalist footwear, whilst others switch to a more anterior

FSP. Furthermore the impact of a shift in foot-strike patterns on other biomechanical, physiological and perceptual responses was analysed. If participants' foot-strike patterns shifted between the conditions this was noted and participants were categorized accordingly. A RFS was defined as a foot-strike in which first contact of the foot was with the heel or rear one-third of the sole (Hasegawa, Yamauchi and Kraemer, 2007; Larson *et al*., 2011). All other foot-strikes beyond the rear one-third were regarded as a non-heel strike foot-strike pattern.

- *Physiological Responses*

The following physiological variables were selected for investigation in the current study: heart rate (HR); oxygen consumption ($\dot{V}O_2$), energy expenditure (EE) and electromyography (EMG). The justification for the selection of these variables is provided below.

Squadrone and Gallozzi (2009), Hanson *et al.* (2011), Franz *et al.* (2012) and Gruber *et al.* (2013) measured similar physiological variables as they provide an assessment of the physiological status of the individuals under the three experimental conditions. Oxygen consumption and energy expenditure were obtained, which provided an accurate comparison of the energy cost of transport associated between the three conditions. This is important, as runners want to use the footwear with the lowest associated energy costs. As previously mentioned, a lot of contention surrounds these measures, and more studies need to investigate the individual responses to different footwear conditions.

Electromyography (EMG) responses were recorded, which provide an indication of the level of activity in selected muscles of the lower extremity, under each of the footwear conditions. Numerous studies into EMG were conducted in the 1970's after which this measure was side-lined, however recent studies, such as Gazendam and Hof (2007) and Olin and Gutierrez (2013), have recognized the potential importance of this measure and have begun incorporating this measure again. EMG was recorded in this study due to a marked shortage of studies into muscle activity, specifically in runners, as noted by Olin and Gutierrez (2013). A few studies have compared EMG responses between the barefoot and shod conditions, however little research has investigated the minimalist condition (Standifird, Mitchell, Hunter, Johnson and Ridge, 2013). Analysing EMG responses enables researchers to determine the muscle recruitment patterns experienced by individuals under various footwear conditions, as shown in (Divert *et al*., 2005a) who found greater activity for the plantar-flexors when running barefoot versus shod. More research is required comparing the differences in muscle activity between the three footwear conditions, and whether these responses are experienced equally in all individuals.

- *Perceptual Responses*

Individual perceptual responses were investigated by obtaining both central and local ratings of perceived exertion (RPE) as well as body discomfort (BD) measures. RPE provides an indication of an individual's perception of each footwear condition, with central RPE referring to an individuals perceived ventilatory and circulatory exertion and local RPE referring to the perceived muscle and joint exertion (Pandolf, Billh, Drolet, Pimental and Sawka, 1984). Central RPE has been shown to correlate strongly with an individuals' heart rate during physically demanding events (Borg, 1982; McArdle *et al*., 2007). This was important as it allowed researchers to understand subjective symptoms and how these related to objective findings under the same conditions. No studies (to the author's knowledge) have assessed BD responses to the footwear conditions. This measure was incorporated, as it was expected that it would provide a suitable link with the EMG and GRF responses, to determine whether the individuals were aware of changes in impact forces or loading rates and the level muscle recruitment between conditions (if any were observed). This measure also provides a more specific location of discomfort, in comparison to local RPE which is more generalized.

SELECTION OF PARTICIPANTS

Participants were required to complete a pre-selection questionnaire (Appendix A) to meet inclusion criteria (Appendix A) for the study. The participants selected for this study were male, injury-free with a shoe size between 8-11, well-trained endurance runners which were characterised by individuals who completed between 30 and 50km per week, at training speeds of between $12km.hr^{-1}$ and $14km.hr^{-1}$ and were capable of running a sub 22 minutes 5km race. Participants were recruited via Rhodes University Intranet, Facebook, running clubs, word of mouth and posters pinned up around campus. In the past, studies have been conducted on both male (Divert *et al*., 2005a; Daoud *et al*., 2012;) and female endurance runners (Milner, Ferber, Pollard, Hamill and Davis, 2006; Lilley, Dixon and Stiles, 2011; Willson *et al*., 2014). Male runners were selected for the current study, due to 1) the availability of a predominantly male population and 2) the amount of comparative literature. It was necessary to exclude certain participants with running injuries in the past 6 months, as studies such as Hreljac (2004) found that runners with previous injuries create greater impact forces and impact loading rates than uninjured runners. Participants were limited to shoe sizes 8-11 due to the availability of these sizes only for the *Vibram*® minimalist footwear. An extensive literature and internet search was conducted, which revealed a wealth of running statistics, however there were no statistics available (to the authors knowledge) which provides a breakdown on the level of runners competing in each running event (5km, 10km etc.). Due to this lack of statistics providing the characteristics of most 5km runners, well-trained runners were selected as it was predicted that the majority of these individuals partake in endurance running events. Correspondingly a number of studies have been conducted on runners with similar levels of athleticism (De Wit *et al*., 2000; Riley, Dicharry, Franz, Della Croce, Wilder and Kerrigan., 2008; Hamill *et al*., 2011; Bonacci *et al*., 2013). Malisoux, Ramesh, Mann, Seil, Urhausen and Theisen (2013) recently found previous running injury as a risk factor for future injury, therefore participants with injuries in the past 6 months were excluded similar to studies by Lieberman *et al*. (2010) and Perl *et al*. (2012).

Habitually shod runners were selected for standardization of the current study, as the comparison of runners with different backgrounds (habitually shod and non-habitually shod runners) leads to increased variance of responses. The extensive literature and internet search referred to earlier, could also not provide reliable statistics on the percentage of runners running in standard, minimalist footwear or barefoot. In 2012, Powell indicated that minimalist contributed 12% of all running footwear sales. Based on this information, it was predicted that the majority of the running population continue to run shod, and train and compete in shoes. While no evidence exists on the runners attempting to run in minimalist shoes or barefoot, it is assumed the majority of these runners switch with the intention of gaining the perceived benefits of running under these footwear conditions. Comparing habitually shod runners allowed for the analysis of individual responses when switching to minimalist or barefoot running for the first time, similar to recent studies by McCarthy, Fleming, Donne and Blanksby (2014), Tam *et al*. (2014) and Cheung and Rainbow (2014).

ACCLIMATIZATION TO FOOTWEAR CONDITIONS

Training Adaptation: Participants in this study were habitually shod, therefore running barefoot or in minimalist footwear was a novel task. Recently Schütte (2012) found that after 7 weeks of exposure to minimalist footwear (in habitually shod runners), participant's running kinetics and kinematics were not significantly altered in comparison to participants who continued running shod. Willson *et al.* (2014) exposed participants to two weeks of minimalistic training and found that FSP and lower extremity running mechanics did not change significantly during a 2-week training period, while Mullen, Cotton, Bechtold and Toby (2014) found no statistically significant differences in strength and proprioception after 8 weeks on a barefoot training program. Olin and Gutierrez (2013) found a greater risk of injury during the initial transition from shod to barefoot; and suggested that runners should undertake the process slowly, cautiously and with proper knowledge. Based on the above studies, a training program was discarded as the evidence was not conclusive to support the implementation of this.

Acclimatization: A study by Hamill *et al*. (2011) utilized a 5-10 minute familiarization to novel footwear conditions period prior to experimentation, and more recently Tung *et al*. (2014) introduced the concept / term of an acclimatization trial to novel footwear conditions prior to experimentation. It was decided that a five minute acclimatization trial would be implemented after the warm up, so that participants could experience the altered kinetics and kinematics associated with each condition (if these were altered). This trial allowed for the familiarization to the barefoot and minimalist conditions, and ensured all participants felt a certain degree of comfort running in these conditions. The acclimatization trial was implemented to ensure that the risk of injuries to participants was minimized as far as possible under these novel conditions.

CONTROLLED AND UNCONTROLLED VARIABLES

A number of variables were controlled throughout experimentation to standardize the protocol and reduce unwanted variance as far as possible. The controlled variables included running speed, warm up, experimental time frame, training status, pre-testing procedure and shoe size. The following variables could not / were not controlled in the experimental set up: shoe-sole stiffness, laboratory temperature, running sole thickness and shoe-mass. These are discussed below.

SELECTION OF RUNNING SPEED

To date, running based studies have conducted running based protocols with running speeds ranging from 9.36km.h^{-1} (Steudel-Numbers *et al*., 2007) up to 21.96km.h^{-1} (De Wit *et al*., 2000). For this study, a single running speed was selected, which was designed to be as close to the participants' preferred running speeds as possible. This was done to ensure running speed was not a factor responsible for variance between conditions. This process is described below.

Running speed was determined from the pre-selection questionnaires (Appendix A), which required participants to report on their 5km time trials times over the previous 3 months. Participants were included if they ran a 5km within 16-22mins, which translates to a speed of between 13.64 and 18.75km.h^{-1}. This time frame was selected to minimize the effect of running speed on the participants that partook in this research project and due to the runners being well trained, it was expected that they could comfortably cope with this running speed. The final running speed was set at 15km.h^{-1}, based on the pilot studies and the selected participants. Running speed was stringently controlled throughout the experimental procedures. A narrow range of 5km times were selected to ensure participants had similar running abilities and therefore similar preferred running speeds. The 5km distance was selected, as endurance running is defined as any distance of 5km or greater (Hall *et al*. 2013). Running speed is known to influence individual responses considerably, such as ground reaction forces as shown in Nilsson and Thorstensson (2008), therefore by selecting individuals of very similar running abilities; the potential impact of running speed would be minimized or eliminated. It is acknowledged that the running speed between footwear conditions might vary between individuals, however due to ethical concerns it was not viable to require participants to complete a 5km time trial in minimalist footwear or barefoot, as this would expose the participants to a potentially increased injury risk.

NUMBER OF EXPERIMENTATION SESSIONS

Participants were required to attend one introductory session, followed by three experimental sessions. Each experimental session consisted of a runway and treadmill protocol. Each experimental condition (shod, minimalist and barefoot) was conducted on a separate occasion to ensure the running form / foot-strike pattern of the previous condition did not affect the next condition and ensured fatigue (muscular or cardiovascular) from the earlier condition did not influence the elicited responses. There was a compulsory one day break between trials, and participants were required to complete all three experimental sessions within a week. These measures were essential to ensure meaningful responses were obtained. Separate sessions also ensured that the risk of injury was reduced, as participants were habitually shod and had no experience with the barefoot or minimalist conditions, by allowing sufficient recovery time between experimental conditions.

WARM UP AND EXPERIMENTAL TIME FRAME

Warm up: A 6 minute warm up was implemented prior to each experimental session, similar to that instigated by Divert *et al*. (2005a). During this time participants were allowed to complete a series of their own stretches, and run on the treadmill or indoor runway. No set stretches were applied, as current evidence does not support the notion that stretching prior to exercise can effectively reduce injury risk or improve performance (Thacker, Gilchrist, Stroup and Kimsey, 2004; Magnusson and Renström, 2006).

Experimental time frame: The experimental time frame in running based experimentation is a fundamental and significant factor, which needs to be long enough for a steady state in biomechanical, physiological and perceptual responses to be achieved which ensures accurate data acquisition. Furthermore this time frame needs to avoid excessive exposure of participants to a potentially increased risk of injury, while providing sufficient recording time to create accurate and meaningful results. Physiological variables achieve steady state within 2-3 mintues post exercise beginning (McArdle, 2007), while according to Divert *et al.* (2005a) measuring biomechanical responses after 4 minutes allows sufficient time to adopt a consistent running form. Weston, Mbambo and Myburgh (2000); Franz *et al.* (2012); Gruber *et al.* (2013) and Olin and Gutierrez (2013) executed running trials of 5-6 minutes in duration, while recently Willy and Davis (2014) implemented a 10 minute experimental duration for their study, which compared shod and minimalist conditions. Willy and Davis (2014) concluded that the mechanics between minute 1 and minute 10 were approximately identical. A 6 minute protocol was therefore selected as it was deemed sufficient to allowed participants to reach both a physiological steady state and a consistent running form.

LABORATORY TEMPERATURE

The Department of Human Kinetics and Ergonomics laboratories maintain a fairly constant daily temperature, which varies within a small range. While the temperature at which experimentation was conducted was not controlled, the temperature was recorded prior to each session and is summarized below (Table V).

Table V: Laboratory temperature and humidity averages during experimentation sessions.

	Temp (°C)	Humidity (%)
Average	22.11	53.68
Min	18	40
Max	26.4	69
Range	8.4	29

SHOE RELATED ISSUES

Standard shoe: Participants were required to run in their own regular running shoes, similar to Cheung and Rainbow (2014) who compared shod versus barefoot running. Participants were habitually shod, so this was the shoe which they used most regularly and competed in. All the participants' running shoes were designed with a heel-rise and medial arch support. Shoe age and wearing patterns have shown to affect the contact time a runner spends on the ground (Kong, Candelaria and Smith, 2009). Correspondingly Liang and Chiu (2010) found the cushioning abilities of the running shoes were attenuated after 300km running distance. Thus, participants were required to estimate the number of kilometres completed in their current running shoes. Participants were excluded if they had completed more than 500kms in their current shoe, to minimize the impact this may have had on elicited responses. This distance was selected as due to socio-economic conditions it was not likely participants acquired new running shoes every 10 weeks. The shoe mass of the participants regular shoes were measured prior to experimentation, and this was taken into consideration during the analysis of individual response data. This was necessary to determine if any changes (if experienced) were due to an added mass of the shoe or not, particularly in individuals who responded to the different conditions.

Minimalist Footwear: The Vibram® Five Fingers (Model: Bikila - Vibram, Albizzate, Italy) minimalist shoe was selected, as this was one of the first minimalist shoes to be developed and one of the more popular minimalist brands available (Altman and Davis, 2012). These same shoes have been used in a number of studies, such as Squadrone and Gallozzi (2009) and Ridge *et al*. (2013). According to Vibram® these shoes have a design with individual slots for each toe and soles made from a rubber like a flexible glove. Each shoe weighed between 165g (size 8) to 191g (size 11).

RUNNING SOLE THICKNESS

The thickness of the heel-rise for all individuals' standard running shoes was not controlled. This was however measured to allow post-hoc analyses, as Hamill *et al*. (2011) found (while not significant) a trend of a decrease in loading rate, with a decreasing midsole thickness.

HYGIENE/HEALTH RELATED ISSUES

Minimalist/Barefoot Condition: Participants were not provided with individual pairs of the minimalist footwear, and as such were required to wash their feet in a Milton solution before experimentation took place. The minimalist shoes also had an antifungal spray sprayed into them prior to each session and these were also washed after every four protocols. The runway and treadmill surfaces were also washed regularly. These measures ensured a reduction of the associated health risks.

Attachment of Electrodes: To attach the electrodes appropriately, participants had the hair on their legs shaved with a razor at the predetermined sites. Each participant was shaved with a different razor and new alcohol swabs to reduce any associated health associated risks. Each electrode was washed using a Milton solution prior to each experimental session.

Heart Rate Monitor: Participants were required to wear this throughout the duration of an experimental session. To avoid any health related concerns, the researcher had a number of straps at their disposal, and these were washed in a Milton solution after each session, along with the heart rate monitor.

Ergospirometer Face Mask: These masks were washed in a Milton solution prior to each experimental session to reduce the associated health risks of this piece of equipment.

EXPERIMENTAL EQUIPMENT

During the experimentation sessions, it was essential that accurate and reliable data was collected from each participant. To ensure that all elicited responses were representative, all equipment utilized during experimentation was appropriately set up, calibrated, fitted to the participant and correctly operated. The following equipment was required for data collection purposes and allows for accurate replication of this study in the future.

Running Speed: ***Photo-electric Timer -*** Running speed over the indoor running track was verified and controlled with a similar setup to Logan *et al.* (2010). This consisted of a photoelectric timing system with sensors positioned 6m apart at hip level on both sides of the force plate. The level of the sensors was consistent for all participants under all three conditions. Participants were required to run within a small margin (+-5%) of the experimental running speed (14.25 to 15.75km.h^{-1}) and maintain this pace for at least 5m after contact with the embedded force plate.

ANTHROPOMETRIC PARAMETERS

Body Mass: ***Toledo™ scale -*** The body mass of each participant was measured to the nearest 0.1kg using a calibrated Toledo™ electronic scale (model 8142). All measurements were taken with participants wearing minimal clothing, once participants had emptied their pockets and removed all footwear, socks and heavy clothing. All body mass measurements were standardized and conducted in the morning between 8am and 11am. Participants were requested to stand still, in the centre of the scale, with their body mass distributed evenly. Two recordings were obtained, directly after each other, to ensure consistent and accurate readings were acquired. This required the participant to get on and off the scale for the second measurement. Body mass was measured once off, as participants were required to complete the experimental protocols within a week of their first session.

Stature: ***Harpenden™ Stadiometer -*** Stature was obtained using a Harpenden™ Stadiometer and recorded to the nearest millimetre (cm) during the first session. Participants wore minimal clothing with no footwear, socks, or any form of headwear. Participants were required to stand on the stadiometer in an upright position facing forward with heels together and heels, buttocks and upper back touching the stadiometer. The head of each participant was placed in the Frankfort plane, with the lower edge of the eye socket in the same horizontal plane as the notch superior to the tragus of the ear. Participants were asked to inhale and the measurement was taken from the Vertex, this was done twice consecutively to ensure that an accurate measure was obtained.

Maximal Calf Girth: ***Anthropometric Tape -*** Differences in running performance in the past have been found to be attributed to differences in anthropometric characteristics such as body mass index (BMI) and body shape (Larsen, 2003 and Lucia, Esteve-Lanao, Olivan, Gomez-Gallego, San Juan, Santiago, Perez, Chamorro and Foster, 2006). No study (to the author's knowledge) has considered differences in maximal calf girth as a possible explanation for variation in individual responses (if any). Participants were required to stand upright, legs slightly parted with their weight equally distributed on both feet, while calf girth (cm) was measured at the largest circumference of the calf, using a standard non-elastic anthropometric tape. This was recorded to the nearest mm on the dominant limb. Duplicate measures were taken simultaneously and a retest performed if the duplicate measures were not within a 5% of one another.

Leg length: ***Holtain™ Anthropometer -*** Participants were required to remove footwear and socks, and stand upright looking forwards with legs slightly parted with their weight equally distributed on both feet. Leg length was measured using a Holtain Anthropometer from the head of the femur to the base of the foot. The head of the femur was determined via the correct anthropometric technique, which required palpation near the participants' hip-joint and the subsequent abduction and flexion of the hip in order to correctly identify this landmark. This ensured accuracy, consistency and reliability of data. This was measured to the nearest 0.1cm. Duplicate measures were taken and a retest performed if the duplicate measures were not within a small 5% error margin.

BIOMECHANICAL PARAMETERS

Stride length (SL) and Stride rate (SR): ***Manual Counter -*** Participants SL were calculated using the pre-determined running speed (converted to meters per minute), running time and SR (cadence) of each condition. SR was obtained using a manual counter, which recorded each foot-strike of the right limb (this was then multiplied by two, to represent both limbs). SR and SL were recorded from minute's four to six, once the steady state running form had been achieved.

Running Speed = Cadence × Stride Length, therefore:

$$\text{Stride Length} = \frac{\text{Running Pace (m.min}^{-1}\text{)} \times \text{Running Time (min)}}{\text{Cadence (St.min}^{-1}\text{)}}$$

Ground Reaction Forces (GRF): ***Bertec® force plate -*** GRF's were recorded using an embedded *Bertec® Force Plate (Bertec Corp, Columbus, OH, Model: 6090-15)*. The *Bertec®* force plate is suited to gait analysis and can handle high impact forces; it can precisely measure six components: three orthogonal forces and the moments about each axis. It internally corrects for cross-talk, to ensure that the output is a true reading and has an excellent resolution and high natural frequency. The collected force plate data was normalized to body-mass. The sampling rate was set at 1000Hz (the same as Shih *et al*. 2013) and an anti-analysing filter was implemented at 500Hz. Participants completed a total of 10 good trials across the 23m indoor running track (with an embedded force plate), from which the best 5 trials were utilized for data analysis purposes; similar to studies done by De Wit *et al*. (2000) Milner *et al*. (2006) and Tam *et al*. (2014). A trial was determined *good* if the participant's whole foot (of right leg) landed on the force plate and they ran within +-5% of the experimental running speed. Trials in which the participant appeared to change gait to target the force platform, as determined subjectively by the investigators, were discarded. Participants performed practice trials to ensure that they could maintain a consistent running speed and make contact with the central portion of the force platform without modifying their gait (Milner *et al*., 2006). The right leg was selected to ensure consistent and accurate responses were collected, similar to (Cheung and Rainbow, 2014). Ground reaction force variables impact peak (IPEAK), vertical impact loading rate (VILR), vertical average loading rate (VALR) and strike time (ST) were determined. Loading rates were calculated between 0 and 100% of the period between foot-strike and IPEAK. Average loading rate was calculated as the total change in force divided by the total change in time over this period.

Foot-strike pattern (FSP): ***Fujifilm® Finepix Digital Camera -*** Recordings were obtained using a Fujifilm® Finepix Digital Camera *(model: JZ100)*. The camera had a 25mm wide lens, with 8x zoom and 14MP HD movie recording. To ensure accurate analysis, the camera was placed 1m from the force plate and motorized treadmill, on the ground/tripod, and aligned so that the plane of the camera was parallel to the indoor runway/treadmill running surface. For the treadmill protocol, a bubble level (attached to the tripod) ensured the camera was level and set to the height of the participant's knee during quiet standing. This camera set up was similar to that used by Bishop *et al.* (2006). Participants were recorded during the 10 trials over the indoor runway, as well as for the entire duration of the treadmill protocol. Only the 5 best trials and minutes four to six recordings were however utilized during the analysis of the data. Participant's identity was at no time disclosed in these recordings.

PHYSIOLOGICAL PARAMETERS

Heart rate: ***Polar™ heart rate monitor -*** Participant heart rates were logged using a wireless Polar® Heart Rate Monitor (Polar Electro Oy, Kempele, Finland). Heart rate was measured in beats per minute ($bt.min^{-1}$). Each participant had a heart monitor strapped around the chest, which connected via telemetry to the Cortex MetaLyser® Ergospirometry unit throughout experimentation. A small amount of gel was applied to the HR sensor before securing this to participant's, to ensure optimum skin contact.

Oxygen consumption and Energy expenditure: ***Cortex MetaLyzer® Ergospirometer -*** Oxygen consumption ($\dot{V}O_2$: in $ml.kg^{-1}.min^{-1}$) and energy expenditure (EE: $Kcal.min^{-1}$) were recorded using the Cortex MetaLyzer® (3B, Leipzig Germany) Ergospirometry unit. The MetaLyzer® is a non-portable, opencircuit spirometer which measures a breath-by-breath analysis of cardiorespiratory function. Participants inhaled ambient air with a known composition of 79.04% nitrogen, 20.93% oxygen and 0.03% carbon dioxide. Energy metabolism could then be calculated via indirect calorimetry, which compares the changes in oxygen and carbon dioxide percentages in the expired air with the percentages in the inspired ambient air. Two factors were analysed via the spirometer: one the volume of air inhaled during a specific time period and two the composition of exhaled air. These together provide a way of measuring $\dot{V}O_2$ and to infer EE. $\dot{V}O_2$ measurements were recorded from the fourth until the sixth minute of each running bout, after a steady-state had been achieved.

Electromyography (EMG): ***Biometrics® data-logger -*** The EMG responses of the lower limb musculature were recorded using the Biometrics® data-logger *(Ref: Datalog MWX8)*, via non-invasive bipolar surface electrodes. Recordings were conducted with sensitivity set at 3mV and a sampling rate set at 1000Hz.

Electrode characteristics: The electrodes used were Biometrics® Ltd precision bipolar, differential EMG sensors *(Ref: SX230 1000)* with integral electrodes at a fixed electrode distance of 20mm. A Biometrics® Ltd R506 ground reference cable was also used. The use of multi-channel electrode arrays has shown that EMG estimations vary along the muscle length with respect to electrode positioning (Rainoldi, Melchiorri and Caruso, 2004). Proper electrode placement was therefore important to limit this potential variation, maximize electrical activity recording of the selected muscle and to minimize cross-talk from adjacent muscles.

Electrode Placement: The right leg was selected to keep the protocol standardized. Participants were positioned in the starting posture for each muscle. This starting posture allowed the researcher to clearly determine (via palpation) the muscle and the anatomical landmark necessary to determine the proper sensor location (Hermens, Freriks, Disselhorst-Klug and Rau, 2000). Each muscle was located according to the Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) recommendations (website - http://www.seniam.org/). Once located the appropriate skin preparation was completed (Hermens *et al*., 2000).

Skin Preparation: Proper skin preparation improved fixation of the electrodes and ensured a reduction in electrode-skin impedance (Hermens *et al*., 2000). Each electrode location was prepared by shaving all hair off, a gentle abrasion using fine sandpaper, and cleaned with an alcoholic swab, in accordance with the SENIAM recommendations for skin preparation (Hermens *et al*., 2000). The electrodes were then secured with *Fixomull*® stretch tape to facilitate a good and stable electrode-skin contact, a limited risk of movement of the sensor over the skin as well as a minimum risk of pulling of cables. The reference electrode was located on the forearm of participants. EMG responses were recorded from minute's four to six once participants had achieved a steady state in physiological responses.

Selected muscles: This study recorded the EMG activity of the tibialis anterior (TA) and the medial gastrocnemius (MG), similar to Olin and Gutierrez (2013) and Shih *et al*. (2013). In addition this study recorded the EMG activity of the biceps femoris (BF) and vastus medialus (VM) muscles, as the limb acts as a kinetic chain, therefore changes to the lower limb affect the responses of the upper limb and the associated muscles. Pilot tests also showed changes to these muscle when participants switched foot-strike patterns.

PERCEPTUAL PARAMETERS

Rating of perceived exertion (RPE): ***Borg scale -*** The central and local rating of perceived exertion more commonly known as RPE, were recorded for each participant using the *Borg Scale* (Borg, 1982). This scale is rated from 6-20: 6 being the easiest and 20 the most demanding. This measure was recorded at the end of minutes five and six. During the familiarization session, participants were informed on what the *Borg Scale* is and how it works, furthermore the differences between central and local ratings were explained in great detail. The researcher made it clear that this response is entirely subjective, and is an indication of how each individual perceived the footwear condition.

Body discomfort (BD): ***Body discomfort scale and map -*** Body discomfort (BD) is a subjective measure and was collected using the Body discomfort map and Likert scale. Body discomfort levels were represented through the use of body discomfort maps with a corresponding colour scale. This scale and map was developed by Corlett and Bishop (1976) and divides the body into 28 regions, distinguished between the anterior and posterior sides of the body (Appendix C). This map allows discomfort to be accurately assigned to a specific region or body part. Participants were required to select their level of discomfort from the scale, with 0 being no discomfort at all and 10 being severe discomfort. Participants only gave discomfort rating for the regions that discomfort was experienced during experimentation. This was recorded at the end of minutes five and six.

OTHER PARAMETERS

Shoe-sole thickness: ***Anthropometric Tape -*** Participants provided a pair of their standard running shoes (those utilized for experimentation) for measurement of the heel-rise. This measurement was taken with the shoes sitting flat on a table or flat surface, from the base of the shoe until the top of the heel-rise (level with the inner sole) using the anthropometric tape measure. This was completed three times on both shoes to obtain an accurate reading. This was measured to the nearest (mm).

EXPERIMENTAL PROCEDURES

The protocol involved three experimental conditions: (1) barefoot, (2) minimalist shoe and (3) a standard shoe. Experimentation was conducted over four sessions. Session one (introduction and collection of baseline data) outlined the main focus and purpose of the study, and facilitated the interaction between the experimenter and participants. The second, third and fourth sessions involved experimentation and collection of the participant's biomechanical, physiological and perceptual responses to each of the three conditions. All experimentation procedures were conducted in the Department of Human Kinetics and Ergonomics laboratories, Rhodes University, Grahamstown.

SESSION I: INTRODUCTION AND COLLECTION OF BASELINE DATA

Prior to selection for experimentation, participants completed a pre-selection questionnaire (Appendix A). Participants were included in the study if they met the pre-selection criteria (Appendix A). Once selected, participants were required to attend a compulsory introduction and familiarization session (Session I) in which the experimenter explained the experimentation procedures; provided participants with a letter of information (Appendix A); provided a verbal explanation of the requirements, risks and benefits of the study and lastly displayed the equipment to be used for experimentation. This session allowed participants the opportunity to make an informed decision before agreeing to participate in the study, and provided a full explanation in the event that they accepted to partake. The participants who agreed to participate were required to sign an informed consent form (Appendix A). Once written consent was obtained, participants were allocated a participant code (Appendix B), which was used to protect the identity of all participant's and ensure the anonymity of all data and information collected over the duration of the study.

Basic anthropometrical data were collected which included the participant's body mass, stature, calf-girth and limb length. Further information collected included the participants' running shoe mass, shoe heel-rise and a reference heart rate. This information was captured on the data collection sheets (Appendix B). Once all participant information was collected, familiarization to the experimental protocol began. Running on an indoor runway (with embedded force plate) and motorized treadmill with equipment, such as the MetaLyser® ergospirometer face mask, heart rate belts or electrodes; is unusual for most participants and therefore familiarization was essential to ensure comfort and familiarity during experimentation. Participants were familiarized with the treadmill, experimental equipment and the experimentation procedure. Familiarization to the treadmill ensured participants were exposed to as few risks as possible, avoided serious injuries and ensured reliable data collection. This was followed by a brief introduction to the indoor running track (with embedded force plate) and the experimental running speed. Participants were encouraged to ask questions throughout the session to avoid any uncertainty over the experimentation procedure. Participants were given pre-experimental instructions (Appendix A) to follow prior to the second session (first experimental session) and allocated a return date and time.

SESSION II, III & IV: EXPERIMENTAL SESSIONS AND DATA COLLECTION

The MetaLyser® was switched on 20 minutes prior to each experimental session, as per the user manual, to allow sufficient time for the unit to be fully warmed up ensuring accurate data collection. The unit was calibrated to the laboratory air, so that ambient air gas concentrations were known. Gas calibration followed, cylinders containing known gas quantities (16.09% oxygen, 4.9% carbon dioxide and nitrogen balance) were utilized. Gas calibration was done once every two weeks, as per the user manual, to ensure the O_2 and CO_2 sensors were functioning appropriately.

During the second session (first experimentation session) one of three pre-determined conditions were completed. A permutation table (Appendix B) ensured a random order of conditions were conducted. Upon arrival to the laboratory, participants' had a heart rate monitor attached to measure their heart rate, which was compared to the reference heart rate (obtained in session 1) to ensure participants had not been drinking, were not ill, or on medication. Participants then performed the brief 6 minute warm up, which was followed by the five minute acclimatization trial. Participants then completed the pre-determined runway protocol. The runway and treadmill protocols were separated by a minimum of five minutes of rest (Bishop *et al*., 2006) or until baseline metabolic responses had returned to normal (within 5% of reference HR). During the recovery period participants were reminded of the treadmill protocol; while the MetaLyser® face mask was attached, and electrodes were placed on the selected limb muscles and connected to the data logger. A tight fit of the mask, using the head harness and straps, was essential to ensure no air entered or escaped around the side of the mask and only entered via the inlets and exited via the mouth piece as intended. Participants were required to embark the treadmill, before the pre-determined six minute protocol (Figure 3) began.

To conclude the session, all equipment was removed and participants were provided with water and the option of a short warm down to avoid potential stiffness the following day. Participants then confirmed their next appointment before leaving. The third and fourth sessions required the participants to complete the additional two conditions. The same procedures, as followed in the second session, were replicated. During the final session, at completion, participants were thanked and given a feedback request form (Appendix B). The feedback form presented participants with the option to receive feedback on the study's results and findings if they desired to. The same tester and assistant were present throughout experimentation and performed the same role during each session. This ensured the standardisation of the experimental procedures.

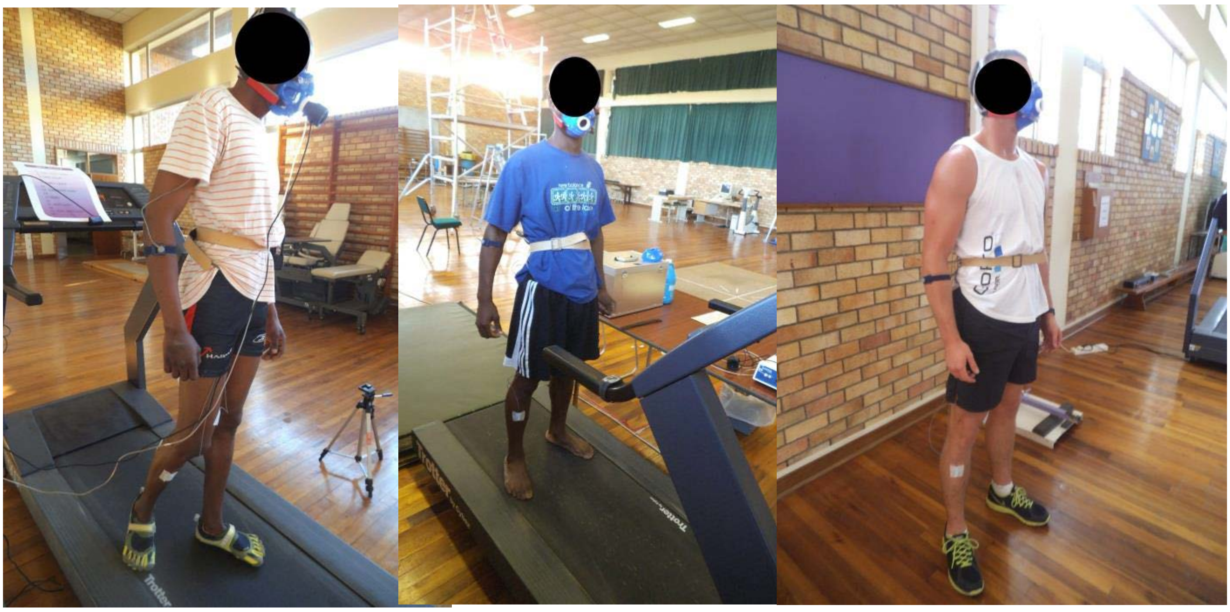

Figure 3: Participants after completion of the minimalist, barefoot and shod conditions.

