The Effect of Minimalist Shoe Training on Lower Limb Kinematics and Kinetics in Experienced Shod Runners

by

Kurt Heinrich Schütte

Thesis presented in partial fulfilment of the requirements for the degree

of Master of Sport Science at

Stellenbosch University

Supervisor: Dr Ranel Venter

Faculty of Education

December 2012

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

December 2012

ACKNOWLEDGEMENTS

To God, for blessing me in countless ways and forms.

My parents Marz and Karl, and brother Malcolm for continuous love, support and belief in me to achieve my dreams.

Dr. Ranel Venter, for her mentoring, encouragement, belief, support and guidance throughout.

Prof. Elmarie Terblanche, for providing me with the opportunity to pursue my passion.

Bradley Fryer, for looking over my shoulder, providing perspective, and for early morning coffees.

Kyle Miles, for his incredible friendship since the beginning of our barefoot research, as well as for his inspiration for “making the impossible possible”.

Riana Breytenbach, for her love and support, even when the laptop screen took first priority.

Lara Grobler, for her analytical eye, Louise Engelbrecht, for her help with the Afrikaans translation, and Carla-Rae Hageman for her patience and understanding.

Tanya Powell and Elbe de Villiers, for their mentoring and support during my Biokinetics internship.

The participants of this study, who travelled for testing and made effort to attend the training sessions.

Allison Gruber, for her influential help with understandings and calculation of strike index, as well as for her mentoring help from the International Society of Biomechanics.

Simon and Eben Opperman, for donating the use of the GPS sports system, along with all their help with understandings.

Alex Hawkins and Roger Zeino from Vibramfivefingers SA for their help and support with organizing the Vibram Fivefingers® minimalist shoes.

Clare from MEDAC © for manufacturing and donating the cleverly designed GPS socks. As well as to Jana De Villiers, who played an instrumental role in organizing the MEDAC© GPS socks.

Prof. Martin Kidd for his advice and help with statistical analysis.

The editors, Carien Janse van Rensburg and Richard Shay, for their technical eyes.

Last but not least, the members of the Tygerberg Physiotherapy motion analysis clinic: John Cockroft, for saving me endless hours of data processing with his programming; Dominic Fischer, for his help in during testing; Sjan-mari van Niekerk, for her help with the Vicon; Jenny du ploy, for organizing and scheduling testing appointments; and Prof. Quinette Louw, for use of her laboratory.

SUMMARY

Limited data exists on a transition process of minimalist shoe running, warranting longitudinally designed studies. The primary aim of this study was thus to determine whether lower limb kinematics can be adapted, whether vertical average loading rate (VALR) can be attenuated, and whether lower limb joint moments can be altered by either novice or short-term (seven-week) minimalist shoe training.

Ten experimental (EXP) habitually shod male endurance runners (age 24.10 ± 1.74; weekly training mileage 29.36 ± 8.51 km; BMI: 22.83 ± 8.55 kg/m^2) volunteered to participate in a seven-week minimalist shoe transition programme. Eleven age and training matched control participants (CONT) (age 24.00 ± 2.18; weekly training mileage 24.90 ± 3.30 km; BMI: 23.78 ± 6.12) continued to run in their usual running shoes during the intervention period. All participants were provided with a pair of Vibram Fivefingers ® (VF). The VF intervention started at ~ 11% to 22% and ended at ~ 52% to 132% of the participants' usual shod training distance, determined by subjective lower limb comfort ratings.

Lower limb biomechanics for barefoot: BF, minimalist: VF, and shod: SH were recorded with an eight-camera Vicon ® motion capture system, synchronized with a Bertec ® force plate, both prior to and after the transition programme. Twelve running trials at self-selected speeds were recorded bilaterally for each shoe condition. An inverse dynamic approach was used to calculate lower extremity joint moments. Primary parameters of interest were kinematic: step frequency (steps/min), step length (m), footstrike angles (FSA, degrees), strike index (SI,%); average vertical loading rate (VALR, BW/S) and sagittal and frontal plane peak joint moments (Nm/kg.m) of the ankle, knee and hip.

At pre-testing, the results showed that for VALR, VF running was significantly higher than SH running but significantly lower than BF running ($P < 0.05$). Statistically significant shorter step lengths, higher step frequencies, greater plantar-flexion FSA, higher strike index, greater knee flexion FSA, and greater ankle inversion FSA were seen in BF and VF conditions compared to SH ($P < 0.05$).

Statistically higher plantarflexion moment peak (PFM) while lower ankle dorsiflexion moment peak (DFM) and knee abduction moment peak (KAM) was found while BF and VF than SH running.

The only statistically significant effect of the VF training intervention on kinematics was that of higher step frequency for the SH condition ($P < 0.05$), and greater inversion FSA in the BF condition. A trend was seen for the EXP group to increase VALR ($P > 0.05$). Ankle PFM peak significantly increased, while knee extensor moment peak (KEM) peak significantly decreased for the EXP group only ($P < 0.05$).

Contrary to the initial hypothesis, novice or short-term VF training did not result in significantly attenuated VALR. However, alterations in joint moments suggest a shift in the distribution of external loads due to the VF training. Insufficient kinematic adaptation with VF training could be attributed to inability to sense higher VALR or due to greater perceived ratings of calf-Achilles discomfort, and may indicate that more than seven-weeks are required to transition and adapt to VF running.

Key words: Barefoot running; Minimalist shoes; Lower limb kinematics; Lower limb kinetics

OPSOMMING

Beperkte data is beskikbaar oor die oorgangs fase van hardloop met minimalistiese skoene, langtermyn studies is dus nodig. Die primêre doel van die studie is om te bepaal of gemiddelde vertikale ladingstempo (VALR) verminder kan word en onderste-ledemaat gewrigsmomente aangepas kan word deur ‘n korttermyn oefenprogram in minimalistiese skoene.

Tien experimentaal (EXP) manlike uithouvermoë hardlopers (ouderdom 24.10 ± 1.74; weeklikse oefen afstand 29.36 ± 8.51; BMI: 22.83 ± 8.55) wat gewoonlik in skoene hardloop het vrywillig ingestem om aan die sewe week minimalistiese-skoen oorgangsprogram deel te neem. Elf kontrole deelnemers wat gepas is volgens ouderdom en oefening, (ouderdom 24.00 ± 2.18; weeklikse oefening 24.90 ± 3.30 km; BMI: 23.78 ± 6.12 kg/m^2) het in hulle gewone oefenskoene bly hardloop. Alle deelnemers het ‘n paar Vibram Fivefingers ®-skoene ontvang. Die VF intervensie het begin met ~ 11% tot 22% en geeinde met ~ 52% tot 132% van die deelnemers gewone afstande in SH.

Biomeganiese aspekte van die onderste ledemate vir kaalvoet: BF, minimalisties: VF, en skoene: SH is deur middel van ‘n agt-kamera Vicon ® bewegingsisteem gesinkroniseer met ‘n Bertec ® kragplatform, voor en na die oorgangsprogram bepaal. Twaalf hardloop-pogings teen ’n self-bepaalde spoed is bilateraal vir elke skoenkondisie gemeet. ‘n Omgekeerde dinamiese benadering is gebruik om die gewrigsmomente van die onderste ledemate te bepaal. Die primêre parameters van belang was kinematies: treefrekwensie, treelengte, voettrefhoeke (FSA), tree-indeks (SI); gemiddelde vertikale ladingstempo (VALR), en sagittale en frontale vlak piek gewrigsmomente van die enkel, knie en heup.

By voor-toetsing, die resultate toon aan dat vir VALR, VF-hardloop betekenisvol hoër was in vergelyking met SH-hardloop, maar betekenisvol laer was in vergelyking met BF-hardloop ($P < 0.05$). Statisties beduidende korter tree, hoër treefrekwnesie, meer plantaarfleksie FSA, hoer “strike index”, meer kniefleksie FSA, en meer enkel inversie FSA is gevind in die BF en VF kondisie in vergelyking met SH ($P < 0.05$). Statistiese betekenisvol hoër plantaarfleksiemoment pieke (PFM), en minder enkel dorsiefleksiemoment pieke (DFM) en knie abduksiemoment pieke (KAD) was gevind by BF- en VF-hardloop in vergelyking met SH-hardloop ($P < 0.05$)

Die enigste statistiese betekenisvolle verskil in die kinematika van die VF intervensie was ‘n hoër tree frekwensie vir die SH kondisie ($P < 0.05$), en groter enkel inversie FSA in die BF kondisie. Die EXP groep neig om ‘n verhoging in VALR te hê ($P > 0.05$). ‘n Aansienlike verhoging is gevind in piek enkel PFM, terwyl piek knie KEM statisties wesenlik verlaag het in die EXP groep ($P < 0.05$).

In teenstelling met die oorspronklike hipotese het onmiddellike en 'n korttermyn VF oefenprogram nie 'n bekenisvolle effek op VALR vermindering nie. Sommige veranderings in gewrigsmomente suggereer dat 'n verplasing in die verspreiding van eksterne ladings plaasvind as gevolg van die VF oefening. Die onvoldoende kinematiese aanpassing kan moontlik toegeskryf word aan die onvermoë om hoër VALR waar te neem, of as gevolg van die hoër waargenome lesings in kuit-Achilles ongemak. Dit kan aandui da 'n VF oorgang proses van meer as sewe weke vereis word om aan te pas aan.

Sleutelwoorde: Kaalvoethardloop; Minimalistiese skoene; Kinematika onderste ledemate; Kinetika onderste ledemate

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

~	:	Approximately
Δ	:	Change
%	:	Percentage
Add	:	Adduction
Abd	:	Abduction
BMI	:	Body mass index
BF	:	barefoot
BW	:	Body weight
BW/s	:	Body weight per second
CECS	:	Chronic exertional compartment syndrome
cm	:	Centimetre (s)
CONT	:	Control group
COP	:	Centre of pressure
EMG	:	Electromyography
ES	:	Effect size
EXP	:	Experimental group
Ext	:	Extension

FFS	:	forefoot strike
Flex	:	Flexion
FSA	:	Footstrike angle
GRF	:	Ground reaction force
hrs	:	Hours
Hz	:	Hertz
i.e.	:	Specifically
ISAK	:	International Society for the Advancement of Kinanthropometry
kg	:	Kilogram (s)
km	:	Kilometre
km/wk	:	Kilometres per week
m	:	Metre (s)
MFS	:	midfoot strike
min	:	Minute(s)
mm	:	Millimetre
Nm	:	Newton metre
Nm/kg.m	:	Newton meter per kilogram BW times height in metres
m/s	:	Metres per second

ms	:	Millisecond
n	:	Sample size
PFP	:	Patellofemoralpain
P	:	Probability
r	:	Pearson’s correlation coefficient
RFS	:	Rearfoot strike
s	:	Second(s)
SD	:	Standard deviation
SI	:	Strike index
SH	:	Shod
Steps/min	:	Steps per minute
VALR	:	Vertical average loading rate
VAS	:	Vas analogue scale
VIP	:	Vertical impact peak
VF	:	Minimalist shoes (Vibram Fivefingers ®)
VO_2	:	Oxygen consumption ($ml.kg^{-1}.min^{-1}$)
vGRF	:	Vertical ground reaction force
VPP	:	Vertical propulsive peak

vs.	:	Versus
yrs	:	Years of age

CHAPTER ONE

INTRODUCTION

Running is considered to be one of the most important training modalities to provide health benefits and improve overall fitness (Buist, Bredeweg, Lemmink, van Mechelen, & Diercks, 2010; Hanson, Berg, Deka, Meendering, & Ryan, 2011; Squadrone & Gallozzi, 2009). Prior to the 1970s, endurance running was limited to elite, competitive athletes and it is likely that long distance running only became a leisure activity with the advent of the running boom (Nigg, 2010; Ogles & Masters, 2003). It may have been the greater shoe cushioning comfort that facilitated the participation of many joggers (Shorten, 2002). With this change in the emphasis from elite to leisure status, a trend towards running-related in injuries was inevitable and an increase in absolute injury numbers was observed (Nigg, 2010). Even with technological advancements, there has been a parallel increase in running-related injuries over the past three decades (Buist *et al.*, 2010; Lieberman *et al.*, 2010). The last epidemiological paper published indicated the running-related injury rates were as high as 79% per annum (Van Gent, van Middelkoop, Bierma Zeinstra, & Koes, 2007).

Since its evolution during the 1970s, running shoes have been thought to decrease impact forces primarily through cushioning and rear-foot stabilisation (Braunstein, Arampatzis, Eysel, & Brüggemann, 2010; Cheung & Ng, 2010; Divert *et al.*, 2008; McNair & Marshall, 1994; Mcpoil, 2000). Indeed, repetitive impacts with high rates and magnitudes of loading - known as impact transients - have been shown to contribute to the high prevalence of running-related injuries such as tibial stress fractures (Milner, Ferber, Pollard, Hamill, & Davis, 2006) and plantar fasciitis (Pohl, Hamill, & Davis, 2009). Alas, research has failed to confirm the frequently claimed ability of running shoes to protect runners from impact related injury (Bacon, Gendle, & Bishop, 2010; Hreljac, 2004). Some authors believe that the prescription of usual running shoes is not evidence-based from an injury prevention standpoint (Richards, Magin, & Callister, 2009).

A simple and currently popular alternative to shoe (shod) running is barefoot (unshod) running. The human foot was anatomically modern long before shoes were invented, with barefoot walking and running being the most natural form of locomotion (D'Acut, Pataky, De Clercq, & Aerts, 2009; Frederick, Clarke, & Hamill, 1984; Hart & Smith, 2008). Advocates of barefoot running believe that running the way our primal ancestors did may decrease running-related injuries (Rothschild, 2011). Some athletes have even excelled at barefoot running on an elite level e.g. Zola Budd, Adebe Bikila, Herb Elliot. Although advocated by some since the 1980s (Robbins & Hanna, 1987), awareness of barefoot running as an alternative to shod running has only recently been discussed in athletic circles, with a surge in media hype surrounding the topic.

The solution to running-related injuries appears to be as easy as promoting barefoot activity; however, there may be practical restraints (Rothschild, 2011; Robbins & Hanna, 1987). Even when the skin on the plantar surface of the foot has thickened, increased plantar pressure under the forefoot on rough terrain could lead to pain and injury (Squadrone & Gallozzi, 2009). In addition, those running barefoot may poorly adapt to man-made surfaces with extreme ground temperatures present in most developed countries (Robbins & Hanna, 1987). As yet, there is only anecdotal evidence suggesting that barefoot activity reduces injury risk in native populations (Robbins & Hanna, 1987).

D'Acut *et al.* (2009) state that the use of footwear remains necessary on unnatural surfaces, in both athletics and some pathologies. Yet it is important that a shoe should respect the foot's natural form and function to maintain normal morphology and biomechanical behaviour (D'Acut *et al.,* 2009). Two decades ago, Robbins and Hanna (1987) speculated that running shoes should be designed to provide sensory feedback similar to that present in barefoot activity. Only recently has the desire for a barefoot running alternative stimulated the infiltration of conceptual barefoot-related or minimalist shoes into the market.

Authorities in the field of footwear biomechanics have suggested that the past three decades of athletic footwear research has been inappropriately aimed at the effects of shoe cushioning and pronation control respectively (Nigg, 2010). The link between biomechanical variables such as overpronation, shoe cushioning, impact forces and running-related injury has been found to be inconclusive, raising important questions as to whether technologically advanced running shoe cushioning is necessary at all, and why the prevalence of running-related injuries remained constant (or even increased) with technological advancement in shoe cushioning. Consequently, athletes, coaches, clinicians, and sport scientists alike are searching for new injury prevention strategies.

A global discussion on barefoot running among athletes, clinicians, coaches and researchers has had a major influence on the marketing strategies of reputable footwear companies. This paradigm shift has resulted in a category of running shoe that attempts to mimic the barefoot condition. Manufacturers have been changing the features of the running shoe to suit a more *natural* running style. Minimalist shoes are characterised as a shoe which lacks foot arch support, stability, and cushioning (Lieberman *et al.*, 2010; Reenalda, Freriks, & Buurke, 2011).

It is claimed that minimalist shoes promote a more natural form of running technique. There is a paradigm shift in footwear biomechanics research (Frederick, 2011), with a body of evidence which suggests that various minimalist shoes may imitate the barefoot running kinematics under acute conditions (Divert, Mornieux, Baur, Mayer, & Belli, 2005; Schutte, Miles, Venter, & van Niekerk, 2011; Squadrone & Gallozzi, 2009). Whether they were designed to copy the shape of the human foot, the movement of barefoot running or the feeling of barefoot movement, minimalist shoes seem to provide benefits to the athlete (Jenkins & Cauthon, 2011; Nigg, 2010). However, if performed incorrectly, running in minimalist shoes may not be appropriate for everyone (www.vibramfivefingers.com). Research is warranted to determine the benefits that a minimalist shoe training programme might hold.

Unsupported claims relating to injury prevention and performance enhancement could already have led to thousands of runners attempting minimalist running. However, there are some runners who remain sceptical and who rate fear of injury as the highest perceived barrier to attempt minimalist running (Rothschild, 2011). There may indeed be logical reasoning behind this irony, considering that there are reports of runners who develop novel injuries such as metatarsal stress fractures when attempting minimalist running (Giuliani, Masini, Alitz, & Owens, 2011).

This study identifies a wide number of unsolved problems and unanswered questions in the literature related to the minimalist shoe transition period. Runners do not have the confidence of scientific evidence to inform them of whether minimalist running is a safer alternative. Many runners remain sceptical or fear that new injuries would arise that would overshadow the suggested benefits. This study should expand the knowledge surrounding the initial transition phase into becoming a minimalist runner. This study will either confirm or refute some of the many suggested benefits of running in minimalist shoes. A question yet to be answered by the literature is how a novice minimalist runner adapts his or her running gait during the initial transition phase in minimalist shoe training. The amount of time required to adapt fully to minimalist running has not been established. Studies are therefore needed to document this process from both a biomechanical and safety perspective.

CHAPTER TWO

THEORETICAL BACKGROUND

INTRODUCTION

The study of the kinetics provides an explanation of the basic mechanisms of human movement (Hamill & Selbie, 2004). According to Novacheck (1998: 84), “the study of kinetics begins to answer the ‘how and why’ of the movement we observe”. Kinetics can be understood as the study of the forces and torques that cause motion of a body (Hamill & Selbie, 2004). A primary question in kinetic analysis has been how an athlete is able control his or her vertical collapse and shock absorption while running (Winter & Bishop,1992). This chapter starts off by defining the mechanical terms necessary to understand lower limb running kinetics. Two branches of kinetics - namely external vertical ground reaction force (vGRF) and external joint moments - are discussed in this regard. A synopsis of what is known about the possible association among lower limb kinematics and kinetics, and running-related injury is provided. The theory behind various methods of attenuating abnormal kinetics is discussed, with particular emphasis on sport performance and the risk of running-related injury.

This review will assimilate the known biomechanical effects of conventional running shoes, barefoot, and minimalist running shoes on running-related injury and lower limb biomechanics. Data on the footwear effect on lower limb biomechanics is presented in the following order: conventional running shoes, barefoot running, and minimalist shoe running respectively. This order has been chosen as minimalist shoes are considered as the middle between the extremes of cushioned conventional running shoes and barefoot running.

The first reported research on minimalist running shoes can be traced to 2005 following the release of the Nike © Free (Potthast, Braunstein, Niehoff, & Bruggemann, 2005). This particular minimalist shoe showed to have a positive effect on lower limb muscle development in soccer players who used them during warm-up. Since then, minimalist shoes have evolved in design and characteristics over several different brands and models. The primary focus of this review is based on a critical analysis of biomechanics literature pertaining to minimalist shoes from 2005 to present. However, many claims regarding both barefoot and minimalist shoe running are mentioned to give a broader concept of this new natural running movement. Evidence to either support or refute such claims will be presented.

Issues concerning a minimalist shoe transition programme are integrated into information that is applicable to both coaches and clinicians. Specific attention is given to practical considerations related to an adaptation period that is needed to make a successful minimalist shoe transition. Where scientific research is available, methodology and conclusions are systematically reviewed. Where no scientific research is available, anecdotal claims from experienced barefoot coaches and proponents of barefoot running is used as a surrogate. This review does not aim to support either conventional shod running or minimalist shoe running, but rather provide a thorough analysis of each case. This review aims to identify potential gaps in knowledge with regard to the minimalist shoe transition and will thus form the primary problem statement of this study.

A. LOWER LIMB KINETICS

External vertical ground reaction force

Rapidly rising vertical ground reaction forces (vGRF) occur when the foot collides with the ground during running (Hreljac, 2004). vGRF is one of the most important types of mechanical stress on the human body (Hreljac, 2004). These ground reaction forces affect the control mechanisms of both musculoskeletal and nervous systems (Potthast, 2011). Runners may experience these repetitive impacts in magnitude of two to three times their body weight approximately 2400 times per kilometre while running (Frederick *et al.*, 1984). The peak magnitude of impact force is associated with the shock of contact with the ground (Novacheck, 1998). Consequently, impact shock has been defined as a "transient condition in which the equilibrium of a system is disrupted by a suddenly applied change of force" (Nigg, Cole, & Bruggemann, 1995: 408). With impact forces being a primary outcome measure of this study, it is important to understand its characteristics, determinants, and clinical relevance. The following section briefly defines, discusses, and describes external vertical ground reaction force to show its relevance to running injury and to better illustrate the aim of this study.

Mechanical definition

Ground reaction force (GRF) is a representation of the inertial effects of the centre of mass of the body (Nigg *et al.*, 1995). GRF is due to the sum of accelerations of all the segments of a body contacting the ground (Nigg, 2010). Of the three dimensions, the vertical ground reaction force component (vGRF) is most extensively studied (Nigg, 2010). The vGRF curve, schematically plotted as GRF (BW) versus time (s), most often shows two distinct peaks. These two peaks are termed the impact force and propulsive force peaks respectively (Figure 2.1). This two-peak phenomenon is only evident in runners who use a heel-toe (rearfoot striking) method (Hreljac, 2004). A detailed comparison of different footstrike techniques shall be discussed in a further section. As much as 80% of runners who run in modern shoes land with their heel first (Hasegawa, Yamauchi, & Kraemer, 2007), and most literature therefore accepts two peaks in the vGRF component.

The two peaks of the GRF curve differ in size (magnitude), time of occurrence, velocity (rate), muscle activation patterns and also localised region of the foot. Depending on several factors, the first peak of the GRF-time curve is usually of magnitude of around 1.5 times body weight and occurs over an extremely brief period of time (< 30 ms) (Hreljac, 2004). During the impact period, the body decelerates and is known as the absorption phase (Novacheck, 1998), which occurs when the centre of pressure (COP) is in the centre of the heel of the shoe (Frederick *et al.*, 1984). The first peak is known as the impact peak (VIP) but was previously termed the *passive* peak due to beliefs that the lower limb muscles had limited ability to control movement during the rapid impact phase (Nigg, 2010). Potthast (2011: 1) describes an impact as a "high force applied over a short period of time and appearing when two bodies collide".

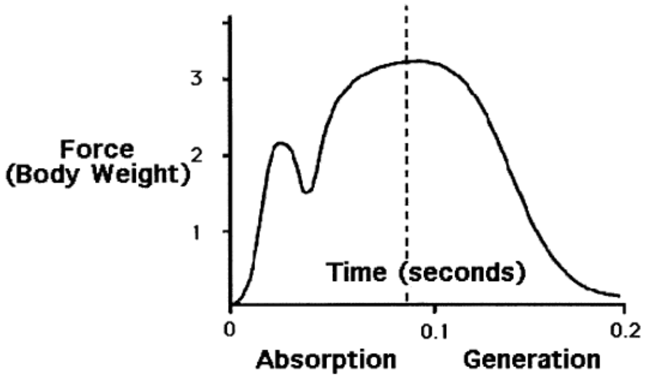


Figure 2.1. Schematic representation of a typical ground reaction force (vertical component). The vertical dashed line separates deceleration (absorption) and acceleration (generation) phases. Adapted, with permission from Novacheck, (1998).

By definition, impact forces in human locomotion are "forces that result from a collision of two objects, reaching their maximum earlier than 50 ms after first contact with the ground" (Nigg, Cole, & Bruggemann, 1995: 408). The magnitude of the VIP is defined as the "maximal amplitude of the force during the impact phase" (Nigg *et al.*, 1995: 408). Due to the short time interval between contact and the VIP, the impact loading rate is defined as the "derivative of the force-time function" (Nigg *et al.* 1995: 408). The impact GRF transient from foot contact to VIP is explained by Newton's second law in Equation 2.1.

$$\sum F = (m.\vec{a}) = c\left(m.\frac{d\vec{v}}{dt}\right) = \frac{d\vec{p}}{dt}$$

Equation 2.1. Newton's second law, in which F is force, m is mass, a is acceleration, v is velocity, and p is momentum (Daoud, 2009).

Impact force is therefore dependent on the rate of change of momentum of the mass acting on the foot during the initial portion of foot contact with the ground. This rate of change measured in the leg during impact is dependent on several factors such as the deceleration of the *effective mass* (support foot and part of the leg), the change in foot velocity, the stiffness of the foot and leg, and the degree of dampening (Daoud, 2009; Nigg, 2010).

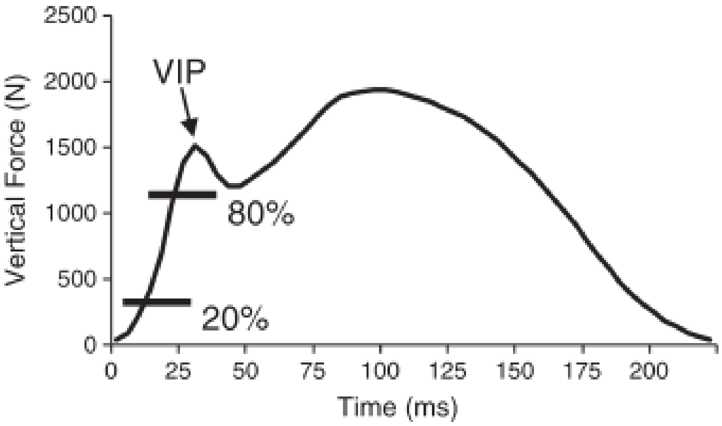


Figure 2.2. Schematic representation of calculation of impact loading rate. VIP indicates vertical impact peak. The vertical average loading rate (VALR) is calculated along the most linear position of the impact force-time slope (between 20% and 80%) of VIP. Adapted from (Crowell & Davis, 2011).

The vertical average loading rate (VALR) is the impact loading rate that occurs between contact and the time of the VIP (Divert *et al.*, 2005; Dixon, Collop, & Batt, 2000; Nigg *et al.,* 1995). Some have quantified the VALR over only the most linear portion (20 – 80%) of the force time curve between contact and VIP (Hamill, Russell, Gruber, & Miller, 2011a; Milner, Davis, & Hamill, 2006a; Milner *et al*., 2006b; Williams, McClay, & Manal, 2000) (Figure 2.2).

In contrast to the VIP, the second vertical GRF peak occurs over the latter part (60 – 75%) of the stance phase, and it may last as long as 200 ms (Hreljac, 2004) and occurs when the COP is located under the ball of the foot (Frederick *et al.*, 1984). Due to its relatively longer duration, it has been considered to be the low frequency component of the vGRF-time curve and thus has been interchangeably termed *active* or *propulsive* peak (Hreljac, 2004). This is because the lower limb muscles are able to activate and control the movement during mid-stance (Nigg, 2010). According to

Novacheck (1998), the active peak is due to active muscle forces and is centred in the stance phase where absorption ends and generation (acceleration) begins.

Association with running-related injury

Biological tissue has the unique ability to respond to increased impact force by either strengthening its material properties or by reacting in the form of an injury (Potthast, 2011). For example, repetitive impact forces experienced during unaccustomed running may typically exceed bone’s homeostatic threshold and therefore result in micro-cracks. Thereafter, bone will undergo a remodelling process and in turn get stronger in the form of additional bone mass (Martin & Burr, 1989). The number of repetitive cycles tolerated, the amount of rest periods taken, and the magnitude of impact forces imparted are all determining factors in developing an impact related injury, and are all said to be dependent on each runner’s individual injury threshold (Hreljac, 2004). For example, if inadequate time is given between loading (running) bouts, there is insufficient time for remodelling to occur, causing bone stress until the bone loses its physical integrity and thus develops a stress fracture (Burr, Martin, Schaffer, & Radin, 1985). Both strength and endurance of the lower extremity musculature, as well as progressive tissue adaptation over time, are required to counteract the large magnitude and repetitive nature of impact forces (Neumann, 2010). Adaptation or injury is believed to be influenced by both magnitude and rate of such impact forces (Potthast, 2011).

One particular retrospective study found the impact loading rate to be higher in injured runners than in non-injured runners. Milner *et al.* (2006b) report instantaneous and average loading rates to be 16.2% and 19% higher in 20 females with previous stress fractures compared to 20 age- and training-matched controls. Their study also defined a difference of 15% in loading rate to be clinically significant. The magnitude of the VIP was not different between injured and uninjured runners.

Similarly, a recent meta-analysis (Zadpoor & Nikooyan, 2011) reported that those with or who developed stress fractures did not have higher magnitude compared to uninjured controls, but they did have a higher rate of impact loading of the ground reaction force. Retrospective studies found that runners with stress fractures had significantly higher impact loading rates compared to their uninjured counterparts, with VALR being 27% higher on average (Bennell *et al.*, 2004; Ferber *et al.*, 2002; Milner *et al.*, 2006b; Hamill, 2006). Unfortunately, such retrospective designs do not provide strong evidence for causality, which indicates that running injuries are caused by higher VALR. However, one of the studies reviewed was prospective and found that runners who developed stress fractures increased their VALR by 40.2% (Davis, Milner, & Hamill, 2004). It is noteworthy that all of the above mentioned-studies recruited females only.

In further support, higher impact loading rates have been associated with runners with a history of plantar fasciitis. A cross sectional study by Pohl *et al.* (2009) found that 25 female runners with a previous diagnosis of plantar fasciitis had significantly higher (21.2%) instantaneous loading rates than 25 age- and training-matched controls. Their study also reported that the maximum VIP was not significantly different between groups.

In contrast to the results of the above mentioned papers, one prospective study (Bahlsen, 1989) found the short-term running injury rate to be higher in runners with the lowest VALR. After six months of monitoring, runners who had the lowest VALR had an injury frequency of around 30%. In contrast, runners who had the highest VALR sustained an injury frequency of ~ 15%. The magnitude of the VIP was not related to injury frequency, which is in agreement with previously mentioned results.

Some researchers remain sceptical of relating impact forces to injury. Nigg (2010: 32) insists that “there is little information that addresses the possible association between impact forces and impact-related injuries”, and that “the current knowledge does not allow for the drawing of conclusions about such a relationship”. As an alternative, Nigg (2010: 32) regards other factors such as muscle vibrations and frequency as a far better predictor of running injury. Furthermore, Hreljac (2004) states that as yet there are no defined limits to the magnitude or rate of impact to imply injury causation.

In light of the studies reviewed above, all of the results undermined the contention that the magnitude of the VIP is related to differences in injury frequency. This may be because the peak GRF is not a true representation of the internal forces occurring at each joint. Force platform measurements assume that the whole body is effectively one point of mass that hits the platform, and thus cannot account for or differentiate between segmental contributions (Shorten & Mientjes, 2011). The vertical impact GRF peak depends on the contribution of the relative decelerations of the support foot, lower and upper portion of support leg, as well as the contribution of the deceleration of the rest of the body (Nigg, 2010). In other words, peak GRF do not provide insight into the movement of individual body segments or internal forces (Nigg *et al.*, 1995). This may account for why injured runners do not have a higher VIP than their non-injured counterparts.

With the exception of one dissertation (Bahlsen, 1989), the notion that VALR is higher in runners who already have or who develop injury is indeed supported. The rate of impact loading rather than the magnitude may therefore be a more relevant parameter when evaluating impact forces. In the context of the present study, most of the reported research made use of females only, perhaps limiting the application of the results to injured male runners. Unfortunately, the question whether male injured runners also have higher VALR remains unanswered until further case-controlled, prospective studies are undertaken.

External joint moments

While external GRF may not be a true representation of forces distributed among joints, ethical and practical considerations make it is equally difficult to directly quantify internal joint forces (Nigg *et al.*, 1995). Additional information is therefore required. A better way to assess forces while running may be with the estimation and calculation of joint moments. The sections that follow discuss the theory behind inverse dynamics method, after which its relevance to running injuries will be illustrated.

Mechanical definition

According to Kristianslund, Krosshaug and van den Bogert (2012: 666) “joint moments correspond to resultant muscle forces and loading of passive tissues”, and are thus imperative to the study of human locomotion. The inverse dynamics method is the specialised branch of mechanics that bridges the areas of kinematics and kinetics, allows for the estimation of internal joint forces (Hamill & Selbie, 2004), and takes the dynamic nature of action into account (Neumann, 2010). The inverse dynamics approach indirectly calculates joint moments and forces from a combination of anthropometric measurements of the individual’s segment masses, location of the segments centre of mass (COM), segment kinematics (positions, velocities, and accelerations), and measured external GRF (Hamill & Selbie, 2004; Neumann, 2010; Novacheck, 1998). The conventional way of calculating joint moments is effected via inverse dynamics by force plate recordings and with passive marker positions from infrared camera systems (Kristianslund *et al.*, 2012). With respect to running specifically, sagittal plane kinetic findings are usually of the most interest (Novacheck, 1998).

Association with running-related injury

During running, muscles and non-contractile tissues such as ligaments and the joint capsule need to counteract the external moment created by the resultant external vertical ground reaction force (vGRF) (Powers, 2010). Abnormal knee frontal plane joint moments are implicated by knee injury. Patellofemoralpain (PFP) has been rated as the highest running-related injury pertaining to the knee (van Mechelen, 1992). Although the aetiology of PFP is multi-factorial (Cheung, Ng, & Chen, 2006), one study found that runners who have or develop Patellofemoralpain during a six-month running season have significantly higher knee abduction impulses than do asymptomatic runners (Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006).

During running, larger varus (abduction) moments are created at the knee when the resultant force vector passes medial to the knee joint centre, where this moment is then restricted mainly by the lateral soft tissues such as the lateral collateral ligament and iliotbial band (Powers, 2010). According to Stefanyshyn *et al*., (2006), landing with greater hip adduction will result in higher knee abduction moment due to the lengthening of the lever arm from the knee joint centre to the line of action of the GRF increases (Figure 2.3). Stefanyshyn *et al.* (2006) also mention that both the contact position and angle of the foot can change the point of application of the vGRF and subsequently the knee abduction moment as well. Moreover, larger abduction moments are said to create greater compression forces within the medial compartment of the knee, compared to that of the lateral compartment (Powers, 2010). This is clinically relevant, considering that the medial compartment of the knee is most prone to degenerative changes (Baliunis & Ryals, 2002; Gok, Ergin, & Yavuzer, 2002). Stefanyshyn *et al.* (2006) assert that both shoes and running style can have a substantial influence on the moments at the knee, which could serve as preventative treatment for PFP. However, no direct link has been found between footwear and the incidence of PTP (Cheung *et al.*, 2006).

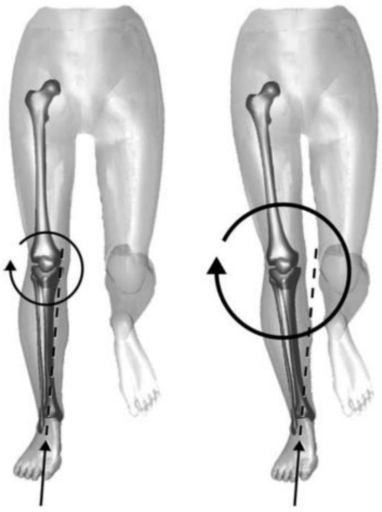


Figure 2.3. Schematic illustration indicating how knee abduction moments are higher due to increased hip adduction angle (right), when ground reaction forces are identical. Adapted with permission from Stefanyshyn *et al.* (2006).

Abnormally high sagittal knee flexion moments are also implicated in injury. During the loading response of running, the resultant ground reaction force vector falls posterior to the knee while anterior to the hip, thereby creating flexion moments at both joints (Powers, 2010). As a result, the hip and knee extensors are required to counteract these moments with eccentric contraction (Powers, 2010). If the knee flexion moment is too large, more work is required by the quadriceps muscles which may cause increased strain through the patella tendon and increased pressure in the patellofemoral joint, leading to Patellofemoralpain syndrome (Reilly & Martens, 1972).

While inverse dynamics is a useful tool to calculate joint moments throughout the lower extremity, there are numerous limitations of this approach that are worth mentioning. Firstly, it is important to note that correlations between abnormal joint moments and running injury have not been studied, and remains speculation until such a study is conducted. Secondly, there are several potential sources for error in the calculation of joint moments. Results from these calculations often depend on correct marker placements (Hamill & Selbie, 2004), the veracity of the assumptions on which the particular modelling technique is based, mathematical techniques employed, the quality of the segmental accelerations (Nigg *et al.*, 1995), different thresholds for kinematic and force plate filtering (Kristianslund *et al.*, 2012), and the anthropometric measurement accuracy of the researcher (Hamill & Selbie, 2004). All of these sources of error make consistency between laboratories poor and cause difficulty when defining normative data. In addition, active (muscles) and passive (capsules, tendons, and ligaments) structures also contribute to internal torque. This being said, it is not always possible to state the relative contributions of active and passive forces towards the generation of internal torque with any degree of certainty (Neumann, 2010). For example, several gait abnormalities associated with muscle weakness often rely more heavily on passive structures to generate internal torque which is required for locomotion at the end of a joint's range of motion.

Having defined loads on the body while running by reference to external vertical ground reaction forces and joint moments, the following section deals with methods of minimizing these loads.

B. IMPACT FORCE ATTENUATION

The human body is said to adapt by adjusting kinematics to regulate external forces in response to different shoes or material properties (Kong, Candelaria, & Smith, 2011). The general idea has been that impact forces should be minimized as much as possible to reduce loading on the locomotor system, and thereby reduce the risk of injury (Nigg, 2010). Impact attenuation has been described as a redistribution of load in the time domain (Mientjes & Shorten, 2011). There are generally two schools of thought regarding the methods to attenuate impact forces, namely the passive and the active methods. The passive method assumes that external support or cushioning, as found in footwear or softer surfaces, are able to passively attenuate VIP and VALR either by dissipating energy or by reducing the rate of change in momentum of the foot through viscoelastic damping. In contrast to this view, the active method assumes that runners can consciously or subconsciously alter their running technique to change their running kinematics and muscle activation patterns, and reduce impact forces by shifting the external load from for one body structure to another. In each section, the clinical importance behind each active or passive method is explained and elaborated on by means of selected results drawn from pertinent studies that have been conducted in relation to each method.

1. External (passive) methods

Shoe cushioning

The purpose of the running shoe has changed dramatically over the last century. Spalding ® running shoes worn by the 1908 American Olympic marathon team consisted entirely of thin gum soles with leather uppers (Puleo & Milroy, 2010). Running shoes were originally designed according to agreement between the athlete and the coach (Cavanagh & Lafortune, 1980). When placed in this context, the running shoes of today undergo a far more sophisticated process, incorporating a host of technological advancements. This process started with the advent of the 1970s “running boom”, which led to running shoes with cushioned soles and special features intended for foot stabilization during ground contact (Shorten, 2002). The cushioned midsole of the modern running shoe is defined as a compliant, elastic material positioned between the upper of the shoe and the outsole (Shorten, 1993). Shock absorption and motion control are considered the essential properties of a running shoe (Cook, Kester, Brunet, & Haddad, 1985; Mcpoil, 2000).

From a clinical perspective, the purpose of the added technological advancements of the modern running shoe as a means to reduce impact related injury appears to be unsupported. Reduced strain and injury to the Achilles tendon from elevated heels (Clement & Taunton, 1981), or diminished sub calcaneal pain in young sportsmen due to efficient energy absorbers under the heel (MacLellan, 1984) are among the many claims of modern running shoes. After conducting a systematic review, Richards *et al*. (2009) concluded that the prescription of distance running shoes featuring elevated cushioned heels and pronation control systems tailored to the individual's foot type is indeed not evidence-based. Richards *et al.* (2009) further contend that modern running shoes negatively affect the runner's ability to monitor impact and foot position with precision, ultimately increasing the risk of injury. Lieberman (2012) agrees, with their suggestion that running shoes actually contribute to injury through limited proprioception.

The soles of athletic footwear commonly make use of compressible materials deigned to attenuate impact forces and enhance the perception of comfort (Mientjes & Shorten, 2011). Good cushioning has been defined as the attenuation of impact forces to the levels that can be tolerated by the musculoskeletal system (Frederick *et al.* 1984: 281). Potthast describes impact and cushioning from a mechanical perspective:

> "Forces acting over a short period of time often have a bigger effect than low forces acting over a longer period of time ... [b]ringing an adequate cushioning material between the collision partners will increase the path of deceleration of the collision, increase the time period of the collision, and decrease the magnitude of the force" (Potthast, 2011: 1).

The field of footwear biomechanics typically employs one of two methods to investigate the cushioning or impact attenuation properties of shoes. Firstly, an impact tester, which is an *in vitro* method of testing shoe cushioning impact attenuation (Shorten & Mientjes, 2011), can be employed. Impact testers are devices that drop a weighted shaft from a distance of 5 cm onto the surface of the heel or forefoot of the sock liner of shoes, and then records acceleration of impact (Frederick *et al.*, 1984). As mentioned by Shorten and Mientjes (2011), the observable results of impact testers have generally been positive and consistent with the expectations of impact attenuation theory.

A second - and perhaps more relevant - method of investigating the impact attenuation records impact forces as a person lands on a force plate imbedded in a runway. This is an example of an *in vivo* method*.* Oakley and Pratt (1988) instructed 18 participants (10 men; age 18 – 32 yrs) to run with a rearfoot striking pattern down an indoor runway (length unspecified) with their right leg contacting the centre of a force plate. Runners were given 10 trials for each footwear condition (three innersoles varying in material thickness and a barefoot condition). The three insoles were cut from a 6 mm sheet of insole material and placed inside a sock. Speed was controlled at 3.3 – 3.6 m/s with light beams. While none of the footwear conditions differed in VIP magnitude, the insole materials were shown to reduce the rate of impact loading by 40%.

The cushioned heels of running shoes may be better suited for impact attenuation compared to the human heel’s fatty pad alone. Robbins, Gouw and Hanna (1989) are of the opinion that although the subcalcaneal (heel) fat pad may prevent a collision between the calcaneal tuberosity and the ground during a rearfoot strike, the deformation of the fat pad is not able to attenuate impact forces. A study by Dickinson, Stephan and Leinhardt (1980) concluded that substances used in the construction of running shoes were effective at dampening both rate and magnitude of impact force, which supports the view propounded by Robbins, Gouw and Hanna. Six male runners (X age 26.3 ± 1.75 yrs.) who ran an average 38.4 ± 10.72 km/wk ran along a 12.5 m wooden runway at controlled running speeds (4.6 m/s). Three left foot trials where a clean force plate hit was observed was recorded for both conditions (barefoot and own conventional running shoes). Impact forces were dramatically less in magnitude (34%), and rate (760%) when running in their own shoes compared to barefoot.

De Clercq, Aerts and Kunnen (1994) had two male participants run along a 6.5 m runway while sagittal plane footstrike was recorded using cineradiography. A force platform was imbedded in the runway and synchronised with the kinematics. The cineradiographic method permitted the recording of how the fatty heel tissue reacts via deformation in response to either barefoot or shod running. Their results showed that during cushioned shoe running, the fatty heel pad deformed 70% less and at a rate of deformation that was two times lower compared to when barefoot. In agreement with previous studies, impact rate of loading was significantly lower (by up to 4.45 times less) when running with shoes compared to barefoot. Interestingly, VIP magnitude was not affected by the shod condition.

In summary, elevated, cushioned running shoes are able to dampen rate of impact loading by ~ 40 to 760%. Running shoes thus allow for comfortable rearfoot striking on hard surfaces (Lieberman *et al.*, 2010; Lieberman, 2012). With the exception of one study (Dickinson *et al.*, 1980), the magnitude of impact force was not influenced by shoe cushioning. Potthast (2011: 1) recognised that the human body does not behave like an artificial basic material, but rather incorporates “multiple processes of a heterogeneous nature”. For example, runners may adjust their body’s kinematics in response to the perceived hardness of the shoe, causing the vertical GRF-time curve recorded from the force plate to change, thereby masking any impact attenuating effect intended by the physical properties of the shoe (Clarke, Frederick, & Cooper, 1983). Shorten and Mientjes (2011) term this the “impact peak anomaly”.

Running surface

Running coaches have suggested that running on softer surfaces such as grass could reduce the risk of developing musculoskeletal injuries (Bloom, 1997). Similarly, Tessutti, Trombini-Souza, Ribeiro, Nunes, & Sacco (2010) contend that longer contact time(s) while running on natural grass promotes greater variability and flexibility in the distribution of loads, which may subsequently improve the musculoskeletal system's ability to absorb plantar pressures. Furthermore, the ideal running surface is a soft, level surface which ensures optimum shock absorption (Noakes, 2003). It has also been argued that the rigidity of the concrete or asphalt in unnatural surfaces may provoke impact related injury.

Dixon *et al.* (2000) compared the impact attenuating abilities of three different sporting surfaces. The first surface used was a conventional asphalt material, the second a new rubber-modified bituminous material, while the third was a commercially available sporting surface consisting of an acrylic carpet on a fabricated shock pad. Both *in vitro* and *in vivo* experiments were conducted to investigate the shock attenuating abilities of the three surfaces. *In vivo* testing using an impact tester showed that the harder surface (asphalt) had a peak acceleration rate that was 2173% and 857% higher than the softer modified and acrylic surfaces respectively. In addition, the peak acceleration was 545% and 285% higher on the asphalt surface compared to the modified and acrylic surfaces. These results confirm the mechanical ability of softer surfaces to attenuate the rate and magnitude of impact forces. However, *in vivo* analysis did not support these results. Six well-trained middle distance female runners ran on all three sporting surfaces at a speed of 3.3 m/s. All surface conditions covered a force plate. Ten trials per condition were recorded for each individual in their own shoes. The authors found that using the participants' own shoes provided a more realistic testing condition, compared to a standardised testing shoe (which was also provided). GRF measurements showed that the softer sports surfaces had no effect on impact force magnitude ($p > 0.05$). Rate of loading was 8% lower in the rubber modified surface compared to the asphalt surface. Each female runner's inherent kinematic adaptations to surface type made explanations difficult: some of the runners adapted their kinematics by increasing their knee flexion angle at contact on the hard asphalt surface, while other runners used various combinations of different kinematic adjustments at the ankle and knee. The authors attributed these inconsistent results to the different shoe wearing patterns of the participants.

Ferris, Louie and Farley (1998) concluded that humans are able to run similarly on surfaces that vary in compliancy because they have the inherent ability to adjust or adapt their leg stiffness. Their results showed that runners may increase their leg stiffness by up to 68% when transitioning within one step from a hard/stiff surface to less stiff (more complaint) surface. The authors explained that a runner's leg is stiffer and compresses less when running on a soft, complaint surface (e.g. grass) compared to hard, non-compliant surface (e.g. concrete). Impact forces may thus be maintained as the body is able to kinematically adapt to each surface.

No definite conclusions as to which running surface is the most appropriate for either reducing loads on the locomotor system or at reducing the likelihood of impact related injury were drawn (Tessutti *et al.*, 2010). It is also unclear how the musculoskeletal system adapts to or is influenced by the running surface (Hardin, Van Den Bogert, & Hamill, 2004). Moreover, it may not even be possible to say with surety which surface conditions are the most likely to enhance the risk of running injury (Dixon *et al.*, 2000). Indeed, a review of epidemiological literature on running showed that running on hard surfaces was not associated with an increase in running injury incidence injuries (van Mechelen, 1992). While more epidemiological studies are needed, running surface does not seem to be related to impact force attenuation or running-related injury. Advocating runners to choose softer over harder surfaces due to impact attenuating properties, as has previously been the case, is a practice that does not appear acceptable.

2. Lower limb kinematic (active) methods

From the previous section it was gathered that when runners land with their heel first, as most runners do (Hasegawa *et al.*, 2007), insole cushioning is able to attenuate VALR significantly compared to being barefoot (Dickinson *et al.*, 1980; Oakley & Pratt, 1988). However, the addition of cushioning appears to encourage a rearfoot landing (Daoud *et al.*, 2012). Robbins, Gouw and Hanna (1989) are of the opinion that even though the subcalcaneal (heel) fat pad prevents a collision between the calcaneal tuberosity and the ground, the deformation of the fat pad does not attenuate impact forces in a heel strike. Similarly, De Clercq *et al.* (1994) demonstrated that the fat heel pad is maximally deformed during a barefoot heel strike, which led to them to conclude that the fat heel pad is unable to reduce impact shock. With this in mind, a rearfoot strike landing, as seen in the studies previously mentioned (De Clercq *et al.*, 1994; Dickinson *et al.*, 1980; Oakley & Pratt, 1988) may be an inappropriate method of investigating or instructing barefoot running. In addition, a runner may not need to depend on external passive cushioning for impact attenuation. However, in the absence of external cushioning, the body may have to adapt to keep impact forces below a certain threshold. These adaptations may take the form of altered running kinematics, such as an increase in knee flexion angle, altered footstrike patterns, and modified stride characteristics. The effect these kinematic alterations have on attenuating impact force and joint torques is the primary focus of the next section. Particular focus is given to the way that these kinematic adaptations influence both running-related performance and injury.

Knee flexion contact angle

The term “adapt” may be defined as “to alter so as to fit new circumstances or environment” (Chambers, 1993: 7). In this context, runners may adapt or alter their lower limb joint angles to fit to new circumstances or environment to attenuate impact force. According to Derrick (2004), impact forces only contribute to injury when coupled with another factor such as abnormal kinematics. Derrick (2004) postulated two explanations for why runners will adapt their kinematics in response to altered environment, namely to prevent injury or improve performance (Figure 2.4).

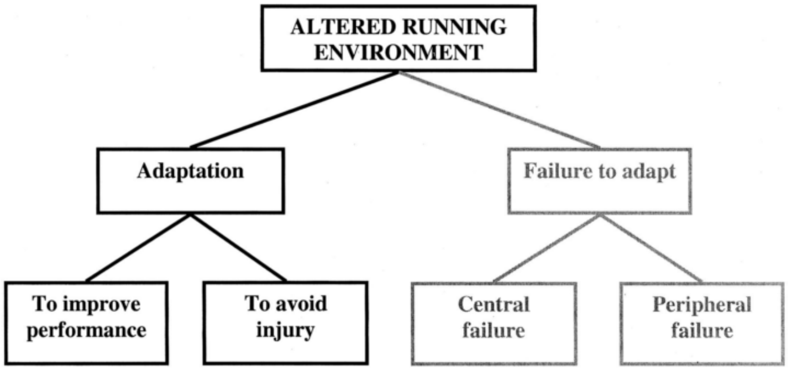


Figure 2.4 Model for adaptation to running environment. An altered running environment forces the runner to make kinematic adaptations to avoid injury and improve performance. Adapted from (Derrick, 2004).