ETHICAL CONSIDERATIONS

Prior ethical approval from the Rhodes University Research and Ethics Committee was required before the implementation of experimental procedures.

INFORMED CONSENT

All participants assisted in this research study on a voluntary basis and were fully informed (both verbally and in writing) about the nature of the current study prior to experimentation. In accordance with the protocols approved by the Rhodes University Research and Ethics Committee, participants provided their informed consent before enrolling to volunteer. Participants were required to sign a consent form (Appendix A) before any experimentation protocols commenced. Participants had the right to withdraw from experimentation at any time.

Participants were informed that there would be video recording throughout experimentation, which was used post-hoc to assess individual foot-strike patterns. Video footage only displayed participants from the knee down. Participants consented to all photographs taken during the different protocols. To ensure anonymity of the participants, all faces were blurred out in any photographs used.

PRIVACY AND ANONYMITY OF RESULTS

No personal information was revealed at any time before, during or after the experimentation procedure. A coding system was implemented to ensure information or data obtained from participants could in no way be traced back to the participants. Participant names on the data collection sheets (Appendix B) were necessary for record purposes only, and all participants were informed that this personal information would only be held on file for statistical purposes. All information was removed once these processes had been completed, with one copy being stored in the Department of Human Kinetics and Ergonomics, Rhodes University, for archive purposes.

STATISTICAL PROCEDURES

The statistical procedures for this study were twofold: firstly, to investigate mean responses and secondly the differences between and within individuals' responses. A repeated test design was used to highlight individual variance between the three experimental conditions, and ensure more statistically powerful data. All values are expressed as mean ± standard deviation (SD). All statistical reductions and analyses were performed using Statistica™ 12 (*StatSoft*, Inc., Oklahoma, USA). A 95% confidence level was used, allowing for a 5% chance of a Type I error occurring (rejecting a correct hypothesis).

Mean responses: Dependant t-tests were completed ($p<0.05$) between minutes 4-5, 5-6 for physiological and perceptual responses, to ensure a plateau (steady-state) had been observed. Data was screened for normality of distribution and homogeneity of variances using the Kolomogorov-Smirnov normality test. A one-way analysis of variance (ANOVA) for repeated-measures was applied to determine the differences between footwear groups. If a main effect was detected, post hoc comparisons were made with Tukeys honestly significant difference (HSD) test for pairwise comparisons. This test determined where significance was present. The magnitude of differences or effect size (ES) was classified as small (>0.2 and <0.6), moderate (≥0.6 and <1.2) and large (≥1.2 and <2) according to the scale proposed by Hopkins, Marshall, Batterham and Hanin (2009). The correlation co-efficient was calculated between a number of variables, to determine the strength and direction of these linear relationships. A strong correlation was indicated by +1 or -1, while the closer to 0 the smaller the correlation between the compared variables.

Individual responses: The co-efficient of variation was used in order to determine the level of individual variance within responses under each condition. To assess this variance, comparisons were done between a) the changes in individual responses when transitioning from the shod to minimalist or barefoot condition and b) between the individual responses under each footwear condition.

PARTICIPANT SELECTION

Initially 40 individuals showed an interest in participating in this research project (Figure 4), of which ten participants were excluded due to various inclusion criterion not being met (four were outside the pre-determined age limits, four did not meet the required fitness level or 5km time trial limit and two did not fit within the shoe sizes required for the study). There were two participants that were not contactable after the initial communication and a further two whose data sets contained errors / were incomplete.

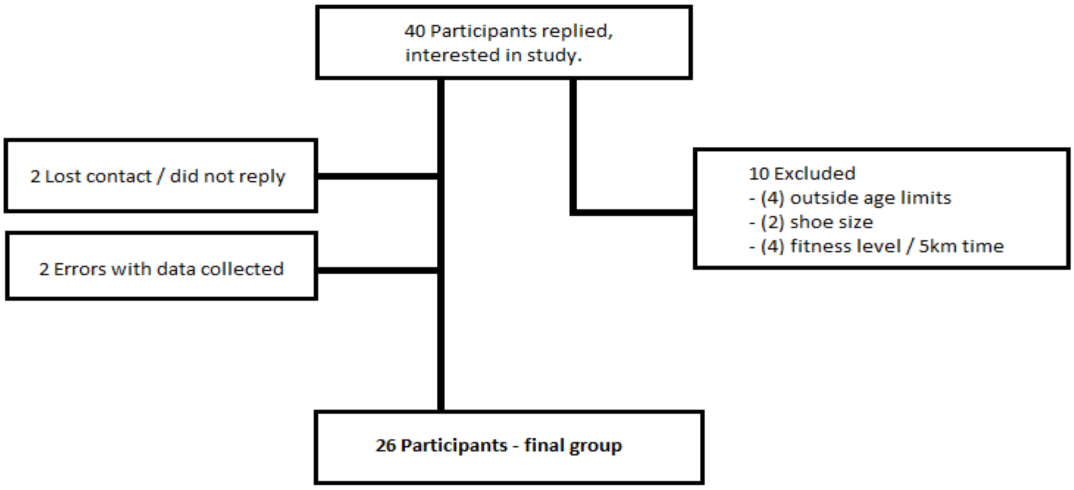

Figure 4: A spider diagram of the participant selection and exclusion process.

PARTICIPANT CHARACTERISTICS

A total of 26 male endurance runners volunteered for participation in the current study. The sample group consisted of well-trained habitually shod male runners that had experience of running and training in shoes. No medical examination took place prior to experimentation, and the researcher relied on subjective self-reports to establish that all participants were free of musculoskeletal injuries to the lower extremities. Participant characteristics were recorded prior to experimentation (Table VI).

Table VI: The mean, standard deviation and coefficient of variation of participants' basic demographic and anthropometric data.

Measure	Mean	SD	CV
Age (years)	22.00	2.22	10.08
Reported weekly mileage (km)	32.50	5.96	18.31
Number of years running experience (yrs.)	6.17	2.78	45.09
Stature (mm)	1761	66	3.75
Body mass (kg)	71.35	9.52	13.35
Leg length (mm)	910.44	51.17	5.62
Calf girth (mm)	362	24	6.68
Reported 5km time trial (mins)	19.57	1.83	9.37
Shoe mass (g)	304.92	56.78	18.62
Shoe size	9.06	1.15	12.69
Heel-rise (mm)	32.40	6.14	18.96

Where: SD = Standard Deviation; CV = Coefficient of Variation (%)

CHAPTER IV

RESULTS

INTRODUCTION

This study provided additional literature to the ever growing running research, as well as an insight into individual responses. The results will be presented through the use of tables, graphs and figures, with mean response values and the accompanying standard deviation and co-efficient of variation values for all variables of interest. In addition, individual responses will be presented in an attempt to better understand the variability of responses between and within individuals under the various conditions. These data will be presented as inter and intra-participant variability.

The biomechanical responses will be presented first, followed by the physiological and lastly the perceptual responses. For all additional statistical tables and graphs (Dependant T-tests, ANOVA's, Effect Size, Tukey Post-hoc and Individual differences in responses) please refer to Appendix C.

BIOMECHANICAL PARAMETERS

The following biomechanical variables were recorded: stride rate, stride length, impact peak, vertical impact loading rate, vertical average loading rate, strike time and foot-strike patterns. These variables were selected and analysed in order to assess how a participants' lower limb biomechanics were affected under each of the three running protocols completed. The interactions between these variables play an important role in determining an individuals' running style, which may have an impact on running performance and injury risk?

STRIDE RATE (SR)

<u>Mean Data:</u>

A statistically significant difference ($p<0.001$) in stride rate was observed between all three footwear conditions (Figure 5), with a moderate effect size of 0.62 (see

Appendix C). The lowest stride rate of 179 (±10) st.min^{-1} was experienced during shod running, increasing by 4.8% to 188 (± 11) st.min^{-1} when running barefoot, with minimalist running as an intermediary condition (183 ±11 st.min^{-1}). Furthermore the variability within conditions was small for all three conditions as demonstrated in the co-efficient of variation (CV) of 5.7, 6.2 and 5.9% for shod, minimalist and barefoot running respectively.

Figure 5: The mean (plus SD) stride rate responses between experimental conditions. (Brackets indicate statistical significance, $p<0.05$).

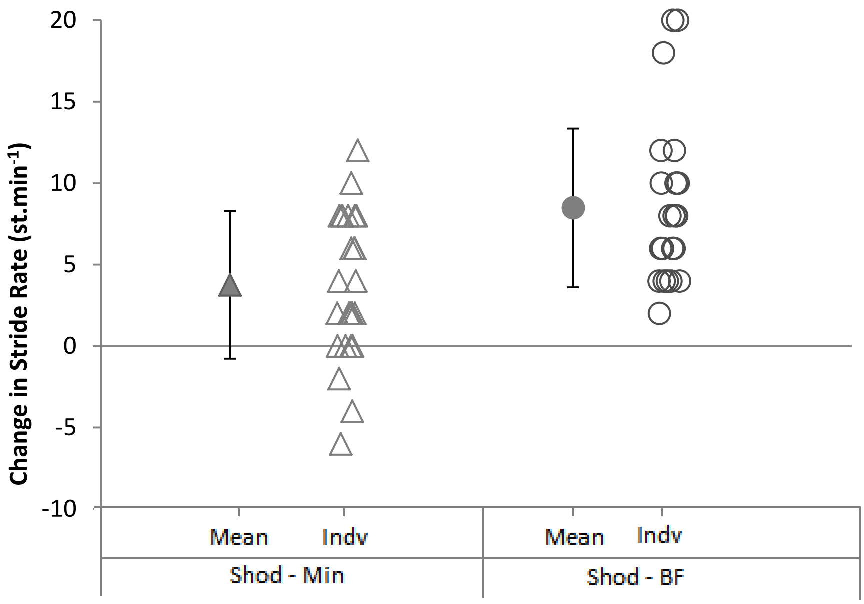

Figure 6: Mean (with SD) and individual changes in stride rate when switching from shod to minimalist and barefoot running.

Individual Data:

Although the use of mean data provides useful insight into the impact of different footwear conditions for stride rate responses experienced by the cohort population, in order to provide a more complete picture the consideration of individual responses is needed. Figure 5 demonstrates the individual changes in stride rate experienced when switching from shod to minimalist running and from shod to barefoot running, as well as the mean and standard deviation for each of these changes. This comparison allows for the investigation of the impact of a change of footwear on the individual and the group as a whole, useful in situations where there maybe responders and non-responders.

There was a significant overall increase in stride rate (positive response) of four (±5) and nine (±5) steps as participants switched from the shod condition to minimalist and barefoot conditions respectively. There was however a large range in responses (i.e. in the changes experienced when switching from shod to minimalist or barefoot running). This was particularly evident when switching to minimalist running with a CV of 120%, about double that seen when switching to barefoot running of 57%. It is further interesting to note that all participants demonstrated an increase in stride rate when switching to barefoot running, with increases ranging from as little as 2 to as high as 20 st.min^{-1}. In contrast, positive and negative responders were found for the minimalist condition, where 18 increased, 4 remained the same and 3 demonstrated a reduction in stride rate (see figure 6).

STRIDE LENGTH (SL)

Mean Data:

The interlinked nature of stride length and stride rate resulted in a corresponding adjustment in stride length (Figure 7) in relation to the observed changes in stride rate. There were statistically significant ($p<0.001$) differences between the stride lengths experienced in all three experimental conditions. A moderate association between stride length and footwear was indicated via an effect size of 0.60. The shod condition elicited the longest stride length of 2.8 (±0.15) m, versus the minimalist condition of 2.75 (±0.17) m and the barefoot condition of 2.67 (±0.15) m.

As with stride rate responses a low CV was found for all footwear conditions, with values between 5.5 and 6% for all three conditions.

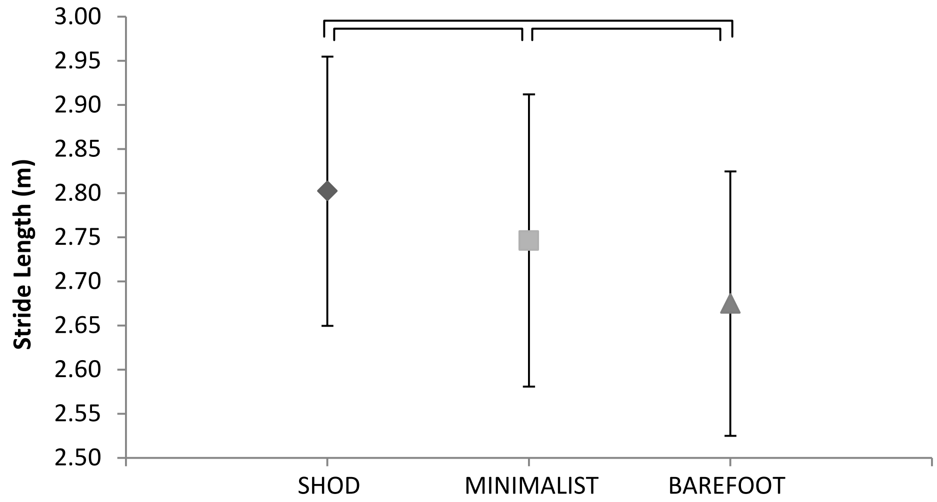

Figure 7: The mean (plus SD) stride length responses between the shod, minimalist and barefoot conditions. (Brackets indicate statistical significance, $p<0.05$).

<u>Individual Data:</u>

Figure 8 displays the change in stride length experienced as participants switched from the shod to minimalist and shod to barefoot conditions. Although a significant reduction in stride length (positive response) of -0.06 (±0.07) m was experienced as participants switched to the minimalist condition, this was noticeably smaller than the -0.13 (±0.07) m reduction observed as participants switched from shod to barefoot.

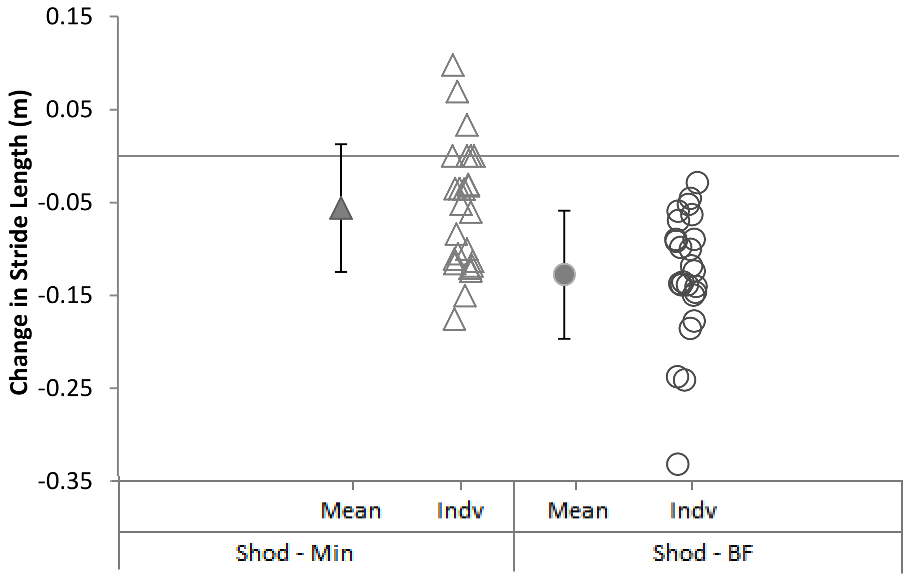

Figure 8: Mean data (with SD) and individual changes in stride length when switching from shod to minimalist or barefoot running.

Switching to the minimalist condition elicited a much greater variability, with a CV of 122.9% versus 54.1% observed as participants switched to the barefoot condition. As with stride rate responses, responders and non-responders were evident for the switch to the minimalist condition; with the majority of participants (19) experiencing a positive response, with the remaining participants experiencing unchanged (4) or negative responses (3). Contrastingly all individuals were shown to experiencing a reduction in stride length when running barefoot, although the extent of this positive response was varied, ranging between as high as 0.33m and as low as 0.05m.

IMPACT PEAK (IP)

Mean Data:

The mean impact peak responses for the shod, minimalist and barefoot footwear conditions are displayed in Figure 9.

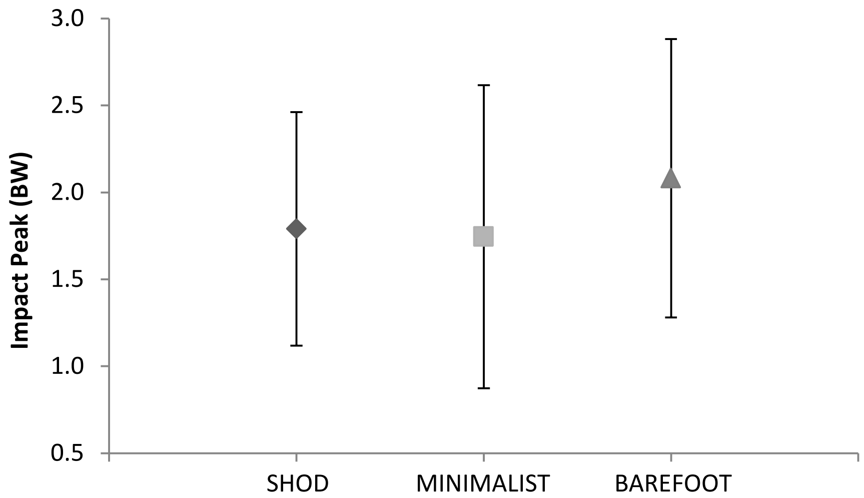

Figure 9: The mean (plus SD) and individual impact peak responses between the shod, minimalist and barefoot conditions.

There were no statistically significant differences between the three experimental conditions, with the highest mean impact peak experienced when participants ran barefoot (2.08 ±0.80 BW). The shod condition had a mean impact peak of 1.79 (±0.67) BW and minimalist the lowest impact peak at 1.75 (±0.87) BW. The minimalist condition experienced a greater variance between individual responses in comparison to the shod and barefoot conditions, with a CV of 49.9% compared to

37.5 and 38.5% respectively, although all three conditions may be considered to have high variability.

Individual Data:

Figure 10 demonstrates that the overall change associated with switching to minimalist or barefoot running was relatively small (a small decrease of -0.045 BW for minimalist and increase of 0.291 BW for barefoot). However this figure also demonstrates significant individual variability with some participants experiencing a substantial increase in impact peak and others a substantial decrease. This is more marked for the switch to minimalist running than for barefoot as demonstrated in the range of responses of 4.96 BW compared to only 3.91 BW for barefoot running. There were clear responders and non-responders for both conditions with approximately half experiencing a positive change for minimalist running and 7 for barefoot running. This may partial explain the lack of significant differences evident in the mean data presenting in Figure 8.

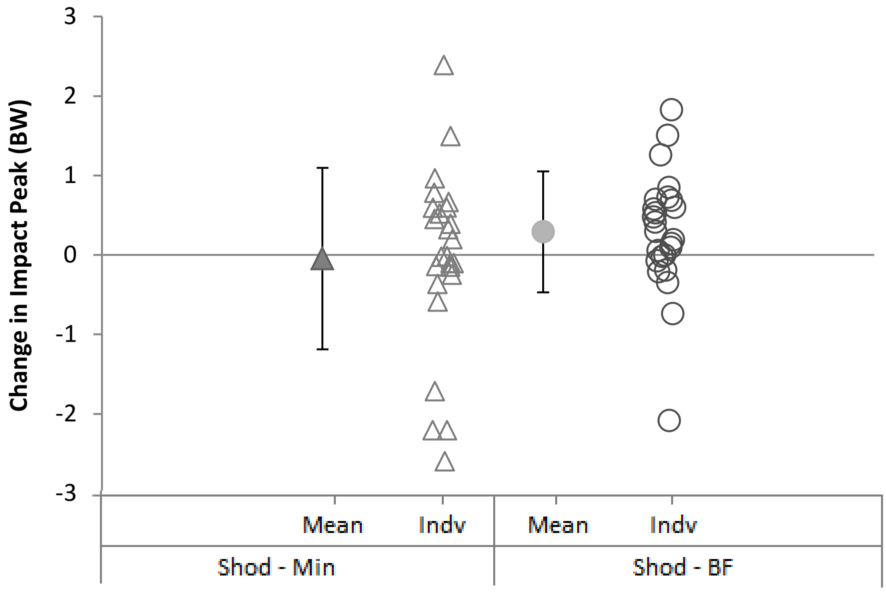

Figure 10: Mean (plus SD) and individual change in impact peak when switching from shod to minimalist and barefoot conditions.

Foot-strike Patterns:

Based on previous findings, it was expected that the foot-strike utilized whilst running would influence the impact peaks experienced. In addition it has been suggested that the footwear used may impact on the type of foot-strike pattern utilized. Consequently it is important to consider the impact peaks within these aforementioned perspectives. When comparing foot-strike patterns that a rear-foot strike (RFS) resulted in a substantially greater impact peak than that elicited by a mid and fore-foot strike (represented as a combined foot-strike - M/FFS) under all the experimental footwear conditions (Figure 11).

A RFS elicited a 45.1, 26.0 and 14.7% greater impact peak than a M/FFS when running shod, minimalist and barefoot respectively. A high variance was found for all conditions; however this was notably higher for the M/FFS group with CV's of 46.5, 40.8 and 50.2% for the shod, minimalist and barefoot conditions respectively. Although a M/FFS resulted in a reduced impact peak in comparison to a RFS, an increase in impact forces was experienced (regardless of foot-strike pattern) when running shod to minimalist to the barefoot condition. The exception was for the shod to minimalist transition with a RFS, where no difference was evident. Running with a RFS, the barefoot condition experienced a 10.3% higher impact peak than running shod. Running with a M/FFS a 24.2 and 42.3% increase was seen when switching from the shod to the minimalist and barefoot conditions respectively.

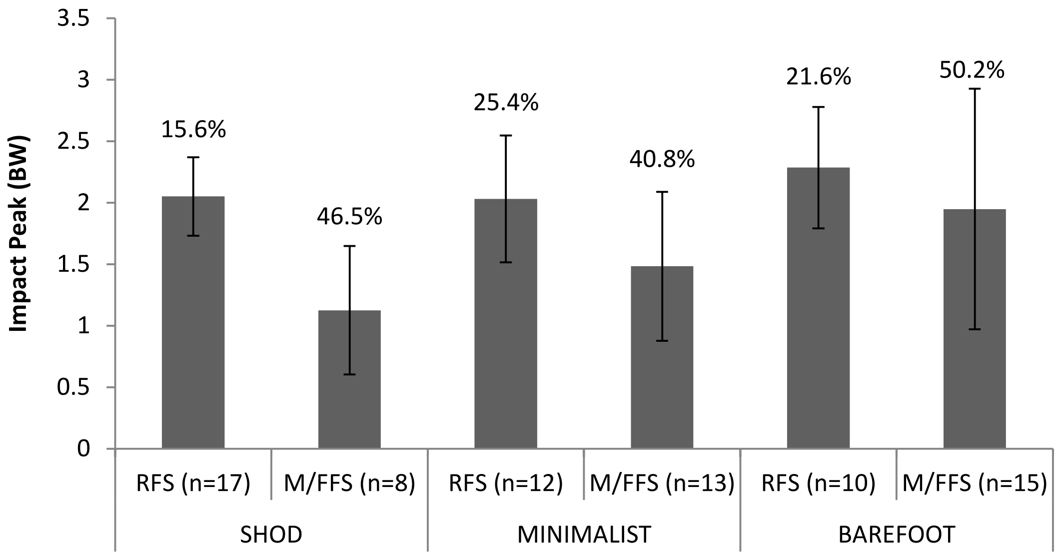

Figure 11: The effect of foot-strike patterns on impact peak values between the three footwear conditions, with relevant CV percentages (above bars).

Individual impact peak responses are displayed in Figure 12, to demonstrate the large variance seen for the mean response. Running with a RFS shows a defined consistent cluster of similar responses regardless of the footwear condition (CV ranging from 15.5-25.4%); however running with a M/FFS it is clear that no cluster of similar responses was present, again for all three conditions (CV of 40.8-50.2%). On average the M/FFS resulted in a reduced impact peak under each footwear condition; however not all individuals experienced such benefits using this foot-strike pattern.

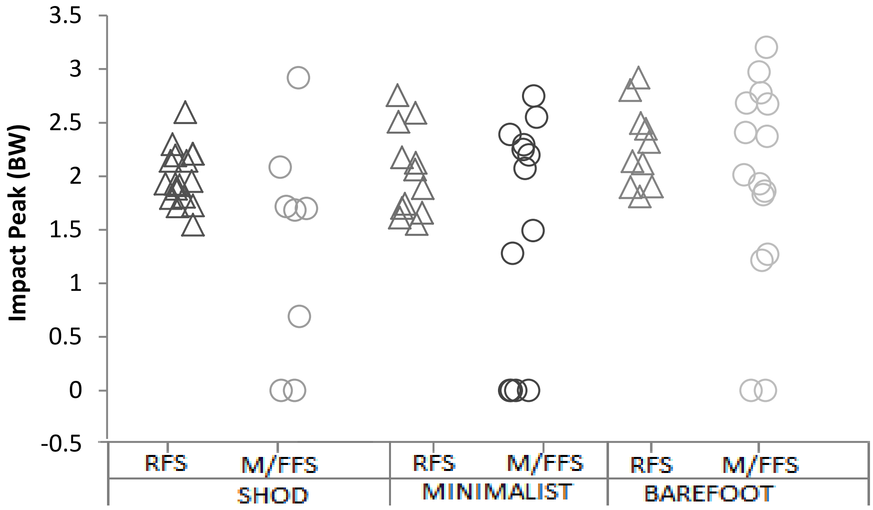

Figure 12: Individual impact peak responses, foot-strike pattern dependant, when running in the shod, minimalist or barefoot conditions.

VERTICAL IMPACT LOADING RATE (VILR)

Mean Data:

The vertical impact loading rate of 173.5 ±104.1 $BW.s^{-1}$ was found to be significantly ($p<0.001$) higher for barefoot running when compared to shod (59.4%) and minimalist (42.7%) conditions (Figure 13).

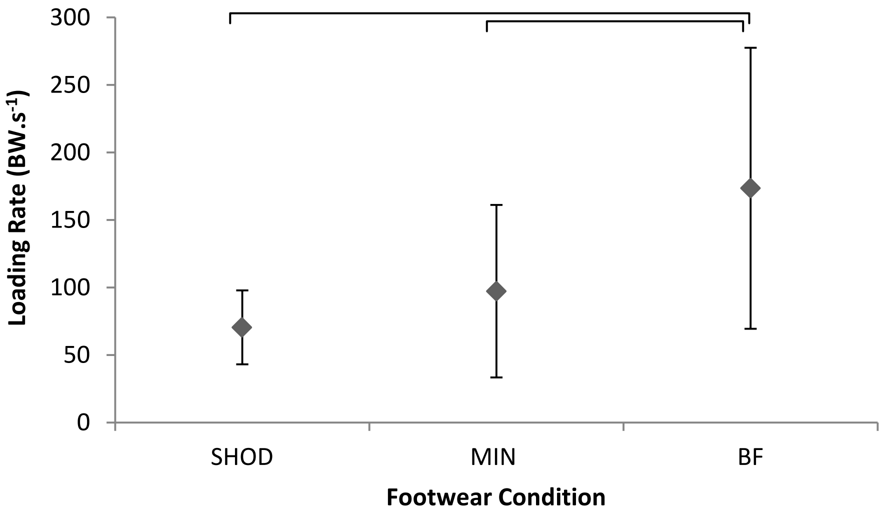

Figure 13: The vertical impact loading rate between the three footwear conditions (brackets indicate statistical significance, $p<0.05$).

A minor association between the footwear worn and the observed differences was observed, with a small effect size of 0.41 seen. Similar loading rates of 70.5 (±27.4) and 97.3 (±61.6) BW.s^{-1} were seen between the shod and minimalist conditions. It is further interesting to note the variability in responses with increasing CV from the shod (39%), to minimalist (62%) and barefoot (60%) conditions.

<u>Individual Data:</u>

Switching to the minimalist condition (Figure 14), participants experienced a significant increase in VILR (negative response: +28.9 ±71.9 BW.s^{-1}), however this response was significantly lower than the increase experienced when participants switched to the barefoot condition (+103 ±104.5 BW.s^{-1}).

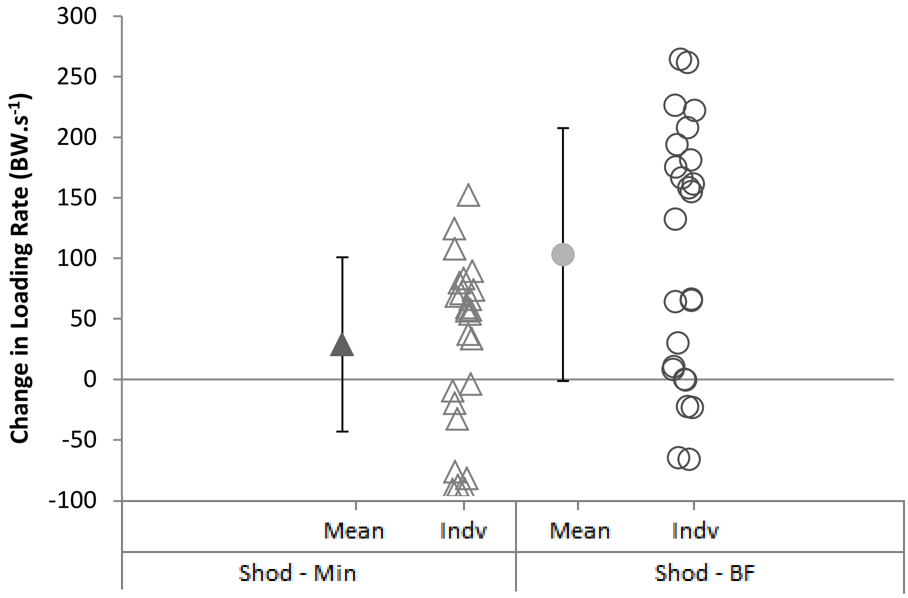

Figure 14: Mean (plus SD) and individual change in vertical impact loading rates experienced when switching from shod to minimalist and barefoot running.

The variability demonstrated in the mean data for both minimalist and barefoot running is further evidenced in the large range of responses shown in Figure 14. As with previous variables the minimalist condition demonstrated a number of positive (9) and negative responders (16). Furthermore the barefoot condition also had participants (5) who demonstrated a reduction in VILR when compared to the shod condition, although it should be noted that most participants (19) increased, with some increasing substantially.

Foot-strike Pattern:

In Figure 15 it is first interesting to note that for all three footwear conditions the M/FFS patterns had lower loading rates than the RFS with the impact peak responses of 59.6 (shod), 73.8 (minimalist) and 118 BW.s^{-1} (barefoot). However it is important to note secondly that the heel-strike had a more consistent loading rate (with CV ranging between 21.8 and 25.4% for the three conditions) when compared to the M/FFS conditions where the loading rates seem to be spread over a much greater range. Furthermore the use of a M/FFS in the minimalist and barefoot condition resulted in a greater loading rate than that experienced when participants ran with either a RFS or M/FFS in the shod condition.

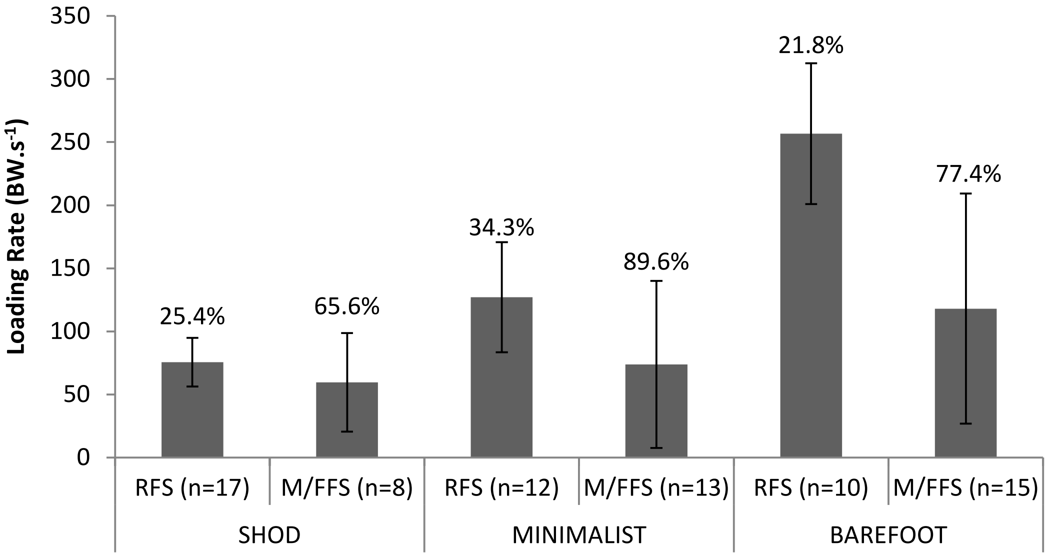

Figure 15: A comparison of vertical impact peak loading rates between the different foot-strike patterns and footwear conditions, with CV percentages.