Derrick's (2004) model suggests that runners who fail to adapt their running kinematics to altered environment may have an increased potential for impact-related injury. Derrick (2004) proposed that most runners will successfully adapt their running kinematics in response to a changing environment by maintaining impact severity below a certain threshold level. Altered running environment could be result from either internal or external changes (Derrick, 2004). Fatigue, injury, uncertainty, frailty, pain, and stress levels are all examples of possible changes to a runner’s internal environment. Light intensity, temperature, shoe selection, and surface selection are examples of possible external changes to an environment (as mentioned in the previous section, some runners adopt greater knee flexion angles when running on softer sport surfaces compared to harder asphalt) (Dixon *et al.*, 2000).

Over a series of different testing protocols, Derrick (2004) showed that runners increase their knee flexion contact angle on average by 2.5 degrees in response to internal factors such as increased fatigue and altered stride length, as well as in response to external factors such as irregular surfaces or longer grass compared to smooth surfaces or shorter grass. Although a 2.5 degree change in knee flexion at contact appears to be minimal at first glance, simulation models have calculated an associated 170 N decrease in impact force (Gerritsen, Bogert, & Nigg, 1995).

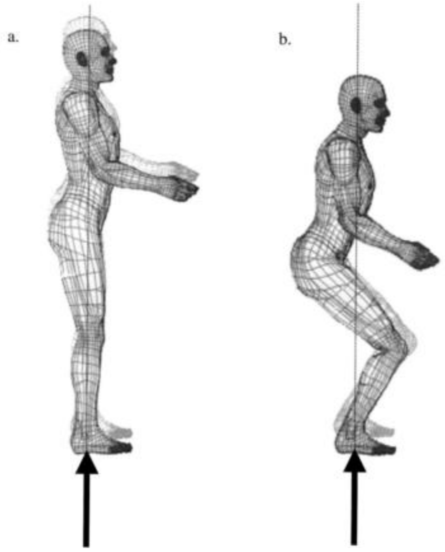


Figure 2.5. Effect of knee contact angle on the line of action of the vertical ground reaction force (vGRF): a) landing with an extended knee result in the line of action going through the joint centres; b) landing with a more flexed knee shifts the line of action of the vGRF posterior to knee joint centre. Adapted from Derrick, (2004).

Mechanically, increasing knee flexion at contact showed to minimise the effective mass of the lower limb that needed to be decelerated at impact. A more flexed knee at contact was also said to allow for maximised stretching of the elastic components of the musculoskeletal complex and thus greater muscular energy absorption. In contrast, landing with a more extended knee at contact caused the line of action of the vertical impact force to go through the joint centres of the ankle, knee and hip. An extended knee at contact also caused the entire lower limb (effective mass) to be decelerated and thus resulted in greater impact force (Figure 2.5). Runners who are not able to adapt to increase their knee flexion angle in response to the various altered environments were termed “adaptation-failures”. Derrick (2004) noted that adaptation-failures are a more difficult population to study, and called for future research to be done on runners who do not successfully adapt to environmental changes.

Increased performance through adaptation to environment is the second outcome proposed by Derrick (2004). In the same study, runners adapted their knee flexion at mid-stance by 4.9 degrees in response to the various altered environments. This increased knee flexion at mid-stance was also shown to correlate with knee flexion at contact (r = 0.67). Therefore, runners were adapting to their altered environment by increasing their knee flexion from contact through to mid-stance. However, Valiant (1990) estimated that every 5 degree increase in mid-stance knee angle predicted a 25% increase in oxygen consumption. Although there are scientific investigations to support this estimation, it still suggests that adaptations in knee flexion angle at contact were an unlikely method to improve performance.

Footstrike kinematics

Forefoot and midfoot running is another kinematic adaptation available to a runner. A seemingly obvious notion is that external cushioning under the heel may be pointless for runners who do not land with their heel first (Mcpoil, 2000). There is only a small percentage of runners who do not land on their heel first when in running shoes (Altman & Davis, 2011; Hasegawa *et al.*, 2007). Notwithstanding, runners are able to consciously adapt their running styles in a manner that may promote active impact force attenuation. Footstrike patterns can be categorised accordingly. A rearfoot strike (RFS) where the heel hits the ground before the ball of the foot does (heel-toe run); a midfoot strike (MFS) where the foot lands flat on the ground (simultaneous landing of the heel and ball of the foot); a forefoot strike (FFS) occurs when the ball of the foot strikes the ground before the heel, and a toe strike is when the ball of the foot lands first but the heel never touches the ground (Altman & Davis, 2011; Lieberman, 2012). Running speed appears to be a primary factor affecting footstrike pattern. Sprinters typically prefer midfoot or forefoot landings over rearfoot landings (Novacheck, 1998). In addition, the percentage of runners who uses midfoot and forefoot strike increased as speed increased during a half marathon (Hasegawa *et al.*, 2007) or along a laboratory runway (Stefanyshyn & Nigg, 1998).

Altering footstrike pattern may have an effect on injury frequency and location. Habitual forefoot strike runners may be less inclined to develop overuse running injuries. A recent retrospective cohort study (Daoud *et al.*, 2012) tracked the injury prevalence of 52 middle to long distance athletes (age 17.75 - 22.5 yrs.) and found that those who were natural rearfoot strikers (n = 36; 59%) in their running shoes had approximately twice the rate of repetitive stress related injuries compared to those who were natural forefoot strikers (n = 16; 31%). This link between forefoot striking and reduced running-related injury was believed by the investigators to be due to altered lower extremity kinematics and kinetics at impact.

If forefoot runners have fewer injuries than rearfoot runners, then it is plausible that converting to forefoot running may be an effective injury management modality. Diebal, Gregory, Alitz and Gerber (2012) found that six weeks' transitioning to forefoot strike running resulted in 10 patients with chronic exertional compartment syndrome (CECS) having significantly reduced intra-compartmental pressures and perceived pain. All patients before the intervention were natural rearfoot strikers at the start of the study. Forefoot strike training consisted of three sessions per week of 45 min each. These authors explained that with forefoot striking, there is more pantarflexion at footstrike, and that this would reduce the activity of the anterior leg compartment leg muscles, thus decreasing symptoms related to CECS.

Kinematic differences between rearfoot and forefoot running may help explain differences in injury prevalence. RFS runners typically land with an extended knee, with the ankle dorsiflexed, and with the foot in front of both the knee and the hip (Daoud *et al.*, 2012). The ankle then remains dorsiflexed during the impact (absorption) phase which results in a stiffer ankle (Lieberman, 2012). In contrast, FFS runners land with a more flexed knee and plantarflexed ankle, with the foot contacting the ground below the 4th and 5th metatarsals (Lieberman, 2012). Greater plantarflexion has also been shown to correlate with high strike index (SI) seen in forefoot strikers (Altman & Davis, 2011). Thereafter, the FFS runner everts and dorsiflexes the foot briefly during load acceptance (impact), resulting in greater ankle and knee compliance (Daoud *et al.*, 2012).

Profound kinematic adaptations from rearfoot to forefoot running consequently have large effects on the vertical GRF–time curve: forefoot running eliminates the VIP all together. Oakley and Pratt (1988) investigated how instructing a runner to land with their forefoot first would affect his or her impact forces. The experimental set-up, as previously explained, involved 18 participants running over a force plate striking with their right leg first. The footwear conditions were also the same, incorporating three different types of insole materials (placed in socks) and a barefoot condition. Over all footwear conditions, forefoot running was shown to eliminate the VIP all together, with a very large decrease (760%) in VALR when compared to landing with their heel first. In addition, this large decrease in impact force was analogous between all footwear conditions, including barefoot. This suggests that impact forces will be reduced while running with a forefoot strike, irrespective of whether cushioned insoles are worn or not.

The elimination of the VIP during forefoot running may be explained by the decrease in effective mass. Effective mass is defined as “the mass that is primarily involved in the initial deceleration process and is decelerated to a zero velocity during impact” (Nigg, 2010: 9) and usually ranges between 5 and 15 kg, depending on running style (Denoth, 1986). In forefoot running, the effective mass may be as low as 0.5 to 2 kg, whereas rearfoot running may be as high as 20 kg (Nigg, 2010).

Even with a large decrease in effective mass, one should acknowledge that a shift in kinematics ultimately leads to a shift in impact load distribution and internal resultant forces. Using a free body diagram, Nigg (2010) estimates the internal Achilles tendon force during a forefoot landing to be 2.5 times body weight. In contrast, internal Achilles tendon force was absent in a rearfoot landing, although a smaller internal tibialis anterior force of 1.5 times body weight was evident. Similarly, in rearfoot strike runners the ankle joint resembles a small net dorsiflexor moment (torque) during the loading (impact) phase of stance (Hamill & Knutzen, 1995) where the forefoot is lowered to the ground under the control of eccentric contraction of the anterior tibial muscles (Novacheck, 1998). In contrast, there is no initial dorsiflexor moment (torque) during a forefoot strike because initial contact is on the forefoot followed by immediate dorsiflexion (Novacheck, 1998). Oakley and Pratt (1988) explain that along with proprioceptive compensation, joint position, and muscles tone, forefoot striking is an active mechanism of shock attenuation. This may be accomplished by using eccentric contraction of the plantarflexor muscles to absorb and store work and then later be used to absorb impact shock. In contrast, landing with the heel first uses more passive shock attenuation, similar to that of the elasticity of bone, cartilage, and soft tissue; the shock absorbing role is taken on passively by the heel pad.

Those attempting to transition to forefoot running should do so with caution, and acknowledge that an adaptation period may be necessary. This observationis founded on the idea that increased internal resultant forces and eccentric action in the Achilles tendon may predispose newly transitioned forefoot runners to injury. Novacheck (1998) stated that a forefoot landing exaggerates the eccentric function of the gastroc-soleus-Achilles' tendon complex as the heel is lowered to the ground (Novacheck, 1998). This may increase the risk of Achilles tendonitis (Oakley & Pratt, 1988). Williams *et al.* (2000) caution that runners should be aware of possible gastroc-soleus problems related to the additional eccentric activity when converting from a rearfoot to a forefoot strike, and even state that novice forefoot strikers may initially overwork the gastrocnemius and be predisposed for Achilles tendonitis. Their conclusions were drawn on reports from their participants who experienced fatigue of calf musculature, and delayed onset muscle soreness when attempting to complete a 20 minute run with FFS for the first time.

In agreement, Gruber, Davis and Hamill (2011) state that FFS running may increase its reliance on active structures (eccentric muscle contractions, and kinematic adjustments) to dissipate low frequency impacts, and thus may contribute to injuries such as muscle strain or tendonitis. In comparison, RFS running may increase the reliance on passive structures (bone and articular cartilage deformation) to dissipate high frequency impacts, and thus may contribute to bone-related injuries. These investigators based their statements on results from their laboratory which showed that the sum of amplitudes for high frequencies (13 – 39 Hz) were 97% lower, while forefoot striking compared to rearfoot striking. The sum of amplitude for low frequencies (5 – 7 Hz) was 21% higher for forefoot striking compared to rearfoot striking.

Some runners may benefit most from finding a balance between rearfoot and forefoot striking. Altman and Davis (2009) speculate that midfoot striking would be a good compromise to reduce the susceptibility of injury found on the extremes of footstrike patterns. In their preliminary study, five healthy runners (three men) with a mileage of at least 26 km/wk (age 26.8 ± 4.8 yrs) were recruited to compare the effects of footstrike patterns on impact force components. Their participants performed 15 minutes of instrumented treadmill running at self-selected speeds (2.3 - 3.3 m/s), which was equally divided among three RFS, MFS, and FFS conditions. A one minute rest period which consisted of walking was given between each condition. Five consecutive strides per condition were recorded. Due to low participant numbers, results were evaluated qualitatively, in that a difference greater than 10% was meaningful. As expected, the VIP was shown to be absent during the forefoot landing (Figure 2.6) in accordance with Oakley and Pratt (1988). In addition, forefoot landings resulted in a drop of at least 10% in instantaneous and average loading rates across all participants. Findings for midfoot landings were characteristically individual. Three of the participants had impact force magnitudes and rates that fell directly in between those of rear and forefoot landings. However, two participants reacted differently to the hypothesized results, as their midfoot landing actually had the highest VALR. The authors speculate that these two interestingly high midfoot impacts were most likely due either to feeling uncomfortable with the MFS landing method, or because they lifted their toes prior to landing.

A final factor to consider regarding footstrike pattern is the metabolic influence. Ardigo, Lafortuna, Minetti, Mognoni and Saibene, (1995) found total external and mechanical work to be higher during forefoot than rearfoot running by 7 – 12% across speeds ranging from 2.50 m/s to 4.17 m/s. However, no differences in oxygen uptake between forefoot and rearfoot running were seen among the eight recreational runners. Similarly, Perl, Daoud and Lieberman (2012) found no differences in oxygen consumption between forefoot and rearfoot running in conventional shoes when participants ran at 3.0 m/s on a treadmill. Ardigo *et al.* (1995) contend/allege that although forefoot running increases the mechanical work needed against gravitational and inertial forces, it allows for a higher storage and release of mechanical energy from the elastic structures of the lower leg. They further suggest that forefoot running should be an obligatory choice for both sprinters and middle distance runners to achieve higher speeds.

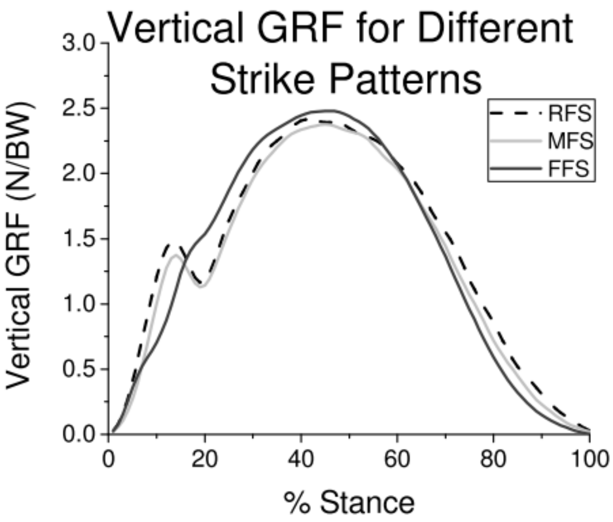


Figure 2.6 Vertical GRF for rearfoot (RFS), midfoot (MFS), and forefoot strike (FFS) patterns. Note the progressively decreased impact peak between the rearfoot, midfoot and forefoot strike patterns. Adapted from (Altman & Davis, 2009).

In conclusion, forefoot striking appears to eliminate the VIP all together, while decreasing loading rates up to 7.6 times. While forefoot landing may decrease external impact forces, internal force in the Achilles tendon will consequently increase. Nevertheless, forefoot running does not appear to have a metabolic affect. Midfoot landing may be a good compromise between the two extremes of landing techniques. However, it should be cautiously noted that there is large individual variation in impact force among those who land on their midfoot and that there is insufficient data to draw accurate conclusions.

Stride kinematics

Step length and step frequency are the primary components of running velocity (Mercer, Devita, Derrick, & Bates, 2003). Understanding the fundamentals of step length and step frequency are essential to understanding their effects on impact force attenuation or injury prevention (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011; Mercer *et al.*, 2003). A step can be defined as the sequence of events which occurs within successive foot contacts of opposite feet, while a stride is the sequence of events taking place between successive footstrikes of the same foot (Neumann, 2010: 631). Step frequency, otherwise known as cadence, is quantified as the number of steps per minute (Neumann, 2010: 631). It has been suggested that by increasing one's step frequency, running injury may be prevented (Heiderscheit *et al.*, 2011; Romanov, 2002).

By increasing preferred step frequency, step length will decrease, and subsequently decrease impact load on the body (Derrick, 2004; Hamill, Derrick, & Holt, 1995). Mercer *et al.* (2003) explain that a decrease in step length would also decrease the perpendicular distance between the line of action of the resultant GRF and knee joint centre of rotation, which would subsequently decrease the need of the knee extensor moment to counteract the impact force and prevent collapse of the lower extremity, resulting in a smaller amount of energy absorbed by the knee.

Increased step frequency has been shown to reduce the occurrence of impact transients and impact absorption at the knee. Heiderscheit *et al.* (2011) comprehensively investigated the effects of various step rates on lower extremity joint loading. Three-dimensional kinematics and kinetics were recorded from 45 recreation runners (25 males; age 32.7 yrs) at fixed speeds while running on a treadmill. Various step rates (preferred, ± 5%, ± 10%) were used to test their hypothesis that decreased impact loading at the knees would occur when step rate was increased. Their results found pronounced kinematic adjustments when their runners increased their step rates, with significantly reduced step length, centre of mass excursion, and knee flexion angle at contact. The finding of increased knee flexion at contact further supports the theory of internal adaptation purposed by Derrick (2004). While VIP and VALR were not directly measured in this study, the frequency of occurrence of VIPs were recorded and tallied. When running at normal step frequency, only 22% rarely had a VIP. When running at 5% and 10% higher than preferred step frequencies, 42% and 56% of participants rarely had VIP's. In contrast, when running at 5% and 10% lower than preferred step frequencies, 31% and 34% of participants rarely had VIP. This shows that the occurrence of VIP diminishes as step frequency increases. The lack of VIP also suggests that VALR would have decreased due to the lack of steep impact transient. Inverse dynamics was also used to calculate joint moments and powers of the lower extremity. Impact absorption at the knee decreased by 34% when preferred step rate increased by 10%. Additionally, the heel was located more towards the bottom of the COM at initial contact, which most likely caused the observed reduction in braking impulse.

An important issue regarding the benefits of increased step frequency that is worth mentioning is the corresponding increase in the number of steps required over a specific distance. Heiderscheit *et al.* (2010) cautioned that this accumulation of steps could potentially offset any perceived advantages of injury reduction, as cumulative loading on the lower extremity may be identical over the same running distance. However, decreasing step length while running has been marked as a potential mechanism to reduce bone strain and tibial stress fractures in runners (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009). Specifically, reducing step lengths by 10% was predicted to reduce the probability of attaining tibial stress fractures by 3 - 6%, despite the corresponding increase in number of load cycles (Edwards *et al.,* 2009). Thus, as Heiderscheit *et al.* (2011) acknowledged, reducing the magnitude of loading may still be beneficial to the runner, even with the accumulated number of loading cycles.

Another aspect to consider with alterations in step frequency is its metabolic consequence and effect on performance. Based on the higher ratings of perceived exertion (RPE) values experienced by their participants when adopting 10% higher step frequencies, Heiderscheit *et al.* (2011) speculate that dramatically increasing one’s step frequency may be difficult to adopt without compromising performance. As stated by Hamill *et al.* (1995), some runners may be reluctant to pay the metabolic price of reducing step length or increasing step frequency to attenuate impact shock. Increased attentional focus with manipulating one’s step length may not be sustainable beyond the short-term (Heiderscheit *et al.*, 2011), and thus may be difficult to maintain throughout an entire training run. To conclude, the studies reviewed suggest that either decreasing one’s step length or increasing one’s step frequency can decrease the impact loads experienced on the knee and may even be effective in the prevention of stress fractures (Edwards *et al.*, 2009; Heiderscheit *et al.*, 2011). However, the possible negative effects on RPE, metabolism, and performance should not be ignored.

This section reviewed the methods of impact force attenuation from both a clinical and performance perspective. Shoe cushioning and agreeable running surface were discussed as examples of passive methods. Both running shoes and softer running surfaces appear to reduce the vertical average loading rate (VALR) but do not affect the magnitude of the vertical impact peak (VIP). The active methods that were discussed were adaptations to joint kinematics. Increasing one's knee flexion angle may decrease the VIP, but there is no literature to confirm a decrease in VALR. Switching from a rearfoot strike to a forefoot strike decreases both VIP and VALR. Furthermore, increasing ones step frequency can reduce the occurrence of the VIP and possibly reduce the VALR. Although focus was drawn to these three kinematic methods, other methods may exist. Different types of footwear or complete lack of footwear may be prominent factors which influence impact force attenuation while running and therefore necessitate evaluation.

C. BAREFOOT RUNNING

There has been a recent surge of interest towards barefoot running among athletes, the media and the sports medicine community (Lieberman, 2012; Lorenz & Pontillo, 2012). A recent survey showed that 75.7% of runners were at least somewhat interested in attempting barefoot running (Rothschild, 2011). Although there is no definite number to the amount of barefoot runners, proponents of the barefoot *movement* suggest thousands are attempting it. Together, the Society of Barefoot Living (http//:www.barefooters.org) and the Barefoot Running Society (www.thebarefootrunners.org) has recruited nearly 6000 members worldwide, including members from countries such as South Africa. The sudden popularity of barefoot running may be due to previous unsuccessful injury prevention interventions such as orthotics or conventional running shoes, anecdotal claims promoting barefoot running, or just curiosity as regards living a more natural lifestyle (Lieberman, 2012). The following section aims to present/analyse claims pertaining to barefoot running, and to critique the body of literature addressing barefoot running from a biomechanical standpoint.

1. Claims

Decreased risk of running-related injury

A recent survey has shown that the primary motivating factor to start barefoot running is to prevent running-related injury (Rothschild, 2011). This generalised assumption possibly stems from a variety of sources, all of which are either anecdotal or the subject of much controversy. Perhaps one of the earliest claims regarding barefoot running and reduced injury rate comes from a single article published in the late 1980s. Robbins and Hanna (1987) provided several examples of unshod populations (Haiti, West Indies, etc.) which appeared to have lower incidences of injury compared to shod populations. However, several researchers have questioned the validity of these reports, suggesting that injury statistics may be obscured in less developed countries where all inhabitants are not able to seek medical attention (Warburton, 2001). Higher injury rates seen in shod populations may also be attributed to other factors such as previous injuries, incorrect fitting shoes, or higher training mileage (Warburton, 2001). Furthermore, it is difficult to determine and compare training surfaces between populations (Nigg, 2010).

Some suggest that this attitude towards barefoot running and reduced injury rate was sparked by Christopher McDougall's *New York Times* best seller, titled *Born to run, the hidden tribe, the ultra-runners and the greatest race the world has ever seen* (Jenkins & Cauthon, 2011; Rixe, Gallo, & Silvis, 2012). McDougall (2010) took note of the Tarahumara Indian tribe of Mexico, who routinely run ultra-marathon distances either barefoot or in thin sandals, and rarely, if ever, get injured. The irony presented is that up to 79% of modern day runners report getting injured yearly (van Gent *et al.*, 2007). There are no scientific reports of injury rates among Indian tribe runners to compare to modern day runners.

Finally, barefoot coaches state that in response to loading the plantar surface of the barefoot becomes tougher and is able to avoid abrasion type of injuries in harsh terrain and environments (Sandler & Lee, 2010; Wallack & Saxton, 2011). Indeed, habitually barefoot populations from Kenya (Lieberman *et al.* 2010) and India (D' Acut, Pataky, De Clercq & Aerts 2009) have been recognised to have thicker, more keratinized skin compared to their habitually shod counterparts. Although indicative, these observations still do not provide evidence that barefoot runners are less prone to injury.

In summary, the reports mentioned above are trivial and have not been supported by case controlled prospective studies. Considering the lack of literature on the topic, it is not safe to say that barefoot runners sustain fewer injuries or are at a lower risk of injury than their shod counterparts. A recent review (Jenkins & Cauthon, 2011) on barefoot running concluded that there is no evidence to confirm or refute fewer injuries in barefoot runners. Similarly, other reviewers on the same topic (Lorenz & Pontillo, 2012) concluded that whether barefoot running has a positive or negative effect on injury has yet to be determined. It is clear that further research on this topic is warranted (Daoud *et al.*, 2012; Jenkins & Cauthon, 2011; Lieberman, 2012; Lorenz & Pontillo, 2012; Nigg, 2010; Rothschild, 2011; Schilling, 2012).

Increased musculoskeletal strength

Barefoot training has been advocated by coaches for decades based on the assumption that it will strengthen the musculoskeletal system and thus contribute to either a reduction in injury or an enhancement of performance (Romanov, 2002; Sandler & Lee, 2010; Wallack & Saxton, 2011). Barefoot training is thought to recruit all the muscles of the ankle as it senses changes in the surface terrain (Hart & Smith, 2008). Nigg (2010) stated that training the small muscles around the ankle can be beneficial. Small muscles around the ankle are responsible for quick joint stability in response to changes in position. These small muscles are not voluntarily selected, but can be trained to increase the general stability of the joint (Figure 2.7).

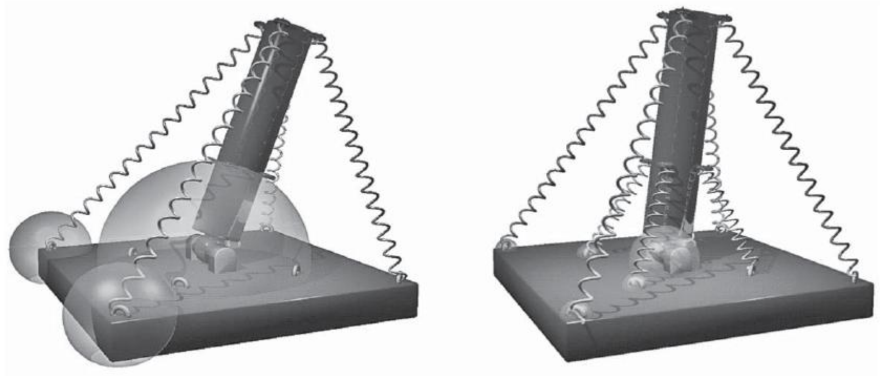


Figure 2.7. The effect of weak (left picture) and strong (right picture) small springs/muscles on forces in the ankle joint and in the attachment locations of the springs (insertion forces). Simulations assume that the smaller springs react faster than large springs. Adapted with permission from Nigg (2010).

A study by Emery, Cassidy, Klassen, Rosychuk and Rowe (2005) reported that the incidence of sport-related injury was less frequent in adolescents who were exposed to wobble board training compared to those who were not exposed to this form of ankle stabilisation training. These authors speculate that the wobble board training increased the strength of both small and large muscles surrounding the ankle joint because of the additional motor control requirements. The assumption that can be made is that barefoot activity functionally trains the smaller muscles surrounding the ankle in similar manner to that of the wobble board training. Indeed, muscles surrounding the ankle have been shown to play a different mechanical role during barefoot running compared to shod running (Kurz & Stergiou, 2004).