Looking at individual loading rate responses, it was found that most shod runners using a RFS were clustered around 75 BW.s^{-1}, with a few participants above and below this (Figure 16). This was similar for the M/FFS condition; however there were two individuals that experienced no loading with this foot-strike pattern. An increase in loading was experienced regardless of foot-strike pattern for most individuals in the minimalist and barefoot conditions; however some individuals experienced a small loading rate (some smaller than the loading rates experienced in the shod and minimalist condition).

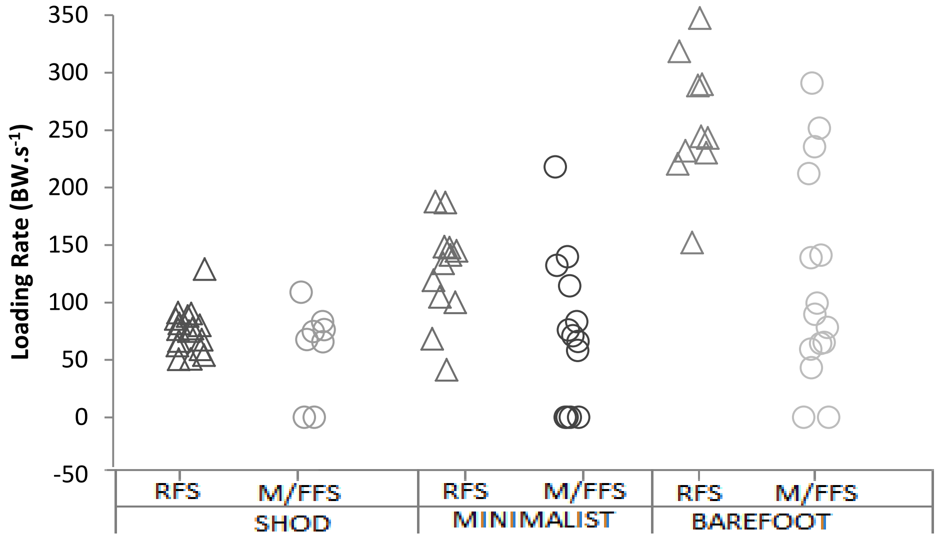

Figure 16: Individual vertical impact loading rate responses, depending on the foot-strike pattern employed and footwear condition worn.

VERTICAL AVERAGE LOADING RATE (VALR)

Mean Data:

Similar vertical average loading rates were observed between conditions; regardless of the experimental footwear condition worn (Figure 17), ranging between 30.2-30.5 BW.s^{-1}.

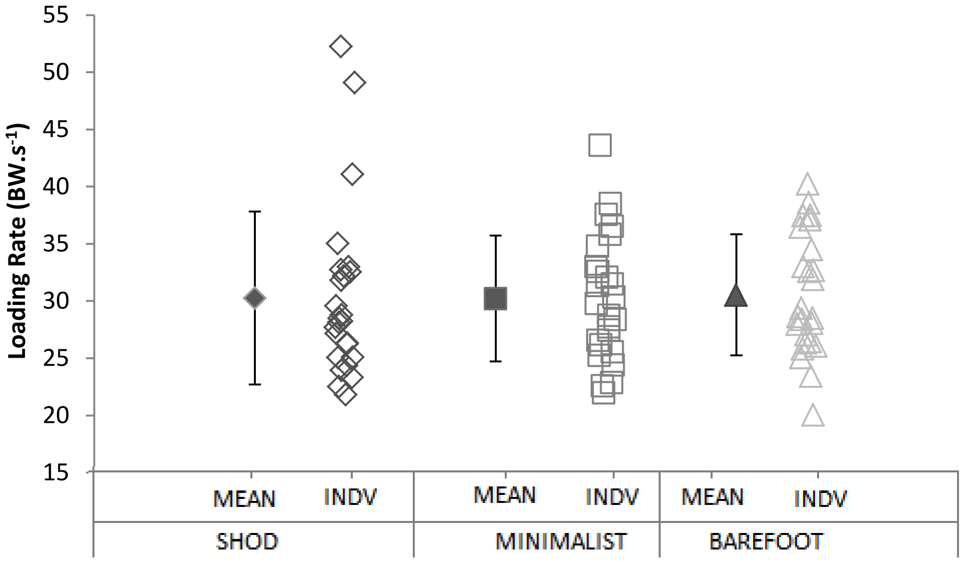

Figure 17: The mean (plus SD) and individual vertical average loading rate responses between the shod, minimalist and barefoot conditions.

A large variance was seen, with CV values in excess of 15% for all conditions. This was the highest when running shod (unlike for the previous variables), with a CV of 25%. The accompanying individual VALR responses display no common response, highlighting this variance between responses.

<u>Individual Data:</u>

Small changes of -0.036 (±4.61) and +0.276 (±5.06) $BW.s^{-1}$ were observed when switching to minimalist and barefoot conditions respectively (See Figure 18).

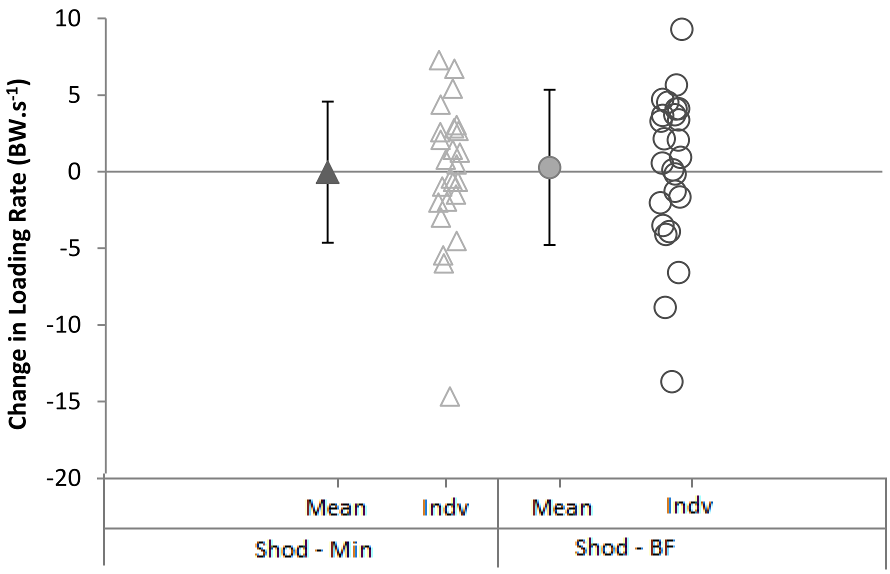

Figure 18: Mean (plus SD) and individual change in vertical average loading rates when switching between the shod and minimalist or barefoot conditions.

It is also evident that significant individual variability exists, with some participants experiencing a substantial increase in loading rates and others a substantial decrease. There is a marginally greater variance between responses when switching to barefoot running versus minimalist, with a range of 22.98 $BW.s^{-1}$ compared to 21.97 $BW.s^{-1}$. There were a number of responders and non-responders for both conditions with approximately half experiencing a positive change for minimalist running and 10 for barefoot running, which may be partially explained by the foot-strike pattern employed.

<u>Foot-strike Pattern:</u>

The use of a M/FFS resulted in an increase in VALR under all footwear conditions (Figure 18). The overall response to a RF versus a M/FF strike was a 17.5, 16.7 and

9% lower loading rate when running in the shod, minimalist and barefoot conditions respectively. Running shod with a M/FF strike resulted in a CV double that of the other conditions, which experienced CV values between 13 and 17.9%.

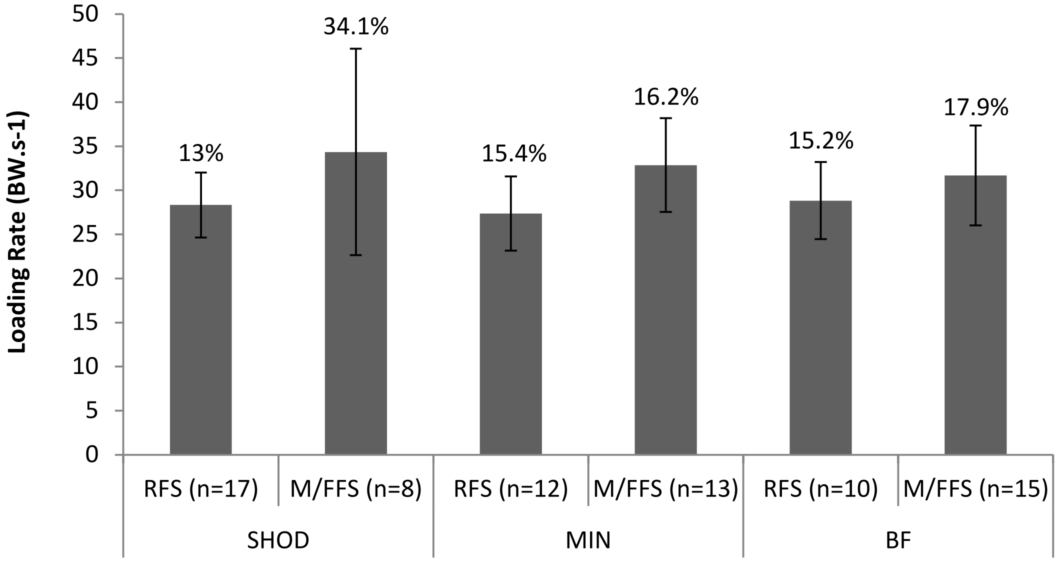

Figure 19: The comparison of vertical active peak loading rates between the different foot-strike patterns and footwear conditions, with CV percentages.

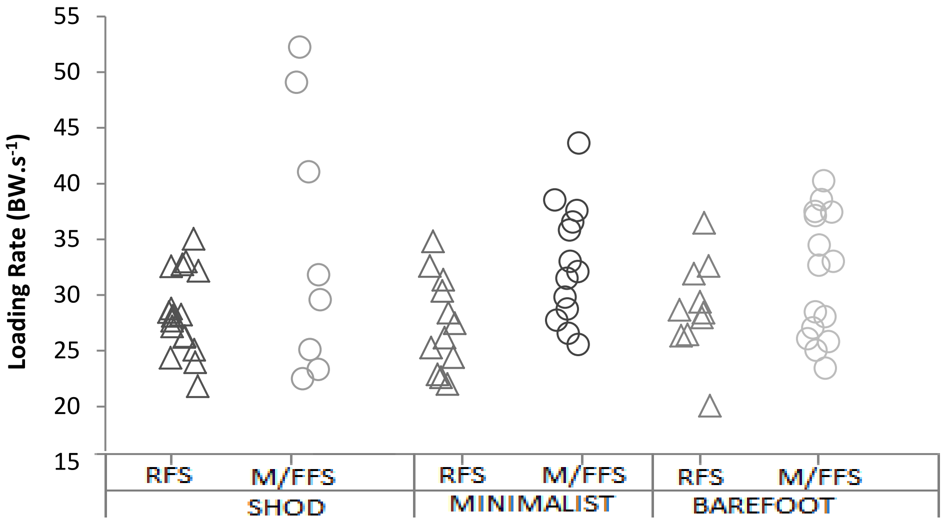

Figure 20: Individual vertical average loading rates, when running with a rear-foot versus a mid-foot / fore-foot foot-strike pattern in the shod, minimalist and barefoot conditions.

The large variance experienced as participants ran with a RFS when shod, is clearly observed in Figure 20, with the other conditions displaying a similar distribution of responses. No foot-strike pattern is shown to result in a reduced loading rate for all individuals; however a number of individuals are shown to experience greatly reduced loading rates when running with either a RF or M/FF strike.

STRIKE TIME (ST)

Mean Data:

The amount of time the foot / footwear spent in contact with the ground was found to be significantly ($p=0.008$) different between the three experimental conditions (Figure 21). It should however be noted that there was a small effect size of 0.18 present.

A longer strike time was observed when participants ran shod (0.212 ±0.02 ms^{-1}) versus in the minimalist footwear (0.211 ±0.015 ms^{-1}), with both these conditions experiencing significantly longer strike times than the barefoot condition (0.205 ±0.015 ms^{-1}). CV values of 9.5, 7.1 and 7.3 for the shod, minimalist and barefoot conditions respectively demonstrate a small variance between responses.

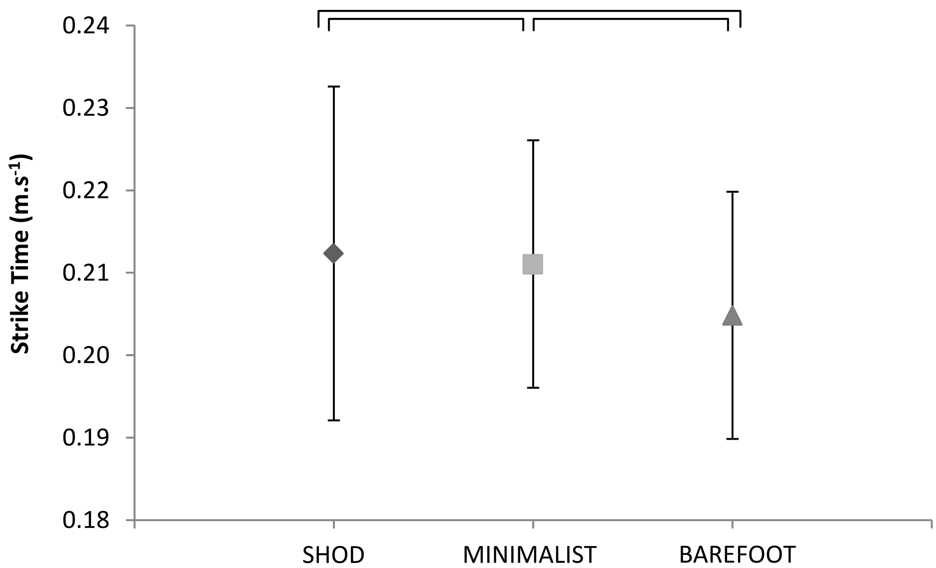

Figure 21: The mean (plus SD) strike time responses between the shod, minimalist and barefoot conditions. (Brackets indicate statistical significance, $p<0.05$).

Individual Data:

Running in the minimalist versus shod condition, participants experienced a reduction in mean strike time (negative response: -0.001 ±0.013 ms^{-1}). In comparison a larger reduction (-0.008 ±0.014 ms^{-1}) was seen when participants switched to the barefoot condition (Figure 22).

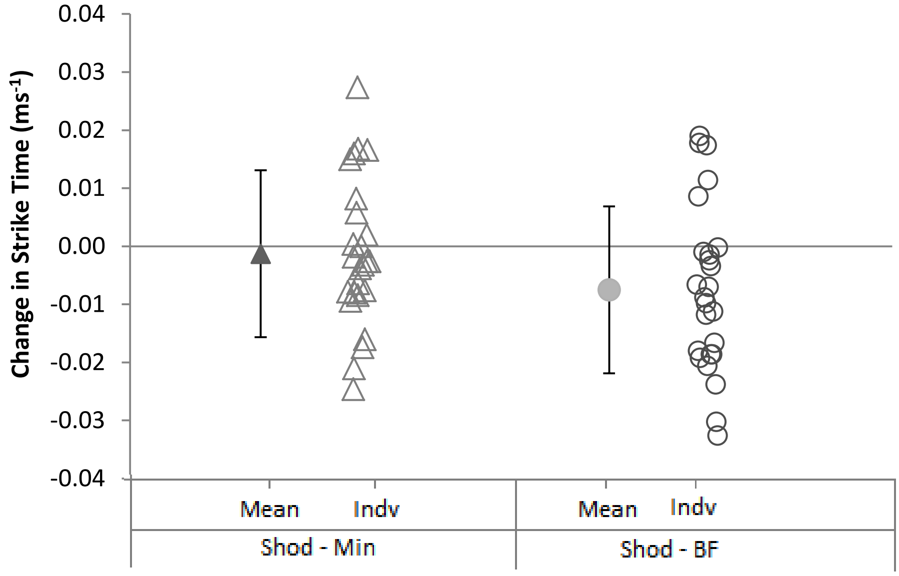

Figure 22: Mean (plus SD) and individual change in strike time when switching from shod to minimalist and barefoot running.

The participants in the current study experienced a great variability in strike time responses, with large CVs found. This was 981% when switching to the minimalist condition, significantly larger than the 191% seen when participants switched from shod to barefoot running.

Comparing the individual change responses, it was observed that nine individuals experienced an increase in strike time (positive response) when switching from shod running to minimalist running, while only five participants experienced an increase in strike time when switching to the barefoot condition.

<u>Foot-strike Pattern:</u>

A reduction in strike time was associated with the use M/FFS; regardless of the footwear condition worn (Figure 23), this was a 11.7% decrease in the shod conditions, versus a decrease of 4.8 and 5.9% experienced for the barefoot and minimalist conditions respectively. The use of a RFS resulted in a decrease in strike time (negative response) as participants switched from the shod to the minimalist and barefoot conditions. The individual responses were fairly consistent, indicated by the small CV under each condition.

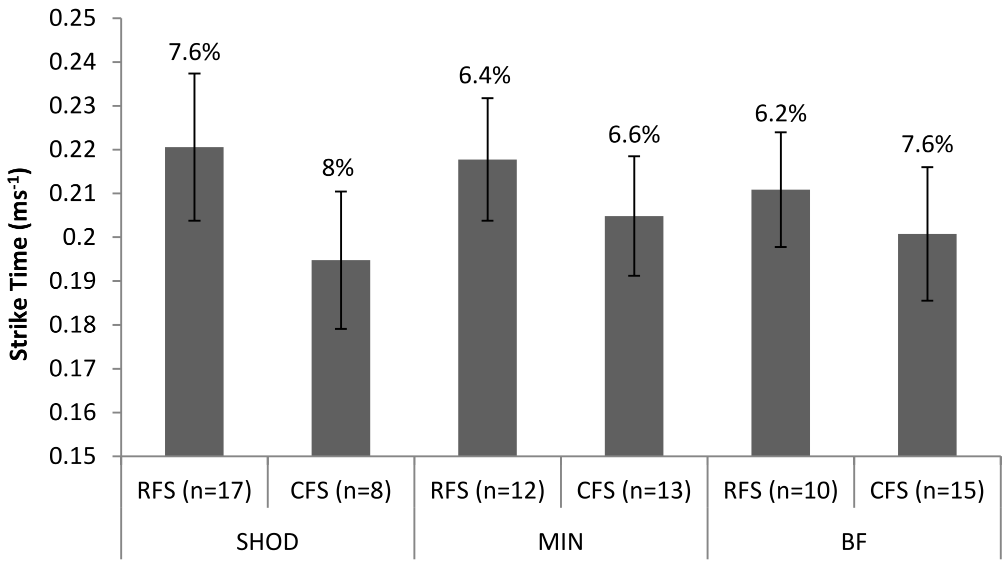

Figure 23: The influence of foot-strike patterns on strike time when running in the shod, minimalist and barefoot conditions, with CV percentages.

There was a reduction in strike time associated with a M/FF versus a RF strike for all three footwear conditions; however Figure 24 demonstrates that not all M/FF strikers' responses were less than the RFS responses obtained.

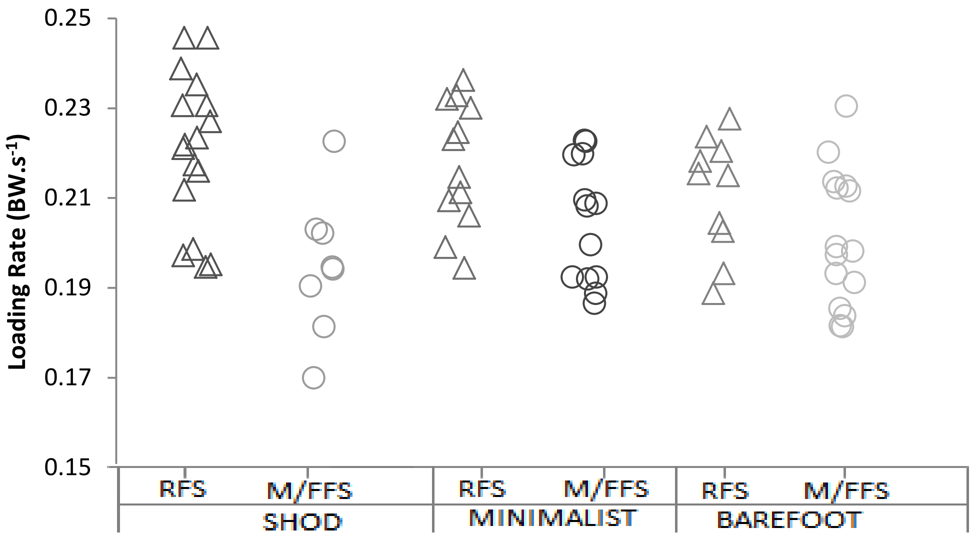

Figure 24: Individual strike time responses, when running with a rear-foot versus a combined foot-strike in the shod, minimalist and barefoot conditions.

PHYSIOLOGICAL PARAMETERS

The following physiological responses were recorded in this study: heart rate (HR), oxygen consumption ($\dot{V}O_2$), energy expenditure (EE) and electromyography (EMG). These were measured in order to accurately compare the participating endurance runners' physiological responses to each of the three different footwear conditions. These variables were assessed and compared, to determine the most energy efficient footwear condition, the impact of individual variability on these variables and factors which may contribute to a better running economy.

HEART RATE (HR)

Mean Data:

The footwear utilized was shown to have a statistically significant ($p=0.02$) impact on heart rate responses. More specifically it was found that running shod (175 ±13 $bt.min^{-1}$) demonstrated a higher heart rate than barefoot running (172 ±12 $bt.min^{-1}$). There were no further significant differences between footwear conditions with the minimalist condition (174 ±12 $bt.min^{-1}$) resulting in similar HR responses to both the shod and barefoot conditions (Figure 25). The effect size observed (0.15) indicates that other factors may be responsible for the significant difference observed.

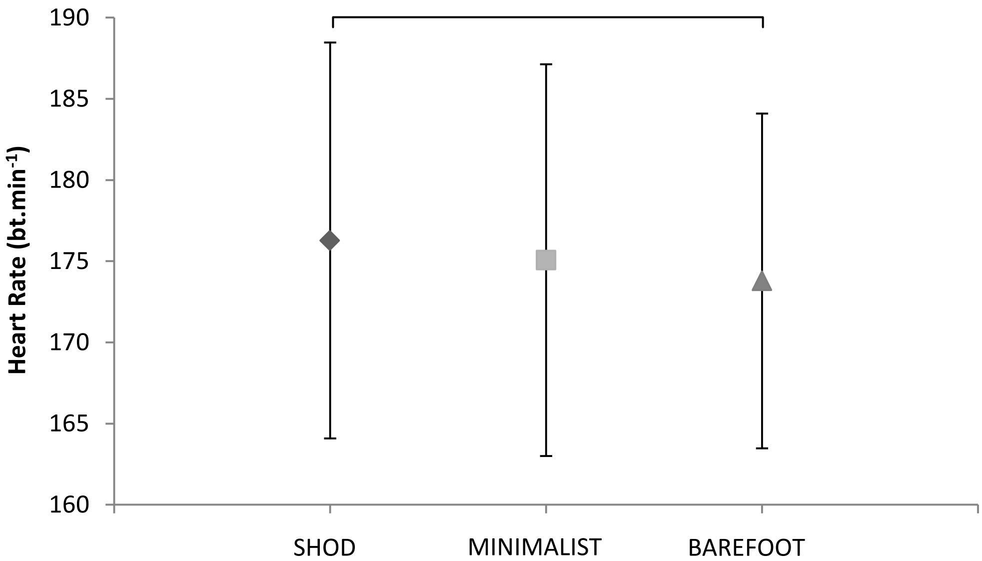

Figure 25: The mean (plus SD) heart rate responses between the shod, minimalist and barefoot conditions. (Brackets indicate statistical significance, $p<0.05$).

Individual Data:

The minimalist condition elicited a positive overall response (reduced HR: -1 ±4.9 $bt.min^{-1}$) in HR, while the barefoot condition experienced a significantly greater reduction of -3 ±4.9 $bt.min^{-1}$ (Figure 26). A large CV was found when participants ran in the minimalist condition versus shod (406%) as well as the barefoot condition versus shod (195%). A large variance is indicative that some participants benefitted greatly from running in these conditions, whilst other participants experienced large decrements.

The individual data shown in Figure 26 provides an indication of the small overall changes evident when switching footwear conditions. For example for the minimalist condition, 48% of participants experienced an increase in HR, while the remaining 52% had a reduction in HR. The barefoot condition showed more consistency, with 76% of individuals experiencing a reduction in HR and the remaining 24% experiencing a negative response. Whether participants responded positively or negatively, individuals experienced a range of responses, from strong positive or negative to weak positive or negative.

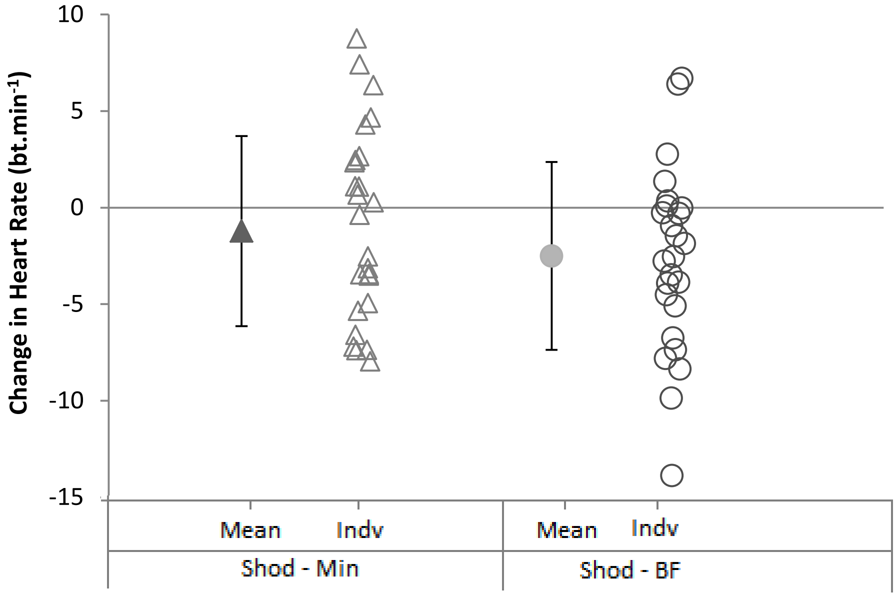

Figure 26: Mean (plus SD) and individual changes in heart rate responses when switching between the shod and minimalist or barefoot conditions.

Foot-strike Pattern:

Running with a RF or M/FF strike when shod elicited a similar HR (Figure 27); however running with a RF versus a M/FF strike in the minimalist and barefoot conditions, a 3.2 and 3.5% respective decrease was found. This is interesting as it suggests that the benefits of M/FFS are not evident when shod, but this helps markedly for the minimalist and barefoot conditions.

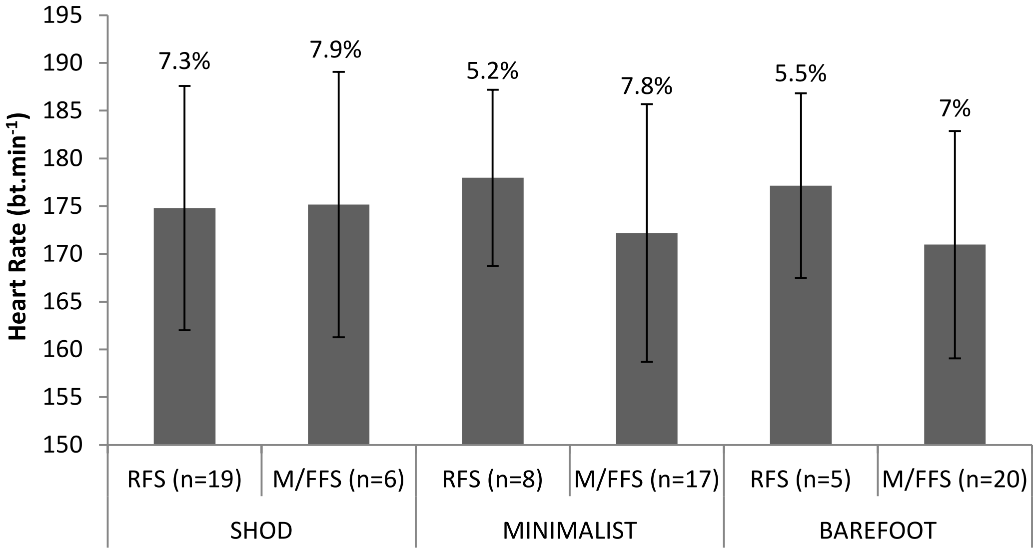

Figure 27: Heart rate responses for different foot-strike patterns when running shod, in minimalist footwear or barefoot, with CV percentages.

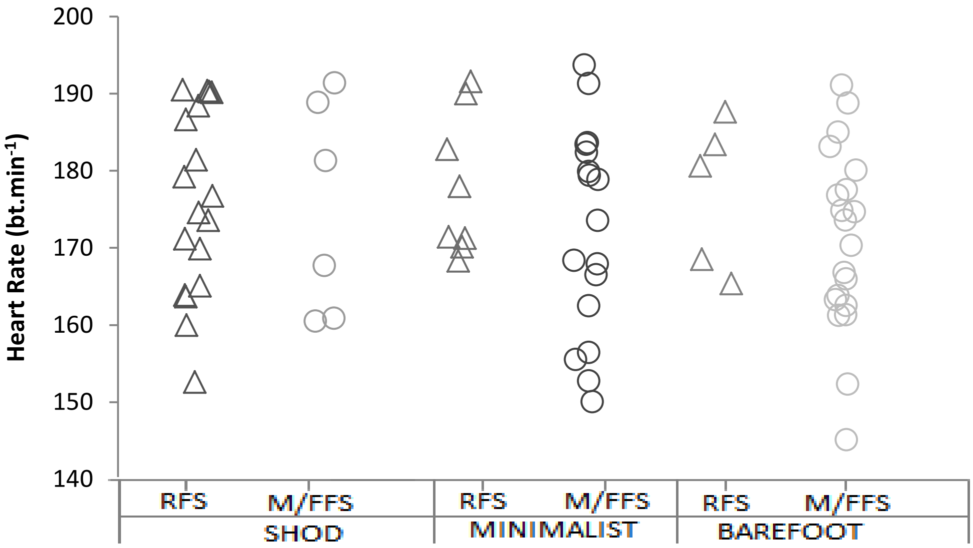

Figure 28: Individual heart rate responses, when running with a rear-foot strike versus a combined foot-strike pattern in the shod, minimalist and barefoot footwear conditions.

The use of a RFS when running in the minimalist and barefoot conditions appeared to result in relatively consistent (and relatively high) individual responses (Figure 28), while the use of a M/FFS resulted in less consistent responses (with some individuals experiencing high and some low). Therefore running with a M/FFS, there appeared to be a number of responders (that experienced positive responses) as well as non-responders (that experienced negative changes).

OXYGEN CONSUMPTION ($\dot{V}O_2$) AND ENERGY EXPENDITURE (EE)

Oxygen consumption rates were recorded using the MetaLyser™, a portable ergospirometer unit. Energy expenditure results were calculated via indirect calorimetry, and were therefore similar to the $\dot{V}O_2$ responses presented below with no statistically significant differences observed.

Mean Data:

There was no statistically significant ($p<0.05$) difference found between the three footwear conditions (Figure 29), with similar rates found ranging between 48.64 and 49.46 mL.kg.min^{-1}. One individual had a consistently greater $\dot{V}O_2$ rate in each footwear condition, while the rest of the individual responses were more normally distributed.

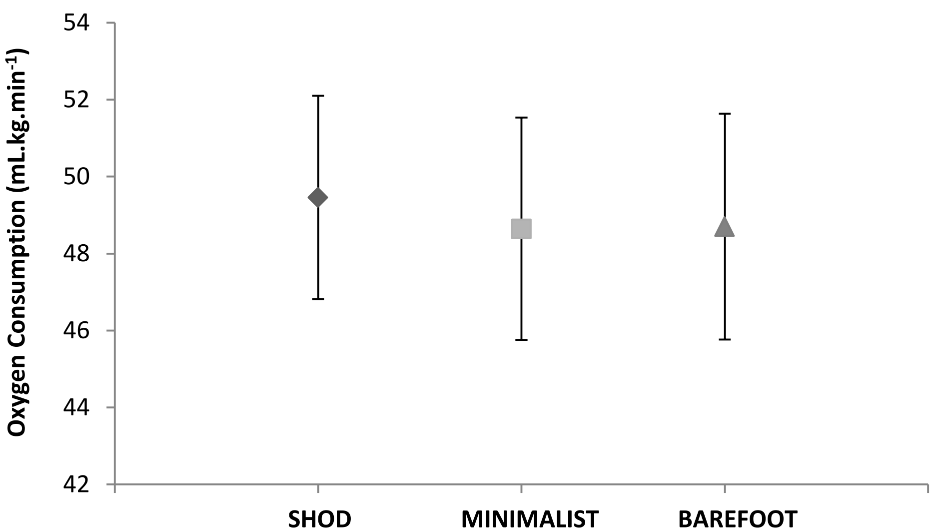

Figure 29: The mean (plus SD) and individual oxygen consumption responses between the shod, minimalist and barefoot conditions.

Individual Data:

Switching to minimalist or barefoot running resulted in only very small changes in the oxygen consumption responses. However, Figure 30 demonstrates that for both barefoot and minimalist running there were definitive responders and non-responders.

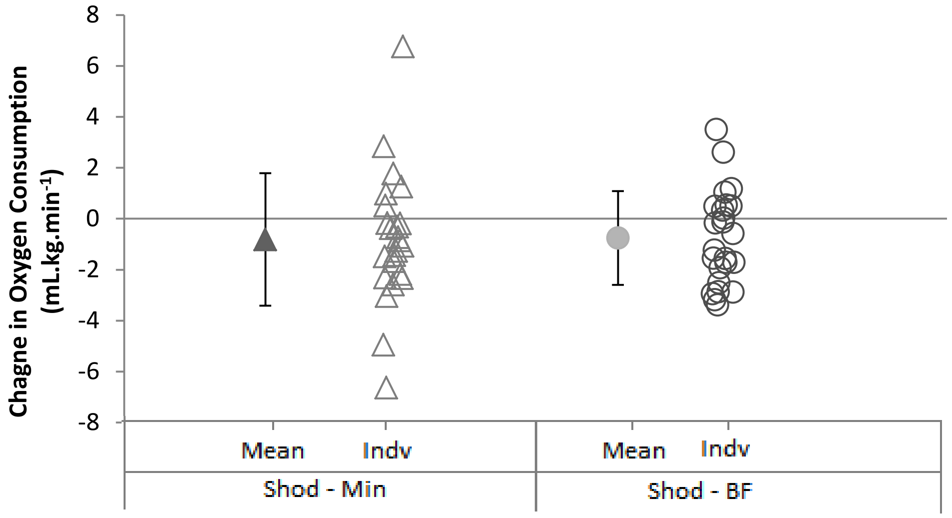

Figure 30: The mean (plus SD) and individual changes in oxygen consumption rates (mL.kg.min^{-1}) when switching from shod to minimalist or barefoot running.

Running in the minimalist footwear a large range of responses were seen, with some participants reducing oxygen consumption by as much as 6.6 mL.kg.min^{-1} and others increasing this by as much as 6.8 mL.kg.min^{-1}. In total 19 participants showed a reduction in oxygen consumption. Contrastingly a smaller range of responses (6.9 mL.kg.min^{-1}) was experienced for the barefoot condition, with participants experiencing much smaller increases and decreases in comparison to the minimalist condition. There were 18 participants that experienced a reduction in oxygen consumption when running barefoot.

Foot-strike Pattern:

Running with a M/FFS versus a RFS was found to reduce the $\dot{V}O_2$ rate in all footwear conditions (Figure 31). This reduction in $\dot{V}O_2$ was 5.1% when shod, 4.2% for the minimalist condition and 3.1% running barefoot.

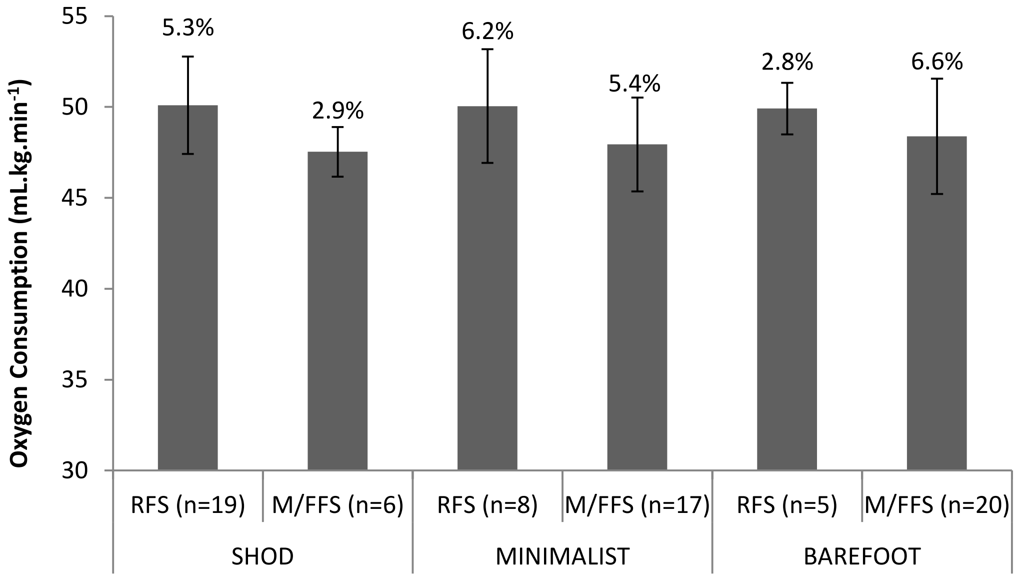

Figure 31: Oxygen consumption rates related to foot-strike pattern utilized under the three footwear conditions, with co-efficient of variation percentages (above each bar).

There was an increase in the number of participants that ran with a with a M/FFS for the minimalist and barefoot conditions (Figure 32), resulting in a switch from a high number of RF strikers when running shod to a high number of M/FF strikers when running barefoot.

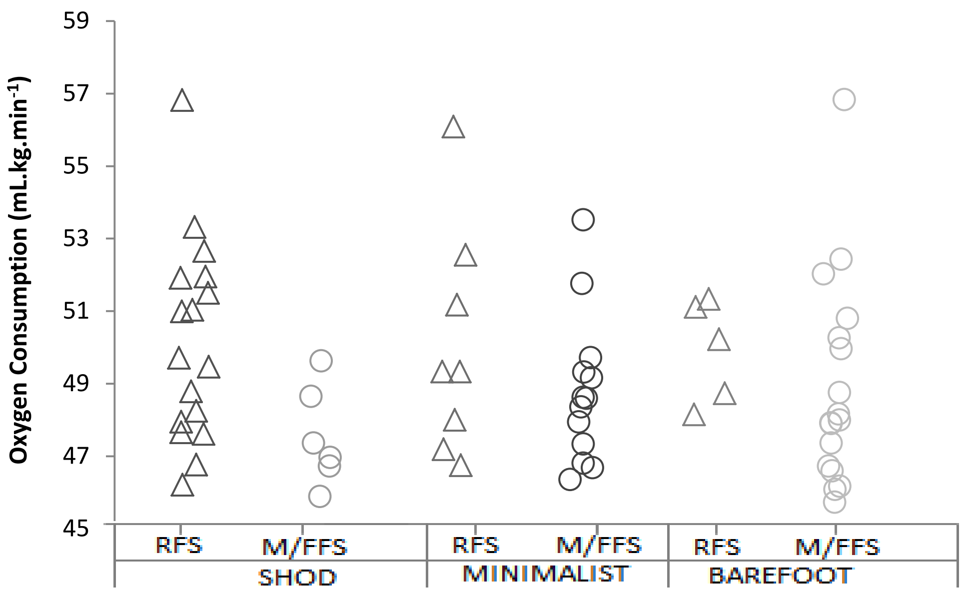

Figure 32: Individual oxygen consumption rates when running with a rear-foot versus a combined foot-strike pattern in the shod, minimalist and barefoot condition.

A correlation between shoe mass and oxygen consumption was completed. The correlations were 0.12 and 0.27 for the shod and minimalist conditions respectively.

ELECTROMYOGRAPHY (EMG)

Electromyography responses were obtained from four different pre-selected lower limb muscles, namely the Tibialis Anterior, Gastrocnemius, Vastus Medialis and Rectus Femoris.

<u>Mean Data:</u>

Running shod (0.1298 ±0.045 mV) resulted in a statistically significant ($p=0.005$) increase in activation (18.5%) of the Tibialis Anterior in comparison to running barefoot (0.1058 ±0.038 mV) as shown in Figure 33.

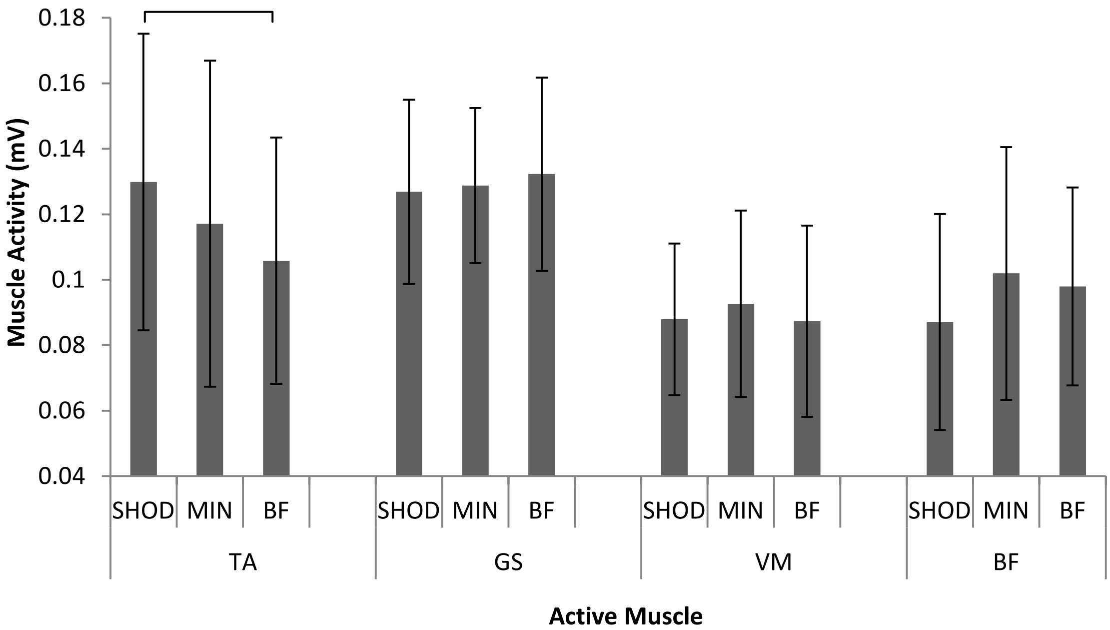

Figure 33: Mean muscle activity of the Tibialis Anterior, Gastrocnemius, Vastus Medialis and Biceps Femoris muscles when participants ran in the shod, minimalist and barefoot footwear conditions. (Brackets indicate statistical significance, $p<0.05$).

A very small effect size (0.194) was seen. A large variance was present when running under each condition; however this was greater for the minimalist condition as indicated by the CV values. The minimalist condition had a CV of 43.8% versus 34.9 and 35.5% for the shod and barefoot conditions respectively.

The Gastrocnemius, Vastus Medialis and Biceps Femoris were found to have no statistically significant differences, however changes of interest are presented here. The Gastrocnemius did however experience a 1.5 (minimalist) and 4.1% (barefoot) increase in activation compared to running shod. Running in the minimalist condition increased activation of the Vastus Medialis and Biceps Femoris muscles by 5.1 and 14.6% respectively, while the barefoot condition elicited the smallest activation of the Vastus Medialis muscle (0.087 ±0.029 mV) and a 4% higher activation of the Biceps Femoris muscle versus the shod condition.

Individual Data:

Tibialis Anterior - a mean reduction in activation (positive response) of -0.017 (±0.034) and -0.024 (±0.032) mV was experienced as participants switched from shod to minimalist and barefoot running respectively (Figure 34).

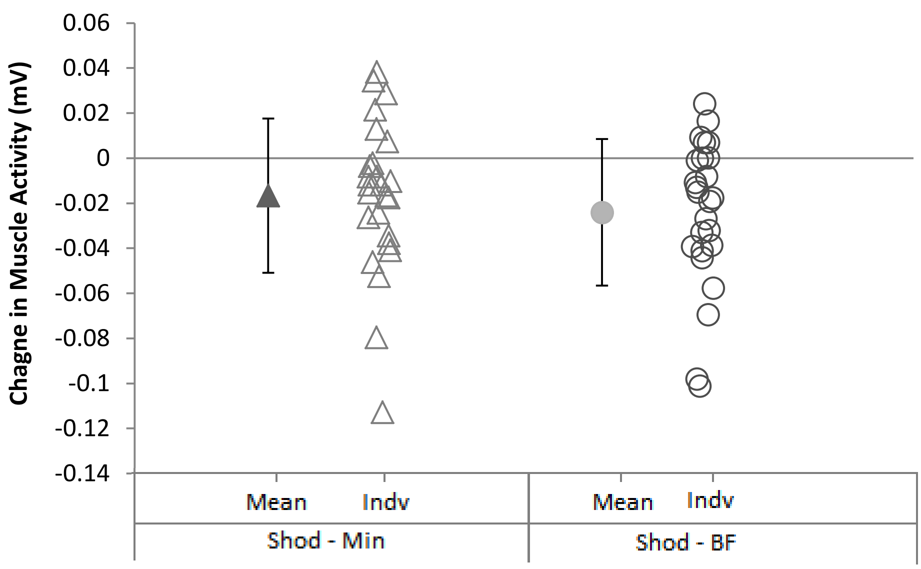

Figure 34: Mean (plus SD) and individual change in Tibialis Anterior muscle activity when switching from shod to minimalist or barefoot running.

The minimalist (206%) and barefoot (135%) conditions experienced a large variance in responses (comparably larger for the minimalist condition), demonstrating that participants experienced both large increases and decreases in activation. There were a number of participants (six) that when running in the minimalist and barefoot conditions these individuals experienced an increase activation (negative response), in contrast to the average finding.

Gastrocnemius - a small increase (positive response) in average Gastrocnemius activity was found as participants switched to both the minimalist (0.004 ±0.019 mV) and barefoot (0.005 ±0.016 mV) conditions (Figure 35). Large CV values were again seen, as seen for the Tibialis Anterior.

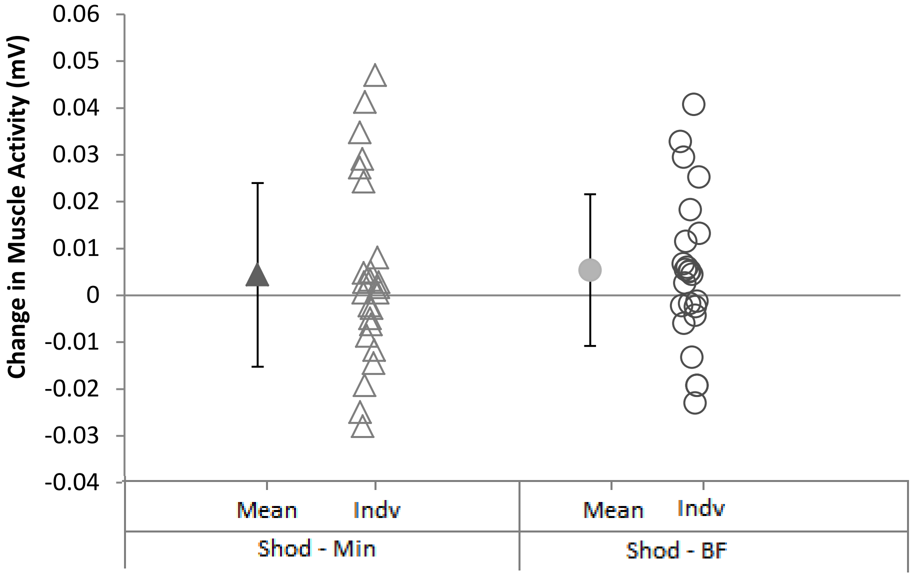

Figure 35: Mean (plus SD) and individual change in Gastrocnemius muscle activity when switching from shod to minimalist or barefoot running.

Individuals were once again found to responded both positively and negatively to the minimalist and barefoot conditions, with some participants reducing muscle activity by -0.028 mV and others increasing this by +0.047 mV when running in the minimalist condition. This was similar the barefoot condition.

Vastus Medialis - switching from shod to minimalist running, an overall increase in muscle activity (negative response) by +0.005 ±0.022 mV was found (Figure 36). Running barefoot as versus shod, the opposite was found, with an overall reduction (positive response) of muscle activity of -0.001 (±0.022) mV. Both conditions experienced a large variance; however this was significantly greater in the barefoot condition (465 versus 3933%).

Close to half of individuals (47.8%) experienced similar responses to the mean when running in the minimalist footwear, with the remaining half (52.2%) experiencing positive responses. This was very similar for the barefoot condition with 43.5% of participants responding negatively and 56.5% responding positively.

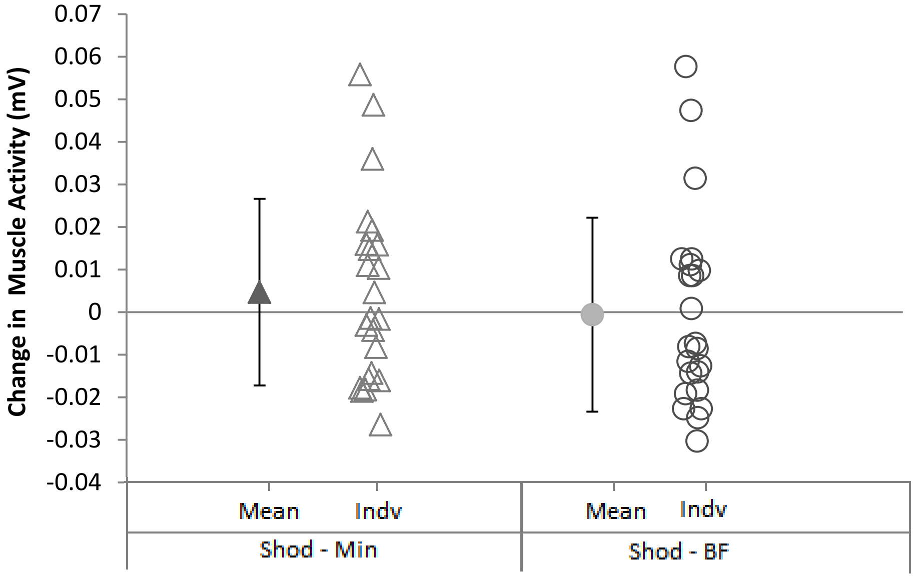

Figure 36: Mean (plus SD) and individual change in Vastus Medialis muscle activity when switching from shod to minimalist or barefoot running.

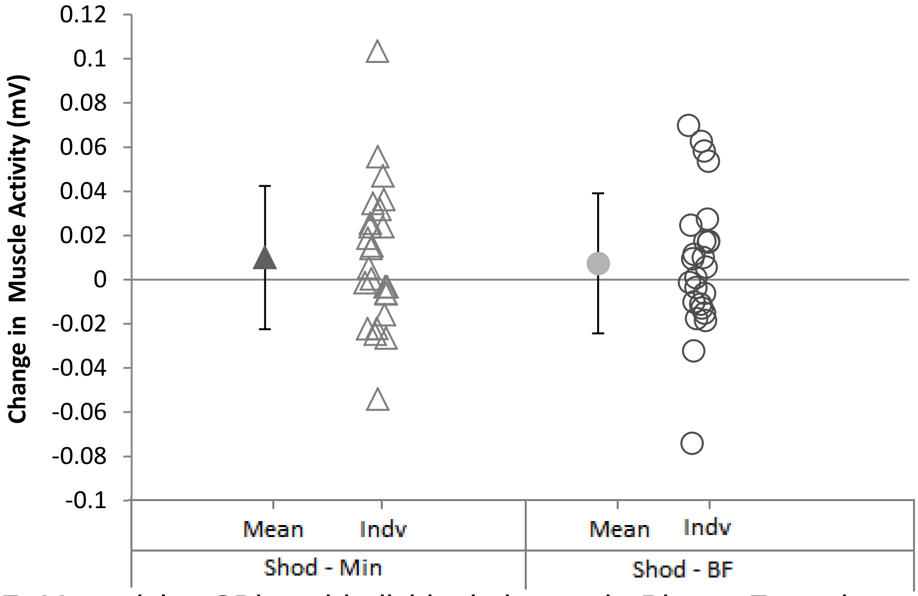

Figure 37: Mean (plus SD) and individual change in Biceps Femoris muscle activity when switching from shod to minimalist or barefoot running.

Biceps Femoris **-** there was 26.6% larger increase in muscle activity when switching from the shod to minimalist versus shod to barefoot condition (Figure 37). As with the other muscles, a large variance was observed, with CV values of 325 and 432% for the minimalist and barefoot conditions respectively. Running in both the minimalist and barefoot conditions, 14 individuals were found to respond negatively and the remaining 11 positively. Negative responses in the minimalist condition ranged from a small increase in activation of +0.005 mV to large increases of +0.103 mV. A similar range of responses was observed for the positive responders.

Foot-strike Pattern:

The use of a M/FF strike resulted in a reduced activation of the Tibialis Anterior and an increase in Gastrocnemius activity, regardless of the footwear condition (Figure 38).

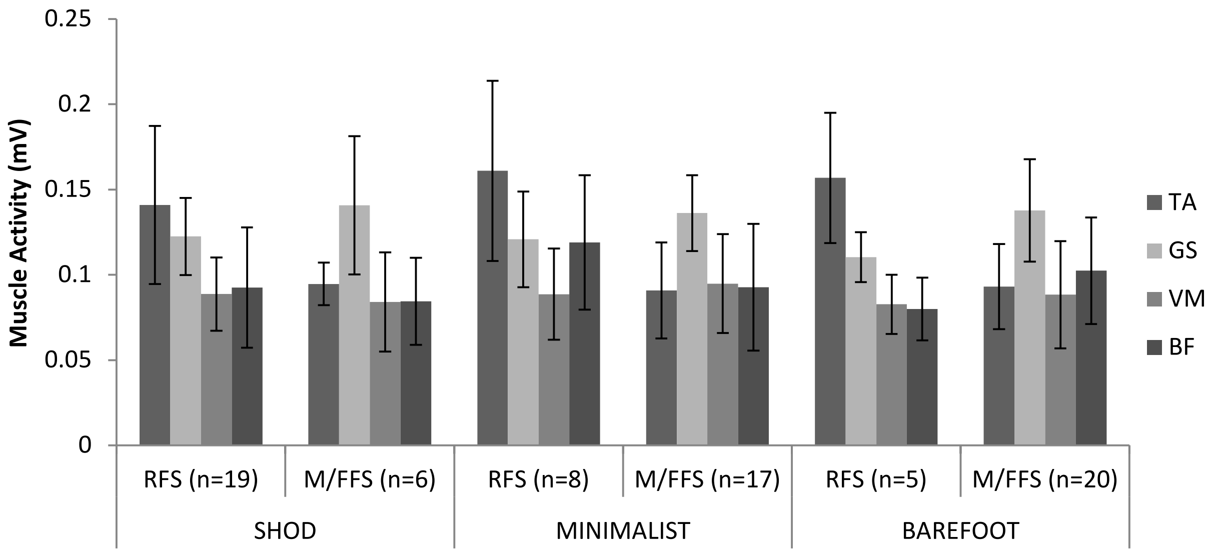

Figure 38: Mean muscle activity for participants running with a rear-foot or a combined foot-strike pattern.

The use of a M/FFS versus a RFS when running shod resulted in a 5.3% smaller activation of the Vastus Medialis muscle; however for the minimalist and barefoot conditions this foot-strike resulted in a 6.9% increase in activation. A reduced activation of the Biceps Femoris was found running the shod and minimalist conditions with a M/FFS versus a RFS, while a small increase was evident when running barefoot.

The Tibialis Anterior muscle, Figure 39, showed a large variance in responses when running with a RFS for the shod and minimalist conditions, with CV values of 32.9 (shod RFS), 32.9 (min RFS). In the barefoot condition, the M/FFS showed a greater variance with a CV of 26.8 versus 24.3% using a RFS. A lower activity level in each of the footwear conditions was associated with a M/FFS; however some RF striking individuals had smaller activity levels than some individuals that used a M/FFS.

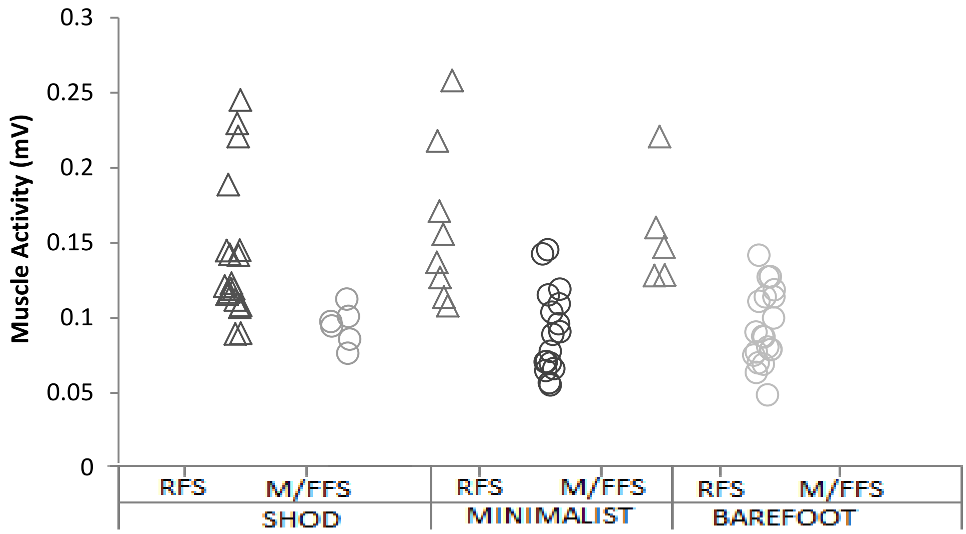

Figure 39: Individual muscle activity responses for the Tibialis Anterior, foot-strike dependant, when running the three experimental footwear conditions.

PERCEPTUAL PARAMETERS

Two perceptual measures were recorded in the current study, namely Rating of Perceived Exertion (both central and local) as well as Body Discomfort. These measures were recorded to determine whether participants perceived any biomechanical and physiological changes (if present) when switching between the footwear conditions and whether these perceptions differ between individuals.

RATING OF PERCEIVED EXERTION (RPE)

Mean Data:

Central - no statistically significant difference in central RPE was found between the three footwear conditions (Figure 40). The shod condition experienced the highest central RPE at 11.84 (±2.2) versus the lowest when running minimalist (11.64 ±2.1). The barefoot condition had a rating of 11.72 (±2.5). While overall ratings were similar, large CV values were found for conditions; this was 21.1% when running barefoot, 17.9% running in the minimalist footwear and 18.8% for the shod condition.

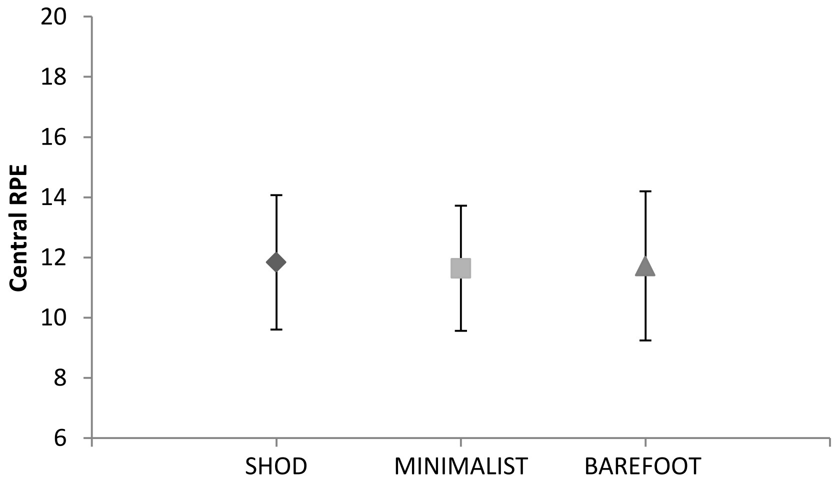

Figure 40: Mean (plus SD) central rating of perceived exertion responses between the shod, minimalist and barefoot conditions.

Individual Data:

Overall, a reduction in central RPE (positive response) occurred when participants ran with the minimalist (-0.2 ±1.58) and barefoot (-0.12 ±1.48) conditions versus shod (Figure 41). Large CV values of 1234 and 791% were found as participants switched from the shod to minimalist and barefoot conditions respectively.

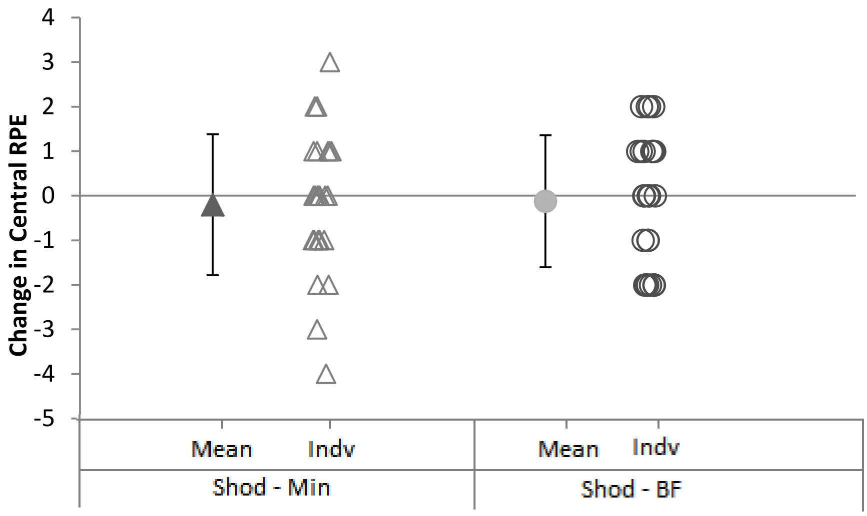

Figure 41: Mean (plus SD) and individual changes in central rating of perceived exertion as participants switched from shod to minimalist and barefoot running.

The average response to minimalist or barefoot running was a reduction; however only ten participants (40%) experienced this, with the remaining individuals experiencing an unchanged rating (seven/five) or an increased rating (eight/ten).

Local – it is evident in Figure 42, that no statistically significant ($p<0.05$) difference was found between the local RPE responses, with the barefoot condition (11.84 ±2.4) experiencing a 4.2% higher rating than the minimalist condition (11.36 ±2.5). Moderate CV values of 21.3, 21.7 and 20.1% were found when running shod, minimalist and barefoot respectively.

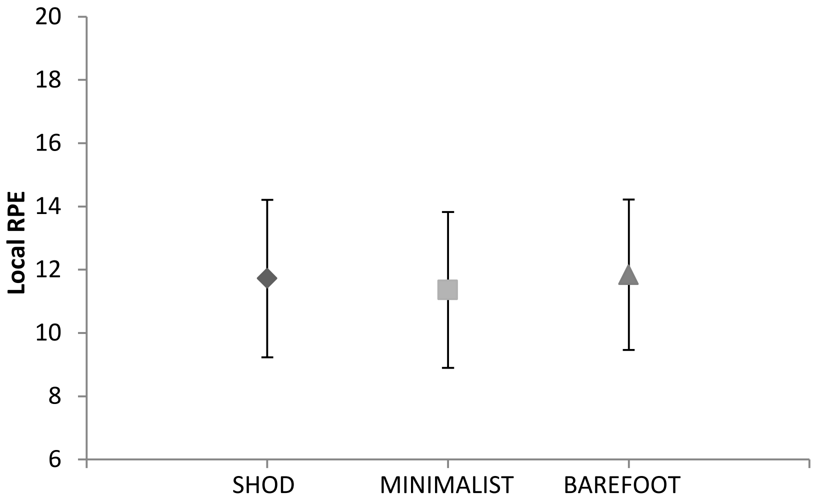

Figure 42: Mean (plus SD) local rating of perceived exertion responses between the shod, minimalist and barefoot conditions.

<u>Individual Data:</u>

The average response was a reduction (positive response: -0.36 ±2.27) in local RPE, running in the minimalist versus shod condition (Figure 43), while running barefoot versus shod resulted in an increase (negative response: 0.12 ±1.09). The observed responses displayed no consistency in responses, with large CV seen.

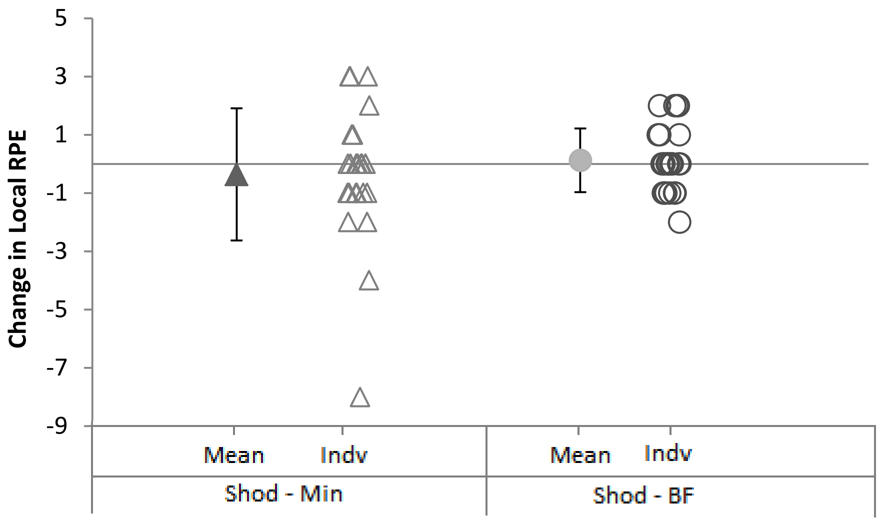

Figure 43: Mean (plus SD) and individual changes in local rating of perceived exertion when switching from shod to minimalist and barefoot running.

Nine individuals experienced an unchanged local RPE and six experienced a negative response switching from shod to minimalist running, which was in contrast to an overall positive response observed. This was similar for the barefoot condition, where an overall negative response was found, yet eleven participants experienced an unchanged rating and seven a positive rating.

Foot-strike Pattern:

Central - a small reduction of 5.6, 1.4 and 2.9% was seen when running shod, minimalist or barefoot with a M/FFS versus a RFS (Figure 44). All conditions showed a large variance, with the greatest CV for the RF strikers when barefoot (31.2%) which was close to double that experienced in some conditions.