Greater eccentric activity and associated increase in eccentric strength of the triceps surae from barefoot locomotion could possibly reduce the likelihood of tibial stress fractures. A study by Divert *et al.* (2005)found muscle activity and eccentric contraction of the calf muscles to be significantly higher when running barefoot compared to shod. Eccentric strength training has been shown to increase cross-sectional area of muscle fibres and is thus beneficial for muscle hypertrophy (Farthing & Chilibeck, 2003; Higbie *et al.*, 1996). While there is no supporting literature, it could be suggested that added eccentric activation of the triceps surae in response to barefoot running could lead to increases in the cross-sectional area of the muscles. Bennell *et al.* (1999) show every 1 cm increase in calf girth to be associated with a four-fold reduced risk of having a running-related tibial stress fracture, and explained that stress fractures could result when the triceps surae are unable to produce adequate eccentric force to counteract the loading at ground contact and excessive bone strain.

Barefoot running enthusiasts claim that the removal of restrictive shoes will allow the foot to recruit more intrinsic foot musculature and thus prevent the incidence of pes planus, otherwise known as flat feet (Sandler & Lee, 2010; Wallack & Saxton, 2011). Sachithanandam and Joseph (1995) reported the prevalence of flat feet to be 1.85 times higher (3.24% vs. 1.75%) in children who start wearing shoes prior to the age of six years, compared to those who only started wearing shoes at the age of 16. In addition, Rao and Joseph (1992) evaluated the feet of 2300 children between the ages of 4 and 13 and showed that the prevalence of flat feet was 3.3 times higher (8.6% vs. 2.8%) in shod children compared to unshod children.

In conclusion, there is some evidence to suggest that barefoot running alters muscle activation patterns and recruits different muscles when compared to that of shod running. However, this does not implicate any reason for reduced running injury or improved performance. Studies that investigate prospective changes in muscles strength through barefoot running would remedy the lack of knowledge on this topic.

Improved running economy

Advocates of the barefoot running community claim that barefoot running is more economical than shod running (Wallack & Saxton, 2011). Several studies have shown that barefoot running results in a diminished cost of oxygen transport and thus improved running economy compared to shod running. Divert measured running economy in 12 habitually shod male runners at 3.61 m/s barefoot, in socks (50, 150 and 350 g), and in shoes (150 and 350 g). Barefoot running resulted in 3% less VO_2 compared to in the 350 g shoes or in the 350 g socks. The investigators primarily attributed the cost difference to the mass effect. Similarly, Squadrone & Gallozzi (2009) found eight experienced barefoot runners to be 1.3 – 2.8% less costly when barefoot compared to shod (341 g shoe) when running at

3.33 m/s on a treadmill. Furthermore, Hanson *et al.* (2011) show improved running economy when 10 healthy recreational runners performed barefoot running over both treadmill and over-ground surfaces. Their participants were required to run six minutes for each experimental condition at 70% VO_2 max. Barefoot running reduced VO_2 by 5.7% and 2.0% when running over-ground and on treadmill compared to shod running. No interaction effect was found between the footwear condition and the training surface.

Perl, Daoud, & Lieberman (2012) point out several factors that are likely to complicate interpretation of the aforementioned results. The first of these is the mass effect of the shoe. The energy demand of running typically increases by 1% for every 100 g added by a running shoe (Divert *et al.*, 2008; Frederick, 1984; Nigg, 2010). Therefore, the decreased cost of running barefoot compared to shod could purely be as a result of the removal of the additional mass of the shoe. Both Squadrone & Gallozzi (2009) and Hanson *et al.* (2011) did not control for shoe mass. Nigg (2010) also found that the effect of mass on the economy of runners increases as running speed increases (Nigg, 2010). The second confounding factor highlighted by Perl *et al.* (2012) is that footstrike pattern may have an effect on running economy. Divert *et al.* (2008) mention that 75% of their participants had no clear VIP when barefoot or in socks. This suggests that the 3% improved running economy could have been due to the change from a rearfoot strike (RFS) in shoes to a forefoot strike while barefoot (FFS). In addition, Squadrone & Gallozzi (2009) reported that their experienced barefoot runners switched from a RFS to a FFS pattern from the shod to barefoot condition. Moreover, although the barefoot condition in the investigation done by Hanson *et al.* (2011) was overall 3.8% more economical, foot strike pattern was uncontrolled for.

Others speculate that barefoot is more economical due to the engagement of the elastic recoil ability of the tendons, ligaments and muscles. Barefoot running with a forefoot strike is said to allow for more elastic energy storage and return of the Achilles tendon as the heel is smoothly lowered to the ground (Perl *et al.* 2012). This elastic energy recoil may offset any additional energy costs caused by the triceps surae muscles from the increased internal plantarflexion torque. Specifically, the Achilles tendon is able to recover up to 35% of mechanical energy with each step (Ker, Bennett, Bibby, Kester, & Alexander, 1987). The Achilles tendon can also produce forces of up to 2.5 times body weight when a runner utilizes a forefoot strike (Nigg, 2010). In contrast, shod running with an elevated heel promotes a rearfoot strike and limits ankle dorsiflexion during stance, which is said to lessen the Achilles strain at impact and thus negate both its ability to store and recoil energy (Perl *et al.* 2012) or produce force (Nigg, 2010). Furthermore, barefoot running could be more economical due to the greater utilization and elasticity of the plantar fasia with the aid of the instrinsic foot musculature (Robbins & Hanna, 1987).

This claim that barefoot running leads to improved running economy appears to be supported by the literature, yet the mechanisms that accommodate this remain unclear. There appears to be an inconsistency in study protocols that make comparisons between studies difficult. Several other factors such as footstrike pattern, shoe mass, and Achilles tendon strain should be a consideration when comparing barefoot and shod running economy.

2. Effect on impact force attenuation and joint moments

Evolutionary theory contends that an evolved, more efficient barefoot running form which eliminates vertical impact force peak and decreases impact rate of loading may allow for a reduced risk of running injury (Lieberman, 2012). However, barefoot running may not induce instinctive changes in running gait or diminish impact force in those who have spent their entire life running in shoes (Wallack & Saxton, 2011). Similarly, Saxby (2011) states that modern running shoes have caused humans to forget how to run. Some runners may therefore lack the intuitive ability to make kinematic adjustments and impact moderating behaviour when running barefoot, and instead experience similar, if not larger impact forces compared to how they ran when shod.

It is suggested that barefoot running induces gait alterations that reduce impact forces and thus running-related injury (Sandler & Lee, 2010; Wallack & Saxton, 2011). This theory is based on the hypothesis that the human body makes kinematic alterations in response to the perceived severity impact forces experienced during barefoot running (Kurz & Stergiou, 2004). This assumption would agree with the adaptation model proposed by Derrick (2004), i.e. the removal of cushioned, protective running shoes would represent a change in external environment, which would raise perceptual uncertainty in the runner, causing protective kinematic adaptations to occur to avoid high impact forces and injury.

The following section tests the hypothesis that runners with more experience in barefoot running have a greater propensity to attenuate impact force compared to novice barefoot runners. The impact moderating behaviour model will be used to evaluate this hypothesis. In keeping with Derrick's (2010) model of kinematic adjustments, the term "adapters" will be assigned to runners who are able to naturally alter or change their barefoot running kinematics (knee flexion angle, ankle plantarflexion, stride characteristics) and subsequently attenuate impact force. The term "adaptation-failures" will be given to runners who are not able to adapt to barefoot running. The following section divides barefoot running according to level of experience, namely novice (acute or immediate changes without any experience), experienced (long-term or trained effects over a substantial period of time), and short-term adaptation (the period or process between acute and long-term effects). Literature that reports on the lower limb kinematic and kinetic adaptations to barefoot running will be discussed.

Innate behavioural impact moderation theory

Innate impact moderating behaviour has been described as a form of altered neural-mechanical behaviour (Divert *et al.*, 2005). Robbins and Gouw (1991) proposed the theory of innate behavioural impact moderation:

> "In humans, avoidance of uncomfortable or painful but locally innocuous plantar cutaneous tactile stimuli moderates shock on subsequent impacts when humans walk, run, or jump

> repetitively. This feedback control circuit is optimized in terms of protection for mechanical interaction of the barefoot and natural surfaces. Eventually learning allows anticipatory avoidance. Modern athletic footwear is unsafe because it attenuates plantar sensations that induce the behaviour required to prevent injury" (Robbins & Gouw, 1991).

The feedback control circuit begins when a runner uses a rearfoot strike landing technique in the barefoot condition, causing deformations and distortions of the plantar skin and heel fat pad (Figure 2.8). Plantar skin deformation is sensed by the cutaneous mechanoreceptors, which respond to the vibrations, touch, pressure and tension experienced (Saladin, 2007). In addition, plantar pain is sensed via the nociceptors, which respond to cutaneous tissue damage resulting from trauma (Saladin, 2007). Pain signals from the plantar surface of the foot travel by way of the spinal cord tracts, known as the spinolathamic and spinoreticular tracts respectively (Saladin, 2007). The pain signal is relayed through the central nervous system to the cerebral cortex where pain is made conscious (Saladin, 2007).

Robbins and Gouw (1991) opine that once these spinal reflexes and central processes are interpreted as pain signals, the runner will be able to perceive the higher plantar discomfort and adjust behaviour (running style) accordingly. Cole, Nigg, Fick and Morlock (1995: 57) are of the agreeing opinion that "the human body makes kinematic adjustments according to the severity of the perceived impact". Indeed, pain signals activate emotional and behavioural reactions such as fear and reflex responses (Saladin, 2007). Behaviours such as landing height moderation, greater amounts of knee flexion at footstrike, and intrinsic foot shock absorption are impact moderating strategies proposed by Robbins and Gouw (1991). Greater knee flexion at contact due to an altered environment supports Derrick's theory/findings (2004). These kinematics strategies are then said to have control over the high impacts over subsequent impacts through the learning of anticipatory avoidance (Robbins & Gouw, 1991). Thus, the barefoot runner will learn to avoid landing on the heels to avoid pain and local deformations through coordinated motor control. These authors further propose that modern footwear is unsafe because it diminishes plantar sensations such as discomfort and pain that are needed to induce impact moderating behaviour required to prevent injury.

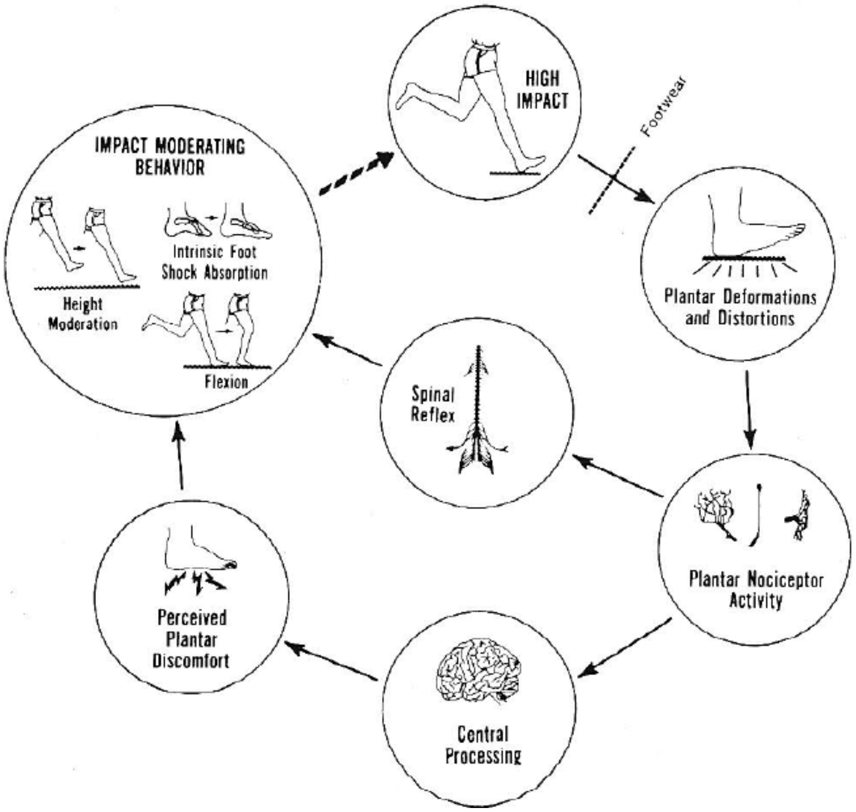


Figure 2.8 Feedback circuit model of innate behavioural impact moderation. Dotted line indicates how footwear diminishes plantar deformations and distortions and the rest of the feedback circuit. Dotted arrow indicates how a barefoot runner learns to avoid rearfoot striking through impact moderating behaviour. Adapted with permission from Robbins and Gouw (1991).

Novice barefoot running

It has been speculated that new demands caused by novice barefoot running in habitually shod runners may lead to either beneficial or detrimental effects through repetitive overloading of newly recruited muscles, tendons, and bones (Samawarawickrame, Hashish, & Salem, 2011). Perhaps, the difference between benefit and harm, or positive and negative adaptation depends on a runner’s ability to learn to naturally moderate his or her running gait. On the one hand there is the innate impact moderating theory that states that runners will automatically sense pain while running barefoot and make kinematic alterations to attenuate impact force (Kurz & Stergiou, 2004). On the other hand there is the preferred movement path theory in which runners will maintain similar running kinematics while barefoot and not attenuate the impact forces (Nigg, 2010). The following section aims to shed light on these two theories and to provide evidence to support them.

One particular study is in support of the innate impact moderating behaviour theory. Hamill *et al.* (2011a) investigated the footstrike patterns and impact forces of 10 experienced shod rearfoot striking runners (5 men). Three shod conditions, differing only in midsole thickness, were compared to a barefoot condition. No instructions were given on how to contact the ground (footstrike pattern) while running in any of the footwear conditions. Participants ran along a 25 m runway (force plate 14 m from the start) at both self-selected and controlled speeds. Ten trials per condition were recorded for each participant. A satisfactory trial was one where a right foot contacted the force platform cleanly within 5% of the prescribed running speed without modifying their gait. Participants rearfoot struck (RFS) in all three shod conditions (strike index < 33% and ankle dorsiflexion angles at initial contact 11.14 ± 4.46 degrees) at preferred running speeds. In the barefoot condition, however, the participants landed with a mid to forefoot strike as indicated by a significantly more plantarflexed ankle position at contact (-7.13 ± 3.00 degrees) and a strike index (> 33% but < 66%) which verified a midfoot strike (MFS) running pattern. To accommodate this midfoot landing, a significantly stiffer ankle was shown in the barefoot condition. Moreover, loading rates were significantly lower (215%) when the participants ran barefoot compared to all three shod conditions combined (30.43 vs. 65.62 BW/s). Similarly, the magnitude of the VIP was significantly reduced by up to 31% of body weight when the participants ran barefoot. Midfoot strike (MFS) landings and increased ankle stiffness seemed to be the adaptation strategy adopted by these participants in response to novice barefoot running. The authors explained that the observed VIP while running barefoot was due to the heel touching down after the initial midfoot contact, and that greater ankle stiffness is necessary in midfoot patterns to prevent the heel from impacting the ground.

In contrast, other research indicates that the majority of novice barefoot runners fail to adapt their footstrike kinematics. Lieberman *et al.* (2010) had eight habitually shod runners (six men; minimum mileage 12 ± 6 km/wk; age 19.1 ± 0.4 yrs) run down a 20 – 25 m track at self-selected speeds in shod (4.2 ± 0.3 m/s) and barefoot (4.0 ± 0.3 m/s) conditions. Neutral running shoes (Asics ©) were provided and standardised for all individuals. Five to seven trials were recorded for both conditions. Full body kinematics and ground reaction data were recorded. All runners were habitually shod runners, and rearfoot struck 100% of the time in their running shoes. When the runners were asked to run barefoot, ankle plantar-flexion angle increased significantly (9.1 degrees). Additionally, knee flexion angle at contact increased by 3.0 degrees while barefoot. However, even with these kinematic adjustments, only 13% of participants adapted a MFS technique while running barefoot. The remaining 83% continued to land on their heels with a typical RFS technique in the barefoot condition, and amounted to a VALR that was 6.64 times higher than rearfoot striking while shod (483.1 vs. 69.7 BW/s). Such high differences in RFS loading rates have been mentioned earlier where participants were instructed to land on their heels (Oakley & Pratt, 1988).

Kinematic strategies such as increased knee flexion angle at contact, a midfoot shifted landing, and shortened step lengths may not be enough for novice barefoot runners to attenuate impact force. De Wit, De Clercq and Aerts (2000) found significantly higher vertical loading rates of 294% (449 ± 139 vs. 91 ± 35 BW/s) when novice barefoot running was performed compared to a conventional shod condition. Their study population consisted of nine trained male long distance athletes (running 30 - 40 km/wk; age 27.3 ± 9 yrs) accustomed to running shoes. Impacts were recorded over a force plate imbedded in a 30 m laboratory runway. In addition, a foot-scan pressure mat was placed on top of the force plate to measure the local pressure under the heel. Runners were instructed to land with their right foot ten times without altering technique, within the force plate/pressure mat area at running speeds of 3.5 m/s ± 5%. Running speed was monitored with timing gates. Two-dimensional kinematics simultaneously recorded the foot movements in the sagittal and frontal plane. Kinematic results showed that when the participants ran barefoot they adopted a flatter foot placement by significantly increasing ankle plantarflexion by 8.3 degrees and knee flexion by 2.3 degrees. Although the participants adopted a more midfoot strike (MFS) pattern, their magnitude of VIP did not change.

Spatio-temporally, participants increased their step frequency when running barefoot by 3.8% (164.4 ± 10.2 vs. 158.4 ± 10.8 steps/min), which consequently reduced their step lengths (Heiderscheit *et al*., 2011). However, even though statistically significant kinematic alterations were seen during novice barefoot running, it was not sufficient to decrease VALR. This suggests that there may be a minimum practical threshold for impact attenuating behaviour which these participants did not achieve. For example, runners may need to decrease their step length by at least 5% for VALR to be attenuated, compared to the 3.8% observed.

Significantly shorter stride lengths in novice barefoot runners predicted lower peak hip and knee flexor joint moments. Kerrigan *et al.* (2009) had their 68 (32 men) habitually shod runners perform instrumented treadmill running while barefoot or in a well cushioned (24 mm heel) control shoe while three-dimensional kinematics were recorded using a Vicon ® motion capture system. All participants (age 34.0 ± 11.3 yrs) that ran a minimum of 24 km/wk were included. Peak joint torques of all three planes of motion were calculated bilaterally using an inverse dynamics modelling approach. Ten consecutive gait cycles were recorded for each footwear condition. Their results showed that torque at all three lower extremity joints (hip, knee and ankle) during the stance phase of the gait cycle decreased when running barefoot compared to shod. The most significant differences were observed with the external knee varus torque, the knee flexion torque, and the hip internal rotation torque which decreased by 38%, 36%, and 54% respectively. Additionally, maximum vertical GRF (active propulsive peak) was lower in the barefoot condition (2.29 ± 27.7 BW vs. 2.38 ± 25.8 BW). Stride lengths (SL) were found to be 6.5% shorter in the barefoot condition compared to shod, which was partially responsible for some of the lower joint torques due to the correlations observed (SL vs. Knee varus torque: R = 0.29; hip internal rotation torque: R = 0.32; and vertical GRF max: R = 0.59). In contrast to De Wit *et al.* (2000), these novice barefoot runners may have achieved a minimum practical threshold required for reduced stride length to have an effect on joint torque.

Adaptation from a rearfoot to forefoot strike technique could account for decreased ankle dorsiflexion joint moments in novice barefoot running. Samawarawickrame *et al.* (2011) recruited three experienced shod participants (aged 40, 34 and 26 yrs.; one man) who had a training history of at least 12 km/wk running mileage. These investigators asked their participants to perform six to eight trials of over-ground barefoot and shod running at self-selected speeds. Although not mentioned, it is assumed that running in their testing laboratory was performed on a hard surface. Three-dimensional kinematic data were recorded and synchronised with a force plate. Data were reported for the right limb only. Standard inverse dynamics was used to calculate joint moments of the foot and ankle. Average self-selected speeds were similar between footwear conditions (barefoot 4.26 m/s vs. shod 4.23 m/s). Their sagittal plane kinetic data showed that the initial dorsiflexion moment experienced at the initial 20% of stance was significantly reduced by 20 - 23% (ES = 8.0) while running barefoot compared to shod. This may be explained by the sagittal plane kinematics, which showed that all three (100%) of the participants shifted from a rearfoot strike to a forefoot strike when running barefoot, as indicated by the significantly more plantarflexed ankle angle (115 – 340%; ES = 7.8) at contact compared to the shod condition. Differences were also apparent in the frontal plane. Peak ankle inverter moment during the stance phase was higher while barefoot compared to shod running (9 – 92%; ES = 1.4). This finding could be due to the 120 – 667% (ES = 3.4) increase in the ankle inversion angle at ground contact when the participants were running barefoot. Although a small sample size, the results of this particular study give further insight into the new demands which occur specifically at the ankle in the sagittal and frontal plane when running barefoot.

High individual variation may help explain why footstrike kinematics in novice barefoot runners does not predict impact loading rate. Becker *et al.* (2011) related footstrike patterns to vertical instantaneous impact loading rate (VILR) in 22 competitive shod runners (mileage >32 km/wk). Full body three-dimensional kinematics and GRF were recorded as participants performed continuous laps around a 25 m laboratory track. Running speed was self-selected and approximated to each participant's normal training run pace. Left and right legs were analysed separately.

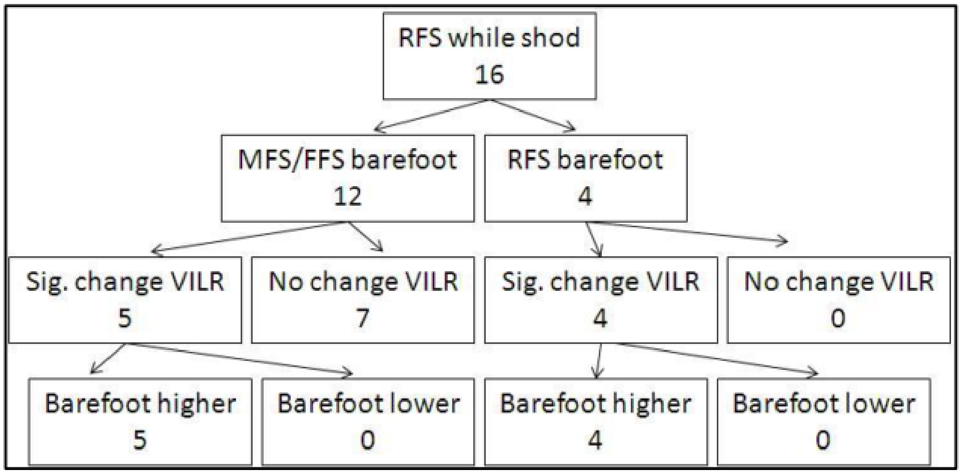


Figure 2.9. Changes in impact loading rates when shod rearfoot strikers ran barefoot. Shod runners either adapt to forefoot-midfoot strike (FFS/MMS) or fail to adapt by maintaining rearfoot strike (RFS). Adapted from Becker *et al.* (2011).

Of the 22 participants, 16 were rearfoot strikers while shod (Figure 2.9*).* Of these, four (25%) remained rearfoot strikers during novice barefoot running, and had significantly higher VILR compared to when they ran shod with a RFS. The remaining 12 (75%) participants naturally adapted to either an MFS or FFS while running barefoot. Contrary to what was expected, none of these 12 adaptors decreased their VILR by using an MFS/FFS pattern. Rather, VILR remained unchanged in seven, and significantly increased in the other five footstrike adaptors. These results reiterate that VILR can be considerably varied between novice barefoot runners.

For barefoot running, the surface may be the strongest predictor of footstrike pattern (Nigg, 2010). The harder the surface while running barefoot, the more likely the runner is to avoid landing on the heel in an attempt to avoid pain (Hamill, Gruber, Freedman, Bruggemann, & Rohr, 2011). As Nigg (2010: 200) questioned, "is it a genetically determined preference for one landing over the other, or is it an adjustment to running surface?" A study by Hamill, Gruber, Freedman, Bruggemann and Rohr (2011) showed that footfall patterns and knee flexion angle at contact for novice barefoot running were merely a function of running surface. Ten healthy college male and females ran barefoot over two surface conditions: one hard (no mat) and one soft (EVA covered mat). Participants ran over both surface conditions at 3.5 m/s ± 5% without any specific instructions on how to land. Vertical GRF components showed that seven (70%) participants had no distinct VIP and thus adapted to land with a forefoot on the hard surface. In contrast, only two (20%) of participants landed with a forefoot technique on the softer surface. This was confirmed with three-dimensional kinematics, as runners on average plantarflexed their ankles by 14.52 degrees more when running on the hard surface. Additionally, runners landed with significantly more knee flexion (15.76 degrees vs. 12.92 degrees) on the hard surface. A second study showed that barefoot running on a hard surface predicts kinematic adaptation. Herzog (1978) instructed 12 runners to jog, run, and sprint on asphalt and grass surfaces. Forefoot landings were observed in 76% of participants when landing on a hard asphalt surface. In contrast, 45% of runners adapted to a forefoot technique when running on soft grass.

In summary, the literature shows that adaptations to impact force in novice barefoot running is highly individualistic and variable (Becker *et al.*, 2011). Each individual may have their own specific or preferred movement path (Nigg, 2010), and therefore respond differently to barefoot running. In addition, barefoot running may be primarily a function of harder surfaces (Hamill *et al.*, 2011b; Herzog, 1978). This being said, impact attenuation and the ability to adapt to correct barefoot running form may be highly individualistic to each runner. The results of the two studies on lower limb joint torques show that adaptation to barefoot running is a highly complex process which involves and affects all of the joints in the lower extremity. However, there are only two studies to report on the effect of barefoot running on lower limb joint torques. In addition, there are no studies which have reported on lower limb joint torques in experienced barefoot runners, or in those who underwent a short-term barefoot adaptation period. More work in this field would certainly help understand inconsistencies found in the literature pertaining to novice barefoot running and vertical impact force.

Experienced barefoot running

Barefoot running experience may be a plausible reason as to why results regarding the innate barefoot running attenuation theory are in such dispute. According to Squadrone and Gallozzi (2009), a major limitation is that no previous studies used participants that had previous experience with barefoot running. Squadrone and Gallozzi (2009) further speculate that runners who are not accustomed to barefoot running have a less efficient barefoot running style as well as a reduced ability to dampen impact shock, due to weakened foot structures and decreased proprioception as a result of long-term footwear use. In agreement, Lieberman (2012) stated that researching only habitually shod runners under acute conditions to study barefoot running could be problematic, as insufficient time has been allowed for the participants to develop musculoskeletal adaptations or kinematic habits similar to that of habitual barefoot runners (Lieberman, 2012). Therefore, habitually shod runners may run differently barefoot and be less equipped to attenuate impact forces initially, compared to those who grew up barefoot or have trained barefoot for a prolonged period of time. For these reasons, studies that make use of runners who have had previous barefoot experience require investigation.

The ability to adapt long-term to barefoot running can be identified from an early age. Lieberman *et al.* (2010) compared Kenyan adolescents (age 11 - 14 yrs) who differed only in barefoot experience. One group of adolescents came from a rural area and had never worn or trained in shoes. The other group of adolescents had the opportunity to wear footwear for most of their childhood. The investigators asked these runners to run barefoot and in shoes over an outdoor dirt track way. Their speeds were self-selected between 5.1 and 6.5 m/s. Five to seven trials were recorded per condition. While running barefoot the adolescents who were habitually unshod adapted to barefoot running by landing 66% of the time on their forefoot, in comparison to the 19% from the shod adolescents. Additionally, ankle plantarflexion was significantly higher (6.8 degrees) in the unshod adolescents.

Barefoot experience during childhood and adolescence may be a primary factor in predicting the ability to adapt to barefoot running in adulthood. The same group of investigators (Lieberman *et al.* (2010)) recruited a population of 14 (13 men) habitually shod adult Kenyan runners (age 23.1 ± 3.5 yrs) to perform the same methodological procedures as the Kenyan adolescents. One difference to most shod populations, however, was that these runners spent their entire childhood and early adolescence unshod. Even though these runners were competitively training in conventional running shoes at the time, 91% of them adapted to the barefoot running condition to land with a FFS. In addition, 78% had maintained either a MFS (18%) or a FFS (54%) when running in the conventional shoe condition. These footstrike patterns were confirmed with two dimensional high speed video which showed extremely large ankle plantarflexion (18.6 degrees barefoot and 15 degrees shod) angles at touchdown. It should be noted that the self-selected speeds selected here were higher than the self-selected speeds used in other studies (De Wit *et al.*, 2000; Divert *et al.*, 2005; Hamill *et al.*, 2011a; Oakley & Pratt, 1988; Squadrone & Gallozzi, 2009), which could account for the higher percentage of FFS runners (Novacheck, 1998).

However, the question remains whether those who have not had the opportunity to run barefoot during childhood and adolescence (i.e. have grown up wearing and training in shoes) can learn to adapt their barefoot technique similarly to those who have had the barefoot experience. Squadrone and Gallozzi (2009) were the first to investigate the lower limb biomechanics of experienced barefoot runners. All eight barefoot runners who participated in their study were male (age 32 ± 5 yrs.) and had completed their 10 km race in 40.3 ± 4 min. Although the exact number of months of barefoot experience of these runners was not specified, some of the participants were routinely running marathons barefoot. To test both kinematic and kinetic differences between barefoot and shod running, an instrumented treadmill with pressure sensors was synchronised with two-dimensional video footage. Treadmill speed was fixed to 3.33 m/s as the running was performed for six minutes in each footwear condition. A third, minimalist shoe condition was also performed, which is discussed in detail in a later section. The study found that their barefoot runners had a high cadence while barefoot (182.4 ± 1.8 steps/min) and shod (172 ± 2.2 steps/min), with barefoot being significantly higher by 6%. In addition, centre of pressure (COP) trajectory data revealed the runners to be midfoot striking in both barefoot (SI 58 ± 6%) and shod (SI 40 ± 6%) conditions. Sagittal plane lower limb joint angles agreed with SI. Knee and ankle angle pre contact (-15 ms) were significantly more flexed (3 degrees) and plantarflexed (7 degrees) while barefoot respectively. Combinations of all the aforementioned kinematic adaptations in the barefoot condition led to a significantly less (6%) VIP magnitude compared to the shod condition. Impact loading rate was not reported.

It is clear that those with barefoot running experience, although spending the majority of childhood and adolescence shod, have the ability to learn to adapt their running style towards the forefoot. Six months' or more barefoot experience appears to be enough to adapt footstrike pattern and attenuate impact forces. In the same investigation by Lieberman *et al.* (2010) alluded to previously, the same procedures under the same experimental setup mentioned was used (indoor runway 20 - 25 m; self-selected speeds; imbedded force plate along a runway). However, this group of participants consisted of previously shod runners who had recently begun training barefoot. Specifically, these runners had to have had at least six months' barefoot running experience and had to have run at least 66% of this time barefoot. These experienced barefoot runners ran along the indoor runway barefoot at self-selected speeds and in their own conventional neutral running shoes . Full body kinematics and ground reaction data were recorded. These recently transitioned barefoot runners adapted to land 75% and 50% of the time on their forefoot in the barefoot and shod conditions respectively. Comparisons regarding external impact forces were made to the 8 habitually shod runners who maintained their RFS in the barefoot condition. The recently transitioned barefoot runners who adopted FFS landings were able to decrease VALR on average by 720% compared to the habitually shod-RFS runners without barefoot experience.

Experience in barefoot running appears to have a beneficial effect on attenuating impact force and provoking kinematic adaptation. Investigating habitually barefoot runners may assist research in barefoot running. Additionally, investigating young, unshod populations could provide some perspective on how humans ran before the invention of modern footwear. One could assume that these perspectives may help establish norms on *true* barefoot running style. It should be noted, however, that more studies are needed to confirm or refute these results.

Training adaptation effect

There are no studies to date that investigate the adjustment of lower limb kinematics or kinetics during the process of runners acclimatizing to barefoot running. Therefore, there are no understandings of how a runner habituated to footwear responds kinematically to the initial few weeks of barefoot training. Each individual may adapt at a different rate, or use different kinematic methods to accommodate the lack of cushioning provided from shoes.

A few runners may learn to adapt their kinematics to barefoot running within one training session. Divert *et al.* (2005) instructed 35 (31 men) habitually shod leisure runners (age 28 ± 7 yrs) to run on a treadmill at a speed of 3.33 m/s. One methodological difference to most aforementioned barefoot running studies is that multiple barefoot strides per foot were performed before kinematic recordings were made. Barefoot and shod (standard cushioned running shoe) conditions were measured for four minutes each to accumulate at least 260 foot strikes per leg per condition. An imbedded treadmill dynamometer measured 3D GRF. Electromyography (EMG) of the plantar flexor muscles were recorded simultaneously for 60 consecutive steps per condition and then analysed. Their results showed that although the rate of vertical impact loading was not different, the magnitude of the impact and propulsive peaks reduced significantly (15% and 5%) when running barefoot. Additionally, barefoot running resulted in shorter contact times (2%) and higher pre-activation of the plantar flexor musculature (medial gastrocnemius 13.7%; lateral gastrocnemius 23.6%; and medial soleus 10.8%). Furthermore, in the anterior-posterior GRF, the magnitude of breaking peak was similar but the magnitude of the propulsive (pushing) peak was 15% higher while barefoot. These authors allege that runners are able to sustain and maintain a high VIP when limited steps are performed, but when multiple barefoot steps are performed, as with increased experience, runners switch from a rearfoot strike to a forefoot strike technique to reduce high mechanical stress at the heel.

It is unlikely that some novice barefoot runners may able to keep the initial kinematic adaptations when fatigue of the lower limb musculatures is experienced, because, for example, adapting to land on the forefoot requires more mechanical work of the calve muscles (Novacheck, 1998). As already mentioned, novice barefoot running requires the lower limb musculature to perform a different mechanical role (Eslami, Damavandi, & Allard, 2006). If calf muscles are weak they may fatigue faster, resulting in localised pain or discomfort. If the novice barefoot runner then persists with a forefoot technique, injury may result to the calf muscles or Achilles Tendon complex (Williams *et al.*, 2000). Research is needed to support this speculation and it should be noted that the relationship between forefoot running, localised fatigue, and injury in novice barefoot running is yet to be investigated.

D. MINIMALIST SHOE RUNNING

A perception that exists among many is that barefoot running is too drastic a change for most shod runners, and that the solution to reducing impact related injury may be to find the common ground between the barefoot and shod condition. In addition, some insist that the risk from acute injury during barefoot running should exclude it as an option, and that footwear protection remains necessary (Kerrigan *et al.*, 2009). As stated by Kerrigan *et al.* (2009), the goal of footwear should be to provide meaningful barefoot functions, while attempting to mimic the natural compliance of the normal foot function. The section that follows discusses the minimalist shoe paradigm according to definition, claims proposed, and their effect on impact force attenuation and joint torques amongst novice and experienced minimalist runners.

1. Minimalist shoes defined

Some consensus exists regarding the definition of minimalist shoes. Hamill, Russell, Gruber and Miller (2011a: 33) define minimalist footwear as “a shoe with a thin, flexible midsole, and outsole, and a light, basic upper with little or no heel counter”. Similarly, Rixe, Gallo and Silvis (2012: 164) stated that “true minimalist shoes are shoes which are lightweight, highly flexible with an expanded toe box, no elevated heel (heel to toe drop < 5 cm), reduced padding, and minimal artificial support (i.e. gel compartments). These combined features allegedly allow the wearer to run barefoot while also protecting them from acute puncturing wounds from the environment (Rixe *et al.*, 2012).

In agreement, Saxby (2011) provides four criteria for a shoe to be called a *barefoot* or *minimal* shoe. Firstly, a shoe should allow for sensory feedback. Secondly, the shoe must protect your foot from punctures or from extreme temperatures that may exist in the running environment. Thirdly, the shoe's weight should not unbalance the foot's natural position, such as heavier running shoes which will often offset the body's centre of gravity and thus affect running style. Lastly, the shoe should not restrict the foot in any way. The toe box of a shoe should be wide enough to accommodate the natural outwards splaying of the toes. Sandler and Lee (2010) designed a minimalist shoe checklist which concurs with these criteria. To be included as a minimalist shoe, it had to be lightweight, flexible, low to the ground and with a wide toe box, while characteristics such as the presence of arch support, motion control features, heavy cushioning, or presence of a heel lift or toe spring were excluded from their checklist.

However, others remain sceptical as to what a true minimalist shoe entails. Rothschild (2011) mentioned that there is no clear definition of a minimalist shoe. This is possibly due to the fact that the minimalist shoe market is saturated with a variety of brands and models with different features (Schilling, 2012). In addition, Nigg (2010) stated that the term "barefoot-shoe" is a contradiction in terms. Minimalist shoes should not be confused with shoes claimed to have a barefoot characteristic or otherwise known as a "barefoot concept". Shoes which have a barefoot concept are shoes which attempt to mimic one specific aspect of the barefoot condition. Nigg (2010: 203) identified three focal barefoot-shoe concepts which shoe companies use to imitate the barefoot condition, namely a) the *shape* of the barefoot, such as the Adidas © *Feet You Wear* concept; b) the *specific kinematics* of the barefoot such as the Nike © *Free* concept; or c) to the *specific feeling* of barefoot movement such as the MTB (Masai Barefoot Technology) concept. However, none of these barefoot-shoe concepts may be suitably called a minimalist shoe, unless they aim to promote a typical barefoot running style pertaining to an experienced barefoot runner (Rixe *et al.*, 2012; Schilling, 2012). Lieberman (2012) agrees with Nigg (2010) that barefoot-shoe is an oxymoron and is partly marketing strategy, yet also recognised a barefoot running style, for which minimalist shoes are most appropriate.

2. Claims

Minimalist shoes have been designed to essentially serve as a safe alternative to barefoot running, which imitates the barefoot condition but is able to maintain the biomechanical performance feature of the running shoe (Paquette, Baumgartner, & Zhang, 2011). Indeed, a shod runner may first wish to run in a minimalist shoe before making the full transition to barefoot running (Rothschild, 2012). There is even the notion among barefoot coaches that minimalist shoes are better than conventional shoes (Sandler & Lee, 2010; Saxby, 2011; Wallack & Saxton, 2011). As a result, many of the claims pertaining to minimalist running stem from barefoot running, such as decreased risk of running-related injury, increased musculoskeletal strength, enhanced proprioception, and improved running economy. These claims form the foundation of why many runners are attempting minimalist running (Rothschild, 2011). Several scientific investigations are analysed to test these claims.

Decreased risk of running-related injury

The claim that minimalist shoes reduce the likelihood of running-related injury coincides with the claims discussed with barefoot running. One difference, however, is that minimal shoes are said to add protection from abrasion type injuries to the plantar surface of the skin (Sandler & Lee, 2010). McCarthy *et al.* (2011) suggested that those maintain a RFS while running in minimalist shoes are more susceptible to injury compared to those who adapt to a FFS (whether it be either naturally or cognitively). Similarly, Giuliani, Masini, Alitzand Owens (2011) believe that the two cases of runners with metatarsal stress fractures that were observed were due to their inability to alter their running gait after six weeks of minimalist shoe running. These authors did not specify which specific gait alterations would be necessary to avoid the stress fractures. One could surmise that the inability to adapt to a forefoot strike would not lead to a metatarsal stress fracture, considering that the VIP and

VALR would be directed more proximally through the foot i.e. calcaneus. Other kinematic factors such as step frequency of length may play a more predominant role in metatarsal fracture development. As yet there is no epidemiological data to show how injury rates are affected by minimalist footwear or by changes in running gate caused by minimalist shoes.

Increased musculoskeletal strength

Minimalist shoes place new and different demands on the muscles of the lower extremities (McCarthy *et al.*, 2011). In support of this notion, Munro *et al*. (2011) showed positive neural-strength adaptations in an elderly population who wore minimalist shoes (Nike © FREE 5.0) over a twelve week walking programme. Specifically, flexor hallucis longus strength and lesser toe flexor strength increased by 18% and 25% compared to a control group who wore their own shoes and improved by 5.8% and 1%. According to Munro, Mickle and Steele (2011), every 1% increase in toe flexor strength equates to a 7% decrease in risk of falling. Therefore, the elderly in this study who walked in minimalist shoes possibly reduced their risk of falling by 175%. While these results focus on an elderly group, the results point to possible benefits in runners (specifically trail) in which risk of falling is higher.

In further support, a longitudinal study by Potthast, Braunstein, Niehoff and Bruggemann (2005) reported improvements in the muscular performance after younger athletes wore minimalist shoes (Nike © FREE 5.0) in their routine warm-up over a five month period. Specifically, metatarsophalangeal joint (MTP) flexion strength, inversion moment, and plantarflexion strength all improved by 20.1%, 21.1%, and 17.7% respectively. In comparison, a control group performed their warm-up in their usual training shoes. The control group improved in MTP flexion strength and inverter moment by only 4% and 1.1%, yet declined in plantarflexion strength by 4.3%. The authors explained that the improvements observed in the experimental group were primarily as a function of strength improvements provided by the flexor hallucis longus and flexor digitorium longus.

Minimalist shoe wearing may not induce adaptations in intrinsic musculature of the foot. Shroyer, Etheredge and Weimar (2011) found no changes in arch height after five males wore minimalist shoes with articulated toe pockets over a period of six months. Overall, participants logged 5.7 ± 2.1 hrs/day in the minimalist shoes.

The claim that minimalist shoes improve strength of the lower extremity musculature is a claim that is supported by long-term prospective studies (Munro *et al.*, 2005; Potthast *et al.*, 2005). However, wearing minimalist shoes may not influence arch height. Future research in this area should include and compare different brands of minimalist shoes. The relationship between increased muscle strength of the lower extremity and adaptations in running kinematics and kinetics has yet to be determined.

Enhanced proprioception

Minimalist shoes may also enhance proprioception. Squadrone and Gallozzi (2011) showed that runners were better able to sense and predict the gradient of treadmill surface while running in minimalist shoes with individual pockets for their toes compared to running barefoot. These authors concluded that conventional shoes significantly impair foot position awareness compared to minimalist shoes and thus play a role in the risk of injury from falling. A study by Shinohara and Gribble (2011) reported no differences in static postural control between barefoot, socks, and five-toed socks among 21 active young adults. Specifically, centre of pressure velocity and time to boundary measures were no different between footwear conditions. Although not directly pertaining to minimalist shoes, this study indicates that thin material surfaces surrounding the foot may not have a strong influence on proprioception. Enhanced proprioception would suggest that runners may be able to have a greater sense for severity of impact while running, and thus be more inclined to attenuating impact force.

Improved running economy

The physiological reasoning behind minimalist shoes is that it is believed to reduce the consumption of oxygen and thus improve running economy and performance. A few studies investigating experienced minimalist and barefoot runners agree with this belief. Recently, a well-controlled study by Perl *et al.* (2012) showed improved running economy when running in minimalist shoes compared to a shod condition. All fifteen participants had significant experience with minimalist shoe running (2.1 ± 1.1 yrs) and had a weekly training mileage of 33.4 ± 16.5 km. Four testing conditions were recorded, namely minimalist shoe with a FFS, minimalist shoe with a RFS, shod with a FFS, and shod with a RFS. Participants ran five minutes per condition until steady state oxygen consumption was reached. Step frequency was controlled by the use of a metronome. In addition, shoe mass was controlled for by placing the appropriate mass around the ankles. Expired gas was collected using a sable flow generator and controller. Minimalist shoe (Vibram Fivefingers ®) running was significantly more economical during forefoot striking (2.41%) and rearfoot striking (3.32%) compared to during a shod condition.

Squadrone and Gallozzi (2009) confirmed these results in eight habitually barefoot runners who were tested in minimalist shoes (Vibram Fivefingers ®), conventional running shoes, and barefoot. Step frequency, footstrike pattern, and shoe mass were not controlled for. Heart rate and oxygen consumption were measured using a portable metabolic system. Steady state oxygen consumption for each footwear condition was measured during the last two minutes of each running bout of six minutes. Oxygen consumption was significantly lower (1.3%) when running in the minimalist shoes compared to shod. No significant difference was found between minimalist and barefoot conditions. This finding suggests that minimalist shoes may also be able to mimic barefoot running from a physiological standpoint.

The two studies investigating the physiological effects of minimalist shoes have done so in runners with significant experience with either barefoot or minimalist running. Future work in this field should include runners who are acclimatising to such minimal conditions, and would contribute to the knowledge of how runners adapt physiologically.

3. Effect on impact force attenuation and joint moments

Some are in favour of the idea that minimalist shoe characteristics are able to induce changes in running style and thus attenuate impact force. Robbins and Waked (1997) postulated that a shoe with a thinner midsole allows runners to sense the severity of impact, adjust kinematics accordingly, and therefore reduce impact forces. Lieberman *et al.* (2010) similarly state that the typical RFS pattern with the ankle landing in the dorsiflexed position is a function of the additional heel height of the modern cushioned shoe. Concurring, Saxby (2011) added that the thickness of shoe cushioning is proportional to the diminished proprioception while running. Thus, running shoes with a thicker midsole could mask the magnitude or severity of impact shock. Reenalda, Freriks and Burke (2011) speculate that higher impact forces experienced while running in less cushioned minimalist shoes would serve as an input signal for the body to adapt its running style (away from rearfoot towards a mid/forefoot strike) through altered muscle activation patterns, and consequently reduced impact forces.

In contrast to the aforementioned theories stands the notion that some runners may be incapable of sensing higher impact and altering their kinematics to suit minimalist shoes. Saxton (2010: 155) states that “no matter how minimal a shoe material is it forms a barrier between the foot and the ground, which interrupts feedback from the mechanoreceptors under the feet”. Similarly, Robillard (2010) emphasises that wearing minimalist shoes insulates the soles of the feet and thus reduces feedback. Moreover, simply putting on shoes with lesser cushioning may not imply that a correct midfoot-forefoot impact attenuating technique will be an automatic kinematic response (McCarthy *et al.*, 2011). These theories support the preferred movement path theory proposed by Nigg (2010).

Novice minimalist running

As with novice barefoot running, those who are novices to minimalist shoe running may be exposed to different mechanical stresses of the lower extremity and adjust kinematics accordingly. Schütte, Miles, Venter, and Van Niekerk (2011) used 12 habitually shod, recreational male runners (age 21.58 ± 1.26 yrs) to compare minimalist shoes (Vibram Fivefingers ®) to barefoot and shod running. Own shoes were used for the shod condition. Sagittal plane kinematics were recorded whilst participants ran six trials per condition at self-selected speeds down a 12 m indoor runway. Running speed was not monitored but was found not to be significantly different between conditions. On average, participants significantly increased both knee flexion and ankle plantarflexion angles at contact by ~ 5 degrees when running in the minimalist shoes as compared to shod. However, individual shoe cushioning thickness for the shod condition was not accounted for and could have influenced these angles. Step frequency was only 2.6% higher in the minimalist shoe condition compared to the running shoes (165.27 ± 5.71 vs.161 ± 6.09 steps/min). Lower limb kinetics were not recorded and thus the influence of these kinematic adaptations on impact force attenuation as well as joint moments are difficult to interpret.

A similar study conducted by Paquette *et al.* (2011) had seven habitually shod male runners (age 27 ± 2.7 yrs) perform over-ground running in three footwear conditions (barefoot, Vibram Fivefingers ®, and conventional running shoes). All of these runners were natural RFS runners in conventional running shoes. 3D kinematics and ground reaction forces were synchronised and recorded. No information regarding runway length, preferred foot chosen for force plate contact, verbal instruction provided, amount of trials recorded per condition, whether the conditions were randomised, or whether control/monitoring of running speed was specified by the authors. Nevertheless, the study found results worthy of reporting. With respect to the vGRF, the minimalist shoe condition had significantly lower impact rate of loading compared to both shod and barefoot conditions. In contrast, the magnitude of the vertical propulsive peak was higher than the barefoot condition but similar to the shod condition. Kinematic parameters which could help explain the lower impact forces in the minimalist condition may be the smaller touchdown angle (more plantarflexion) observed, yet the amount of degrees difference as well as footstrike was not mentioned. Based on their increased ankle plantarflexion angle at contact, it can be assumed that the runners adapted well as they landed with a more midfoot-forefoot technique. An additional kinematic finding was that both minimalist and barefoot condition had smaller knee range of motion compared to shod, most likely due to the smaller initial knee angle at contact. Strike index was not used for analysis due to high variability between trials (within participants). It was concluded that minimalist shoes reduced the amount of loading rate and allowed for greater push off forces compared to being barefoot.

In contrast, an investigation by Reenalda *et al.* (2011) opposes kinematic adaptation and impact force attenuation with minimalist shoes. Eighteen experienced male runners (mileage at least 30 km/wk) were divided into a large group of natural rearfoot strikers (n = 12) and a group of natural forefoot strikers (n = 6). All runners performed five trials of running along a 15 runway for both conventional and minimalist shoe (Feelmax ® Osma) conditions. The study concluded that all 12 rearfoot strikers and all 6 forefoot strikers remained unchanged between footwear conditions. Thus, no individuals adapted their footstrike pattern when running in the minimalist shoes. Unfortunately, there was no data available on impact magnitude or rate of impact loading to allow for quantitative comparisons to be made. However, on visual inspection the impact transient of the ground reaction force curve appeared steeper, yet the VIP occurred at the same height. This would suggest that VALR was indeed higher in the minimalist shod condition for the natural rearfoot strikers. In comparison, the natural forefoot strikers had similar GRF- time curves that showed no distinct VIP. The authors speculate that the design of the particular minimalist shoe used gave the runners the perception that they were still running in their conventional running shoes.

An investigation by Hamill *et al.* (2011a) is in agreement with the above finding. Footstrike patterns and impact forces of ten (five men) experienced shod runners were tested in three midsole thickness conditions. All testing shoes had identical uppers, and differentials of 4 mm, and only differed in midsole thickness. Shoe A had a heel height of 4 mm and only thin outsole in the forefoot; shoe B had a heel height of 12 mm and a forefoot height of 8 mm; and shoe C had a heel height of 20 mm and a forefoot height of 16 mm. No instructions were given on how to contact the ground (footstrike pattern) while running in any of the footwear conditions. Participants rearfoot struck in all three shod conditions (strike index < 33%; ankle dorsiflexion angles at initial contact 11.14 ± 4.46 degrees) at preferred running speeds. Therefore, a decrease in midsole thickness had no effect on footstrike pattern adaptation, with all the participants maintaining a typical RFS pattern. Impact force parameters such as magnitude of the VIP, time to VIP, and vertical loading rates were not significantly different between all shod conditions. However, a non-significant trend was seen with thinner midsole thickness relating to higher loading rates (72.23, 65.06, and 59.59 BW/s for the 4/0, 12/8, and 20/16 mm shoe conditions respectively). The authors concluded that impact characteristics during running were not dependent on the thickness of midsole cushioning.