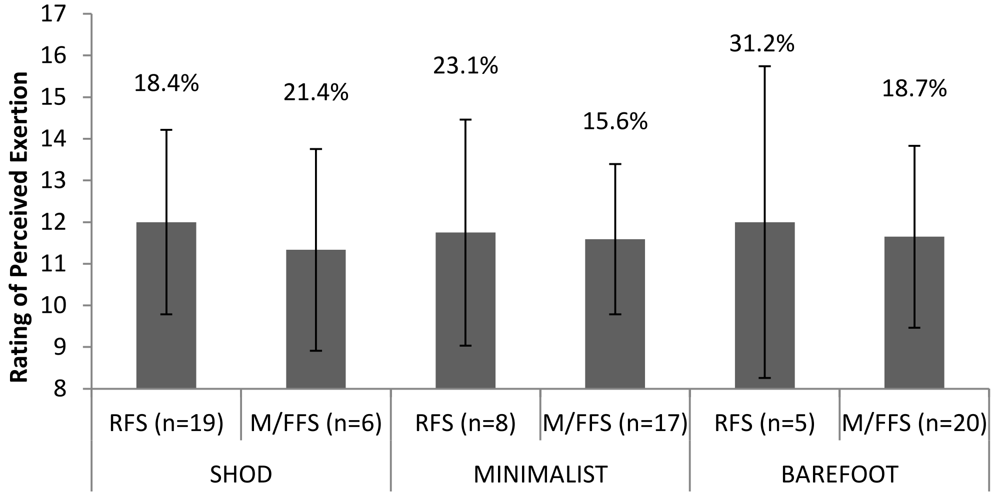

Figure 44: Central RPE responses in relation to the foot-strike pattern employed under each of the experimental footwear conditions.

Local - a RFS was found to elicit a much larger local RPE response under all footwear conditions (Figure 45). The M/FFS resulted in a 6.1, 10.7 and 12.9% decrease compared to the RFS for the shod, minimalist and barefoot condition respectively. Large CV values were again present.

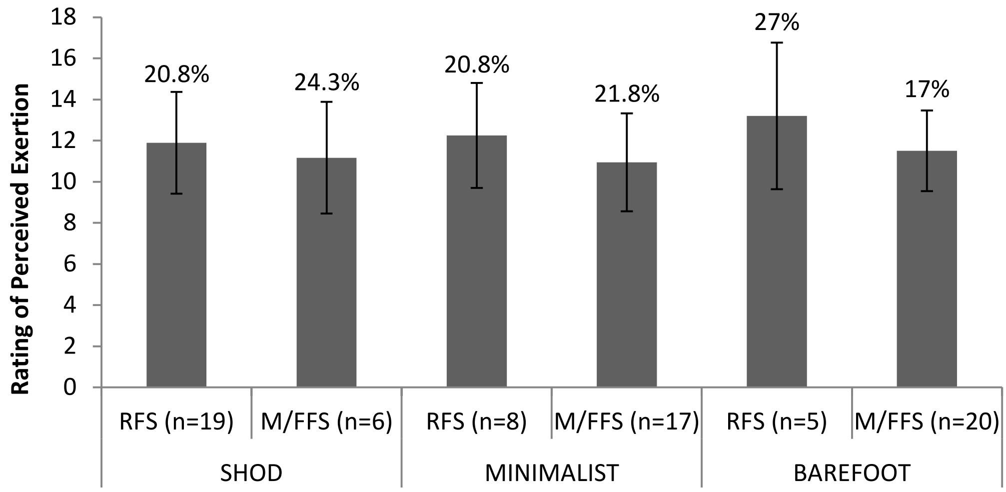

Figure 45: Local RPE responses in relation to the foot-strike pattern employed under each of the experimental footwear conditions.

BODY DISCOMFORT (BD)

An increased discomfort level was experienced at the level of the knee running in the minimalist condition versus both the shod and barefoot conditions (Figures 46, 47 and 48). The barefoot condition reported no discomfort scores for the knee. There was an increase in calf discomfort for the barefoot condition.

Interestingly, the shod condition recorded the highest discomfort at the level of the ankle and foot compared to the minimalist and barefoot conditions. The upper limbs, on the posterior side, showed a predominance of discomfort in the shod condition, with only one discomfort rating in the minimalist condition.

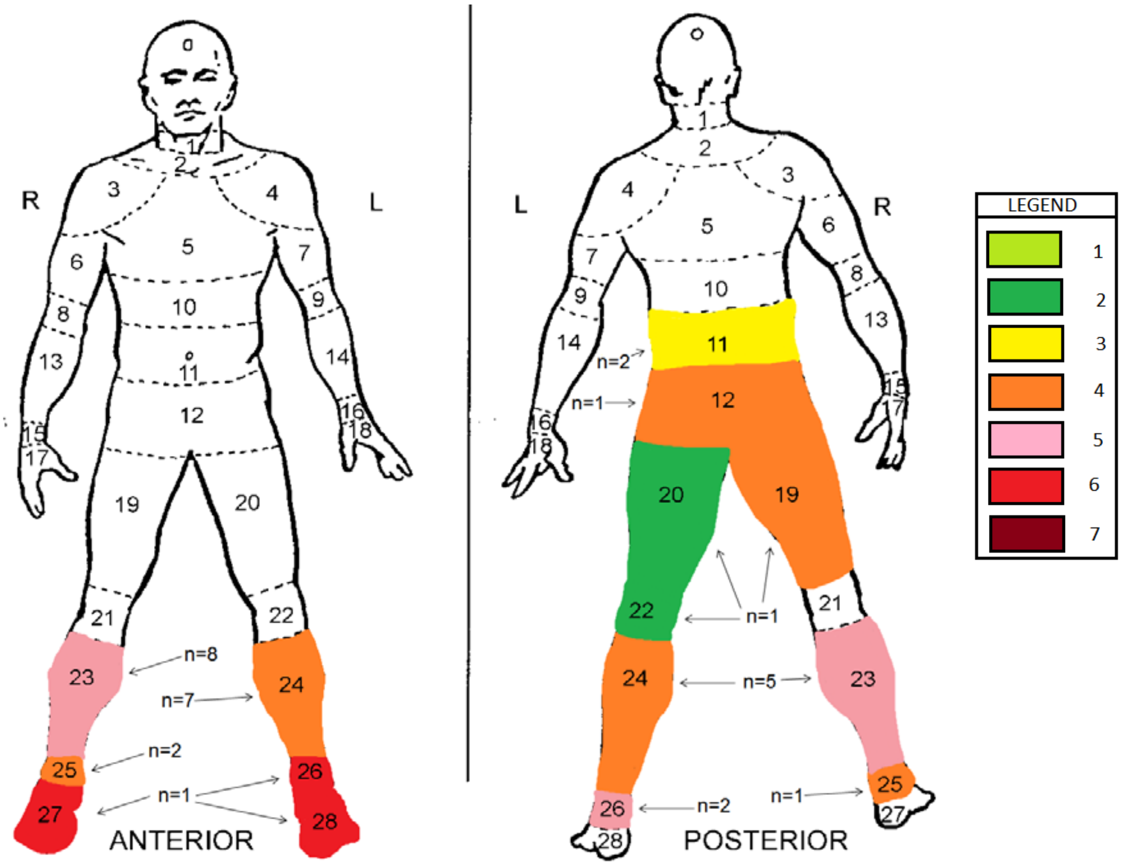

Figure 46: Rating of Body Discomfort for the shod condition.

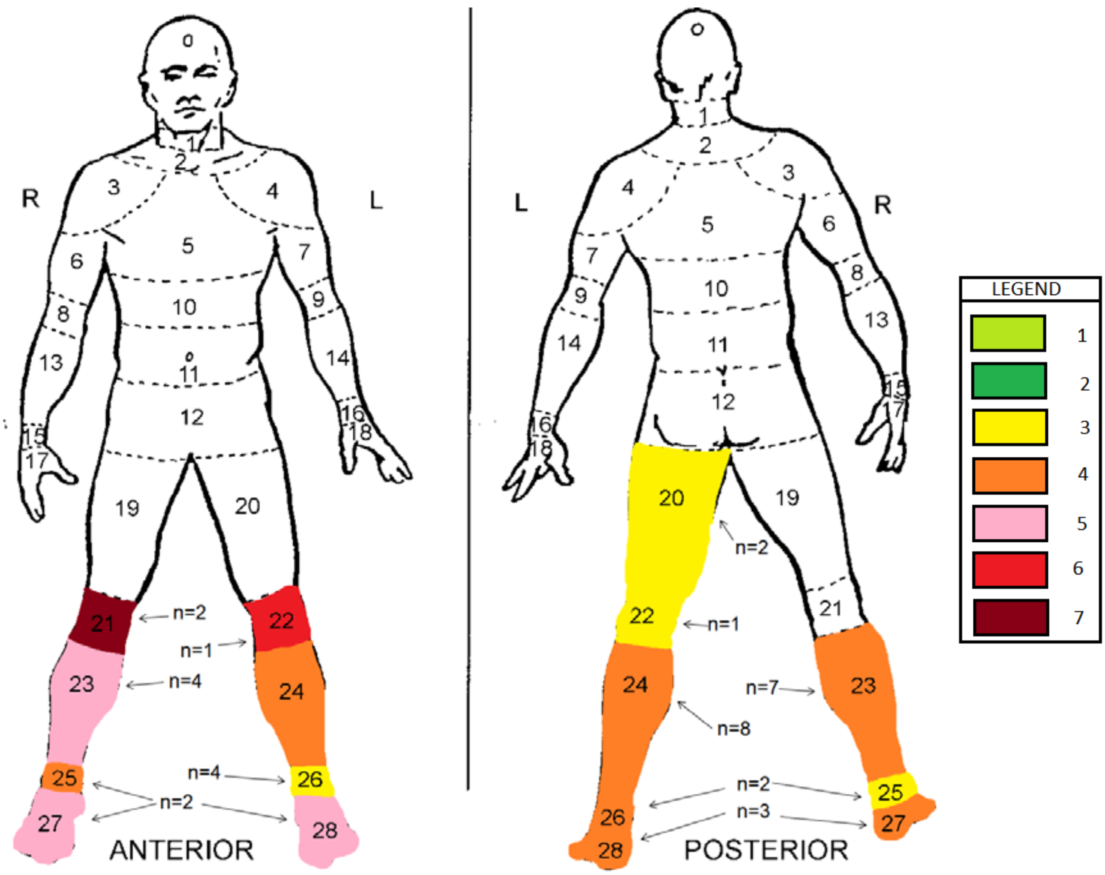

Figure 47: Rating of Body Discomfort for the minimalist condition.

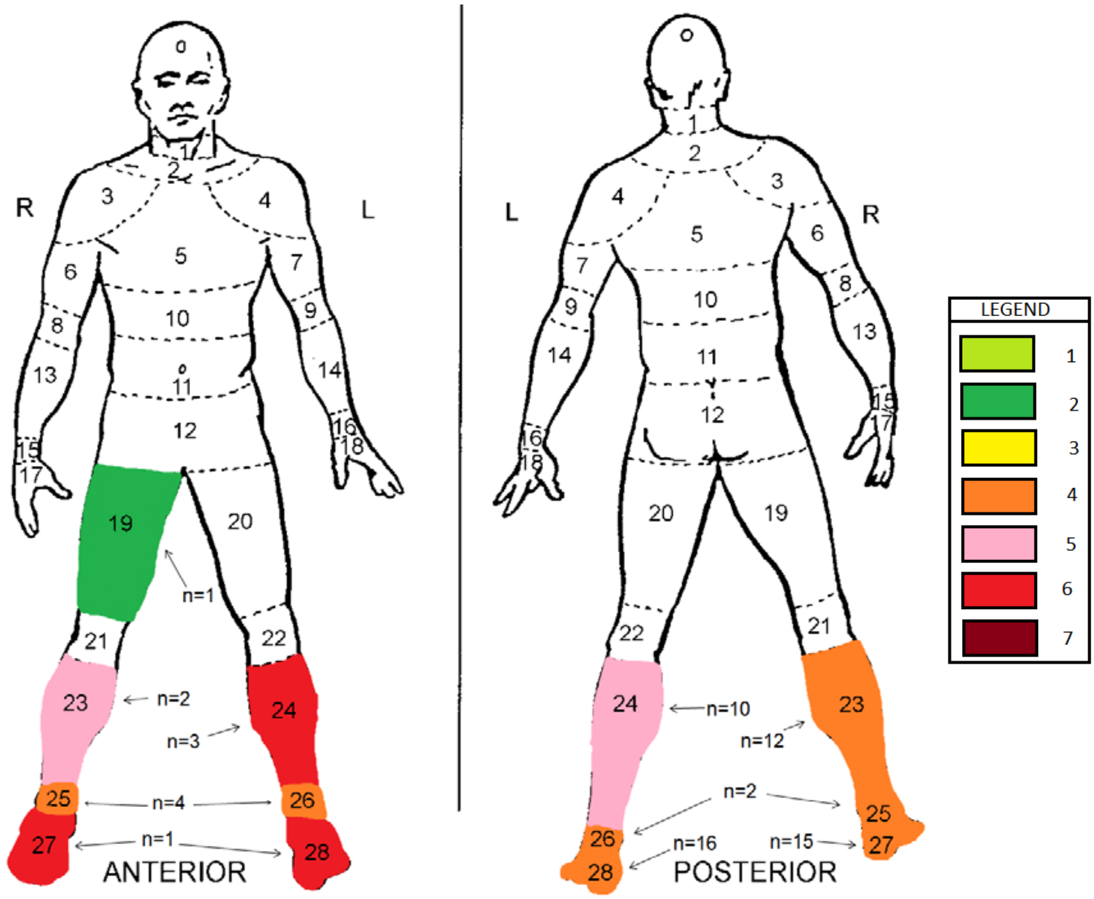

Figure 48: Rating of Body Discomfort for the barefoot condition.

SUMMARY OF RESULTS

Table VII: Summary of mean biomechanical, physiological and perceptual variables.

	Biomechanical data		
Variable	**Shod**	**Minimalist**	**Barefoot**
Stride Rate ($st.min^{-1}$)	179 (±10.12)	183 (±11.36)	188 (±11.05)
Stride Length (m)	2.80 (±0.15)	2.75 (±0.17)	2.67 (±0.15)
Impact Peak (BW)	1.79 (±0.67)	1.75 (±0.87)	2.08 (±0.80)
Vertical Impact Loading Rate ($BW.s^{-1}$)	70.5 (±27.40)	99.4 (±61.58)	173.5 (±104.52)
Vertical Average Loading Rate ($BW.s^{-1}$)	30.26 (±7.57)	30.23 (±5.49)	30.54 (±5.29)
Strike Time (ms^{-1})	0.212 (±0.020)	0.211 (±0.015)	0.205 (±0.015)
	Physiological data		
Heart Rate ($bt.min^{-1}$)	176 (±12.19)	175 (±12.06)	174 (±10.31)
Oxygen Consumption ($mL.kg.min^{-1}$)	49.46 (±2.64)	48.64 (±2.89)	48.70 (±2.94)
Electromyography (mV)	TA: 0.129 (±0.045) GS: 0.127 (±0.028) VM: 0.087 (±0.023) BF: 0.091 (±0.033)	TA: 0.113 (±0.049) GS: 0.131 (±0.025) VM: 0.093 (±0.028) BF: 0.101 (±0.039)	TA: 0.106 (±0.038) GS: 0.132 (±0.029) VM: 0.092 (±0.038) BF: 0.098 (±0.030)
	Perceptual data		
Central RPE (6-20)	11.84 (±2.23)	11.64 (±2.08)	11.72 (±2.48)
Local RPE (6-20)	11.72 (±2.49)	11.36 (±2.46)	11.84 (±2.37)

CONCLUSION

The completion of the various running protocols requiring the use of three different footwear conditions resulted in a number of biomechanical, physiological and perceptual changes. There were significant differences in SR and SL responses between the shod, minimalist and barefoot conditions, highlighting the impact that footwear has on running form (Table VII). Significant differences in the VILR and strike time between these three footwear conditions was also found. Such factors are proposed to contribute significantly to the causation of injuries and running performance, and are hence of extreme importance. The physiological difference between the shod, minimalist and barefoot conditions was found to be very similar, except for the HR elicited between the shod and barefoot condition. The perceptual measures, rating of perceived exertion and body discomfort, exhibited similar responses between the footwear conditions. The mean data in the current study highlighted a few significant changes, however the analysis of individual data revealed a wealth a variability between individuals for all variables compared. The findings of the current study highlight the importance of individual variability and the important role footwear plays in the prevention of injury and performance enhancement.

CHAPTER V

DISCUSSION

INTRODUCTION

The following chapter will relate the findings of the current study to the relevant (comparable) literature available and discuss the implications of these findings to endurance runners.

BIOMECHANICS

GAIT ANALYSIS: STRIDE RATE (SR) AND STRIDE LENGTH (SL)

<u>Mean Data:</u>

Stride rate and stride length are biomechanical variables which are inherently interlinked, with an increase in stride rate associated with a reduction in stride length. The current study found a statistically significant increase in stride rate as participants switched from the shod to both minimalist and barefoot conditions. Consequently a significantly reduced stride length was experienced when participants ran barefoot versus shod. Numerous authors (De Wit *et al*., 2000; Divert *et al*., 2005; Squadrone and Gallozzi, 2009; Bonacci *et al*., 2013 and Moore, Jones and Dixon, 2014) have found similar responses in a variety of contexts. Furthermore the extent of the increase in stride length (4.3%) was similar to the range of 3.3 to 6% found by Kerrigan *et al*. (2009) and Franz *et al*. (2012) for switching to barefoot running.

An intermediate stride rate and stride length was found for the minimalist condition in comparison to the shod and barefoot conditions, similar to the findings of Squadrone and Gallozzi (2009). A 2.2% higher stride rate running in the minimalist condition compared to the shod condition, shows a similar increase to the 2.7% found by Warne and Warrington (2014).

A statistically significant difference in stride rate and length parameters between the minimalist and barefoot conditions suggests that the argument put forward by a number of authors (Bootier, 2012; Bonacci *et al*., 2013; Tung *et al*., 2014), that minimalist running mimics barefoot running, did not hold true in the current study. Due to the findings of the current study it could be tentatively concluded that minimalist running does not mimic barefoot running as far as stride rate and stride length are concerned. Furthermore it is important to note that it does result in differences to shod running, and therefore should not be considered simply as different 'shod' condition but may have merits/concerns of its own.

The change in running form or biomechanical adjustment of an increase in stride rate and subsequent reduction in stride length, has previously been proposed to reduce both impact and braking forces (Divert *et al*., 2005a; van Gent *et al*., 2007) as well as joint moments at the hip and knee joints (Altman and Davis, 2012). Such forces have been associated with an increase in running injuries (Divert *et al*., 2005a; van Gent *et al*., 2007). Chumanov *et al*. (2012) found that this adjustment (increased stride rate and reduced stride length) may be of particular benefit to sufferers of anterior knee pain. More recently Willson *et al*. (2014) found a direct relationship between stride length and patella-femoral joint loads, with an increase in stride rate and shortening of stride length resulting in a reduction of patella-femoral joint loads. The positive responses associated with these adjustments, have the potential to reduce and prevent running injuries; however not all individuals over-stride in shoes. It is these individuals (over-striders), which may benefit the most from such changes in running form associated with the minimalist and barefoot conditions. In the current study it was found that a large percentage of participants in the minimalist condition and all barefoot runners experienced this proposed positive change, which is speculated to result in a positive change (reduction in injury risk) for all individuals.

<u>Individual Data:</u>

In 2010, Logan *et al.* published a running based paper in which they found a high variability within groups of participants. These authors concluded that analysing participants individually could help to strengthen running based conclusions. This particular study did not however assess individuals. No other studies have since been published investigating individual variability (to the authors' knowledge); however recently the concept of responders and non-responders has been introduced. This concept was first used (to the authors' knowledge) in a non-running related study by Mann *et al*.(2014). The first running based paper to recognize the importance of individual variance (ultimately the underlying concept of responders versus non-responders) was the recent paper by Tam *et al*. (2014)**.** None of the abovementioned studies have actually assessed or compared individual responses, and as such the current study undertook not only to investigate the average data, but also to interrogate individual data. Such an analysis allows for further investigation into the concept of 'responders' in the context of barefoot and minimalist running. This is presented below.

There is a scarcity of data comparing individual stride rate and stride length responses to the shod, minimalist and barefoot conditions. The current study conducted such a comparison and found some interesting findings, with all individuals experiencing an increase in stride rate when running barefoot versus shod (Table VIII). This indicates that barefoot running may promote a good running form in most individuals (and in the case of the current study, all individuals).

Table VIII. The number of responders and non-responders for each biomechanical variable when transitioning from shod to minimalist and barefoot running.

	Stride Rate	Stride Length	Impact Peak	VILR	VALR	Strike Time
	SHOD TO MINIMALIST					
Mean Response	+	+	+	-	+	-
Responders (+)	18	18	13	9	12	9
Non-responders (-)	3	3	12	16	13	15
No Change	4	4	0	0	0	1
	SHOD TO BAREFOOT					
Mean Response	+	+	-	-	-	-
Responders (+)	25	25	7	5	10	5
Non-responders (-)	0	0	17	19	15	20
No Change	0	0	1	1	0	0

Running in the minimalist condition, the average response was an increase in stride rate; however not all individuals experienced an increase, with 12% of participants experiencing a reduction (negative response) in stride rate. These findings, provide support to the argument that not all individuals increase stride rate and reduce stride length (associated with better running form according to Divert *et al.* 2005a; van Gent *et al*. 2007 and Altman and Davis, 2012) when using minimalist running technology. Instead the specific individual's needs should therefore be taken into consideration, a concept which is supported, partially by the contention of authors such as Tam *et al.* (2014) who emphasise the importance of considering the individual.

The findings presented here have important practical implications, as recommendations made based on the mean data (for these variables of minimalist running) may not provide a true reflection of what is experienced by all participants. For example, if an individual already over-strides, the shift to minimalist running may exacerbate this problem (if this individual is one of those who respond negatively). Such findings provide support to the theory that individual responses should be considered when providing recommendations for a) the improvement of performance and b) the reduction of injury risk.

FORCE ANALYSIS: IMPACT PEAK (IP), VERTICAL IMPACT LOADING RATE (VILR), VERTICAL AVERAGE LOADING RATE (VALR) AND STRIKE TIME (ST)

<u>Mean Data:</u>

The impact peaks in the current study were found to differ from those found in previous studies by Squadrone and Gallozzi (2009), Lieberman *et al*. (2010) and Hamill *et al.* (2011). These studies found a significant reduction in impact peaks when participants ran barefoot versus shod, while the current study found non-significant changes under these conditions. These differences are partially explained due to the methodological inconsistencies between these studies and the current one. For example Lieberman *et al*. (2010) assessed five groups of runners, ranging from habitually shod to habitually unshod, while the current study used habitually shod runners only. These same authors used athletes that had faster running times than those recruited in the current study. However the purpose of the current study was to investigate the impact of switching to minimalist and barefoot running in recreational runners rather than elite or sub-elite athletes justify the methodological differences at this point. More elite athletes have been associated with a greater percentage of anterior foot-strikers (Hasegawa, Yamauchi, and Kraemer, 2007 and Larson *et al.* 2011). Furthermore, differences in foot-strike patterns between runners are likely to partially explain why differences were observed and will be discussed in detail later.

The impact peaks observed in the current study (1.7-2.1 BW) while running at $15km.h^{-1}$, were comparatively smaller than those observed by Lieberman *et al*. (2010) and Hatala *et al*. (2013), which approached 3-4 times body weight at higher endurance running speeds of 21.6 to $23.9km.h^{-1}$. Hamill *et al*. (2011) found that running at a speed of $14.485km.h^{-1}$; higher impact peaks were experienced versus running at $12.85km.h^{-1}$. This provides support to the argument that a faster running speed results in larger impact peaks and therefore the smaller impact peaks observed in the current study were likely to be due to the difference in experimental speeds between this study and those mentioned above. Hamill *et al*. (2011) used a similar running speed to the current study and a comparison revealed a smaller impact running shod in the current study (1.79 versus ±2 BW). The major difference was in the barefoot responses, with the current study experiencing much larger impacts when running in this condition (2.1 versus ±1.6 BW). A reduction in impact peaks has been associated with injury-free runners (Hreljac *et al.*, 2000).

As with the impact peaks there were no significant differences between the VALR between the three footwear conditions. The same has previously been found by Shih, Lin and Shiang (2013). Hamill *et al*. (2011) compared the vertical loading rate between barefoot and three shod conditions, and found a significantly reduced VLR for the barefoot versus shod conditions. Hamill *et al*. (2011) noted a shift in foot-strike pattern (to a mid-foot strike) when running barefoot, which was suggested to result in the decrease observed. The current study however experienced an increase with such a shift in foot-strike pattern, and therefore it is unclear as to why the current study and Shih *et al*. (2013) differs to that found by Hamill *et al*. (2011)**.**

Comparing VILR and strike time responses, a statistically significant difference was found between all three footwear conditions for strike time and between the barefoot and the two shod conditions for VILR. A negative response was found to both the minimalist and barefoot conditions (increased VILR); however this increase was significantly larger in the barefoot condition. Little comparative literature is available to compare the VILR responses to; however a prospective cohort study by Bredeweg *et al*. (2013) found that runners with higher loading rates were associated with a higher risk of injury. Furthermore Willson *et al*. (2014) proposed that the continued exposure to increased loading rates over time, may have detrimental effects on runners. The current findings therefore provide further insights into the impact of footwear on VILR responses.

Based on these findings, barefoot running appeared to expose runners to an increased injury risk, which was similar in the shod and minimalist conditions. It is however acknowledged that additional research is still needed to provide accurate and reflective recommendations for this variable, particularly the role it plays in injury causation and prevention.

Strike time responses were consistent with Squadrone and Gallozzi (2009) who found a significant reduction when running barefoot versus shod or minimalist. This adjustment in running form (a reduced strike time) has been associated with a higher risk of injury (Bredeweg *et al*., 2013) and a higher oxygen uptake (Michele and Merni, 2014). Using these studies as a reference, the average response for the barefoot condition appeared to expose all participants to a much greater injury risk in comparison to the shod or minimalist conditions. Recommendations based on these findings are speculative, and further comparable studies are needed to provide more accurate conclusions. Whether all individuals respond equally under these footwear conditions is unknown, and as such this was analysed and is discussed below.

<u>Individual Data:</u>

Nine and five individuals, switching to the minimalist and barefoot conditions respectively, experienced a reduction (positive response) in VILR (Table VI). Comparing these positive responders, it was found that a range of reductions were experienced, with some individuals decreasing VILR by as little as -3.81 $BW.s^{-1}$ and others by as much as -87.7 $BW.s^{-1}$. The same variability between individuals was found for the negative responders. It can be concluded that the degree to which individuals benefit from a reduced VILR is unequal and all positive responders cannot be assumed to respond equally. This was the same for negative responders - where some experienced small increases and others much larger decreases.

These findings question the validity of the use of average data to provide recommendations to the entire running population.

Foot-strike Patterns:

The influence of foot-strike patterns on various force variables has previously been conducted, with Kurz and Stergiou (2004), Lieberman *et al*. (2010) and Hatala *et al*. (2013) concluding that barefoot running with the use of a FFS, generates impact forces at collision which are much smaller than those experienced when running shod with a RFS. The current study supports these findings with the use of a RFS (under all footwear conditions) resulting in a greater impact peak on average than those experienced when running with a M/FFS. Minimalist and barefoot runners experienced greater impact forces than those experienced running shod when running with a M/FFS. This is expected as the shod condition provides cushioning, which lowers these impact peaks. Lieberman *et al*. (2010) found the same, with individuals that continued to RFS running barefoot, shown to experience impact forces 8.6% greater than running shod.

Impact peaks increased when switching from the shod to the minimalist and barefoot conditions. Impact peaks were also reduced when running with a M/FFS versus a RFS. These findings indicate that both footwear and foot-strike patterns are important in determining the impact peaks experienced. It is unclear whether this was the case for all individuals, and this is discussed in more detail below. Tam *et al*. (2014) propose that the acute response to first time barefoot and minimalist runners is an anticipated increase in impact forces and loading rates in comparison to shod running. This proposal may explain why the responses in the current study were observed, as all participants were first-time minimalist and barefoot runners.

Individuals were found to respond irregularly and not as presented by the mean data. Running with a M/FFS resulted in a large variance in impact peaks for the majority of individuals, with some experiencing no or small impact peaks and others impact peaks much greater than the majority of RF strikers. This was a common occurrence for all the force variables (IP, VILR, VALR and strike time). An example of this large variance is shown for the barefoot responses when running with a M/FFS (Figure 49), where participants experienced impact peaks ranging from 0 to 3.2 BW. Based on the current understanding (which is currently inconclusive on the role of impact peaks), it is assumed that an individual experiencing an impact peak of 3.2 BW is bound to experience a severely increased injury risk in comparison to an individual with an impact of 0 BW. However until the role of impact peaks on injury risk is determined, this is just an assumption. This individual is therefore not suited to running barefoot with a M/FFS. While the foot-strike pattern is important, the influence of an individual's loading pattern needs to be recognized. It is clear that some of the M/FFS strikers were loading towards the back of the foot, which is known to increase impact forces experienced.

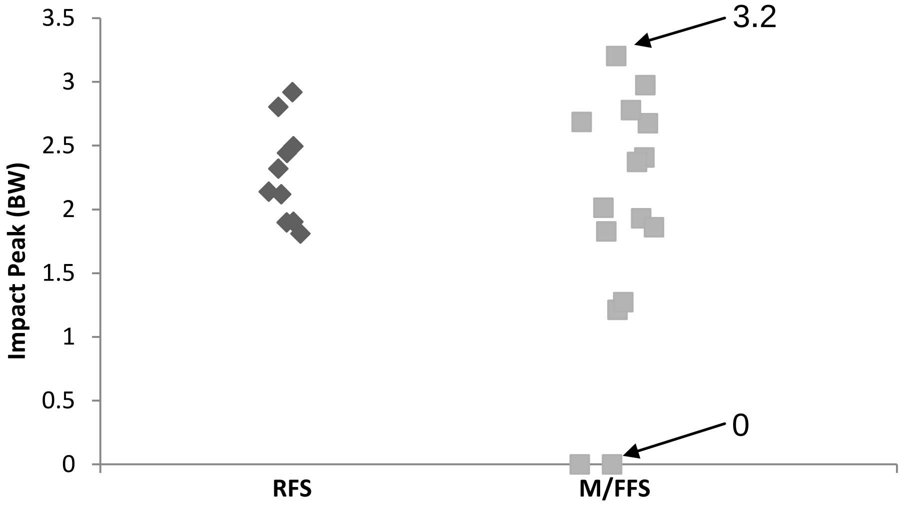

Figure 49: Individual impact peaks when running barefoot with a RFS versus a M/FFS.

The use of a M/FFS resulted in a reduced VILR; however the rate of loading was greater as participants switched from the shod to minimalist and barefoot conditions accordingly, regardless of foot-strike pattern (Figure 50).

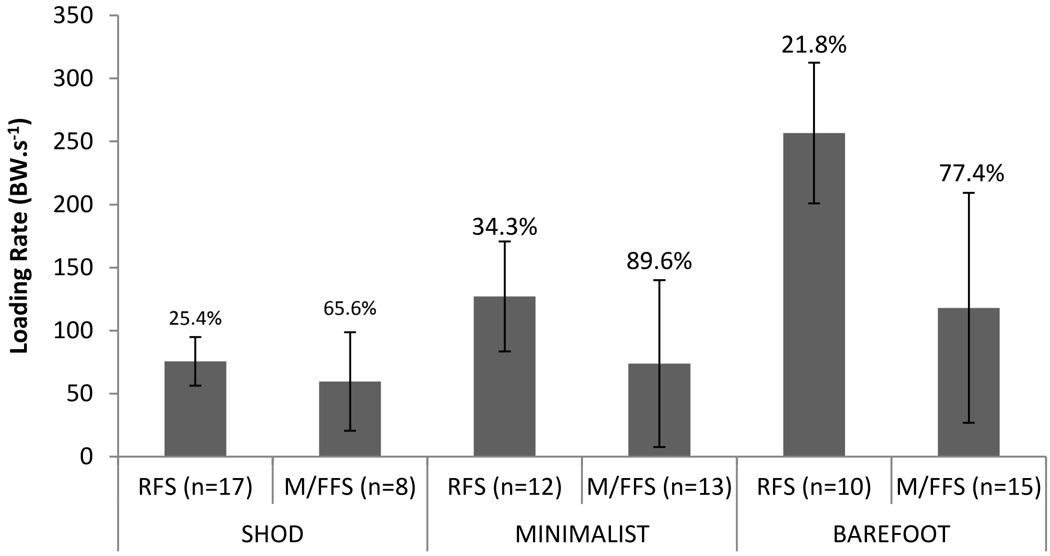

Figure 50: Vertical impact loading rates when running with a RFS versus M/FFS in the shod, minimalist and barefoot conditions.

This figure provides an indication that the responses were not exclusively determined by the footwear worn or foot-strike patterns used, but rather a combination of these factors. The use of a M/FFS resulted in an increase in VALR versus a RFS; however a small percentage of these runners experienced smaller loading rates than a large number of RF strikers. A few M/FF strikers experienced much larger loading rates than all RF strikers.

A reduction in strike time was observed when participants ran with a M/FFS versus a RFS, which is similar to Michele and Merni (2014) who found a significantly shorter ground contact time associated with a MF strike. An increase in strike time was recorded with a M/FFS in the barefoot and minimalist conditions versus the shod condition. Based on the earlier speculation that an increase in strike time leads to a reduced injury risk and an increase in performance, the minimalist and barefoot conditions appeared to result in a favourable running form.

Biomechanics Summary - Based on the observed biomechanical responses, it appears that most variables displayed responses similar to those found in previous studies. The individual responses in the current study however revealed a wide variance between individual responses, with a number of positive and negative responders observed. It is becoming increasingly apparent that recommendations should no longer be solely based on mean response data, but rather through an approach which moves away from 'the assumption that the group average represents a typical response for most individuals as recently proposed by Mann *et al*. (2014). This was particularly pertinent within the context of the minimalist running condition, while responses to the barefoot condition tended to be more consistent. Furthermore it is apparent that it is important to consider not only the footwear worn but also the type of foot strike pattern the footwear elicits as the interaction of these two variables was shown to be relevant.