Increased ankle plantarflexion angle at contact has shown to reduce peak sagittal plane joint torques at both the knee and ankle. Paquette *et al.* (2011) investigated over-ground running of three footwear conditions (barefoot, Vibram Fivefingers ®, and conventional running shoes), performed by seven habitually shod male runners (age 27 ± 2.7 yrs.). All runners were natural rearfoot strikers while shod. 3D kinematics and ground reaction forces were synchronised and recorded, and used to calculate peak sagittal and frontal plane joint moments of the knee and ankle at impact using inverse dynamics. With respect to the lower limb joint moments specifically, peak plantarflexion moment and knee extensor moment were significantly smaller in the minimalist shoe condition compared to the shod condition, although the barefoot running was similar to the minimalist shoe condition. In addition to the lower impact forces already mentioned, these lowered peak joint moments may be due to the more plantarflexed angle at touch-down while running in the minimalist shoes.

Runners with previous barefoot experience may adapt more quickly to novice minimalist running. The study by Squadrone and Gallozzi (2009) also included minimalist shoes (Vibram Fivefingers ®) as a third footwear condition to barefoot and conventional shoes. Their eight experienced barefoot runners adapted their footstrike pattern when in minimalist shoes compared to shod, as indicated by the significantly more plantarflexed ankle angles at contact (4 degrees) with a strike index of 56 ± 5%. In comparison, their runners had a strike index of 40 ± 6% when shod. Step frequency was overall high in the minimalist shoe condition (176.6 ± 1.8 steps/min), although not significantly different to shod (172.2 ± 2.2 steps/min). From a kinetic point of view, VIP was significantly decreased in the minimalist shoe condition by 8% compared to the shod condition.

In light of the studies reviewed above, many runners novice to minimalist shoes do not alter their footstrike kinematics or regulate impact force, and perhaps qualify as adaptation-failures. However, as was the case in the previous section on barefoot running, one study (Squadrone & Gallozzi, 2009) suggests that experience with barefoot running enables runners to adapt more readily to minimalist shoes. Some studies did not report on changes in step frequencies or step lengths (Hamill *et al.*, 2011a; Paquette *et al.*, 2011; Reenalda *et al.*, 2011), which could substantiate why impact force attenuation did not always occur with the minimalist shoes. The theory that footstrike pattern is a function of heel height in a cushioned shoe should be interpreted cautiously. Moreover, differences in minimalist shoe construction makes comparison of studies difficult. Thus, it may be inappropriate to assume that all minimalist shoes promote the same running technique.

Experienced minimalist running

As yet there are no studies which have focused on the running biomechanics of experienced minimalist runners. One study which investigated the metabolic effects of experienced minimalist runners did however have some biomechanical observations. Perl *et al.* (2012) reported their runners who had 2.1 ± 1.1 (0.6 – 4.0) yrs. of minimalist experience all preferred to use a FFS landing pattern with step frequencies of ~ 186.8 ± 12.6 steps/min at 3.0 m/s. The step frequencies reported in their study are a great deal higher than when either habitually shod runners (Schütte *et al.*, 2011) or even when habitually barefoot runners (Squadrone & Gallozzi, 2009) attempt novice minimalist shoe running. This would indicate that experience with minimalist shoes may be a primary factor in the adaptation of spatio-temporal kinematics. The authors also qualitatively reported that their participants had less extended knee angles at footstrike when running in minimalist shoes compared to shod. This kinematic finding is similar to the findings seen when habitually shod runners (Hamill *et al.,* 2011a; Schutte *et al.,* 2011) attempt novice minimalist shoe running.

There are no other studies on experienced minimalist runners that allow for definite conclusions to be drawn. One can only speculate at this point that experienced minimalist runners are able to adapt their kinematics more proficiently and attenuate impact forces to a greater degree.

Training adaptation effect

A study under the American Council of Exercise (ACE) (McCarthy *et al.,* 2011) set out to determine the effect of two weeks of minimalist shoe training on a group of habitually shod runners. Sixteen healthy females who were recreational joggers (age 19 – 25 yrs.) were asked to familiarise themselves with six running sessions of 20 minutes each in minimalist shoes. All women were given a pair of Vibram Fivefingers ® to train in. After the two week training period, 3D motion capture and impact forces were recorded as they ran along a 20 m runway in three footwear conditions, namely, barefoot, neutral running shoes, and minimalist shoes. Seven trials were given per condition and all runners were encouraged to use a forefoot landing technique. Half of the runners did indeed follow instruction and adapted their footstrike pattern to the forefoot, even in the shod condition. Of these forefoot adaptors, both barefoot and minimalist shoe conditions had significantly lower VALR compared to the shod condition (Figure 2.10). However, as a whole (including shod condition), these adaptors had significantly smaller impact rate of loading compared to the other half of women who were unable to follow instruction (and remained rearfoot strikers) across all conditions. These adaptation-failures had the highest VALR when in the barefoot and minimal shod conditions.

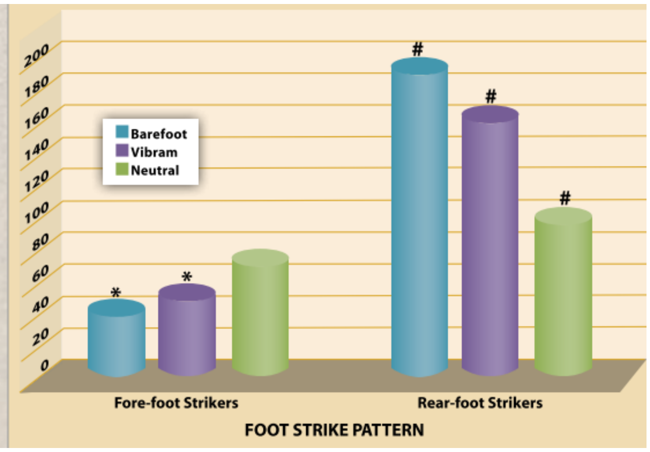


Figure 2.10. Impact loading rate among forefoot and rearfoot strikers between barefoot, minimalist shoes, and neutral running shoes, adapted from (McCarthy *et al.,* 2011) * Significantly different from neutral conventional running shoes; # All shoe conditions significantly different from one another.

A longitudinal study by Lieberman *et al.* (2010) asked 14 (10 men) runners (age 21.4 ± 1.8 yrs.; mileage > 32 km/wk) to undergo a six week transition programme to minimalist shoe (Vibram Fivefingers ®) running. All runners were accustomed to conventional running shoes at the start of the study at a mileage of more than 32 km/wk. Runners were requested to start at a mileage of 1.6 km per day in the new pair of minimalist shoes. Thereafter, mileage was increased by 10-20% per week until the runners were at a mileage of ~ 16 – 20 km/wk entirely in the minimalist shoes. Testing before and after the six week intervention required the runners to run down a 20 m indoor track at self-selected speeds (speed quantitative data not mentioned) in the barefoot condition. Initially, 28% of the runners adapted to run with MFS or FFS. Of the initial 72% of runners who landed with their rearfoot, half (36%) of them adapted to land in the mid-forefoot region after the intervention (Table 2.1). Thus, after the six weeks of minimalist shoe training, there was still a large percentage (36%) of adaptation-failures still landing on their heels. It should be noted, however, that on average participants adjusted towards a more plantarflexed ankle (5.8 ± 3.8 degrees) change at contact. This suggests that there was an overall inclination towards footstrike adaptation.

Table 2.1. Relative change in footstrike pattern after six weeks minimalist shoe training, adapted from (Lieberman *et al.,* 2010).

Strike type	**Week 0 (%participants)**	**Week 6 (%participants)**
Rearfoot strike (RFS)	72	36
Midfoot strike (MFS)	14	0
Forefoot strike (FFS)	14	57
Toe strike (TS)*	0	7

*Defined as forefoot strike with no heel contact

E. TRANSITION PROGRAMME

Rothschild *et al* (2011) concluded that "additional development and availability of evidence-based supervised transition programs will support the runner during the transition while minimizing adverse effects". One of the most widely unanswered questions is what the best way for a runner to transition to barefoot or minimal running is (Lieberman, 2012: 8). Fear of injury being was listed as the highest perceived barrier in transitioning to minimalist shoe running (Rothschild, 2011).

1. Adaptation period

Runners should acknowledge that the time it takes to transition from conventional running shoes to minimalist shoes is highly individualistic with no set amount of days or weeks (Rixe *et al.,* 2012). Researchers are largely in agreement that the transition process must be gradual, which takes time and patience (Rixe *et al.,* 2012; Sandler & Lee, 2010; Schilling, 2012; Wallack & Saxton, 2011). The transition period may necessitate a minimum of a few weeks (Robbins, 2011), or even several months to become a full time minimalist runner (Rothschild, 2012). According to Rothschild (2012), a feasible transition period should be gradual over 4 - 8 weeks, reasoning that this is typically the ideal period required for musculature to adapt and to allow for strength gains (Sale, 1988). Hart and Smith (2008) emphasise the importance of the gradual removal of external support provided by cushioned footwear, and that barefoot activity should be gradually progressed over several weeks or months. These authors insisted that weakened structures of the foot due to footwear would not benefit from the complete elimination of footwear, as it would increase the risk of injury to these structures. Similarly, Vibram $^{®}$ accentuates the importance of transitioning slowly when wearing their Fivefingers minimalist shoes to allow for strength to build up in the musculature of the feet and lower legs (www.vibramFivefingers.com). Moreover, Hart and Smith (2008) are of the opinion that failure to abide by such guidelines would results in injury similarly to how runners accustomed to cushioned shoes get injured when switching to racing flats.

2. Factors determining adaptability

Slow progression and regular monitoring are two key principles that should be applied to all runners wishing to transition to minimalist running, irrespective of their athletic ability (Schilling, 2010). However, the possibility that some runners are able to adapt or respond faster than other runners should be respected. According to Robillard (2010), there are a number of factors which determine the speed at which the transition from traditional shoes to barefoot or minimalist shoes occurs. Robillard (2010) rates previous barefoot experience as the most important factor, and argues that greater previous barefoot experience will increase the rate of progression due to better developed muscles, tendons, ligaments, bones and skin of the lower extremity. Indeed, the prevalence of flat feet rises in proportion to the earlier age of shoe wearing (Sachithanandam & Joseph, 1995) or children who wear more closed, restrictive shoes (Rao & Joseph, 1992). These findings suggest that previous footwear history may have an effect on the ability of the feet to respond to a transition towards increased barefoot or minimalist shoe activity. Barefoot experience during childhood may play a critical role in the success of barefoot running in adulthood.

Other factors that may also play a role in the rate of transition are previous forefoot striking experience, age, gender, prior injury history, ability to listen to one’s body, previous training surface history, inherent body biomechanics (anthropometrics, body weight, foot arch type, muscle dimensions, muscle strength of the lower extremity, foot stiffness, tendon length, and body alignment), and previous injury history (Robillard, 2010; Rothschild, 2012; Sandler & Lee, 2010; Saxby, 2011; Wallack & Saxton, 2011).

3. Skill component

In contrast to sports such as tennis, golf, and swimming, running does not always include a skill component due to the assumption that running is learnt naturally according to each individual's inherent ability (Lieberman, 2012). Consulting a running coach or professional (7.2%) has been reported as the least utilized information resource by runners who have considered barefoot-minimalist running transition (Rothschild, 2011). The irony is that a vast amount (85.5%) of runners would be more likely to continue with or attempt barefoot or minimalist shoe running if provided with adequate instruction from a professional (Rothschild, 2011).

Rothschild (2012: 3) declares that reducing the rearfoot strike component is fundamental in the transition process to barefoot-minimalist running, and also suggests that specific drills should be incorporated to learn correct landing techniques as well as to adapt step kinematics. A study by Bergmann, Kniggendorf, Graichen, & Rohlmann (1995: 820) found that VALR was reduced by 60% when they instructed their participant to "run as smoothly as possible" compared to being instructed to "hit the ground very hard" with a rearfoot strike. These investigators argued that the *smooth* running gait is the best and possibly the only way to reduce joint loading. These results are positive, considering that minimalist and barefoot conditions lack cushioning under the rearfoot.

According to McCarthy *et al.* (2011), runners who are considering to transition to minimalist running should be willing to adapt their running gait pattern and allow enough time to acclimatise to this new gait pattern. McCarthy *et al.* (2011) also commented that although adopting a novel running style could be good for some, others may require explicit instruction and practice, providing the example of how runners should practice landing on the ball of their feet. Although there is no study to support this claim, Crowell and Davis (2011) showed that VALR and VIP magnitude was decreased by 32% and

19% after eight sessions of real time visual feedback of tibial acceleration via a monitor. Implicit instruction to “run softer and make your foot falls quieter” was also provided. These participants were also able to retain this decrease in loading rate after a one month period. This study indicates that gait retraining and instruction to alter technique may reduce impact forces. Studies such as this should be applied to minimalist or barefoot running, where instruction such as “land in the ball of your foot” should be given, as suggested by McCarthy *et al.* (2011).

“Do not over stride” is one of the most commonly used phrases in the barefoot running community, and implies that foot landing should not occur too far in front of the hips (www.vibramFivefingers.com; Saxton 2010; Saxby 2010). It has already been mentioned that reduced step length or increased step frequency may reduce impact forces and joint moments while running (Edwards *et al.,* 2009; Heiderscheit *et al.,* 2011). Rothschild (2012) states that barefoot runners should aim for a high step frequency. Reputable barefoot coaches are in agreement and usually recommend a minimum step frequency of 180 steps/min (Sandler & Lee, 2010; Saxby, 2011; Wallack & Saxton, 2011). Considering the aforementioned studies, barefoot step frequencies in habitually shod runners have ranged from 154.2 – 174.4 (De Wit *et al.,* 2000) , while in habitually barefoot populations ranged from 180.6 - 184.2 steps/min (Squadrone & Gallozzi, 2009) or 174.2 - 199.2 steps/min (Perl *et al.,* 2012). Clearly, habitually shod runners undergo an adaptation in step frequency as they as exposed to barefoot running experience through practice.

SUMMARY

This review took a comprehensive look at the available evidence pertaining to lower limb biomechanics and its relationship to barefoot and minimalist shoe running. This chapter aimed to cohesively review previous experimental data presented on barefoot and minimalist shoe running. The best way to perform a minimalist shoe transition was addressed, as well as factors which play a role in the speed of transition. The various methodologies of these studies were explained and compared, and are used as the foundation for this present study. This literature review also identified a wide number of unsolved problems and unanswered questions related to the barefoot-minimalist shoe paradigm. A summary of the pertinent literature as well as the limitations thereof is provided as a point of departure in the following chapter.

CHAPTER THREE

PROBLEM STATEMENT

A. SUMMARY OF THE LITERATURE

Although limited to female runners, the majority of studies have established that runners with a current injury or who have developed a running-related injury sustain higher vertical impact loading rates, but do not sustain higher vertical impact peaks (Zadpoor & Nikooyan, 2011). Attenuation of impact loading rates appears to be a plausible strategy to reduce the risk of running-related injury. Studies show that passive forms of impact attenuation, such as footwear cushioning, reduces the impact loading rate yet encourage a runner to use a rearfoot striking method, which does not eliminate the impact peak (Dickinson *et al.,* 1980; Oakley & Pratt, 1988). Most of the results indicate that active forms of impact attenuation such as forefoot striking and reduced stride length significantly reduce impact loading rate and may eliminate the impact peak all together, but do not necessarily imply that all runners are at less of a risk of injury through applying these methods (Derrick, 2004; Diebal *et al.,* 2012; Heiderscheit *et al.,* 2011; Lieberman *et al.,* 2010; Oakley & Pratt, 1988).

Evidence supports the premise that barefoot running could be a more natural method of impact attenuation, but only under acute conditions and within context to those who have experience with it. Impact attenuation may only occur after multiple strides are performed barefoot (Divert *et al.,* 2005), on hard surfaces (Hamill *et al.,* 2011b; Herzog, 1978), or after at least six months of barefoot training or adequate time spent barefoot during childhood (Lieberman *et al.,* 2010). This being said, impact attenuation and the ability to adapt to correct barefoot running form may be highly individualistic to each runner (Becker *et al.,* 2011).

Many studies were not in favour of the notion that runners will automatically sense higher impact and change their running kinematics for footstrike pattern accordingly when running in minimalist shoes (Hamill *et al*., 2011a; McCarthy *et al.,* 2011; Reenalda, Freriks, & Buurke, 2011). This suggests that there are many factors that play a role in kinematic adaptations and impact force rate of loading attenuation other than the obvious elimination of characteristics (cushioning and arch support) found in conventional shoes. The ability to attenuate impact forces in minimalist shoes may be multi-factorial and requires a learning process. Yet, the length of time of this process has not been established .The minimalist shoe transition may necessitate the practice and integration of new skills, similar to other sports such as swimming, golf, and tennis (Lieberman, 2012).

Although not based on scientific evidence, the general consensus is that runners need a substantial amount of time to adapt and transition to minimalist running. On the one hand there are reports that most runners completely transition successfully within two weeks (Rothschild, 2011). On the other hand there are reports of runners getting injured after six weeks (Giuliani *et al.,* 2011). To date, there are no scientifically based training guidelines on how to make a successful minimalist transition.

B. LIMITATIONS IN THE LITERATURE

While novice barefoot running is widely elaborated upon in the literature, the response of previously habitually shod runners to a barefoot transition programme requires clarification. This gives reason to expand on the literature using studies which are longitudinal in design and that investigate the training effects of barefoot running.

Perhaps one of the greatest limitations facing research in minimalist footwear is the “lack of uniformity among minimalist footwear designs” (Schilling, 2012: 4). For example, the strengthening benefits of minimalist shoes were found in the Nike © Free minimalist shoes, while the running economy benefits were found using the Vibram Fivefingers ® minimalist shoes. As a result, comparisons among different minimalist shoes which differ in design and materials become difficult. Nevertheless, fundamental characteristics of the minimalist shoe (i.e. flexibility, less arch support and less cushioning) may play a more important role than the actual footwear brand and model of shoe compared.

There is an overall lack of literature pertaining to lower limb joint moments while running under different footwear conditions. This may be due to a number of reasons, including the novelty of the inverse dynamics procedure, or because of differences in methodological set-ups or inconsistencies between laboratories. Nevertheless, quantifying and comparing lower extremity joint moment between shod and minimalist running can add knowledge and understanding to this debated topic.

Interpretations regarding minimalist shoes and their ability to attenuate impact force require further investigation and cannot be fully supported or dismissed based on the current results from the literature. Most studies are cross-sectional in design and do not offer application to studies which are longitudinally designed. No studies have to date investigated the impact attenuating ability of minimalist shoes after a short-term training period. The transition process from being a habitually shod to an experienced minimalist runner has been neglected in the literature, and the gap between these two populations of runners is yet to be addressed.

The results and conclusions from the survey by Rothschild *et al.* (2011) expose several unanswered questions with regard to the transition process, such as what the best way to transition is and which people adapt successfully and which do not. Such gaps in knowledge are what future research should attend to. Well controlled, prospective studies that draw conclusions based on scientifically sound principles may help runners, coaches, and clinicians alike.

Research on running has generally been done under indoor laboratory conditions, without any consideration for other outdoor terrains (Creagh, Reilly, & Lees, 1998). A study that is able to document the detailed experiences of runners making the transition to minimalist running can help runners address practically relevant issues. A study that is to overcome at least some of the aforementioned limitations would contribute substantially to the running community.

C. SIGNIFICANCE OF THE STUDY

Several justifications exist for this study. Firstly, with a dearth of knowledge on the minimalist shoes, this study may resolve issues regarding the transition process. Runners, athletes, coaches, health care professionals and strength and condition specialists can benefit from the results and implications of this study. Secondly, this study will also be valuable to the research community with respect to its study design, and help clarify areas of uncertainty pertaining to minimalist shoe running from a longitudinal perspective.

D. STUDY AIM

The primary aim of this study was to determine whether lower limb kinematics can be adapted, whether vertical impact loading rate (VALR) can be attenuated, and whether lower limb joint moments can be altered by either novice or short-term (seven-week) minimalist shoe training.

1. Specific objectives

Research objective one: To determine active kinematic predictors of average vertical loading rate (VALR) attenuation and joint moments for minimalist shoe (VF) running compared to barefoot (BF) and shod (SH) running.

H 1: It was hypothesized that VF running would depend on active kinematic methods to attenuate VALR; and b) alter joint moments lower than compared to both BF and SH conditions.

Research objective two: To determine the effect seven-weeks of VF training has on kinematic adaptation, VALR attenuation, lower limb joint moments and circumferences.

H 2: Seven weeks of VF training would a) promote a learning effect of active VALR attenuation; b) alter lower limb joint moments; and c) increase calf circumference, with thigh circumference to remain unchanged.

2. Intervention characteristics

Another goal of this study is to document, evaluate and report on the implementation of a plausible seven-week minimalist shoe transition programme according to a) training characteristics; b) lower-limb comfort; c) adverse reactions experienced; and d) surface selection.

CHAPTER FOUR

METHODOLOGY

A. INTRODUCTION

Limitations in contemporary literature points to the need for a study that investigates the longitudinal effects of minimalist shoe running. This chapter starts by defining and describing the design and outline of the present study. An illustration of participant recruitment is used to explain the procedures that were followed to achieve the final study population. Mention is made of the ethical procedures and guidelines that were abided by. Thereafter, a detailed and chronological description of how the experimental design was implemented is provided, with primary emphasis of the minimalist shoe transition programme. Procedures regarding all measurements and tests taken during the study period are described. The chapter ends with a list of outcome variables and statistical methods that were used to quantify and test the study objectives mentioned in the problem statement.

B. STUDY DESIGN

According to Knudson (2009), important issues related to the internal and external validity of biomechanical studies are the design of the study as well as the sampling method used (Knudson 2009). In accordance with the research objectives purposed, this experimental study followed a pre-test post-test randomised-groups design. This longitudinal study design was chosen to determine the amount of change in lower limb biomechanics variables produced by the minimalist shoe transition programme. This study design was also chosen as it is able to control for several potential threats to internal validity (Thomas, Nelson, & Silverman, 2005). The history effect occurs when an unintended event occurs during an intervention programme which decreases internal validity (Thomas *et al.*, 2005). In this study, the experimental (EXP) group received the minimalist shoes to train in (treatment), whereas the control (CONT) group did not receive any minimalist shoes to train in during the intervention period, thus negating any unexpected changes observed due to the history effect. In some cases, internal validity can be reduced when participants acquire the testing/learning effect from the pre-test, which is carried over to the post-test (Thomas *et al*., 2005). In the field of running biomechanics, inter-day (session) variation has been discussed as a potential threat to internal validity due to acclimatisation to the laboratory runway in the first session, but no further accommodation effect is evident in the second session (Maiwald, Axmann, & Grau, 2011). Thus, for this study a control group was chosen to determine inter-day variance or change which may occur as a result of reasons other than the intervention, such as bias from laboratory runway accommodation (Maiwald *et al*., 2011).

Experienced shod runners who volunteered were selected for this study if they met the inclusion requirements. Participants were equally and randomly divided into an experimental training group and a control group. All participants were tested before and after a seven-week training (intervention) period. Originally, a power analysis performed with STATISTICA Version 10 (StatSoft ©, Inc. Tulsa, OK, 2010) determined that a sample size of 22 (11 experimental and 11 control group) was required to achieve a level of significance of lower limb kinetic data ($\alpha < 0.05$ and power goal of 80%) (Lieberman *et al.,* 2010).

C. PARTICIPANTS

1. Recruitment

Participants were recruited by means of an advertisement shown on the Stellenbosch University intranet blog, to which 36 runners responded. Initial screening was done on information received from respondents via email (Figure 4.1). Participants were recreational amateur runners based in the Stellenbosch region and were thus a sample of convenience.

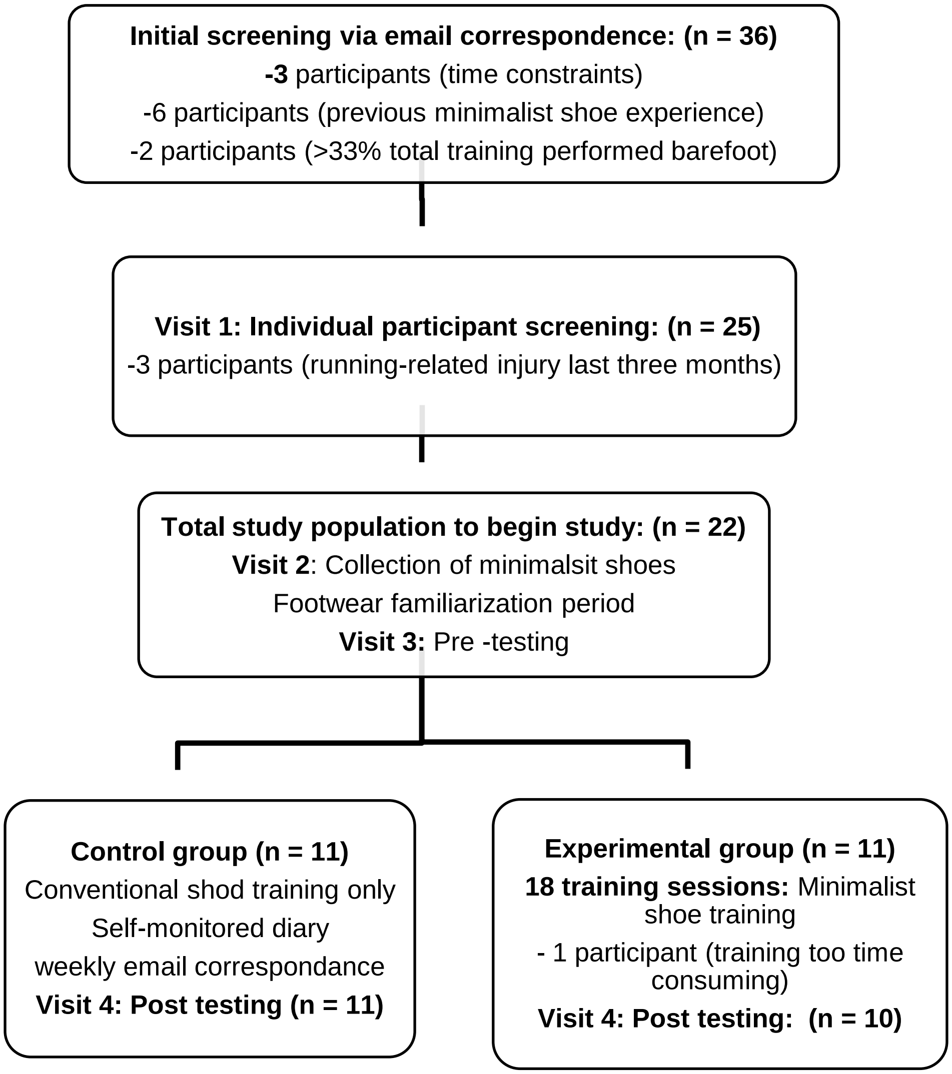


Figure 4.1 Schematic representation of participant recruitment and study design.

2. Inclusion and exclusion criteria

Participants were included in the study if they a) were men between 21 and 30 years old (Rothschild, 2011); b) ran recreationally for a minimum of 20 km/week; c) trained in conventional modern running shoes (with cushioned heels and or stability features); and d) were able to train in one pair of personal running shoes for the duration of the study. Participants were excluded from the study if a) they had any musculoskeletal injury or lower limb pain within the previous three months prior to the study which required a cessation of normal training or the seeking of medical attention; or b) train in, or had any experience with, minimalist shoes.

D. STUDY OUTLINE

The aim of this section is to show the number of visits attended by the participants of this study chronologically. A footwear familiarisation period occurred between visits two and three, while an intervention period occurred between visits three and four.

1. First visit

Of the 36 email respondents, only 25 were invited to visit the researcher for individual participant screening (Figure 4.1). This was because of various reasons such as time constraints, or having previous minimalist shoe running experience. All 25 potential participants were requested to visit the Biomechanics Laboratory at the Department of Sport Science at Stellenbosch University for an information session regarding the study. Participants were expected to arrive in their athletic attire and their running shoes. The procedures of the study were explained to the participants. Thereafter, participants completed a questionnaire regarding their injury and training history (Appendix B). The primary researcher, a qualified Biokineticist (Kurt Schütte, BK no.0020346) registered with the Health Professions Council of South Africa (HPCSA) and Biokinetics Association of South Africa (BASA), performed an anthropometric assessment on each participant. Anthropometric measurements were recorded. Potential participants were then told that they would be contacted in the near future if they met the full requirements of the study. Of the 25 runners who attended the individual screening session, 22 were recruited as the final study population. The three runners who did not qualify for the study were excluded due to having running-related injuries within the previous three months.

2. Second visit

The final 22 participants revisited the Biomechanics Laboratory at the Department of Sport Science at Stellenbosch University to pick up their new pair of minimalist shoes (visit two). A recent survey has indicated that those who attempt minimalist running prefer to do so in Vibram Fivefingers ® (Vibram SpA, Albizzate, Italy) (Rothschild, 2011). All 22 participants who partook in the study were provided with their own new pair of Vibram Fivefingers ® (Bikila model) (Figure 4.2).


a) b)

Figure 4.2 Experimental minimalist shoes (Vibram Fivefingers ® , Bikilas) chosen for this study: a) superior view; b) view of soles of shoes. (Photographs by K Schütte).

Footwear familiarisation period

Footwear comfort has been regarded as an important subjective factor relating to the success of lower limb interventions (Mündermann, Nigg, Stefanyshyn, & Humble, 2002). An uncomfortable shoe can alter the plantar pressure distribution (Hennig, Valiant, & Liu, 1996), foot sensitivity (Mündermann, Stefanyshyn, & Nigg, 2001), muscle activation (Anne Mündermann, Nigg, Humble, & Stefanyshyn, 2003; Nigg, 2001; Nigg *et al.,* 2003), impact loading rate (Hennig *et al.,* 1996) and increased oxygen consumption (Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009). For these reasons it may be necessary to reduce the potential for novelty bias when running in new shoes for the first time. To eliminate this potential initial discomfort and novelty bias, some support the notion that a brief acclimatisation or familiarisation period should precede any testing performed in new shoes (Squadrone & Gallozzi, 2011). All participants were asked to follow a familiarisation period in their new minimalist shoes. All participants were required to sit, stand or walk for a minimum duration of one hour and a maximum duration two hours a day in their minimalist shoes. The familiarisation period lasted over a period of seven days prior to pre-testing. One particular research focus of the study was to observe the participants running in minimalist shoes for the first time. Therefore, the participants were informed not to perform any activities such as jogging, running, sprinting, jumping, skipping, climbing, etc. in their new minimalist shoes during the familiarisation period. Participants were warned that they would be excluded from the study if this requirement was not met. Participants were, however, asked to maintain their usual weekly running mileage of at least 20 km/week in their own conventional running shoes during the familiarisation period. To confirm adherence, participants kept a daily log of the activities and time spent sitting and walking in the minimalist shoes during the familiarisation period (Appendix G).

3. Third visit

Participants were required to visit the Biomechanics Laboratory, Department of Physiotherapy, Stellenbosch University for pre-testing of lower limb running biomechanics. The purpose of the visit was verbally explained to the participants. Participants were expected to refrain from competing in any races or intensive training within 48 hours prior to testing. The testing procedures are discussed in a later section. Participants were randomly divided into either an experimental or control group. After the pre-testing session, participants of the control group were requested to hand their new minimalist shoes back to the researcher. The control group would only get their pair of minimalist shoes again at the post-testing stage. Participants in the experimental group were allowed to keep their minimalist shoes to use during the experimental intervention period.

Intervention period

Participants divided into the control group were expected to self-train at their usual weekly training mileage in their usual running shoes. To improve adherence, these control participants were asked to document their training using the training log provided by the researcher (Appendix H) and email it back to the researcher on a weekly basis. This routine occurred over the seven-week intervention period.

Several considerations were taken into account to determine the appropriate length of the intervention period. In terms of previous study deigns, most research reporting longitudinal changes or adaptations in running biomechanics or physiology have used six-weeks as their intervention duration (Davis & Harfmann, 2012; Diebal *et al*., 2012; Stanton, Reaburn, & Humphries, 2004; Turner, Owings & Schwane, 2003; Lake & Cavanagh, 1996). From an experimental research perspective, a six-week intervention was thus determined as the lower limit with respect to intervention duration. With regard to minimalist shoe transitioning, there is no literature to suggest how long an appropriate intervention duration should be. To the knowledge of the author, the only study to perform an intervention on lower limb kinematics using minimalist shoes did not specify their choice of a six-week intervention period (Lieberman *et al*., 2010). Rothschild (2012) does, however, speculate that a feasible transition period should be gradual over 4 - 8 weeks, reasoning that this is typically an ideal period required for musculature to adapt and to allow for strength gains (Sale, 1988). Therefore, eight weeks was considered as the upper limit for the minimalist shoe intervention. A seven-week transition period with the addition of a one-week familiarisation period (prior to pre-testing) was thus thought as a sufficient time period for the minimalist shoe transition process for this study.

Participants allocated to the experimental group were asked to attend a minimum of 14 and a maximum of 18 minimalist shoe training sessions under the supervision of the primary researcher. Detailed descriptions of these sessions can be found in the following section (experimental design).

4. Fourth visit

Post-testing followed the same procedures as pre-testing. On completion of the post-testing, participants from the experimental group were asked to complete a post-intervention questionnaire regarding their experiences and opinions towards minimalist shoes. All participants (including from the control group) were allowed to keep their pair of minimalist shoes.

E. ETHICAL ASPECTS

The study protocol was approved by and carried out in a manner that conformed to the principles set out by the Ethics Committee of Research Subcommittee A at Stellenbosch University (Appendix C). Informed consent forms (Appendix A) with study information was emailed to all potential participants during initial screening via email correspondence with the researcher. Informed consent and the study protocol were also explained verbally to each participant upon arrival to the individual participant screening process (first visit). Opportunities to ask questions about the study were provided. Participants were informed that participation was completely voluntary and they were allowed to withdraw from participating in the study at any time without justification. All of the participants signed the consent forms. The study did not involve any invasive procedures or serious risks. All information obtained in the study was handled with strict confidentiality and was not disclosed. All documentation or questionnaires were handled by the participants, the researchers and the study leader. The documents were filed and stored in a locked room to which only the researcher and study leader had access. Electronic copies were saved on a personal computer (password protected) and on an external drive and could only be accessed by the researchers. All data used for analysis was safely and securely stored after completion of the study.

Conflict of interest statement

There were no conflicts of interest to disclose for this study. No financial assistance was received from any shoe manufacturing company. Instead, a letter was sent to a number of shoe manufacturers with the request that minimalist shoes be donated for research purposes (Appendix I). Branded Footwear™ agreed to donate 12 pairs of Vibram Fivefingers ® minimalist shoes, while the other 10 pairs of Vibram Fivefingers ® were bought at cost price (funded by researcher).

F. INTERVENTION CHARACTERISTICS

The following section describes the procedures followed that were required to help answer research objective four (to document, evaluate and report on the implementation of a plausible seven-week minimalist shoe transition programme). The place and duration of the study, how minimalist shoe monitoring took place, how running mileage was approximated, how running surface was decided, and questions relating to post completion of the intervention will be discussed.

1. Training characteristics

Throughout the intervention period participants were asked to arrive at various locations surrounding the sports grounds at Stellenbosch University. Minimalist shoe training sessions occurred at running times (morning or afternoons) that the participants were accustomed to. This was done to minimise changes to their usual training routine. Although some runners may prefer to train in the mornings or in the evenings, the difference between morning and evening training has been shown to have no significant effect on injury rate (Macera, 1989). Thus, time of day was not seen as a restraint to the minimalist shoe training schedule.

According to Lieberman (2012), the best way to transition to barefoot or minimalist running is still unknown. In addition, the ideal time or length of intervention needed to alter a runner's technique is yet to be determined (Diebal *et al.,* 2012). The only two previous studies that have investigated a training programme in minimalist shoes have done so over a two-week (McCarthy *et al.,* 2011) or six-week (Lieberman *et al.,* 2010) intervention period. Another study (Diebal *et al.,* 2012), not pertaining to minimalist running, but rather the teaching of forefoot strike running technique, constructed their transition programme over a seven-week period. The current study intervention was therefore performed over a period of seven weeks. Runners who could not complete all their sessions in the allocated week were allowed to use the seventh week to complete training sessions.

The initial mileage in the minimalist shoes was approximated at 1.6 km (1 mile), as recommended by Lieberman *et al.* (2010). Increments of running mileage were decided upon by the primary researcher on the day of each individual training session. Participants' running characteristics were recorded with a global positioning system (GPS) unit (TSPI Pro; GPSports, Canberra, Australia), sampled at 5 Hz. The GPS signal provided information regarding speed, distance, position and acceleration of the runners. The GPS unit also included a tri-axial accelerometer and a gyroscope sampling at 100 Hz, to provide more accurate information on speed and acceleration. To minimise measurement error, the GPS unit was enclosed around the shins with straps made of specific material named Breath-O-Prene ® (Medac ©, *AccuMED Technologies LLC, Cape Town, South Africa)* (Figure 4.3). These Breath-O-Prene ® straps have an open-cell construction that allows for stretch ability while maintaining durability. This versatile material is ideal for the athletic, medical and orthopaedic markets. The upper border of the Breath-O-Prene ® straps was placed at the height of the fibula head to standardise position between all participants. In addition, a placebo strap was placed around the other shin to avoid participants from either intentionally or subconsciously favouring the leg with the GPS unit while running.

a) b)

Figure 4.3. a) Box containing GPS units for each runner (left); b) participant wearing GPS unit encased in the Medac© straps (right). (Photographs by K Schütte).

Training routes were predetermined using Google Earth Version 6.2.2.6613 (Google Inc.©). Each route distance was approximated and traced using the ruler tool option. An example of a training route is given in Figure 4.4. Care was taken to trace routes that would be most realistic to the training participants, covering several different surfaces. Prior to the fifth week, incline-gradients remained relatively flat. Several route options were printed prior to each training session. This procedure allowed the researcher to decide on an appropriate distance for each participant, depending on their level of lower limb comfort on the day.

Hills or significant inclines or gradients were introduced only in the fifth week of the intervention. Training surfaces were isolated and rotated from session to session for the first three weeks (session 1 – 9) of intervention, for example Monday grass, Wednesday tartan, Friday asphalt. This design was chosen to give participants contrasting experience on different surfaces which varied in hardness, texture, and regularity. Weeks four through to six (session 10 – 18) incorporated a mixture of surfaces in each training session.

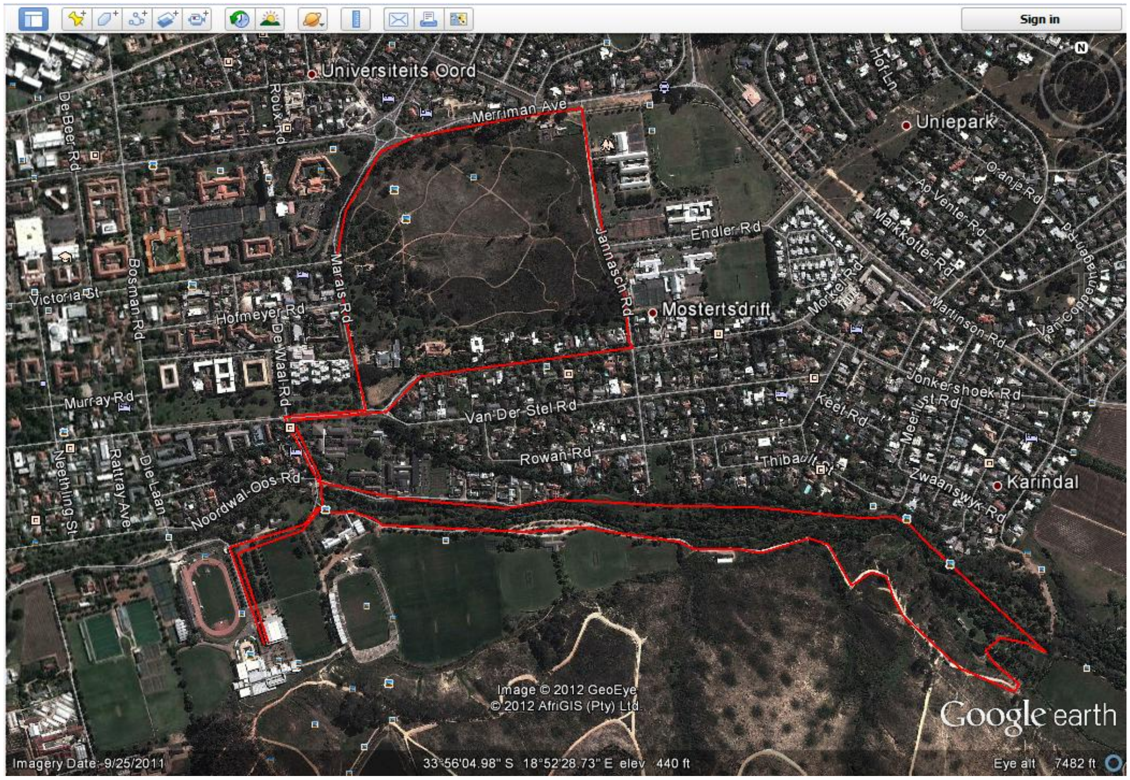


Figure 4.4. Example of training route mapped and traced using Google© earth.

2. Lower limb comfort

Supervised and monitored training sessions of slow progression appear to be the fundamental basics to a minimalist shoe transition programme (McCarthy *et al.,* 2011; Rothschild, 2012; Sandler & Lee, 2010; Schilling, 2012; Wallack & Saxton, 2011). Thus, participants in the experimental group were supervised and monitored by the same primary researcher. Immediate feedback on subjective feelings of pain/discomfort, running surface, and shoes were collected from the participants regarding each training session in the minimalist shoes.

According to Nigg (2010: 274), “comfort is probably the most important variable for sport shoes”, and the current knowledge base and understanding of comfort-related questions is insufficient and requires further research. At the start of each training session in the minimalist shoes, participants were requested to complete a pre-training data capturing form (Appendix E), consisting of the Lower

Limb Comfort Index (LLCI). The LLCI is a subjective scale developed to provide a tool for clinicians and athletes to a) monitor lower limb comfort at multiple anatomical regions (foot, ankle, calf-Achilles, shin, knee, and footwear/shoes), b) create baseline for comfort norms for individual athletes for future assessment, and c) use prospectively in the event of injury to monitor rehabilitation progress (Kinchington & Ball, 2010; Kinchington, Ball, & Naughton, 2010). The LLCI has been shown to be a reliable tool to assess lower limb well-being in football players (Kinchington & Ball, 2010). Although originally designed for football players, the anatomical regions used are similar and thus also relevant to endurance runners.

<table>
<tr><td rowspan="2">Lower Limb Comfort:
Rank each body area from 0-6 using the comfort descriptors</td><td colspan="6">Place a score 0 to 6 in each box</td><td rowspan="2">Sum comfort /36 maximum score</td></tr>
<tr><td>Foot</td><td>Ankle</td><td>Calf-Achilles</td><td>Shin</td><td>Knee</td><td>Footwear</td></tr>
<tr><td colspan="8">COMFORT DESCRIPTORS
0 = extremely uncomfortable (unable to run or jump);
1
2
3 = neither uncomfortable or comfortable (more or less uncomfortable / comfortable)
4
5
6 = zero discomfort (extremely comfortable; best ever feel)</td></tr>
</table>

Figure 4.5. Lower limb comfort Index (LLCI) adapted from Kinchington, Ball, and Naughton (2010). The LLCI shows a numeric rating scale with fixed anchor points at key positions on the scale. Visual-descriptive explanations are used to provide interpretations of the anchors.

Each item of the LLCI was read out aloud by the primary researcher to the participant. An integer from zero to six was called out by the participant to represent the subjective discomfort (Figure 4.5). Each anatomical area was scored between 0-6. A score of 0 indicated extreme discomfort, as being unable to run or jump, while a score of 6 was used to indicate extreme comfort. Each comfort item represented an average of the left and right lower limbs. LLCI was recorded personally between the researcher and participant before every minimalist shoe training session over the entire intervention period. This procedure was followed to avoid any possible group influence.

A custom (self-designed) comfort-mileage rating scale for minimalist shoe running guidelines was specifically designed for this study (Table 4.1). If a participant experienced a comfort score of 0 (extremely uncomfortable), 1, or 2 for any LLCI item, the participant was in the red zone and not allowed to perform minimalist running, rather being asked to rest until the level of comfort improved (increased). Longer rest periods have been advised to assure that positive remodelling occurred between training sessions (Hreljac, 2004) to minimize the risk of injury. If a comfort level score had a rating of 3 (neither uncomfortable or comfortable) or 4, the participant was in the black zone and thus either maintained the same mileage as the previous run, or increased the mileage by a maximum of 20% of the previous run. If a comfort score had a rating of 5 or 6 (zero discomfort), the participant was in the blue zone, and thus training mileage was increased by 20 – 40% of previous run.

Table 4.1. Lower limb comfort-mileage rating scale and guidelines for minimalist shoe training.

Zone	**LLCI level rating**	**Investigator decision regarding mileage**
Blue	Any area 5 or 6	20 - 40% increments
Black	Any item 3 or 4	0 - 20% increments
Red	Any item 0, 1, or 2	Rest. Minimalist shoe training resumes only when all items 3 or above

3. Adverse reactions

Minimalist shoe training was expected to cause muscle soreness or discomfort in the triceps surae. However, immediate caution was raised if any signs or symptoms relating to bone, joint, or soft tissue were observed (Rothschild, 2012). Thus, if a situation would present itself where pain or severe discomfort was experienced, the participant was asked to rest until comfort returned to its usual range and pain had subsided. This procedure was applied, as Hart and Smith (2008) cautioned that injured runners should not persist with barefoot running until symptoms have subsided. Verbal reports of any adverse reactions to the minimalist shoes were noted.

4. Surface selection

There is no research to suggest which surface is the best to train on when barefoot or in minimal footwear. Shod runners are sometimes advised to avoid hard concrete surfaces (Noakes, 2003). However, one cannot assume that barefoot or minimalist running should follow the same principles. Thus, due to the perception that minimalist shoes attempt to mimic the barefoot condition, it may be better to follow training surface principles advocated for barefoot running. According to Hart and Smith (2008), large terrain variability is a key factor in a successful transition to barefoot running, yet they warn that surface variance should be introduced in a barefoot training programme only once the skin on the plantar surface of the foot, as well as the muscles, have had adequate time to acclimatise to the surface. Unlike a bare foot, minimalist shoes provide protection of plantar skin abrasion from training surface, and thus waiting for plantar skin of the foot to recover from minimalist shoe training should be ruled out as a factor for surface selection. However, minimalist shoes encourage recruitment of different muscles surrounding the foot and ankle (Potthast *et al.,* 2005). Increased musculature recruitment should thus be taken into account when selecting an appropriate surface.

There are contrasting theories regarding surface progression. Some suggest a soft to hard surface approach (Hart & Smith, 2008; Rothschild, 2012) starting with grass and rubberised tartan track and progressing to roads and smooth trails. Others suggest a hard to soft approach (Robbins & Hanna, 1987; Wallack & Saxton, 2011), arguing that harder surfaces allow for greater sensory feedback and spare the tender metatarso-phalangeal joints from intense plantarflexion of the digits. A third view is that a wide variety of terrains should be used when barefoot running (Robillard, 2010). The minimalist shoes that were used in this study (Vibram Fivefingers ® ; Bikila model) have been advertised to "offer more traction over a variety of surfaces". Several training surfaces were therefore chosen for this study (Figure 4.6).

a) b) c) d)

Figure 4.6. Participants in experimental groups running over various surfaces: a) grass; b) tartan track; c) asphalt; d) off-road/gravel road . (Photographs by K Schütte).

G. MEASUREMENTS AND TESTS

The purpose of this section is to describe the protocols used that were needed to measure and test the various outcome variables of this study. The section begins by explaining the protocol selected to measure body anthropometrics. Thereafter, the necessary methods to measure control shoe characteristics and minimalist shoe comfort are provided. The section ends with a detailed explanation to how lower limb kinematics and kinetics were recorded.

1. Anthropometric assessment

Participants were barefoot and wore light-weight clothes (running shorts and shirt). Recommendations from the International Standards for Anthropometric Assessment (ISAK) published by the International Society for the Advancement of Kinanthropometry (Marfell-Jones, Olds, Stewart, & Carter, 2006), were followed during the various anthropometric measurements. Stretched stature, body mass, leg length, knee width, ankle width, thigh circumference 10 cm superior to patella, and maximum left and right calf circumference were measured. All anthropometric measurements were taken by the same ISAK level one qualified researcher.

Stature

Participants were positioned with the heels together and the heels, buttocks and upper back touching the stadiometer. The head of each participant was placed in the Frankfort plane, the lower edge of the eye socket (Orbitale) in the same horizontal plane as the notch superior to the tragus of the ear (Tragion). Once aligned, the participants were asked to inhale and the measurement was taken at the highest point of the skull, the Vertex. A stadiometer was used and the reading was taken to the nearest 0.1 centimetre (cm).

Body weight

Body weight (kg) was determined using a calibrated electronic scale (Salter, model 9106, Kent, UK) rounded off to the second decimal. Participants had to stand in the middle of the scale with weight equally distributed on both legs looking straight ahead.

Leg length

Leg length (mm) was measured with a standard measuring tape between the anterior superior iliac spine (ASIS) marker and the medial malleolus via the knee joint. Participants were in the standing position with body weight equally distributed. This protocol was used as advised by the Vicon instruction manual.

Knee width and ankle width

Knee (femur bi-epicondylar) width (mm) was defined as the medio-lateral width of the knee across the line of the knee axis, while ankle (bi-maleolar) width (mm) was defined as the medio-lateral distance across the malleoli. Both of these distances were measured with a small sliding calliper while the participants were standing with knees in resting flexed position, with their feet flat and apart, with their weight equally distributed.

Thigh and calf circumference

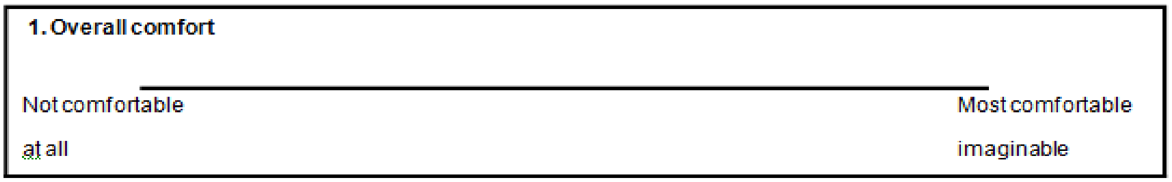
Thigh circumference (TC) (cm) was measured at a level of 10 cm above the superior pole of the patella, and was taken perpendicular to the long axis of the thigh. Maximum calf circumference (MCC) (cm) was defined at the maximum girth between the ankle and knee joint, perpendicular to the long axis of the lower leg. For both girth measurements, participants' assumed a relaxed standing position with their arms hanging by the sides. Participants had their feet separated with their weight evenly distributed on a box elevated 30 cm from the ground to align the researcher's eyes at the level of the tape. The cross over technique was used and care was taken to ensure that the measuring tape did not slip or indent the skin while taking the measurement.

2. Control shoe measurements

Footwear characteristics of control shoes are needed when no standardised footwear control shoe is provided for footwear biomechanics research. Some studies use a new, standardised control shoe (McCarthy *et al.,* 2011; Squadrone & Gallozzi, 2009), while other studies make use of the participants' own shoes that they have already trained in (Dickinson *et al.,* 1980; Dixon *et al.,* 2000; Lieberman *et al.,* 2010). According to Dixon *et al* (2000), using own shoes provides more insight into realistic running conditions. However, differences in shoe cushioning thickness has been suggested as a primary determinant of footstrike pattern and vertical impact forces (Robbins & Hanna, 1987). It is thus necessary to account for shoe cushioning height. Cushioning height was determined by subtracting each participant’s standing height without shoes (barefoot) from stature with shoes on. Shoe age and wearing patterns have shown to affect the contact time a runner spends on the ground (Kong, Candelaria & Smith, 2009). Thus, participants were asked to estimate the age of their running shoes in months used since purchase.