The factors which determine why some individuals are suited to minimalist or barefoot running still need to be established. Future research needs to acknowledge the importance of human variability. It is proposed that such research will contribute significantly to the current understanding of endurance running (specifically injuries and performance) and directly help to reduce the high injury rates currently experienced and to increased performance.

PHYSIOLOGY - ELECTROMOGRAPHY (EMG)

Mean Data:

Numerous studies have assessed the activation of various lower limb muscles in the past; however few have compared the shod, minimalist and barefoot conditions collectively. Nigg and Wakeling (2001), von Tscharner, Goepfert and Nigg (2003) and Olin and Gutierrez (2013) are a few of the studies which have compared these conditions. A significant reduction in Tibialis Anterior activity was found when running barefoot versus shod in the current study. von Tscharner, Goepfert and Nigg (2003) found an increase in muscle activation associated with heel-striking and shod running, while a reduction is commonly associated with a more anterior foot-strike pattern (Komi, Gollhofer, Schmidtbleicher, and Frick, 1987 and Divert *et al*., 2005a). It is therefore expected (based on these conclusions) that the reduction in activity when running barefoot was a result of a shift in foot-strike patterns to the anterior of the foot. It can also be concluded that the average response of the Tibialis Anterior muscle to the barefoot condition is fairly consistent and likely to result in reduced activation for the most individuals (in the case of the current study there were 18 participants who demonstrated this response). The influence of the different foot-strike patterns is discussed in more detail later as this was anticipated this could be responsible for the significant difference measured.

The remaining muscles (Gastrocnemius, Vastus Medialis and Biceps Femoris) were assessed and found to exhibit no statistically significant difference between the three footwear conditions. A practical significance was however found for the Gastrocnemius activity levels, which was similar to the findings of Divert *et al.* (2005a), Olin and Gutierrez (2013) and Shih, Lin and Shiang (2013). These authors found an increase in muscle activity for the Gastrocnemius when running barefoot or with a FFS versus shod or with a RFS. Practical significance in this context refers to findings which although not statistically significant (for whichever reason/s) in the current study, are important to note and may play a bigger role than found in the current study. It is proposed that statistically significance differences for these muscles were not found due to the current analysis being based on mean data. This data does not acknowledge different foot strike patterns, which have been shown (De Wit *et al*., 2000; Lieberman *et al.,* 2010; Kövecses and Kovács, 2011 and Lorenz and Pontillo, 2012) to be an important contributing factor to the forces required during running and are therefore likely to have an impact on the muscle recruitment patterns. The abovementioned studies concluded that an increase in Gastrocnemius activity is likely to lead to reduced heel impacts (impact peaks), an adjustment in biomechanics associated with a reduction of injury risk. They also concluded that the increased activation of the Gastrocnemius running with a fore-foot strike is expected to increase the likelihood of fatigue occurring, in this muscle. Findings of the current study (although not significant) support the conclusion that running with a M/FFS will result in an increase in Gastrocnemius activity and therefore a reduction in impact peaks. The barefoot condition did not result in a reduction of impact peaks; however this is likely due to individual variability and the resultant variance (as proposed earlier).

Vastus Medialis activation was lowest when participants ran barefoot and the greatest when running in the minimalist condition, tentatively suggesting that the minimalist condition does not elicit a muscle recruitment pattern that is similar to the barefoot condition. The Biceps Femoris muscle was found to experience a large increase in activation for the minimalist and barefoot conditions versus the shod condition, however this was not significant. All the muscles displayed a large variance between responses, indicated by the large CV values observed between the footwear conditions. It is likely that individual variability and differences in foot-strike patterns utilized was responsible for the increased variance experienced within each footwear condition. Without these large variances, it was expected that these findings would have been significant.

Individual Data:

Transitioning from the shod to minimalist condition revealed a significant portion of participants (24%) who experienced a negative response in Tibialis Anterior muscle activation (Table VIIII). There were also responders and non-responders for the other muscles, with 60% (Gastrocnemius), 48% (Vastus Medialis) and 56% (Biceps Femoris) of individuals responding negatively when running in the minimalist condition versus shod. It is clear from these findings that utilizing the mean responses may not be sufficient to illustrate the bipolar nature of the responses. As such utilizing mean data these individuals may be provided with recommendations which are inappropriate and therefore result in an increased injury risk and reduced performance. The appropriate recommendations and conclusions can be provided through the comparison of individual responses. Such a comparison enables researchers to ascertain which individuals respond (positive) and which individuals do not (negative).

Table VIIII. The number of responders and non-responders for each muscle when transitioning from shod to minimalist and barefoot running.

	TA	GS	VM	BF
SHOD TO MINIMALIST				
Mean Response	+	-	-	-
Responders (+)	19	10	12	11
Non-responders (-)	6	15	12	14
No Change	0	0	0	0
SHOD TO BAREFOOT				
Mean Response	+	-	+	-
Responders (+)	18	10	13	11
Non-responders (-)	6	15	11	14
No Change	1	0	0	0

Foot-strike Pattern:

There was a large reduction in Tibialis Anterior muscle activity while running with a M/FFS versus a RFS shod (-32.9%), minimalist (-43.6%) and barefoot (-40.7), similar to findings by Nigg and Wakeling (2001), von Tscharner, Goepfert and Nigg (2003) and Olin and Gutierrez (2013). These findings suggest that the foot strike pattern adopted may be more important in determining muscle recruitment than the type of footwear adopted. However, it is important to note that not all M/FF strikers responded similarly and instead a large variance was found, resulting in a range of responses between 0.076 to 0.113 mV. The assumption that running with a M/FFS will always result in a reduced muscle activity of the Tibialis Anterior muscle should therefore be used cautiously. This is demonstrated by a number of individuals running with a RFS, who experienced activation levels which were smaller than many of the M/FFS individuals. The labelling of a particular foot-strike pattern as positive or negative is an over-simplification and instead individuals need to be assessed independently, these findings are in support of the conclusion of Nigg and Enders (2013).

An increase in Gastrocnemius activity running with a FFS or barefoot, confirms what has been found in the literature previously by Nigg and Wakeling (2001), von Tscharner, Goepfert and Nigg (2003), Divert *et al.* (2005a), Olin and Gutierrez (2013) and Shih, Lin and Shiang (2013).

The use of a RFS when running in the shod or minimalist conditions resulted in an increased recruitment of the Vastus Medialis muscle in comparison to the M/FFS. The barefoot condition however experienced a reduction in Vastus Medialis when using a RFS versus a M/FFS. A reduction in Vastus Medialis activity with a RFS running barefoot is similar to the findings of Cunningham, Schilling, Anders and Carrier, (2010). These authors compared planti-grade (RFS) versus digit-grade (M/FFS) foot-striking, with planti-grade running resulting in a reduced activation. It is not specified whether the participants in this Cunningham *et al*. (2010) paper ran shod, minimalist and barefoot using these foot-strike patterns, which is a possible explanation for the differences in findings between this study and those seen in the current study.

The Biceps Femoris showed a reduced activation when participants ran with a M/FFS in both the shod and minimalist conditions; however running with a M/FFS when barefoot resulted in an increase in activation for this muscle. As with the Vastus Medialis responses, Cunningham *et al*. (2010) found the same increase as that shown in the barefoot condition when running with a M/FFS. Both the Vastus Medialis and Biceps Femoris showed a high variance between responses (as found for the Tibialis Anterior and Gastrocnemius muscles).

Running barefoot, it appears running with a RFS may result in a positive decline in Vastus Medialis activation and potentially a negative increase in Biceps Femoris activation. The implications of this are unknown, and further research into this should be conducted.

Electromyography Responses Summary – Running in the minimalist or barefoot conditions was found to result in a more anterior placed foot-strike pattern for many individuals. This adaption has been associated with a reduced muscle activity of the

Tibialis Anterior and an increased activity of the Gastrocnemius. While the majority of participants responded similarly, the electromyography responses in the current study highlighted the importance of individual variability, as many individuals were found to respond differently.

Further investigation of the role of foot-strike patterns and individual variability needs to be done, to provide more a comprehensive and accurate understanding of electromyography responses when transitioning to either the minimalist or barefoot conditions.

CARDIOVASCULAR: HEART RATE (HR) AND OXYGEN CONSUMPTION ($\dot{V}O_2$)

Mean Data:

A number of previous studies (Squadrone and Gallozzi, 2009; Hanson *et al.,* 2011 and Sobhani *et al*., 2014) have been conducted comparing heart rate responses during various footwear conditions. Hanson *et al.* (2011) establish that a significant difference existed between the shod and barefoot running, similar to the current study. However, several other studies have not found these differences, such as Squadrone and Gallozzi (2009) who found the barefoot condition to have the highest heart rate in comparison to the shod and minimalist conditions (this was howver not significant). The potential reasons why so few studies have obtained the same findings are discussed below.

Methodological inconsistencies need to be considered when comparing studies of a similar nature, as a lack of consistency between studies makes a true comparison difficult. Comparing experimental shoe masses, the average shoe mass in the current study was 305g, this however ranged between 203-431g between the participants. In contrast, Squadrone and Gallozzi (2009) used a standard shoe with a mass of 341g, and Sobhani *et al*. (2014) an average mass of 541 ±44g. On average participants in the current study had lighter shoes than both comparative studies, however a significant difference was still observed (while this was not in the other studies which had a greater mass difference between the conditions), indicating that a difference in shoe mass did not appear to influence the responses seen.

The two shod conditions (minimalist and shod) elicited almost identical responses, the same as found by Squadrone and Gallozzi (2009), Sobhani *et al*. (2014), Moore *et al*. (2014) and Warne and Warrington (2014). From these findings, one is given the impression that running barefoot results in the lowest heart rate, and therefore may provide increased performance in all endurance runners. A large variance between responses was however seen for both the minimalist and barefoot conditions, resulting in a number of responders and non-responders being identified (Table X). Therefore barefoot running does not result in a decreased heart rate for all individuals. It has previously been proposed that minimalist running mimics barefoot running biomechanics (and indirectly the energy costs of barefoot running). Numerous authors (Bootier, 2012; Bonacci *et al*., 2013 and Tung *et al*., 2014) have found contradictory findings; however this proposal cannot be ruled out based on the physiological findings observed in the current study. Minimalist running may therefore result in similar physiological responses to barefoot running.

Table X. The number of responders and non-responders for each physiological variable when transitioning from shod to minimalist and barefoot running.

	Heart Rate	Oxygen Consumption
SHOD TO MINIMALIST		
Mean Response	+	+
Responders (+)	13	19
Non-responders (-)	12	6
No Change	0	0
SHOD TO BAREFOOT		
Mean Response	+	+
Responders (+)	19	15
Non-responders (-)	6	10
No Change	0	0

The oxygen consumption responses in previous studies by Burkett *et al*. (1985), Flaherty (1994), Divert *et al*. (2008), Hanson *et al.* (2011), Perl *et al*. (2012), Tung *et al*. (2014) and Moore *et al*. (2014) were found to be significantly reduced when running barefoot versus shod. These reductions ranged between 1.3 to 5.7% in these studies. The current study found no statistically significant difference in $\dot{V}O_2$ rates between the three experimental footwear conditions, which is in contrast to the abovementioned findings. Although it should be noted that mathematically there was a difference of 1.5% in the $\dot{V}O_2$ between the shod and barefoot condition, which may have practical consequences and is at the bottom of the range found within the literature. Potential reasons for a non-significant difference in the study are a) the large variability in individual responses, b) the use of different foot-strike patterns under each footwear condition and c) the methodological inconsistencies.

The methodological inconsistencies and foot-strike patterns used appear to contribute largely to these differences between these studies and the current study. Comparing these studies, it was established that Divert *et al*. (2008), Hanson *et al.* (2011) and Moore *et al*. (2014) never specified the foot-strike pattern utilized by participants. Perl *et al*. (2012) compared the FFS to a RFS; however they used participants that were habitually minimalist or barefoot runners. Tung *et al*. (2014) selected participants that ran with a MFS only and had minimalist and barefoot running experience. Furthermore other confounding factors such as shoe mass, participant selection and running experience make accurate and reflective comparisons difficult. For example, Hanson *et al.* (2011) and Moore *et al*. (2014) also did not specify the mass of the footwear utilized in these studies, while Divert *et al*. (2008) used two masses of 150 and 350g.

Running in minimalist footwear, there was no difference in heart rate compared to the shod condition, similar to Sobhani *et al*. (2014). The majority of previous studies (Squadrone and Gallozzi, 2009; Perl *et al*., 2012; Lussiana, Fabre, Hébert-Losier and Mourot, 2013; Warne and Warrington, 2014 and Moore *et al*., 2014) have however concluded that running in the minimalist condition results in a significant reduction in $\dot{V}O_2$ versus running shod. As with the shod versus barefoot comparison above, a number of factors (as discussed to date i.e. methodological differences) may explain why the current study did not find significant differences as previous studies have. Without going into too much detail, the following inconsistencies were identified. Three studies used the Vibram FiveFingers minimalist shoes, as used in the current study, however Squadrone and Gallozzi (2009) gave participants 10 days to habituate and train in these shoes, Perl *et al*. (2012) used experienced barefoot or minimalist runners who habitually fore-foot striked and Warne and Warrington (2014) gave participants a habituation period of 4 weeks. All of these inconsistencies between these studies may provide a reason as to why the current study did not find a statistically significance as the others did. If these discrepancies are not responsible for the non-significance observed, then it is proposed that the participants in the current study were not as homogenous as those selected in the other studies.

More importantly, while no statistically significant findings were recorded, the importance of individual responses and individual variability were found to prove more useful than the use of mean responses. Based on the mean response, it could be concluded that running barefoot results in a similar oxygen consumption rate as running in the minimalist and shod conditions. Comparing individual responses, responders and non-responders were however observed, indicating that the mean response does not paint the appropriate picture and in fact there were a number individuals suited (and not suited) to these footwear conditions.

<u>Individual Data:</u>

The average heart rate response was reduced when participants ran in the minimalist versus shod condition. However almost half (48%) the participants actually experiences a negative responses (i.e. an increase in heart rate). This was the same for the barefoot condition (Table X); however fewer negative responders (24%) were observed. Important practical implications arise from this observation. Recommendations based on the mean data suggest that running in the minimalist or barefoot condition is favourable; however as already pointed out there were numerous individuals that were negative-responders to these conditions. This finding is more pertinent to elite athletes, as performance is ultimately the factor which determines their success and livelihood. Recreational runners also pursue such increases in performance and this is just as important for these individuals.

Similarly for $\dot{V}O_2$ rates, the average response was a reduction in $\dot{V}O_2$ when switching to the minimalist and barefoot conditions; however there were 6 and 10 individuals respectively who responded negatively. The positive and negative responders were found to vary significantly, with the positive responders ranging from decreases of -0.13 in some to -3.38 $mL.kg.min^{-1}$ in others. Switching to the minimalist condition, the same was observed with a range of decreases between -0.18 to -6.63 $mL.kg.min^{-1}$. This was the same for the negative responders, with a switch to the barefoot condition resulting in increases between +0.5 to +3.5 $mL.kg.min^{-1}$. In the minimalist condition, this range was +0.5 to +6.8 $mL.kg.min^{-1}$. It is clear that an individual reducing oxygen consumption by 6.63 $mL.kg.min^{-1}$ is far better suited to minimalist running compared to the individual increasing it by 6.8 mL.kg.min^{-1}.

Which factors are responsible for some individuals responding better than others? This is unclear; however potential factors are discussed further. The use of alternate foot-strike patterns is one such factor which has previously been suggested to result in an increased performance (reduced oxygen consumption). In the current study it was found that a M/FFS resulted in a reduced oxygen consumption (of 5.2, 4.3 and 3.1% for the shod, minimalist and barefoot conditions respectively); however this was not the case for all individuals and as with the range seen in positive and negative responders, the same was found for M/FF strikers. It was evident in the current study that many individuals that alternated foot-strike patterns from a RFS when shod to a M/FFS in the minimalist and barefoot conditions, experienced significantly larger oxygen consumption responses than those who started with this foot-strike pattern. However not all individuals that started as RF strikers resulted in large responses when switching to the use of a M/FFS (Figure 51). This is similar to the recent proposal by Tam *et al*. (2014) that the acute response to barefoot running is an increase in oxygen consumption. The acute response (in the current study) to the first time use of a M/FFS appears to result in an increased oxygen consumption.

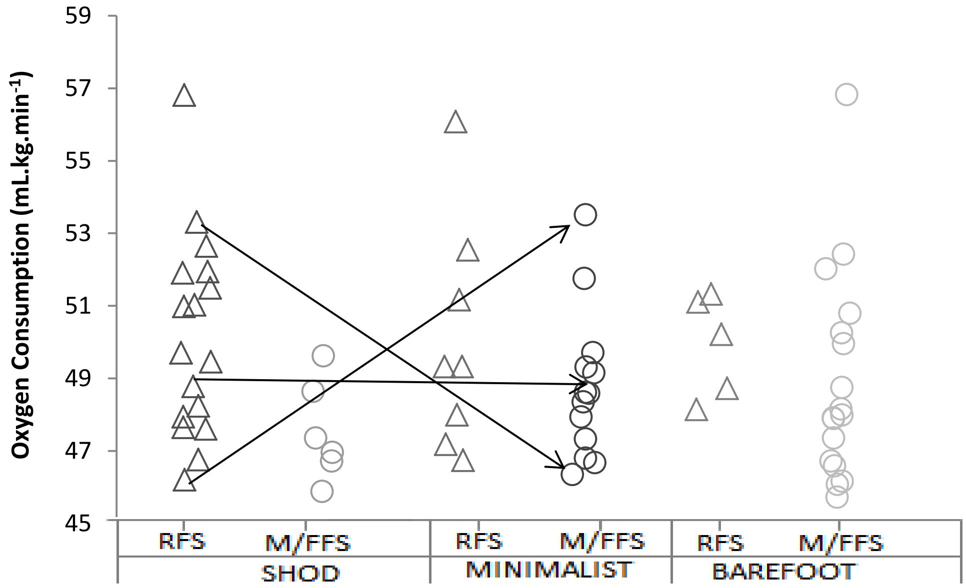

Figure 51: Individual responses oxygen consumption responses when running with a RFS versus M/FFS in the shod, minimalist and barefoot conditions.

The influence of shoe mass on oxygen consumption was analysed and it was found that a weak correlation existed between an increase in shoe mass and an increase in oxygen consumption. These correlations were 0.12 and 0.27 for the shod and minimalist conditions respectively. While these correlations were weak, such findings do provide a partial explanation for the findings observed and begin to illustrate the complexity in determining what factors ultimately lead to an increase in energy efficiency. Many questions remain uncertain pertaining to energy efficiency, such as whether or not a single factor determines this or are there many factors (individual dependant) that determine this? From the findings of the current study it appears that this is individual dependant, and more than one factor determines this.

The barefoot (no mass) condition resulted in a lower oxygen consumption for 68% of participants versus running shod (mass), with the remaining 32% of individuals experiencing reduced oxygen consumption rates even when running in the heavier shod condition. This is a high percentage, and as a result it can be concluded that shoe mass alone in the current study did not correlate with the oxygen consumption rates found. Stride rate was also compared to the oxygen consumption rates. This comparison revealed weak correlations of 0.24, 0.27 and 0.34 for the shod, minimalist and barefoot conditions respectively.

It can be concluded that footwear and foot-strike patterns are partially responsible for differences in oxygen consumption observed; however more research is needed to determine what other factors (such as shoe-mass and stride rate) ultimately lead to a reduction in oxygen consumption. It is likely that the combination of several factors (footwear, foot-strike pattern, shoe-mass etc.) determine energy efficiency. It is proposed that the factors that determine energy efficiency are also individual dependant and as a result the combination of factors vary between individuals, rather than certain factors resulting in the same individual responses. Providing the recommendations on the mean data in this scenario is misleading, as it has been shown that a large percentage of this population may experience performance benefits using alternate footwear conditions, stride frequencies etc. The current study begins to provide some answers; however more related research is needed to support or refute these findings.

Foot-strike Pattern:

There were no noticeable changes in heart rates when running shod with a M/FFS. This foot-strike pattern did however result in a reduction in heart rate when running either minimalist (-1 ±5 $bt.min^{-1}$) or barefoot (-3 ±5 $bt.min^{-1}$). There was no comparative literature on heart rate responses between the foot-strike conditions, which makes comparisons impossible. The use of a M/FFS does however appear to lead to favourable heart rate responses.

A number of studies (Ardigò, Saibene and Minetti, 1995; Cunningham *et al*., 2010 and Perl *et al.,* 2012) have previously compared oxygen consumption between foot-strike patterns and found no significant differences. Oxygen consumption rates in the current study were reduced under all footwear conditions when using a M/FFS versus a RFS. This reduction was as much as 5.1% for the shod condition and 4.2 and 3.1% minimalist and barefoot conditions respectively. Reasons for a decrease in oxygen consumption associated with a M/FFS are discussed below.

In human running, the muscles, tendons and ligaments of the lower limb and the foot store elastic energy during the loading phase of the gait and return that energy during the pushing phase (Bramble and Lieberman, 2004; Bishop *et al*., 2006; Cappellini *et al.*, 2006). Running economy is therefore favourably influenced by the effective exploitation of this elastic energy, and for biomechanical reasons the effectiveness of this mechanism is strongly affected by a runner's strike pattern. A more fore-footed strike allows a runner to store and return a higher amount of elastic energy (Perl *et al.,* 2012), which may explain why a decrease in oxygen consumption occurred when participants ran with a M/FFS. A M/FFS has however been shown to result in a shorter strike time (as shown in the current study), which has been associated with increase in oxygen consumption (Michele and Merni, 2014). This therefore affects running economy negatively; however it appears that this alteration does not impact energy costs as much as the elastic storage mechanism, as a reduction in oxygen consumption was still seen with the use of a M/FFS in the current study. To conclude, although the exact mechanisms for a reduction in oxygen consumption are not decided upon, the use of a M/FFS was shown to reduce the energy cost of running.

The shod condition showed little difference between the lowest responses in both the RFS (46.21 $mL.kg.min^{-1}$) and M/FFS (45.89 $mL.kg.min^{-1}$) groups. There were however many RF striking individuals that experienced exceptionally higher $\dot{V}O_2$ rates in comparison to the M/FF strikers. The highest shod M/FFS response was

49.62 $mL.kg.min^{-1}$, whilst for the RFS strikers the highest was 56.81 $mL.kg.min^{-1}$. Close to half of RF strikers (47.4%) experienced oxygen consumption rates greater than the highest M/FFS respondent. It was evident that numerous individuals that were RF strikers with high $\dot{V}O_2$ rates when shod switched to a M/FF striker when running in the minimalist and barefoot conditions, with the majority of these individuals still displaying high $\dot{V}O_2$ rates. A total of 13 individuals switched from a RFS shod to a M/FFS in the minimalist and barefoot conditions. A switch led to a decrease in responses for ten participants running minimalist, while three experienced an increased associated with this switch. In the barefoot condition there were six individuals with a positive decrease in oxygen consumption, while the remaining seven experienced an increase. For these negative responders, it appears that the switch to a M/FFS did not relate to a positive response (reduced $\dot{V}O_2$ rates) commonly associated with this foot-strike. This provides strong support to the argument against the oversimplified argument that a M/FFS results in an increase in energy efficiency and that inexperienced M/FFS are not likely to experience the positive benefits of this foot-strike initially (which may change with further acclimatization to this pattern). RF strikers when running barefoot were found to experience similar levels of oxygen consumption (low variance), while the M/FF strikers were more varied, with some experiencing high rates (56.83 $mL.kg.min^{-1}$) and others very low rates (46.08 $mL.kg.min^{-1}$). As a result, many of the barefoot M/FF strikers did not experience smaller $\dot{V}O_2$ rates than many of the RF strikers (Figure 51).

The impact of foot-strike patterns does not appear to elicit a reduction in oxygen consumption rates for endurance runners (not significant); however it is important to assess individuals independently, as many were found to experience substantial benefits running with a M/FFS while others did not. The use of mean data does not allow for the identification of these individuals.

Physiological Responses Summary - A significant reduction in heart rate was found when participants ran barefoot versus shod, while no other significant changes were present. The comparison of $\dot{V}O_2$ rates showed no significant differences between the footwear conditions. Closer analysis of the foot-strike patterns however revealed a reduced $\dot{V}O_2$ rate for the majority of M/FF strikers. This was however not evident for all M/FF strikers and a number actually exhibited much greater rates than those running with a RFS. A recurring trend was again evident in the physiological responses, with the repeated significance of individual variability in responses. The mean data (in most instances) was shown to inadequately display what was occurring.

PERCEPTUAL - RATINGS OF PERCEIVED EXERTION (RPE)

Mean Data:

There were no statistically significant differences observed between the three footwear conditions for both central and local ratings of perceived exertion. The findings observed for the central RPE responses have previously been found in studies by Sobhani *et al.* (2014) and Warne and Warrington (2014). The implications of these findings are not discussed in these studies.

Although there were some physiological differences, seen in the current study, these were not demonstrated in the participants' perceptions (i.e. they did not perceive a change in footwear to have a significant effect on their responses). This was similar for the local RPE.

A correlation was run between local RPE responses and impact peak responses. This analysis revealed a weak correlation between the shod (0.2) and barefoot (0.09) conditions, while a moderate correlation was seen for the minimalist condition (0.31). Not all individuals responded equally, demonstrated by the large variance between responses. Based on these findings, it does not appear that local RPE responses can be used to predict the degree of impact experienced.

Individual Data:

A large variance between responses resulted in a wide distribution of individual responses. The average central RPE response was positive for both the minimalist and barefoot conditions; however there were eight (32%) and ten (40%) individuals respectively that responded negatively. This is a large portion of participants, who appear to have been camouflaged by the average data. To demonstrate this participant nine is used as an example: this individual experienced a positive response to the minimalist (-4) and barefoot running (-2) conditions. These responses are beneficial to this individual as these conditions are perceived as being less uncomfortable in comparison to the shod condition. Participant fifteen on the other hand experienced a negative response to the minimalist (+1) and barefoot (+2) conditions, a response which is unlikely to benefit this individual. The average data displayed no significant difference between these conditions; however it is clear from these individuals that the majority (if not all) individuals were found to respond uniquely. The same was evident when comparing the local RPE responses.

<u>Foot-strike Pattern:</u>

Both the central and local RPE displayed a reduction in responses when participants ran with a M/FFS under all footwear conditions. For the central RPE, these findings reflect those found when comparing the effect of foot-strike patterns on the physiological variables (heart rate and oxygen consumption), with a reduction experienced. For the local RPE responses, these findings were found to display a similar trend to that seen for the impact variables (impact peak, vertical impact loading rate and vertical average loading rate), which was an increase in perceived rating for the RFS versus the M/FFS.

BODY DISCOMFORT (BD)

<u>Mean Data:</u>

A comparison of body discomfort levels between the footwear conditions has not been conducted prior to this study (to the authors' knowledge). As a result there is no comparative literature available. An increased level of discomfort was found at the knee when participants ran in the minimalist footwear condition versus the shod and barefoot conditions. Barefoot running has been found to create lower sagittal moments at the knee in comparison to running shod (Kerrigan *et al*., 2009; Lieberman, 2012). A further study by Hamill *et al.* (2011) found that knee stiffness did not differ between the shod and barefoot conditions. The findings of the current study tend to support the findings of Hamill *et al.* (2011); however it is suspected as a result of the shod condition being the participants habitual footwear, this condition was familiar and hence participants scored it low. It is unclear why the minimalist condition elicited the highest discomfort at the knee; however based on these findings it appears that this condition does not replicate barefoot running biomechanics as has been previously proposed.

The minimalist condition experienced the least calf discomfort, followed closely by the shod condition and lastly the barefoot condition experiencing the greatest discomfort. This was expected as an increase in Gastrocnemius muscle activity was experienced when participants ran barefoot (Divert *et al.,* 2005a; Shih, Lin and Shiang, 2013). These authors also found increased muscle activity of the Gastrocnemius associated with a FFS, which could explain the relatively high discomfort found for the shod condition. Based on these findings, it is tentatively stated that minimalist running does not appear to replicate barefoot running.

There was an increase in discomfort at the ankle and foot region when participants ran shod. Studies by Hamill *et al.* (2011) and Williams, Green, Wurzinger and Allen (2012) both found an increase in plantar-flexion at the ankle as participants ran barefoot. One would expect that a lower discomfort would be experienced in the familiar shod condition; however this was not the case. It is proposed that a more plantar-flexed ankle at initial contact may result in a more comfortable ground contact.

Lastly, the shod condition resulted in the greatest discomfort in the upper posterior of the limbs. This is an interesting observation, as the current study found a reduced muscle activity of the Biceps Femoris when participants ran shod versus the minimalist and barefoot conditions. The author suggests that alternate muscle/s may be triggered when running in the shod condition versus the minimalist and barefoot conditions, which may explain an increase in discomfort experienced.

The body discomfort scale provided a useful indication of regions that participants experienced increased or reduced discomfort when running in the three experimental footwear conditions. This perceptual measure is useful to provide a comparison with the quantitative data obtained; however it must be recognized that many participants, in the current study, did not record any discomfort, while those that did respond generally experienced high levels of discomfort. This data is therefore distorted and may provide an inaccurate representation if used as average data. The use of such data may be best suited to analyse on an individual basis.

Perceptual Responses Summary - The perceptual measures appeared to be misunderstood / improperly responded to in the current study, even though the researcher made every effort to explain and habituate participants to these measures. It appears that participants responded with ratings which were lower than they perceived during the completion of the various conditions, either due to them being intimidated by the experimenter's presence, not totally understanding this measure or in order to boost their own self-confidence during the protocol. This is always a difficulty during measurements of this nature, and perhaps this requires further review in order to make these measures more accurate.

A number of interesting observations were found; however, overall it appears that these perceptual measures did not provide a useful (accurate) indication of any perceptual differences which may exist between the different footwear conditions. These responses did however demonstrate (in line with the underlying theme which has arisen in the current study) that the consideration of individual responses is pertinent.

Further studies are needed to further determine the usefulness of central and local RPE measures as indicators of increased physiological effort and impact forces. If these are proven accurate, these could provide a useful in-field analysis without the use of complex equipment within the laboratory setting. This is however tentatively proposed, and it is suggested that further studies should incorporate this measure to determine the accuracy with which it reflects the physiological effort and impact force variables.

HOLISTIC INTEGRATION

A combined assessment of the effectiveness of each footwear condition for all biomechanical, physiological and perceptual variables was conducted. The barefoot condition was found to result in the best overall effectiveness, with a positive response for the stride rate stride length, strike time, heart rate, electromyography variables. The minimalist condition closely followed this, while the shod condition was shown to result in the least effective combined response.

Responders and non-responders were found for all the variables assessed. These responders and non-responders were found to vary considerably from one individual to the next, indicating that not all responders or non-responders experienced the same responses.

CONCLUDING COMMENTS

The completion of the three different experimental footwear protocols resulted in a number of biomechanical, physiological and perceptual changes. These changes experienced by the cohort population, were in most instances similar to those seen in previous studies conducted. For instance, a large increase in stride rate and corresponding reduction in stride length was elicited when participants ran in either the minimalist or barefoot condition versus the shod condition. Such adaptations have previously been related to an improved running form and reduced injury prevalence. Impact peak and vertical average loading rate showed no significant difference between the three experimental footwear conditions, whilst the vertical impact loading rate and strike time responses were shown to differ significantly.

The impact variables had one thing in common, this was a significant variance found between individual responses, something which appears to have previously been missed, ignored or neglected.

A reduced strike time found when running barefoot or in the minimalist condition versus shod was strongly related to the significant increase in vertical impact loading rates seen.

A significant difference in heart rate between the shod and barefoot condition indicated that the barefoot condition may elicit a reduced cardiovascular load on endurance runners. Not all individuals were however found to experience such positive responses, and in fact, many experienced a negative response to the barefoot condition. The small reduction seen in heart rate responses was not consistent with the oxygen consumption responses, and no significant differences were found for this variable. Based on mean data, running in either the shod, minimalist or barefoot condition does not appear to have elicited an improved running economy; however based on individual’s data there were a large percentage of individuals that benefited whilst running in each of these conditions.

The use of a M/FFS resulted in a reduced heart rate, oxygen consumption and corresponding reduction in central RPE. However as seen for the previous variables, not all individuals responded equally, and non-responders were also seen when running with this foot-strike pattern.

A significant difference in Tibialis Anterior muscle recruitment was evident between the shod and barefoot conditions, with the other muscles showing no significant differences. This change is associated with the more anterior placed foot-strike pattern when participants ran barefoot.

Rating of Perceived Exertion and Body Discomfort variables indicated no differences between the three experimental conditions. In many cases these were almost identical. There were a number of individual variances, however this was not consistent and many individuals appeared to misunderstand these variables.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

Running is a popular recreational and competitive physical activity, undertaken by millions of individuals daily. The popularity of running is largely related to its association with many health benefits (Rixe *et al*., 2012). Since the rapid increase in running participation in the 1970's, a concomitant increase in running injuries has been documented (Novacheck, 1998; Rixe *et al*., 2012). As a result, much research has focussed on running injuries, in particular the causality of these injuries and potential methods to reduce their prevalence. The recent interest in minimalist running footwear was initiated by previous research conducted on barefoot running (the proposed method by which our ancestors ran) as an alternative to reduce running injuries (Altman and Davis, 2012). Current literature is inconclusive as to which footwear condition (if any) has the lowest injury prevalence and greatest performance benefits. The focus of much previous research has been on the mean responses to a variety of contexts; however recent research has started to acknowledge the importance of understanding the individual response (Tam *et al*., 2014) – particularly in situations where there may be responders and non-responders (Mann *et al*., 2014). Therefore a key concern for current and future research is a focus on individual variability and establishing the factors which may affect this variability. This approach should be taken for the added benefits in the circumstances when it is applicable.

Several studies (Divert *et al*., 2008; Squadrone and Gallozzi, 2009; Lieberman *et al.,* 2010; Perl *et al*., 2012 and Bonacci *et al*., 2013) have compared biomechanical and physiological responses when running; however few have focussed on the perceptual responses. The literature surrounding these parameters is contentious and as a result there is a need for more conclusive studies which can add to the body of knowledge. The primary objective of the current study was therefore to quantify the biomechanical, physiological and perceptual changes between the shod, minimalist and barefoot footwear conditions, as well as to investigate the presence of individual variability within a cohort of well-trained South African endurance runners.

SUMMARY OF PROCEDURES

Participants were required to attend four sessions. The experimenter collected participants' basic anthropometric, demographic, and physiological data during the first session. Furthermore, background information and experimental procedures were thoroughly explained to participants. A consent form was voluntary signed, after which participants completed a brief habituation / familiarization to the experimental procedures (over-ground and treadmill protocols) and equipment (treadmill, force plate, heart rate belt, ergospirometer mask, electromyography electrodes and footwear conditions). Lastly participants were provided with a list of pre-experimentation instructions to adhere to.

In each of the subsequent sessions (3), participants completed one of three experimental conditions (shod, barefoot and minimalist footwear), which were intended to investigate the biomechanical, physiological and perceptual responses to different running footwear. The protocol was split into two sub-protocols, namely the over-ground protocol and treadmill running protocol. The over-ground protocol required a minimum of 10 trials over an indoor runway with an embedded force plate. The treadmill protocol consisted of six minutes at a pre-selected running speed (of $15km.h^{-1}$). On arrival, participants were fitted with a heart rate belt and resting heart rate was recorded. This was followed by a standardized warm up consisting of five minutes of self-selected stretches followed by five minutes running on the over-ground runway and treadmill (two and a half minutes each). Participants returned to resting heart rate, before completing the over-ground protocol. The remaining equipment (face mask, electrodes) was fitted as participants recovered. The six minute treadmill protocol followed, after which participants were instructed to complete a short cool down.

The following dependant variables were collected, in an attempt to obtain a holistic approach to research:

Biomechanical Parameters: Stride rate, stride length, impact peak, vertical impact loading rate, vertical average loading rate and strike time.

Physiological Parameters: Heart rate, oxygen consumption, energy expenditure and electromyography.

Perceptual Parameters: Central and Local rating of perceived exertion and body discomfort ratings.

SUMMARY OF RESULTS

The cohort of well-trained South African endurance runners recruited for participation in the present study were indicated to have the following mean demographic characteristics: age of 22 (±2.2) years, stature of 1761 (±66) mm, body mass of 71.4 (±9.5) kg, limb length of 910.4 (±51.2) mm and a calf-girth of 362 (±24) mm.

Stride rate responses were compared between the shod, minimalist and barefoot footwear conditions, and a significant difference ($p<0.001$) was found between all three conditions. There was an increase from the shod to minimalist (+4 ±5 $st.min^{-1}$) and barefoot conditions (+9 ±5 $st.min^{-1}$) respectively. All individuals experienced an increased stride rate when switching to barefoot running, while not all individuals did when switching to the minimalist condition. Stride length and stride rate are biomechanically linked, and it was found that corresponding decreases in stride length were observed, with a significant ($p<0.001$) decrease in stride length present when switching from shod to minimalist and barefoot running. The largest decrease was seen in the barefoot condition (-0.13 ±0.07 m). As with stride rate responses, all individuals experienced a decreased stride length when running barefoot, however only 72% did when running in the minimalist condition.

A comparison of the force variables, showed a significantly ($p<0.001$) higher vertical impact loading rate for the barefoot condition, as opposed to shod (59.4%) and minimalist (42.7%) conditions. While there was a significantly ($p=0.008$) reduced strike time experienced when participants ran barefoot versus the shod or minimalist conditions. The minimalist condition also had a significantly reduced strike time compared to the shod condition. The remaining force variables, impact peak and vertical average loading rate showed no significant differences between the shod, minimalist or barefoot conditions. However comparing individual responses when switching from shod to both the barefoot and minimalist conditions, responders and non-responders were present (some individuals benefited from the change while others did not).

A significant (p=0.02) mean reduction of -3 (±4.9) $bt.min^{-1}$ in heart rate was observed amongst participants when they ran barefoot versus shod. The minimalist condition was intermediate to the shod and barefoot conditions, with no significant differences between these conditions. Oxygen consumption was found to be similar between the three experimental footwear conditions ranging from 48.64 to 49.46 $mL.kg.min^{-1}$. As with the biomechanical variables, the assessment of the individual responses, revealed a number of positive and negative responders in each variable when utilizing the various footwear conditions, indicative of individual variability in responses.

Running barefoot (0.1058 ±0.038 mV) resulted in a statistically significant (p=0.005) 18.5% reduction in Tibialis Anterior muscle activity compared to running shod (0.1298 ±0.045 mV). The Gastrocnemius, Vastus Medialis and Biceps Femoris were found to have no statistically significant differences. The Gastrocnemius did however experience a 1.5 (minimalist) and 4.1% (barefoot) increase in activation compared to running shod. Running in the minimalist condition increased activation of the Vastus Medialis and Biceps Femoris muscles by 5.1 and 14.6% respectively, while the barefoot condition elicited the smallest activation of the Vastus Medialis muscle (0.087 ±0.029 mV) and a 4% higher activation of the Biceps Femoris muscle versus the shod condition. The use of a M/FF strike resulted in a reduced activation of the Tibialis Anterior and an increase in Gastrocnemius activity, regardless of the footwear condition. The impact of foot-strike patterns were found to vary for the other muscles.

During the completion of various footwear conditions, participants experienced body discomfort in regions ranging from the lower back to the ankles. The most commonly reported sites where the shins followed by the calves when participants ran shod, the calves and ankle region for the minimalist condition and the bottom of the feet and calves for the barefoot condition. This variable had a large range of responses, making an accurate inference difficult. Both the central and local RPE responses were found to be similar with no statistically significant difference present. Individual responses did however indicate that not all participants responded similarly.

The role of the various foot-strike patterns on the measured variables was significant. Running with a M/FFS participants experienced a reduction in impact peak, VILR, strike time, heart rate (for the minimalist and barefoot conditions), oxygen consumption, muscle activity of the Tibialis Anterior and central and local rating of perceived exertion. While this foot-strike pattern resulted in an increase in VALR responses and muscle activity of the Gastrocnemius. Individual variability was observed between these foot-strike patterns, with a large variance for the impact peak, VILR, VALR and rating of perceived exertion responses. A conclusion for all individuals is therefore difficult, and for these variables individuals should be analysed individually. The other variables however showed consistency in responses, with small variances present. It was evident from the findings that foot-strike patterns alone did not determine how individuals respond, but rather the combination of footwear and foot-strike pattern used. Lastly it was observed that the influence of different foot-strike patterns had a larger impact on some individuals than others.

STATISTICAL HYPOTHESIS

1. Mean Hypothesis

There will be no change in biomechanical, physiological and perceptual responses between the three footwear conditions.

$\mathbf{H_O: \mu_{SHOD} = \mu_{MININMALIST} = \mu_{BAREFOOT}}$

There will be a change in biomechanical, physiological and perceptual responses between the three footwear conditions.

$\mathbf{H_A: \mu_{SHOD} \neq \mu_{MININMALIST} \neq \mu_{BAREFOOT}}$

For the biomechanical variables it was concluded that stride rate, stride length, vertical impact loading rate and strike time could be rejected while for vertical average loading rates this had to be tentatively accepted.

For the physiological variables it was concluded that heart rate and electromyography (Tibialis Anterior) could be rejected while for these variables it had to be tentatively accepted: oxygen consumption, energy expenditure and electromyography (Gastrocnemius, Vastus Medialis and Biceps Femoris).

For the perceptual responses it was concluded that rating of perceived exertion (central and local) and body discomfort had to be tentatively accepted.

The null hypothesis was therefore rejected and the alternative accepted.

2. Individual Hypotheses

> There will be no change in individual biomechanical, physiological and perceptual responses between the footwear conditions.
>
> **H_O: $\mu_{SHOD} = \mu_{MINIMALIST} = \mu_{BAREFOOT}$**
>
> There will be a change in individual biomechanical, physiological and perceptual responses between the footwear conditions.
>
> **H_A: $\mu_{SHOD} \neq \mu_{MINIMALIST} \neq \mu_{BAREFOOT}$**

For the individual biomechanical variables it was concluded that stride rate, stride length, impact peak, vertical impact loading rate and vertical average loading rate could be rejected while for strike time this had to be tentatively accepted.

For the individual physiological variables it was concluded that electromyography (Tibialis Anterior) could be rejected while for the following variables it had to be tentatively accepted: heart rate and oxygen consumption.

For the individual perceptual responses the following variables had to be tentatively accepted: rating of perceived exertion (central and local) and body discomfort.

The null hypothesis was therefore rejected and the alternative accepted.

CONCLUSION

The completion of the current study, revealed a number of important findings with practical implications; however the three most significant findings are discussed.

Firstly, it is concluded that running footwear plays a critical role in determining the biomechanical, physiological and perceptual responses in runners. The impact that footwear has however differs from one individual to the next as well as from one variable to the next. Running with the different footwear conditions, participants were shown to experience a number of significant changes in the biomechanical, physiological and perceptual variables such as an increase in stride rate and corresponding reduction in stride length. This response resulted in a positive change in running biomechanics when switching to either the minimalist or barefoot condition as opposed to running shod, which has been associated with a reduction in injury risk and an increase in performance.

Secondly, an individual's foot-strike pattern was found to play a significant role in determining the response to the biomechanical, physiological and perceptual measures. The use of a different foot-strike pattern affected the responses significantly for some of the assessed measures, and as with the footwear conditions, the degree of this impact was varied from one individual to the next as well as from one measure to the next. For example the use of a M/FF strike resulted in a positive response in heart rate responses when participants ran in the minimalist and barefoot conditions; however there were M/FF strikers who experienced a negative heart rate response. It appears that the interaction between these two factors (footwear and foot-strike pattern) played an important role for the observed responses in the current study.

The last and potentially most noteworthy finding was that of individual variability. It was found that most individuals did not respond according to the mean response, but rather experienced a large variance in responses. A large distribution of individual responses was evident in measures such as impact peaks and vertical impact loading rates. Within the large variance of responses, responders and non-responders could be identified. Not even the responders and non-responders responded similarly, and a large range within these groups also occurred. Ultimately it can be concluded that individuals will respond uniquely (to varying degrees depending on the measure) and as such the use of average responses to provide recommendations should only be used in the appropriate situation. Assessing individuals separately appears to be the most accurate and appropriate measure to help and actively reduce the number of running injuries experienced by runners and indirectly increasing performance.

RECOMMENDATIONS

The prevalence of injuries in endurance runners is high, and in most instances been suggested to be increasing further. The main focus of much running based research has been around the mechanisms of running, and establishing methods in which these can be altered or manipulated to reduce the frequency of injuries for all runners. Based on the findings of the current study, the following recommendations are made to further the understanding of running injury and performance, as well as to facilitate research which pursues the correct questions:

Firstly it is pertinent that further research be conducted into the biomechanical, physiological and perceptual impact of footwear in endurance runners, with a particular focus on individual variability. It is proposed that research of this nature will aid in the provision of recommendations that suit individuals or groups of individuals (individuals who are found to respond similarly). This research will also facilitate an increased understanding on the complexities of running injury causality, which will allow preventative measures and techniques to be developed and implemented. The end goal of all related research should be to ensure that running is less injurious to all individuals.

Secondly from the findings of the current study, minimalist running was not shown to mimic barefoot running biomechanics. Comparing the biomechanical variables, it was found that minimalist running had a significantly altered stride rate, stride length, vertical impact loading rate and strike time compared to running barefoot. The only variables which were not significantly different were impact peak and vertical average loading rate; however for impact peak responses, the mean responses showed less variance between the shod and minimalist conditions in comparison to the minimalist and barefoot conditions. It must be stressed that this is based on the mean responses obtained, and that certain individuals may have experienced similar biomechanics when running in the minimalist and barefoot conditions.

Thirdly the current study used a unique sample group consisting of habitually shod runners, that were well-trained, no specific foot-striking pattern and unfamiliar with the minimalist and barefoot conditions. The selection of a population group to conduct such investigations into is imperative and needs to be carefully deliberated. Future studies should look to compare habitual shod, minimalist and barefoot runners that a) rear-foot strike, b) mid-foot strike and c) fore-foot strike. A comparison of such a population may provide some more accurate insights into the various footwear and foot-strike patterns as well as the individual responses and how these are affected by the different habitual runners.

The fourth recommendation is an integrated approach to running research. This approach is imperative, as this provides an overall indication on the effectiveness of a certain condition or protocol. It appears that in the past much literature has focussed on a single variable or variables, rather than considering all aspects. For instance, by simply comparing biomechanical variables between shod and barefoot running, which may indicate that biomechanically running barefoot is better, one is ignoring the impact this has on a runners performance. Does better biomechanics when barefoot result in better physiological results? These questions cannot be answered until more integrated and holistic research is completed.

The fifth recommendation is around the topic of fatigue, and the role this plays in running biomechanics, physiology and injury mechanisms. The effect of fatigue was not within the scope of the current study, however it is recommend that future studies incorporate this component as it may play a significant role within the running domain.

Finally in order to achieve accurate, reflective and comparable literature, studies need to increase methodological compliance through either increased collaboration or the establishment of norms to conduct such research. More collaboration between academics and experts in the field will enable more pertinent research to be conducted, without the duplication of certain studies.

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APPENDIX A: GENERAL INFORMATION

Pre-selection questionnaire

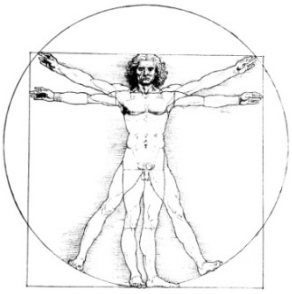
Pre-selection criteria

Letter of information

Participant consent form

Pre-experimental procedure

PRE-SELECTION QUESTIONNAIRE



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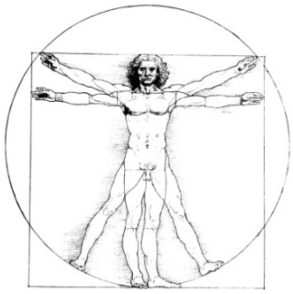


DEPARTMENT OF HUMAN KINETICS & ERGONOMICS

Cell: 073 253 0501 • Fax: (046) 603 8934 • Email: g09m0188@campus.ru.ac.za

Name: ____________________________ Age: ______

5km Time (min: sec): __________________ Date of Birth: _______________

Habitually shod (do you train/run in running shoes only): YES / NO

Shoe size: 8 / 9 /10 / 11

Average distance run per week (km): _________

Number of years running experience (years): _________

Completed a 5km race / time trial in last two months: YES / NO

In good health (no recent illness, health concerns, operations?): YES / NO

If no, please provide more detail: ____

Previous treadmill experience: YES / NO

Running injury in last 6 months: YES / NO

Describe: ____

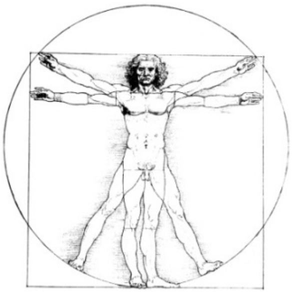
Training intensity/speed (for example 5km 3x weekly, under 30 mins etc.):

____

PRE-SELECTION CRITERIA

Participants were included if they were well trained, male, endurance runners between the ages of 18 and 30 years old and ran habitually shod. Other criteria included a history of no running injuries in the past six months, complete between 30-50km.wk^{-1}, run a 5km time trial within a time of 16-22 minutes, have a shoe size of 8, 9, 10 or 11 and had no barefoot or minimalist footwear experience. Participants will not be exclusively from Rhodes University, but also from the broader Grahamstown and Eastern Cape Community (if they meet inclusion criteria).

LETTER OF INFORMATION



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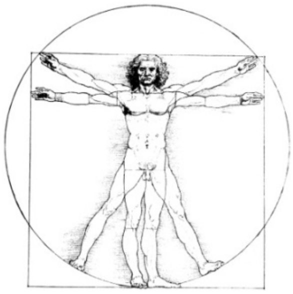


DEPARTMENT OF HUMAN KINETICS & ERGONOMICS

Cell: 073 253 0501 • Fax: (046) 603 8934 • Email: g09m0188@campus.ru.ac.za

Dear Participant

Firstly, thank you for showing an interest in my Masters Research project entitled, **"The impact of footwear on individual biomechanical, physiological and perceptual running responses*".*** This letter explains the purpose of this project, the procedures to be followed and the potential risks and benefits associated with conducting such research. Please read this document carefully and ensure that you understand its contents before making a decision to sign the consent form.

The aim of this study is to compare the biomechanical, physiological and perceptual variables associated with shod, unshod (barefoot) and minimalist footwear at a predetermined running speed, in male endurance runners. Currently much controversy exists in the scientific literature surrounding this issue, in particular with regards to running efficiency and the causation of running injuries. Running shoes were developed to aid in protecting the foot from the rough surfaces upon which many runners run. Besides protecting the feet from puncture wounds, the influence running shoes have on running biomechanics and metabolic costs is poorly understood. Running shoes are perceived as ineffective in reducing running related injuries. Numerous factors have led to many runners considering switching to barefoot running, which is said to mimic the *"natural"* running style humans have evolved over millions of years. The impact of switching to barefoot running or minimalist footwear on injury rates, limb biomechanics and metabolic costs in the runners is currently undefined. Regardless, many runners are transitioning without realizing the impact switching footwear abruptly could have on their injury risk. Recent literature is showing that individual responses vary under various types of footwear, some individuals that make a footwear transition experience positive responses while other experience negative responses. This study intends to investigate individual responses further in order to establishing traits which could pre-determine positive and negative responders.

A number of biomechanical (stride length, stride rate and ground reaction forces), physiological (heart rate, oxygen consumption, energy expenditure and electromyography) and perceptual responses (rating of perceived exertion and body discomfort) will be measured throughout the experimental conditions. In order to measure some of these responses, you will be required to wear a face mask, a heart rate belt, EMG electrodes on your legs and run over a force plate and treadmill. You will be required to complete a pre-experimentation questionnaire, to establish whether you meet the inclusion criteria of the study. These criteria are that you are a male between the age of 18-30 years, well-trained, habitually shod, run between 30-50km per week, free from ligamentous or bony injury in the lower extremity and lumbar spine over the past 6 months, in a good physical condition, accustomed to running on treadmills and have run a 5km within the last 3 months within 16-22 minutes. Further inclusion criteria are that you have a shoe size between 8 and 11 and have no previous barefoot or minimalist running experience. If you decide to participate in this study you will be required to sign a consent form. Once your consent has been obtained you will be required to attend four sessions held in the Department of Human Kinetics and Ergonomics, Rhodes University, Grahamstown.

The first session is an introductory session where the risks and benefits of your participation and requirements for the study will be explained. This will be followed by the collection of basic anthropometric data, namely; stature, calf girth and leg length. Your reference heart rate and shoe mass will also be recorded. Once all these measures have been obtained, a basic habituation to the experimental equipment and procedures will commence. This will consist of an explanation and demonstration of the equipment and experimental procedure, exposure to the pre-determined running speed and the unfamiliar unshod (barefoot) and minimalist conditions. At any time during this session you will be able to voice any concerns or questions on the study. The reported 5km time will be used to select participants of the most similar running ability, and select a running speed which is as close to each individual's preferred running speed as possible. Some participants will be excluded from the study at this stage. This session will be a maximum of 30 minutes in duration. If selected, you will be required to attend three experimental sessions of roughly 30 minutes each, at your convenience.

Three experimental sessions (session 2, 3 and 4) will require you to complete three conditions, one per session. The conditions are: running shod, running unshod and running in minimalist footwear at the pre-determined running speed. For each condition you will complete 10 good trials over an indoor running track before completing a 6 minute run on the treadmill. The order of experimentation will be randomly assigned to you. At the beginning of each experimental sessions you will be given 6 minutes to complete a brief warm-up of your choice (3 minutes of static and dynamic stretches followed by 3 minutes on the treadmill). Exposure to the footwear conditions will be completed via a 5 minute acclimatization trial, prior to completing the two protocols (indoor runway trials and the 6 minute protocol). A minimum of 5 minutes rest or until your heart rate is within 5% of your reference values will be provided between these two protocols. Video recordings of your lower limbs will be obtained during each condition in order to analyse the foot-strike pattern used.

Your data will be kept anonymous at all times and your name will not be used at all. All data collected will be used for statistical purposes only and a copy of the data will be kept anonymously in the Department of Human Kinetics and Ergonomics, which may be used for teaching and research purposes. The option to withdrawal without negative consequences is available to you during all stages of the experimentation. Following the completion of data collection, I will gladly discuss the results of the project with you (at your request). Below are the potential risks and benefits to your participation in this study.

The risks of this study include: that you may be at an increased injury risk due to novel conditions (minimalist and unshod) which may alter your running biomechanics. These conditions may also impose post-experimental muscle soreness and discomfort as a result of potentially altered biomechanics. There is a risk of injury from slip, trip and fall hazards particularly on the treadmill, but also on the indoor runway. If you suffer from claustrophobia, there may be some discomfort and slight unease associated with the face-mask you will wear. Lastly you may experience some discomfort associated with the muscle electrodes, specifically during the skin surface preparation, when any hair will need to be removed via a razor. While these risks exist, every effort has been made to reduce these as far as possible.

The benefits from your participation include: the opportunity to participate in research aimed at reducing running injuries and increasing the scientific understanding of different running footwear, the exposure to different running footwear / conditions (which you could potentially be more suited to). There are health benefits through the fitness provided by completing this research. Your participation will also allow for a better understanding of your own running form and potential techniques to reduce your injury risk while increasing your performance ability.

Thank you for showing an interest in my research project. If you have any questions or queries please feel free to contact or ask me at any time. If you have any queries or concerns, do not hesitate to contact my supervisor (Mr. Andrew Todd: a.todd@ru.ac.za).

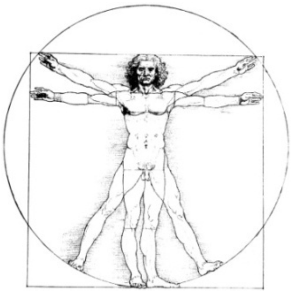
Yours sincerely

Justin McDougall

B.Sc. (hons.) (Human Kinetics and Ergonomics)

M.Sc. Student

PARTICIPANT CONSENT FORM



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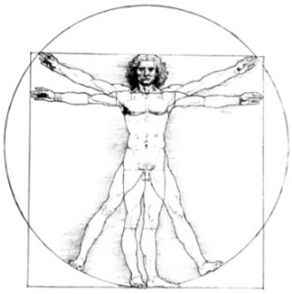


DEPARTMENT OF HUMAN KINETICS & ERGONOMICS

Cell: 073 253 0501 • Fax: (046) 603 8934 • Email: g09m0188@campus.ru.ac.za

The Impact of Footwear on Individual Biomechanical, Physiological and Perceptual Running Responses.

I, ____ having been fully informed of the research project titled "*The impact of individual biomechanical*, p*hysiological and perceptual running responses",* and do hereby give my consent to act as a participant in the above mentioned research.

I am fully aware of the research procedures involved in this study, as well as the potential risks and benefits associated with my participation, which was extensively explained to me both verbally and in writing. I am aware that the researcher will be taking a video-recording of my lower limbs for the various conditions, and provide my consent for this to occur. In agreeing to participate in this research study I waive any legal recourse against the researchers from the Department of Human Kinetics and Ergonomics (HKE), Rhodes University, from any and all claims resulting from personal injuries sustained whilst participating in the above mentioned research. I am aware and fully understand that the Department of HKE is not responsible for any injuries due to personal negligence and non-compliance. I am also aware that the Department of HKE does have a responsibility to act in the off chance of a protocol induced injury. I realise that it is necessary for me to report any signs or symptoms indicating any abnormality or distress to the researchers promptly during any of the protocol undertaken. I am aware that I may withdraw my consent and from participation in the research at any time without any negative ramifications. I am aware that the researcher may take photo's during the different protocols, and that if these are published my identity will be protected. I am aware that my anonymity will be protected at all times by the researcher, and agree that all the information collected by this research study may be used and published for statistical or scientific purposes.

I have read the letter of information accompanying this form and understand it completely. Any questions which may have occurred to me during this time have been answered entirely and to my satisfaction.

I therefore consent to voluntarily participate in this research project.

PARTICIPANT PROVIDING CONSENT:

_____________________	___________________	_________________
(Print Name)	(Signed)	(Date)

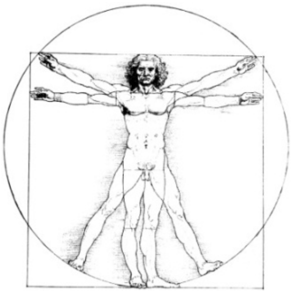
WITNESS:

_____________________	___________________	_________________
(Print Name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

_____________________	___________________	_________________
(Print Name)	(Signed)	(Date)

PRE-EXPERIMENTAL PROCEDURE



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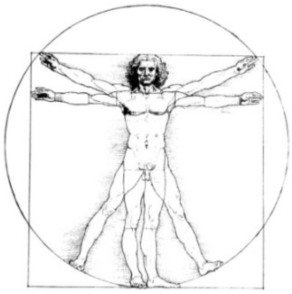


DEPARTMENT OF HUMAN KINETICS & ERGONOMICS

Cell: 073 253 0501 • Fax: (046) 603 8934 • Email: g09m0188@campus.ru.ac.za

In order for accurate data collection and assessment, it is requested that you follow these pre-experimental guidelines strictly before completing any experimental session. Please inform the researcher of any factors that you think may influence your responses on the day of experimentation, for example if you are taking any prescription medication, are asthmatic, or ill.

24 HOURS PRIOR TO EXPERIMENTAL SESSION:

- Do not consume alcohol.
- Do not participate in any strenuous exercise.
- Do not take any medication (i.e. painkillers, aspirin, flu tablets etc.) unless absolutely necessary - please inform the researcher if you do.

ON THE DAY OF EXPERIMENTAL SESSION:

- Eat a decent meal about 2 hours before the experimentation session.
- Do not eat or drink anything for at least 1.5 hours prior to the experimentation session (especially caffeinated drinks).

Please endeavour to comply with these rules as stringently as possible as it will help greatly in the collection of accurate data. Your cooperation in this regard is greatly appreciated.

APPENDIX B: DATA COLLECTION

Order of experimentation procedure

Participant codes

Data collection sheets

Permutation table

Feedback request form

Rating of Perceived Exertion Scale

Body Discomfort Map and Scale

ORDER OF EXPERIMENTATION PROCEDURE

Session I: Introduction, habituation, basic data collection and speed determination protocol

~ All equipment to be laid out ready for use in the laboratory
~ Welcome participant - name (researcher)
~ Introduction and explanation of protocol to be conducted - 9 responses measured (SL, SR, GRF, HR, EE, $\dot{V}O_2$, EMG, RPE, BD)
~ Describe participant requirements (stick to guidelines and run at natural ability), risks and benefits (slip-trip and fall, barefoot/minimalist = soreness)
~ Give participants letter of information – allow time to read (emailed)
~ Give consent form - give time to read and participant to sign if happy with procedure
~ Ask if there are any questions
~ Obtain basic participant characteristics i.e. age, distance run per week etc.
~ Provide full briefing on what the RPE scale and BD maps measure, and how to utilize these appropriately.
~ Weigh the participants shoes
~ Measure mass and stature - no shoes, no socks
~ Measure leg length - no shoes, no socks
~ Measure calf girth
~ Measure shoe heel-rise
~ Put the HR belt onto participant – ensure tight, lie supine for 2 minutes in order to obtain baseline/reference HR
~ Remove HR belt and place on face mask - allows participant to become familiar running with this piece of equipment, please remember for the experimentation that once the mouth piece has been inserted - no talking, coughing, laughing or abnormal breathing is allowed
~ Brief 2 minute warm-up - own stretches
~ Allow participants a short familiarization with the over-ground runway and treadmill at the experimental running speed
~ Closing procedure – ask if any questions?

- ~ Thank participant for their time and arrange a time and date for the next session at their convenience (keep at similar time) and hand pre-experimentation instructions (Session 1)
- ~ Clean HR monitor and facemask- switch all equipment off

Session II, III and IV: First, second and third experimental sessions, complete three conditions over three sessions

- ~ Calibrate *MetaLyser*™ ergospirometer 30 minutes prior to experimentation
- a. Room air calibration
- b. Gas calibration (once every two weeks)
- c. Turbine calibration
- ~ Turn on and calibrate force plate 10 minutes prior to experimentation
- ~ Turn treadmill on (run for 3 minutes at varied speeds)
- ~ Set video-camera in position and turn on - ready to record
- ~ Welcome participant
- ~ Check participant followed pre-experimental procedure and general health
- ~ Get to wash feet (for ***minimalist footwear*** only)
- ~ Attach heart rate monitor
- ~ Give the participant time to warm up (6mins - stretches and running of own selection), whilst informing them of proceedings for this session (order of experimentation)
- ~ Begin acclimatization trial (5 minutes in allocated footwear condition - both over indoor runway and treadmill)
- ~ Participant seated and allowed to return within 5% of HR_R
- ~ Start the force plate protocol (10 trials)
- ~ Allow a further recovery period (attach facemask and straps - leave the mouthpiece off and tighten properly to ensure no air escapes or enters)
- ~ Prepare skin (via guidelines) and attached electrodes at corresponding locations (before treadmill protocol)
- ~ Attach mouthpiece (and remind not to talk, laugh or breath abnormally once test begins)
- ~ **Ensure participants fasten footwear laces properly**

~ Begin video-recording (for Foot-strike Pattern and Cadence)

~ <u>Mount treadmill, begin treadmill protocol</u>

~ Gradually increase the treadmill speed to the predetermined speed, inform participant that the test is starting, start test on the *MetaLyser*™

~ At four minutes:

- Mark on the computer (to start recording $\dot{V}O_2$,EMG and EE)

~ At five minutes

- Record local and central RPE (min 4-5)

~ At six minutes:

- Record local and central RPE (min 5-6)
- Mark on the computer (to stop recording $\dot{V}O_2$ EMG and EE)

~ End the test

~ Stop the treadmill, allow participant to lie on the mats with fan on

~ Remove the mouth piece from mask

~ Export the data to Microsoft Excel and save under the appropriate code

~ On completion the participant may choose to cool-down and recover

~ Provide water if requested

~ Thank participant for their time and arrange a time and date for the third and fourth sessions at their convenience (Session 2 and 3)

~ Thank participants - provide feedback sheet to participants (Session 4)

~ Participant can leave

~ Clean HR monitor, facemask, electrodes and any additional equipment used - switch all equipment off

PARTICIPANT CODES

PARTICIPANT	PARTICIPANT CODE
Participant 1	01
Participant 2	02
Participant 3	03
Participant 4	04
Participant 5	05
Participant 6	06
Participant 7	07
Participant 8	08
Participant 9	09
Participant 10	10
Participant 11	11
Participant 12	12
Participant 13	13
Participant 14	14
Participant 15	15
Participant 16	16
Participant 17	17
Participant 18	18
Participant 19	19
Participant 20	20
Participant 21	21
Participant 22	22
Participant 23	23
Participant 24	24
Participant 25	25

DATA COLLECTION SHEETS

SESSION 1: INTRODUCTION AND FAMILIARIZATION

Code: Test Date:

ANTHROPOMETRIC CHARACTERISTICS

Mass (kg)	
Stature (mm)	
Leg Length (mm)	600 + =
Calf Girth (mm)	

PHYSIOLOGICAL CHARACTERISTICS

Reference Heart Rate (bt.min^{-1})	

OTHER CHARACTERISTICS

Shoe Mass (g)	
Heel-rise (mm)	

SESSION 2, 3 & 4: EXPERIMENTATION

(1) Shod

Code: Date: Test Time: Temperature: HR_R:

RUNWAY PROTOCOL

10x trials Speed for protocol: 14.25 - 15.75km.h^{-1} (+- 5%)

TREADMILL PROTOCOL

Time (min)	**RPE**		**BD**		
	Central	**Local**	**Anterior/Posterior**	**Area**	**Rating**
4-5					
5-6					

Comments:____

____

(2) Unshod

Code: Date: Test Time: Temperature: HR_R:

RUNWAY PROTOCOL

10x trials Speed for protocol: 14.25 - 15.75km.h^{-1} (+- 5%)

TREADMILL PROTOCOL

Time (min)	RPE		BD		
	Central	Local	Anterior/Posterior	Area	Rating
4-5					
5-6					

Comments:____

(3) Minimalist

Code: Date: Test Time: Temperature: HR_R:

RUNWAY PROTOCOL

10 x trials Speed for protocol: 14.25 - 15.75km.h^{-1} (+- 5%)

TREADMILL PROTOCOL

Time (min)	RPE		BD		
	Central	Local	Anterior/Posterior	Area	Rating
4-5					
5-6					

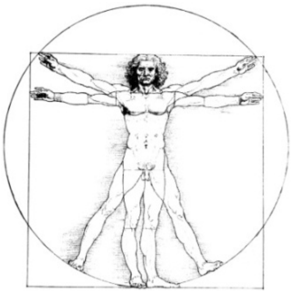
Comments:____

PERMUTATION TABLE

Participant	Session I	Session II	Session III
1	S	B	M
2	S	M	B
3	B	S	M
4	B	M	S
5	M	S	B
6	M	B	S
7	S	B	M
8	S	M	B
9	B	S	M
10	B	M	S
11	M	S	B
12	M	B	S
13	S	B	M
14	S	M	B
15	B	S	M
16	B	M	S
17	M	S	B
18	M	B	S
19	S	B	M
20	S	M	B
21	B	S	M
22	B	M	S
23	M	S	B
24	M	B	S
25	S	B	M

Where: I, II and III represent the order in which the three running conditions were completed by the participants, with I being first and III being last. S - Shod, B - Unshod/Barefoot and M - Minimalist.

FEEDBACK REQUEST FORM



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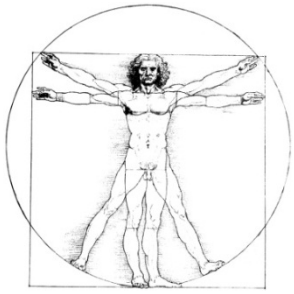


DEPARTMENT OF HUMAN KINETICS & ERGONOMICS

Dear participant,

Thank you for your participation in my research project titled "The impact of footwear on individual biomechanical, physiological and perceptual running responses". Your help and effort in this regard are invaluable and greatly appreciated in enabling me to complete this research project. At the completion of this project, I will have feedback available to all interested participants. Please select a method of feedback should you wish to obtain this information.

I ______________________________ would like to / would not like to received feedback from this research project. Please could you send me individual / overall feedback to the following email address: ________________________________.

*(Circle/underline your choices)

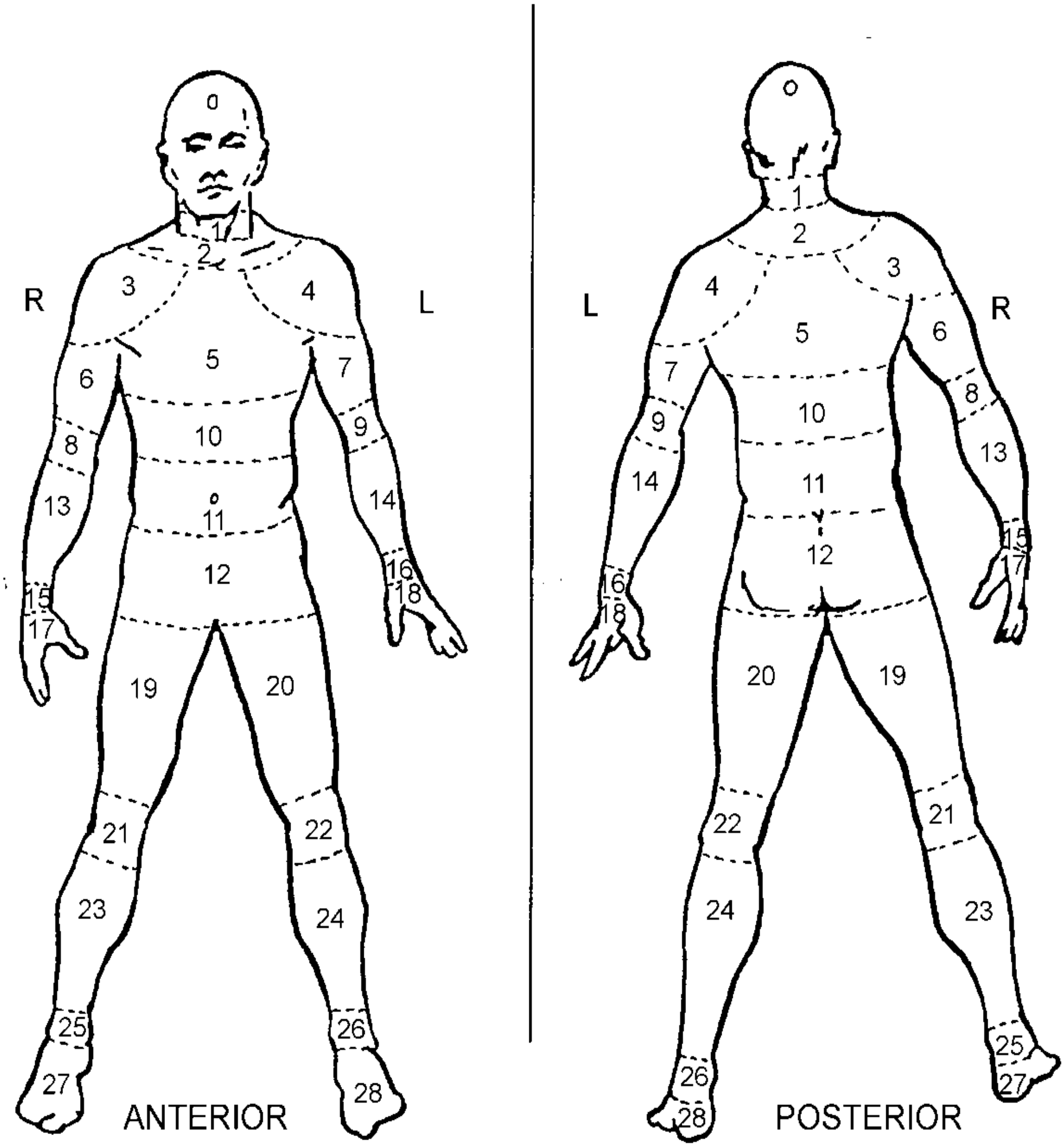
BORGS' RATING OF PERCEIVED EXERTION SCALE

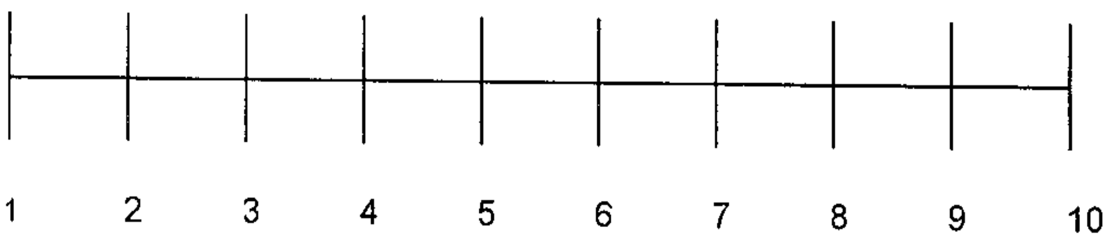
RPE SCALE

6.	
7.	VERY, VERY LIGHT
8.	
9.	VERY LIGHT
10.	
11.	FAIRLY LIGHT
12.	
13.	SOMEWHAT HARD
14.	
15.	HARD
16.	
17.	VERY HARD
18.	
19.	VERY, VERY HARD
20.	

Adapted from Borg, G.A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, 14(5): 377-381.

BODY DISCOMFORT MAP AND SCALE





Minimum Discomfort

Maximum Discomfort

APPENDIX C: SUMMARY REPORTS

Statistical Analyses

Individual Responses (Additional)

STATISTICAL ANALYSES

Biomechanical Responses - (1) ***STRIDE RATE***

ANOVA

Effect	Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 18.05547				
	SS	Degr. of Freedom	MS	F	p
Intercept	2513505	1	2513505	7710.139	0.000000
Error	7824	24	326		
FW	920	2	460	36.680	0.000000
Error	602	48	13		

Effect Size

Effect	Repeated Measures Analysis of Variance with Effect Sizes and Powers (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	140.8782	1	140.8782	8291.755	0.000000	0.997114	8291.755	1.000000
Error	0.4078	24	0.0170					
FW	0.0510	2	0.0255	38.674	0.000000	0.617068	77.349	1.000000
Error	0.0316	48	0.0007					

Post-hoc Tukey HSD Test (Footwear)

Cell No.	Tukey HSD test; variable DV_1 (BIOMECHANICAL VARIABLES FILLED) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .00066, df = 48.000			
	FW	{1} 1.4011	{2} 1.3731	{3} 1.3374
1	SL S		0.001116	0.000126
2	SL M	0.001116		0.000152
3	SL B	0.000126	0.000152	

(2) STRIDE LENGTH

ANOVA

Effect	Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .1303463				
	SS	Degr. of Freedom	MS	F	p
Intercept	140.8782	1	140.8782	8291.755	0.000000
Error	0.4078	24	0.0170		
FW	0.0510	2	0.0255	38.674	0.000000
Error	0.0316	48	0.0007		

Effect Size

Effect	Repeated Measures Analysis of Variance with Effect Sizes and Powers (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	2513505	1	2513505	7710.139	0.000000	0.996897	7710.139	1.000000
Error	7824	24	326					
FW	920	2	460	36.680	0.000000	0.604483	73.360	1.000000
Error	602	48	13					

Post-hoc Tukey HSD Test (Footwear)

Cell No.	Tukey HSD test; variable DV_1 (BIOMECHANICAL VARIABLES FILLED) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 12.547, df = 48.000 FW	{1} 178.96	{2} 187.52	{3} 182.72
1	SR S		0.000126	0.001450
2	SR B	0.000126		0.000167
3	SR M	0.001450	0.000167	

(3) *IMPACT PEAK*

ANOVA

Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED)
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: .8604028

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	263.0647	1	263.0647	355.3521	0.000000
Error	17.7670	24	0.7403		
FW	1.6655	2	0.8327	1.4986	0.233700
Error	26.6715	48	0.5557		

(4) *VERTICAL IMPACT LOADING RATE*

ANOVA

Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED)
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 83.19075

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	982528.3	1	982528.3	141.9695	0.000000
Error	166096.8	24	6920.7		
FW	141233.0	2	70616.5	16.6855	0.000003
Error	203145.8	48	4232.2		

Effect Size

Repeated Measures Analysis of Variance with Effect Sizes and Powers (BIOMECHANICAL VARIABLES FILLED)
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	982528.3	1	982528.3	141.9695	0.000000	0.855395	141.9695	1.000000
Error	166096.8	24	6920.7					
FW	141233.0	2	70616.5	16.6855	0.000003	0.410109	33.3710	0.999479
Error	203145.8	48	4232.2					

Post-hoc Tukey HSD Test (Footwear)

Cell No.	Tukey HSD test; variable DV_1 (BIOMECHANICAL VARIABLES FILLED) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 4232.2, df = 48.000 FW	{1} 70.496	{2} 99.353	{3} 173.52
1	VILR S		0.269182	0.000128
2	VILR M	0.269182		0.000685
3	VILR B	0.000128	0.000685	

(5) *VERTICAL AVERAGE LOADING RATE*

ANOVA

Effect	Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 9.862843 SS	Degr. of Freedom	MS	F	p
Intercept	69048.06	1	69048.06	709.8183	0.000000
Error	2334.62	24	97.28		
FW	1.46	2	0.73	0.0808	0.922516
Error	434.23	48	9.05		

(6) *STRIKE TIME*

ANOVA

Effect	Repeated Measures Analysis of Variance (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0266013 SS	Degr. of Freedom	MS	F	p
Intercept	3.289213	1	3.289213	4648.192	0.000000
Error	0.016983	24	0.000708		
FW	0.000804	2	0.000402	5.273	0.008508
Error	0.003661	48	0.000076		

Effect Size

Effect	Repeated Measures Analysis of Variance with Effect Sizes and Powers (BIOMECHANICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	3.289213	1	3.289213	4648.192	0.000000	0.994863	4648.192	1.000000
Error	0.016983	24	0.000708					
FW	0.000804	2	0.000402	5.273	0.008508	0.180133	10.546	0.811344
Error	0.003661	48	0.000076					

Post-hoc Tukey HSD Test (Footwear)

Cell No.	Tukey HSD test; variable DV_1 (BIOMECHANICAL VARIABLES FILLED) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .00008, df = 48.000 FW	{1} .21235	{2} .21106	{3} .20485
1	ST S		0.859751	0.010658
2	ST M	0.859751		0.040159
3	ST B	0.010658	0.040159	

Physiological Responses - (7) *HEART RATE*

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 20.69033 SS	Degr. of Freedom	MS	F	p
Intercept	2263018	1	2263018	5286.312	0.000000
Error	10274	24	428		
FW	94	2	47	4.164	0.021499
Error	544	48	11		

Effect Size

Effect	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Repeated Measures Analysis of Variance with Effect Sizes and Powers (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition								
Intercept	2263018	1	2263018	5286.312	0.000000	0.995480	5286.312	1.000000
Error	10274	24	428					
FW	94	2	47	4.164	0.021499	0.147848	8.328	0.707061
Error	544	48	11					

Post-hoc Tukey HSD Test (Footwear)

Tukey HSD test; variable DV_1 (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 11.329, df = 48.000

Cell No.	FW	{1} 174.88	{2} 174.03	{3} 172.20
1	HR 6 S		0.647294	0.018716
2	HR 6 M	0.647294		0.141424
3	HR 6 B	0.018716	0.141424	

Dependant t-test results

Shod

T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED)
Marked differences are significant at p < .05000

Variable	Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
HR 5 S	172.8848	12.97397								
HR 6 S	174.8847	12.76573	25	-1.99983	1.149140	-8.70142	24	0.000000	-2.47417	-1.52549

Minimalist

T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED)
Marked differences are significant at p < .05000

Variable	Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
HR 5 M	171.9978	11.55047								
HR 6 M	174.0344	12.39111	25	-2.03664	1.775873	-5.73418	24	0.000007	-2.76968	-1.30359

Barefoot

T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED)
Marked differences are significant at p < .05000

Variable	Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
HR 5 B	170.5625	11.08133								
HR 6 B	172.1971	11.58637	25	-1.63466	1.608384	-5.08170	24	0.000034	-2.29857	-0.970756

(8) *OXYGEN CONSUMPTION*

ANOVA

Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED)
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 4.219533

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	173726.8	1	173726.8	9757.486	0.000000
Error	427.3	24	17.8		
FW	21.2	2	10.6	2.191	0.122919
Error	232.6	48	4.8		

Dependant t-test results

Shod

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
VO2 5 S	48.87787	3.484491								
VO2 6 S	49.91244	3.452806	25	-1.03457	1.299161	-3.98168	24	0.000552	-1.57084	-0.498301

Minimalist

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
VO2 5 M	47.81235	2.963012								
VO2 6 M	48.74982	2.876645	25	-0.937472	1.025708	-4.56988	24	0.000124	-1.36086	-0.514081

Barefoot

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
VO2 5 B	47.69544	2.563869								
VO2 6 B	48.60680	2.913428	25	-0.911366	0.783909	-5.81295	24	0.000005	-1.23495	-0.587784

(9) ENERGY EXPENDITURE

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 4.409199 SS	Degr. of Freedom	MS	F	p
Intercept	17117.62	1	17117.62	880.4889	0.000000
Error	466.58	24	19.44		
FW	26.19	2	13.10	0.7621	0.472263
Error	824.84	48	17.18		

Dependant t-test results

Shod

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
EE 5 S	14.57126	1.040003								
EE 6 S	14.88114	1.034178	25	-0.309875	0.380920	-4.06745	24	0.000444	-0.467111	-0.152638

Minimalist

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
EE 5 M	14.25397	0.896794								
EE 6 M	14.52389	0.872652	25	-0.269917	0.338673	-3.98492	24	0.000547	-0.409715	-0.130120

Barefoot

Variable	T-test for Dependent Samples (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
EE 5 B	14.23392	0.778468								
EE 6 B	14.50765	0.880659	25	-0.273731	0.223290	-6.12949	24	0.000002	-0.365900	-0.181561

(10) *ELECTROMYOGRAPHY - Tibialis Anterior (a)*

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0679672 SS	Degr. of Freedom	MS	F	p
Intercept	1.014177	1	1.014177	219.5402	0.000000
Error	0.110869	24	0.004620		
FW	0.007575	2	0.003787	5.8079	0.005510
Error	0.031300	48	0.000652		

Effect Size

Effect	Repeated Measures Analysis of Variance with Effect Sizes and Powers (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	1.014177	1	1.014177	219.5402	0.000000	0.901454	219.5402	1.000000
Error	0.110869	24	0.004620					
FW	0.007575	2	0.003787	5.8079	0.005510	0.194844	11.6158	0.849355
Error	0.031300	48	0.000652					

Post-hoc Tukey HSD Test (Footwear)

Cell No.	Tukey HSD test; variable DV_1 (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Approximate Probabilities for Post Hoc Tests Error: Within MSE = .00065, df = 48.000 FW	{1} .12984	{2} .11321	{3} .10581
1	TA S		0.065142	0.004828
2	TA M	0.065142		0.565003
3	TA B	0.004828	0.565003	

Gastrocnemius (b)

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0456269 SS	Degr. of Freedom	MS	F	p
Intercept	1.253945	1	1.253945	602.3315	0.000000
Error	0.049964	24	0.002082		
FW	0.000249	2	0.000124	0.5655	0.571788
Error	0.010557	48	0.000220		

Vastus Medialis (c)

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0473148 SS	Degr. of Freedom	MS	F	p
Intercept	0.657208	1	0.657208	293.5678	0.000000
Error	0.053729	24	0.002239		
FW	0.002507	2	0.001254	1.1055	0.339315
Error	0.054426	48	0.001134		

Biceps Femoris (d)

ANOVA

Effect	Repeated Measures Analysis of Variance (Spreadsheet2 in PHYSIOLOGICAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0458450 SS	Degr. of Freedom	MS	F	p
Intercept	0.696201	1	0.696201	331.2458	0.000000
Error	0.050442	24	0.002102		
FW	0.001339	2	0.000669	0.9637	0.388745
Error	0.033345	48	0.000695		

Perceptual Responses - <u>(11) *CENTRAL RATING OF PERCEIVED EXERTION*</u>

ANOVA

Effect	Repeated Measures Analysis of Variance (PERCEPTUAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 3.535533 SS	Degr. of Freedom	MS	F	p
Intercept	10325.33	1	10325.33	826.0267	0.000000
Error	300.00	24	12.50		
FW	0.51	2	0.25	0.1733	0.841394
Error	70.16	48	1.46		

Dependant t-test results

SHOD

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 **Mean**	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5C S	11.60000	2.236068								
RPE 6C S	11.84000	2.230097	25	-0.240000	0.723418	-1.65879	24	0.110171	-0.538612	0.058612

MINIMALIST

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5C M	11.24000	1.920937								
RPE 6C M	11.64000	2.079263	25	-0.400000	0.763763	-2.61861	24	0.015056	-0.715266	-0.084734

BAREFOOT

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5C B	11.36000	2.177154								
RPE 6C B	11.72000	2.475210	25	-0.360000	0.700000	-2.57143	24	0.016750	-0.648946	-0.071054

(12) *LOCAL RATING OF PERCEIVED EXERTION*

ANOVA

Effect	Repeated Measures Analysis of Variance (PERCEPTUAL VARIABLES FILLED) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 3.745070 SS	Degr. of Freedom	MS	F	p
Intercept	10161.72	1	10161.72	724.5146	0.000000
Error	336.61	24	14.03		
FW	3.12	2	1.56	0.8005	0.455028
Error	93.55	48	1.95		

Dependant t-test results

SHOD

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5L S	11.60000	2.449490								
RPE 6L S	11.72000	2.491987	25	-0.120000	0.439697	-1.36458	24	0.185045	-0.301498	0.061498

MINIMALIST

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5L M	11.20000	2.327373								
RPE 6L M	11.36000	2.464413	25	-0.160000	0.687992	-1.16280	24	0.256341	-0.443989	0.123989

BAREFOOT

Variable	T-test for Dependent Samples (PERCEPTUAL VARIABLES FILLED) Marked differences are significant at p < .05000 Mean	Std.Dv.	N	Diff.	Std.Dv. Diff.	t	df	p	Confidence -95.000%	Confidence +95.000%
RPE 5L B	11.48000	2.043689								
RPE 6L B	11.84000	2.374868	25	-0.360000	0.757188	-2.37722	24	0.025761	-0.672552	-0.047448

INDIVIDUAL RESPONSES (ADDITIONAL)

Biomechanical Responses - (1) ***STRIDE RATE***

Ranking (Absolute)				
	SHOD	MIN	BF	
1	8	7	12	**
2	21	22	21	**
3	23	19	23	**
4	16	11	16	**
5	13	15	7	
6	23	24	24	**
7	16	15	19	**
8	1	1	2	**
9	2	2	4	**
10	2	3	1	**
11	4	9	9	**
12	9	8	7	**
13	13	19	16	
14	7	5	6	**
15	4	5	5	**
16	21	22	24	**
17	13	9	9	**
18	9	14	12	**
19	9	11	12	**
20	18	19	12	
21	4	4	3	**
22	25	18	16	
23	19	24	20	**
24	20	17	21	**
25	9	13	9	**

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	8	3	20	
2	21	14	10	**
3	23	9	10	**
4	16	3	10	
5	13	19	4	
6	23	14	14	**
7	16	14	20	
8	1	19	20	**
9	2	1	20	
10	2	12	1	
11	4	19	25	
12	9	3	6	**
13	13	25	14	
14	7	3	6	**
15	4	9	6	**
16	21	14	20	
17	13	3	6	**
18	9	19	14	**
19	9	12	14	**
20	18	23	4	
21	4	3	3	**
22	25	2	1	**
23	19	24	14	
24	20	9	14	**
25	9	14	10	**

(Green = 5 lowest SR / Red = 5 highest SR) (** indicating consistent)

(2) STRIDE LENGTH

Ranking (Absolute)				
	SHOD	MIN	BF	
1	18	19	11	**
2	4	3	4	**
3	2	5	2	**
4	9	14	8	**
5	11	10	18	
6	2	1	2	**
7	9	10	7	**
8	25	25	24	**
9	23	24	22	**
10	23	23	25	**
11	20	16	15	**
12	14	18	18	**
13	11	5	8	
14	19	20	20	**
15	20	20	21	**
16	5	3	1	**
17	11	16	15	**
18	14	12	11	**
19	14	14	11	**
20	8	5	11	
21	20	22	23	**
22	1	8	8	
23	7	1	6	**
24	6	9	4	**
25	14	13	15	**

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	18	20	4	
2	4	11	14	**
3	2	17	16	**
4	9	23	13	
5	11	4	21	
6	2	12	16	**
7	9	9	5	**
8	25	4	2	
9	23	24	3	
10	23	13	24	
11	20	4	1	**
12	14	21	19	**
13	11	1	9	
14	19	19	18	**
15	20	15	15	**
16	5	10	6	**
17	11	22	20	**
18	14	4	7	**
19	14	14	7	
20	8	3	22	
21	20	18	23	**
22	1	25	25	**
23	7	2	10	
24	6	16	11	**
25	14	8	12	**

(Green = 5 shortest SL / Red = 5 longest SL) (** indicating consistent)

(3) IMPACT PEAK

Ranking (Absolute)				
	SHOD	MIN	BF	
1	16	1	8	
2	22	13	4	
3	8	19	16	
4	21	12	11	
5	24	20	20	**
6	24	6	24	
7	9	2	24	
8	20	7	1	
9	2	22	10	
10	13	14	18	**
11	18	18	12	
12	10	16	23	
13	23	21	22	**
14	12	11	14	**
15	14	15	21	
16	19	22	15	
17	15	17	17	**
18	5	22	6	
19	3	9	9	
20	4	22	19	
21	17	5	13	
22	7	3	7	**
23	1	4	2	**
24	6	10	3	
25	11	8	5	

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	16	3	6	**
2	22	8	3	**
3	8	21	22	**
4	21	10	7	**
5	24	2	1	**
6	24	1	18	
7	9	5	25	
8	20	6	2	**
9	2	25	21	**
10	13	14	19	**
11	18	16	8	
12	10	19	24	**
13	23	7	9	**
14	12	12	14	**
15	14	17	20	**
16	19	22	13	
17	15	18	16	**
18	5	23	11	
19	3	15	15	**
20	4	24	23	**
21	17	4	12	
22	7	9	10	**
23	1	20	17	**
24	6	13	5	
25	11	11	4	

(Green = 5 lowest IP / Red = 5 highest IP) (** indicating consistent)

(4) VERTICAL IMPACT LOADING RATE

Ranking (Absolute)				
	SHOD	MIN	BF	
1	5	18	14	
2	21	9	2	
3	1	21	21	
4	14	17	15	**
5	24	19	20	**
6	24	15	24	
7	18	1	24	
8	7	8	3	**
9	4	22	18	
10	11	5	8	
11	16	7	4	
12	17	14	23	
13	15	20	19	**
14	20	4	12	
15	23	11	7	
16	12	22	6	
17	22	13	10	
18	3	22	17	
19	13	10	11	**
20	8	22	22	
21	19	3	5	
22	9	2	13	
23	2	16	16	
24	6	6	1	**
25	10	12	9	**

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	5	19	16	**
2	21	6	1	**
3	1	23	24	**
4	14	17	14	**
5	24	10	15	**
6	24	5	20	
7	18	1	25	
8	7	13	5	
9	4	24	21	**
10	11	8	9	**
11	16	7	4	**
12	17	16	23	
13	15	18	18	**
14	20	4	10	**
15	23	9	6	**
16	12	21	8	
17	22	14	7	
18	3	25	19	
19	13	12	12	**
20	8	22	22	**
21	19	2	3	**
22	9	3	13	
23	2	20	17	**
24	6	11	2	
25	10	15	11	**

(Green = 5 lowest VILR / Red = 5 highest VILR) (** indicating consistent)

(5) VERTICAL AVERAGE LOADING RATE

Ranking (Absolute)				
	SHOD	MIN	BF	
1	13	8	11	**
2	25	24	20	**
3	8	19	16	
4	3	4	7	**
5	19	20	14	
6	1	3	2	**
7	9	2	3	
8	23	14	18	
9	7	9	9	**
10	22	25	25	**
11	16	15	6	
12	20	22	24	**
13	24	13	22	
14	15	12	13	**
15	18	21	15	
16	10	18	21	
17	21	23	19	**
18	4	7	8	**
19	12	10	10	**
20	17	16	23	
21	11	11	12	**
22	6	6	4	**
23	2	1	1	**
24	14	17	17	**
25	5	5	5	**

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	13	4	8	**
2	25	12	4	
3	8	24	22	**
4	3	22	23	**
5	19	13	9	**
6	1	25	25	**
7	9	2	2	**
8	23	3	7	**
9	7	14	15	**
10	22	19	21	**
11	16	11	1	
12	20	15	18	**
13	24	1	10	
14	15	7	13	
15	18	17	11	
16	10	21	20	**
17	21	18	12	
18	4	20	19	**
19	12	5	5	**
20	17	10	17	
21	11	8	14	
22	6	9	3	
23	2	23	24	**
24	14	16	16	**
25	5	6	6	**

(Green = 5 lowest VALR / Red = 5 highest VALR) (** indicating consistent)

(6) STRIKE TIME

Ranking (Absolute)				
	SHOD	MIN	BF	
1	17	19	21	**
2	7	2	6	**
3	19	12	10	
4	16	18	24	
5	24	15	15	
6	25	25	25	**
7	22	21	18	**
8	20	13	9	
9	18	24	22	
10	1	1	2	**
11	14	20	18	
12	5	17	1	
13	15	9	12	
14	1	5	7	
15	4	3	14	
16	9	8	5	**
17	5	6	3	**
18	20	23	20	**
19	3	7	8	**
20	8	10	11	**
21	11	11	13	**
22	12	14	16	**
23	23	22	23	**
24	10	4	4	
25	13	16	17	**

Ranking (Change)				
1	SHOD	MIN Δ	BF Δ	
2	9	14	8	
3	7	13	4	
4	4	3	22	
5	13	22	23	**
6	1	2	9	
7	3	4	25	
8	11	7	2	**
9	5	1	7	
10	20	16	15	**
11	21	18	21	**
12	23	19	1	
13	25	6	18	
14	2	5	10	**
15	24	24	13	
16	14	25	11	
17	10	9	20	
18	17	12	12	**
19	12	10	19	
20	22	23	5	
21	15	15	17	**
22	16	17	14	**
23	19	21	3	
24	8	11	24	
25	6	8	16	
	18	19	6	

(Green = 5 lowest ST / Red = 5 highest ST) (** indicating consistent)

Physiological Responses - ***(7) HEART RATE***

Ranking (Absolute)				
	SHOD	MIN	BF	
1	24	25	24	**
2	5	7	5	**
3	12	13	11	**
4	19	20	19	**
5	17	17	16	**
6	10	8	10	**
7	22	19	20	**
8	1	1	1	**
9	4	5	2	**
10	20	18	14	
11	14	16	15	**
12	8	10	6	**
13	7	6	8	**
14	11	15	18	
15	3	4	3	**
16	21	23	23	**
17	2	2	7	**
18	13	11	12	**
19	15	9	9	
20	6	3	4	**
21	9	12	13	**
22	23	22	22	**
23	16	21	17	**
24	18	14	21	
25	25	24	25	**

Ranking (Change)				
1	SHOD	MIN Δ	BF Δ	
2	24	14	8	
3	5	23	20	**
4	12	15	12	**
5	19	6	7	**
6	17	11	10	**
7	10	10	18	
8	22	2	3	**
9	1	8	9	**
10	4	21	11	
11	20	4	1	**
12	14	16	19	**
13	8	22	15	
14	7	19	23	**
15	11	25	25	**
16	3	13	14	**
17	21	20	5	
18	2	9	24	
19	13	5	6	**
20	15	1	2	**
21	6	7	16	
22	9	17	22	**
23	23	18	4	
24	16	24	17	
25	18	3	13	
	25	12	21	

(Green = 5 lowest HR / Red = 5 highest HR) (** indicates consistency)

(8) OXYGEN CONSUMPTION

Ranking (Absolute)				
	SHOD	MIN	BF	
1	14	13	9	**
2	7	8	4	**
3	12	24	22	
4	17	7	17	
5	25	25	24	**
6	11	14	15	**
7	15	11	18	
8	21	16	23	
9	5	4	2	**
10	2	1	1	**
11	4	6	5	**
12	9	10	3	
13	1	5	20	
14	6	9	11	**
15	19	20	8	
16	23	22	19	**
17	10	3	13	
18	3	21	6	
19	18	17	14	**
20	20	12	16	
21	8	15	12	
22	24	23	25	**
23	22	2	7	
24	16	18	10	
25	13	19	21	

Ranking (Change)				
1	SHOD	MIN Δ	BF Δ	
2	14	19	23	**
3	7	8	15	
4	12	3	2	**
5	17	23	14	
6	25	6	10	**
7	11	12	9	**
8	15	20	8	
9	21	21	13	
10	5	18	19	**
11	2	15	17	**
12	4	10	12	**
13	9	9	22	
14	1	1	1	**
15	6	5	3	**
16	19	14	24	
17	23	16	16	**
18	10	24	11	
19	3	2	7	**
20	18	17	18	**
21	20	22	21	**
22	8	4	6	**
23	24	11	5	
24	22	25	25	**
25	16	13	20	
	13	7	4	**

(Green = 5 lowest VO2 / Red = 5 highest VO2 responses) (** indicates consistency)

(10) ELECTROMYOGRAPHY - Tibialis Anterior

	Ranking (Absolute)			
	SHOD	MIN	BF	
1	12	14	12	**
2	1	1	3	**
3	22	25	25	**
4	18	5	11	
5	25	22	24	**
6	20	9	10	
7	24	18	21	
8	15	15	17	**
9	4	12	15	
10	13	11	14	**
11	2	2	2	**
12	17	16	23	
13	9	20	19	
14	11	8	5	
15	10	4	6	
16	19	17	13	
17	3	13	1	
18	8	10	4	
19	16	19	18	**
20	21	24	9	
21	5	7	7	**
22	14	21	20	
23	6	6	16	
24	7	3	8	**
25	23	23	22	**

	Ranking (Change)			
	SHOD	MIN Δ	BF Δ	
1	12	14	9	**
2	1	5	24	
3	22	19	20	**
4	18	1	5	**
5	25	11	11	**
6	20	4	2	**
7	24	9	10	**
8	15	15	16	**
9	4	24	25	**
10	13	8	15	
11	2	13	23	
12	17	16	19	**
13	9	23	21	**
14	11	6	3	**
15	10	2	4	**
16	19	12	8	**
17	3	25	7	
18	8	18	6	
19	16	21	17	**
20	21	20	1	
21	5	10	13	**
22	14	22	18	**
23	6	7	22	
24	7	3	12	
25	23	17	14	**

(Green = 5 lowest EMG / Red = 5 highest EMG) (** indicates consistency)

(11) CENTRAL RATING OF PERCEIVED EXERTION

Ranking (Absolute)				
	SHOD	MIN	BF	
1	11	15	18	
2	21	25	21	**
3	16	24	7	
4	11	5	5	
5	16	9	13	
6	25	23	23	**
7	5	5	1	**
8	7	5	7	**
9	1	15	7	
10	19	19	13	
11	7	5	5	**
12	1	3	1	**
13	21	19	24	**
14	1	1	1	**
15	7	3	1	
16	16	19	18	**
17	21	9	24	
18	11	9	7	**
19	5	9	7	**
20	11	9	18	
21	11	15	15	**
22	19	19	15	**
23	1	2	7	
24	21	15	21	
25	7	9	15	

Ranking (Change)				
	SHOD	MIN Δ	BF Δ	
1	11	16	19	**
2	21	22	11	**
3	16	24	1	
4	11	4	1	**
5	16	4	5	**
6	25	2	5	**
7	5	16	5	
8	7	9	11	**
9	1	25	19	
10	19	9	1	
11	7	9	5	**
12	1	16	11	**
13	21	4	19	
14	1	4	11	
15	7	4	1	**
16	16	16	16	**
17	21	1	19	
18	11	9	5	**
19	5	22	16	
20	11	9	19	
21	11	16	16	**
22	19	9	5	**
23	1	9	19	
24	21	2	11	
25	7	16	19	**

(Green = 5 lowest RPE / Red = 5 highest RPE) (** indicates consistency)