3. Minimalist shoe comfort

Participants’ perception of footwear comfort was quantified to determine the effect of the familiarisation period on subjective feelings of the minimalist shoes. A sheet of paper with various footwear comfort items were handed to each participant for recording the minimalist shoe comfort (Appendix F). Participants were asked to rate their perceived minimalist shoe comfort in the standing position while wearing their pair of minimalist shoes. Participants drew a vertical line along a 150 mm visual analogue scale (VAS), an example of which is provided in Figure 4.7. The VAS scale has been shown to be a reliable method of assessing footwear comfort (Mündermann, Stefanyshyn, & Nigg, 2001), and has been preferred over the likert scale. The VAS scale requires the participant to make a vertical line according to each perception item provided. For the purposes of this study, the VAS scale was modified to suit characteristics specific to the minimalist shoe provided.



1. Overall comfort

Not comfortable at all

Most comfortable imaginable

Figure 4.7. Example of item (shoe overall comfort) from footwear comfort questionnaire (horizontal line in the middle represents 150 mm scale; vertical line represents participant’s choice).

Several perception items pertaining to the minimalist shoes were listed, which included overall comfort, heel cushioning, arch cushioning, forefoot cushioning, fit for individual toe pockets, support, fit around top of foot, flexibility, forefoot width, and length. Definitions of these items can be found in Table 4.2. Items were averaged to indicate a total comfort score. Participants were blinded to their previous comfort ratings to prevent bias. The left hand side of each item on the scale referred to the minimum possible value of "not comfortable at all", which increased to the right hand side with a maximum value of "most comfortable imaginable". The following instructions were given to the participants prior to completing the footwear comfort questionnaire: "These are scales used to measure different characteristics of your pair of minimalist shoes. Please mark a vertical line along the scale for each item provided. The further to the right you mark the line, the more comfortable the specific item of the shoe is. These comfort items represent how you feel at this very moment with the minimalist shoes on your feet." A ruler was used to measure the distance (mm) from "not comfortable at all" to the point where the participant drew a vertical line on the VAS scale. This distance was a raw measurement out of 150 mm, and was used for statistical analysis.

Table 4.2. Relative footwear comfort items and corresponding definitions

Comfort Item	**Definition**
Overall comfort	Overall comfort of the shoe.
Heel cushioning	Hardness/softness of the material in the heel region.
Arch cushioning	Hardness/softness of the material in the region of the arch of the foot.
Forefoot cushioning	Hardness/softness of the material in the forefoot region.
Fit for individual toe pockets	Correct fit for toes in each pocket
Arch support	Instability/stability of shoe for foot and ankle.
Fit around top of foot	Tightness/looseness of material around foot bridge (transverse arch) region.
Flexibility	Overall flexibility of shoe sole.
Forefoot width	Width of the shoe in the forefoot region.
Length	Length of the shoe.

4. Lower limb kinematics and kinetics

Kinematic and kinetic data were acquired from both left and right lower extremities from all the participants. Three-dimensional kinematic data was collected with an eight-camera motion capture system (Vicon ®, Oxford, UK). Ground reaction force data were simultaneously recorded using a Bertec (Bertec ®, Columbus, OH, USA) force plate. An illustration of the experimental set-up is presented in Figure 4.8.A 6 mm thick rubber-vinyl surface (Plasti-lock©, Gauteng, RSA) covered the force plate and entire laboratory runway. Thus, the force plate was unidentifiable to the participants. Masking tape was placed in positions on the runway to help the researchers to identify the position of the force plate imbedded in the runway. The laboratory runway surface covered a wooden floor.

Participants were asked to warm-up for five minutes at a comfortable pace. The barefoot condition was chosen for the warm-up as it has been found that runners acclimatise to barefoot running once multiple strides are performed (Divert *et al.,* 2005). It may thus be more appropriate to allow runners to warm-up and acclimatise to the barefoot condition. Participants rolled a die to determine a random order of all three footwear testing conditions. The numbers one, two, or three on the land of the die were associated with the barefoot, Vibram Fivefingers ® and shod conditions respectively.

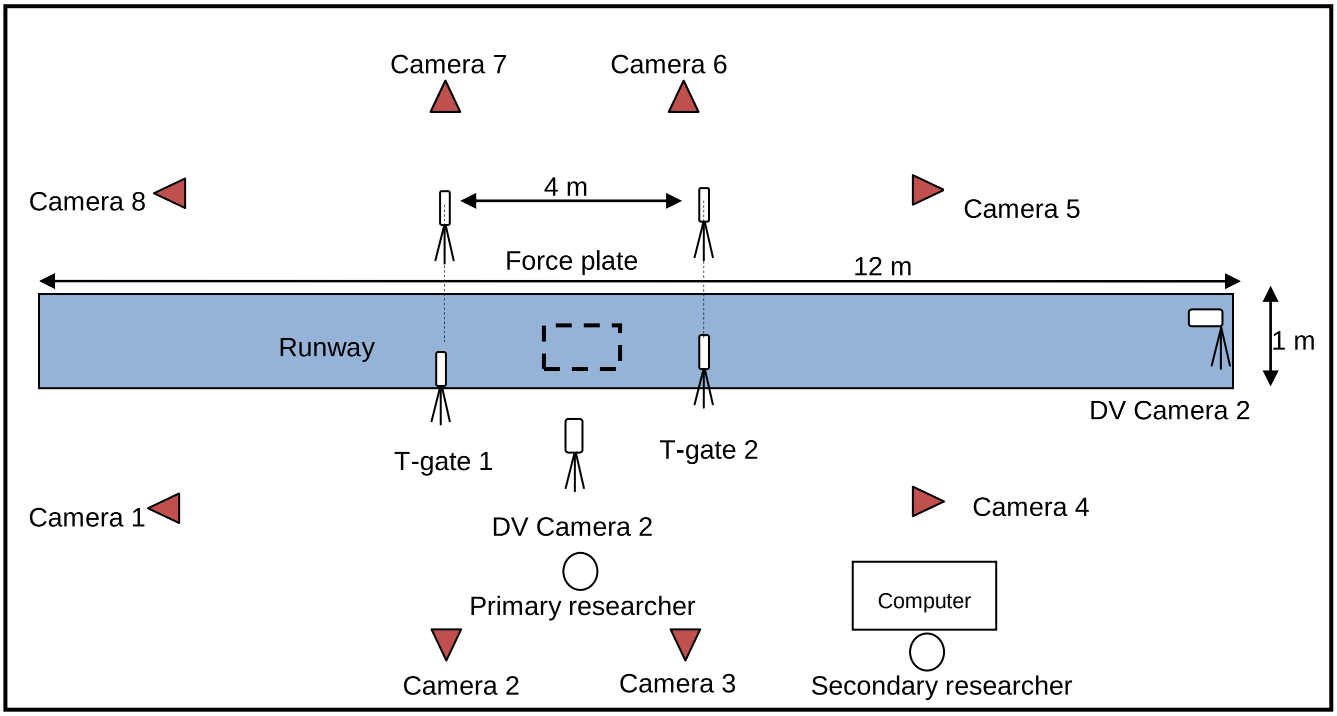


Figure 4.8. Experimental set-up for 3D kinematic and kinetic, and running speed analysis

To record the motion of the lower extremities, several reflective markers (diameter 9 mm) were placed bilaterally on the thigh, shank, ankle and foot (Figure 4.9). Additional markers were placed on the left and right anterior superior iliac spines (ASIS) and posterior superior iliac spines (PSIS). All of these markers served as tracking markers during the running trials. To help model the legs, two additional markers were placed on the medial malleoli and served as calibration markers. All markers remained unchanged between conditions with exception to the markers placed over the heels and second metatarsal heads. Heel markers of the left and right foot were placed on the shoes or bare heel of the participants while standing in the visual field of the Vicon ® cameras. One researcher would carefully adjust the height position of the heel markers to align it with the second metatarsal head markers. Another researcher provided feedback from the Vicon ® Nexus software regarding the height (mm) difference between the heel and second metatarsal head markers. This procedure ensured that the heel markers were in the same horizontal plane as the second metatarsal head markers in the standing calibration position.

a) *b)* *c)*

Figure 4.9. Participant standing during calibration. Photos represent a) lateral; b) posterior; c) anterior views respectively. (Photographs by K Schütte)

A standing calibration trial was collected for each participant during quiet stance. Prior to calibration, the skin (at the anatomical locations of the reflective markers) of the participants was prepared with Friars balsam to remove any sweat. This procedure prevented the double sided tape from losing its adhesiveness due to sweat and skin movement during the running trials. Prior to shoe marker placement, masking tape was used to block out any reflective material on the surface of the participants' own running shoes, as well as the minimalist shoes.

Following standing calibration, participants remained standing with their feet next to each other in the centre of the force plate. The participants were provided with the relevant instructions (typed in bold on an A4 page and read out allowed to the participants for consistency) regarding the manner in which they should run: 1) "Select a running speed that is your own, comfortable speed, and represents a speed you would select on an easy training run" (Arendse *et al.,* 2004); 2) "Regardless of footwear condition, select a running technique which is most comfortable for you" (no instruction was provided to the participants on how to contact the ground during the run, as suggested by Hamill, Russell, Gruber, and Miller (2011a)); and 3) "While running over the runway, keep your eyes focused on an object on the wall at eye level in front of you", as this instruction has been said to help avoid searching for the force plate in the runway (Queen, Gross, & Liu, 2006). It should be mentioned that the force plate was unidentifiable as it was covered by the sports surface. Nevertheless, the primary researcher was watching the area of the force plate clearly to make sure that the participant for the given trial was indeed hitting the force plate cleanly. Thus, to prevent the participants from watching where the researcher was watching, the instruction to keep their eyes focused on the wall in front of them seemed appropriate. Running speed was monitored with photoelectric timing gates (Speed Light, SWIFT Performance Equipment, New South Wales, Australia) timing gates, by recording the time between two photoelectric sensors placed 4 m apart.

Figure 4.10. Example of participant running during a barefoot trial along the laboratory runway (Photograph by K Schütte).

Several (5 -10) practice runs over the laboratory runway were given per condition to ensure that the participant was landing in the centre of the force plate. A photo of a participant running along the laboratory runway is provided in Figure 4.10. The precise numbers of practice trials were dependent on a) when the participant felt comfortable with the runway, and b) when the researcher saw that the participant was landing in the centre of the force plate. A trial was considered good and accepted if the participant landed with a foot completely within the edges of the force plate, while running naturally in a straight line. For the run-up start, the participants were asked to stand with their feet next to each other under their base of support and to select a leading leg. Participants' run-ups were then measured from either side of the force plate (longitudinally positioned). Several white chalk lines (± 15 cm apart) were drawn on the floor in the area of the run-up start. If the participants' were not able to accomplish a "good" force plate hit, then they were asked to adjust their run-up to start on another chalk line closer to or further from the force plate respectively. Once the participants were able to achieve three consecutive "good hits" during practice, the testing trials commenced. To prevent any possible effect of anticipation, participants did not know when the actual recording of testing trials data commenced, nor did they know when the recording of data for each condition would stop. Participants had to complete six "good" running trials for each leg for each of the three footwear conditions.

Running speed for each individual trial was monitored with the Speed light timing gates positioned 4 m apart on either side of the force plate.

H. OUTCOME VARIABLES

The outcome variables of this study were chosen to best represent the first and second objectives of this study. Matlab© (The Mathworks, Natick, MA) was used to process all running trials with clean force plate hits (pre- and post-testing for both experimental and control groups) from the Vicon ® Nexus software. Each outcome variable is briefly defined and the results of the data processing are explained where necessary.

1. Lower limb kinetics

Ground reaction force and lower limb joint moments were filtered with a recursive forth order low pass Butterworth digital filter with a cut-off frequency of 75 Hz. All data were normalised to percent stance phase. Ground reaction forces were normalised to each participant's body weight (kg). Body weight was taken at both pre- and post-testing to account for changes that would occur during the intervention period. Three-dimensional joint moments were calculated over the stance phase using a standard inverse dynamics method implemented by the conventional Vicon ® Plug-in gait model. This model is used for the majority of clinical gait analysis laboratories. Joint moments were normalised to each participants body weight and barefoot height, as previously performed (Kerrigan *et al.,* 2009; Williams *et al.,* 2000). Normalisation of joint moments to body weight and height has shown to be effective in reducing unnecessary variance (Moisio, Sumner, Shott, & Hurwitz, 2003).

External vertical ground reaction force (vGRF)

The vertical average loading rate (VALR) is the impact loading rate that occurs between contact and the time of the vertical impact peak (VIP) (Divert, Mornieux, Baur, Mayer, & Belli, 2005; Dixon, Collop,

& Batt, 2000; Nigg *et al.,* 1995). Some have quantified the VALR over only the most linear portion (20 – 80%) of the force time curve between contact and VIP (Hamill *et al*., 2011a; Milner *et al*., 2006a; Milner *et al*., 2006b; Williams *et al*., 2000). As discussed, the impact peak is only distinct when a runner uses a rearfoot strike (RFS) or midfoot strike (MFS) landing technique. However, forefoot strikers (FFS) often show a missing VIP (Altman & Davis, 2009; Lieberman *et al.,* 2010; Oakley & Pratt, 1988; Williams *et al.,* 2000). For this reason it can be difficult to quantify the VALR when the VIP is absent. Some investigators found that the time (% stance) to impact peak correlated with the VIP (r = 0.49; p = 0.03), and proposed that a percent stance of 13% should be used as a surrogate for when the VIP is absent (Willy, Pohl, & Davis, 2008). This method has been used by at least one other researcher (Altman & Davis, 2009).However, the percentage of stance to which the VIP occurs is influenced by footwear (Dickinson *et al.,* 1980; Oakley & Pratt, 1988), and thus assuming 13% of stance for all footwear conditions may be inappropriate. Another study took the VALR using the percent of stance where the VIP occurred for each footwear condition (barefoot; minimalist shoe; shod) (Lieberman *et al.,* 2010). This method was adopted for this study as it appears to be more appropriate when comparing footwear conditions. Definitions for the various vGRF parameters used in this study are listed in Table 4.3.

Table 4.3. External vertical ground reaction force (GRF) outcome variables.

Variable	Unit	Definition
Vertical Impact peak (VIP)	BW	Clear impact peak observed: Maximum magnitude of impact ground reaction force No clear impact peak: Group average percentage of stance as determined for each condition in trials with an impact peak (Lieberman *et al.* 2010)
Time to vertical impact peak (TVIP)	ms	Time from contact to vertical impact peak
Average rate of impact loading (VALR)	BW/s	Vertical rate of loading from the steepest section (20 - 80%) of the transient between foot contact (60 N) and impact peak.
Vertical propulsive peak (VPP)	BW	Maximum value of vertical GRF (F_Fz1)

External joint moments

For this study, only the maximum and minimum joint moments during stance phase were considered for parameters of interest (Table 4.4).

Table 4.4. Peak joint moment outcome parameters.

Joint moment peak (Nm/kg.m)	Occurrence (stance phase)	Plane	Positive/ Negative
Dorsiflexion moment (DFM)	Initial-stance	Sagittal	Negative
Plantarflexion moment (PFM)	Mid-stance	Sagittal	Positive
Ankle inversion moment (AIM)	Mid-stance	Frontal	Positive
Knee flexion moment (KFM)	Foot contact	Sagittal	Negative
Knee extension moment (KEM)	Mid-stance	Sagittal	Positive
Knee abduction moment (KAM)	Mid-stance	Frontal	Negative
Hip flexion moment (HFM)	Terminal-stance	Sagittal	Negative
Hip extension moment (HEM)	Initial-stance	Sagittal	Positive
Hip abduction moment (HAM)	Mid-stance	Frontal	Negative

2. Lower limb kinematics

Spatio-temporal kinematics

Three-dimensional (3D) kinematic data of the lower limbs were filtered with a low pass, fourth order, zero lag Butterworth digital filter with a 12 Hz cut-off frequency. Lower limb kinematics was further divided into spatio-temporal and lower limb joint angles. Spatio-temporal parameters are listed in Table 4.5*.*

Table 4.5. Spatio-temporal outcome variables.

Variable	Unit	Definition
Step frequency	steps/min	Number of steps completed per minute
Step length	m	Distance within successive foot contacts of opposite feet
Step time	ms	Time within successive foot contacts of opposite feet
Contact time	ms	Time from foot contact to toe- off ground during stance phase
Flight time	ms	Time from toe-off to foot contact

Joint angles

Lower limb joint angles of the ankle, knee and hip in three dimensions were processed into relevant discrete time points: footstrike angle (FSA) and ankle at vertical propulsive peak (VPP). Sagittal plane joint range of motion was calculated by subtracting the difference in joint angle from VPP to FSA.

Strike index

Even though footstrike pattern can be visually classified into a rearfoot strike (RFS), midfoot strike (MFS) or forefoot strike (FFS), the strike index (SI) was designed to be used as a tool to quantify footstrike pattern, using a force plate (Cavanagh & Lafortune, 1980). SI has been quantified as "a measure of the location, at initial contact, of the centre of pressure (COP) along the long axis of the foot as a percentage of the total foot length" (Altman & Davis, 2011: 2). SI has been defined as the point of intersection of a perpendicular drawn from the centre point of pressure (COP) at initial foot contact to the long axis of the foot. The point of intersection is then reported as the total foot length from the heel (Hamill *et al.,* 2011: 35). Several studies have used SI to determine the effect of footstrike patterns on impact force (Altman & Davis, 2009; Becker *et al.,* 2011; Hamill *et al.,* 2011; Milner, Hamill, & Davis, 2007). Strike index has been shown to have a positive correlation (r = 0.92) to ankle footstrike angle. The calculation of SI is shown in Figure 4.11. A SI of 0 – 33% indicates a RFS, 34 – 67% a MFS, and 68 –100% a FFS (Altman & Davis, 2011).

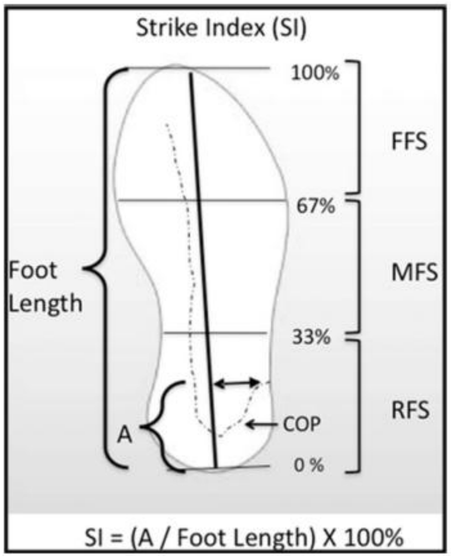


Figure 4.11. Strike index (SI) calculation for a rearfoot striker, adapted from (Altman & Davis, 2011) The location of the COP at initial contact along the longitudinal axis of the foot coordinate system (A), is normalised by the foot length and multiplied by 100 to obtain a percentage of the foot length.

SI is calculated using the positioning of the heel and toe reflective markers with respect to the centre of pressure (COP) line of action measured on the force plate during contact. Figure 4.12 illustrates how strike index is calculated using simple mathematical procedures.

Calculation of distance A in Figure 4.12 is used to represent SI according to the following mathematical steps:

$$TFL = \sqrt{[(Xtoe - Xheel)^2 + (Ytoe - Yheel)^2]}$$

$$\theta_1 = \mathrm{atan}\left(\frac{Y1}{X1}\right)$$

$$C = \sqrt{[(Xcop - Xtoe)^2 + (Xcop - Xtoe)^2]}$$

$$\theta_2 = \mathrm{atan}\left(\frac{Y2}{X2}\right)$$

$$\theta_3 = \theta_1 - \theta_2$$

$$A = C(cos\theta_1)$$

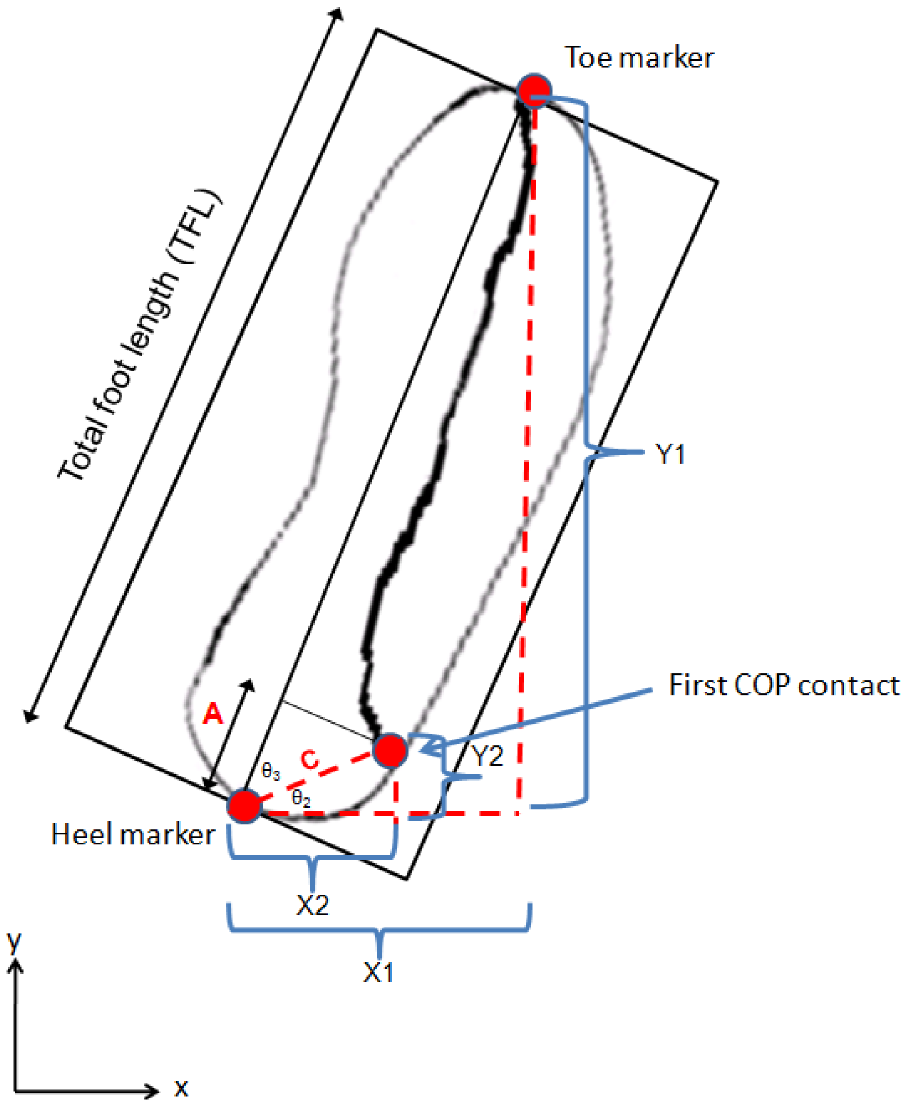


Figure 4.12. Calculation of strike index (SI) for the right foot. The purpose is to calculate distance A, representing point of intersection of a perpendicular drawn from the x and y coordinate centre of pressure (COP) at initial foot contact to the long axis of the foot, which is then reported as the total foot length (TFL) from the heel. The only knowns are the coordinates of the red dots of the heel and toe marker respectively. The box around the foot is used to illustrate that the foot is not orthogonal with the x-y coordinate system due to toeing out. θ_1 is the sum of angles θ_2 and θ_3 and represents the angle between TFL and X1. Adapted with permission from Gruber (personal communication, 18 May 2012).

I. STATISTICAL ANALYSIS

Given the normality of the data, parametric tests were used for statistical analysis. The level of significance was set at 95% ($P \leq 0.05$). Independent t-tests were used for descriptive training and anthropometric measurements. ANOVA's followed by a Least Significant Difference (LSD) post hoc was used to compare the three footwear conditions namely barefoot (BF), minimalist shoes (VF), and shod (SH) from pre-test data. Dependent t-tests were performed to compare footwear comfort items pre- and post-familiarisation period. Independent t- tests were also used to compare differences in mean differences (pre-post) between experimental (EXP) and control (CONT) groups. Hopkins (2002) effect sizes were used for practical significance where necessary, and were defined according to the criteria shown in Table 4.6. Pearson correlation coefficients were used to quantify the strength of relationships between various outcome variables, and are quantified in Table 4.7

Table 4.6. Effect size intervals according to strength of practical significance and associated qualitative outcomes, adapted from Hopkins (2002).

Effect size (ES) interval	**Qualitative outcome**
≥ 0 – 0.15	Negligible (N)
≥ 0.15 – 0.40	Small (S)
≥ 0.40 – 0.75	Medium (M)
≥ 0.75 – 1.10	Large (L)
≥ 1.10 – 1.45	Very large (VL)
≥ 1.45	Huge (H)

Table 4.7. Pearson correlation coefficients according to strength of association between two variables and associated qualitative outcome.

Pearson's correlation coefficient interval (r)	**Qualitative outcome**
r = 0	No correlation (NC)
0.00 ≤ r ≤ 0.24	Weak correlation (W)
0.25 ≤ r ≤ 0.49	Moderate correlation (M)
0.50 ≤ r ≤ 0.74	Moderate to good correlation (MG)
0.75 ≤ r ≤ 1	Strong correlation (S)
r = ± 1	Perfect correlation (P)

CHAPTER FIVE

RESULTS

A. INTRODUCTION

After having stated the various methodological procedures used in chapter four, the pertinent results of this study are now reported. One of the experimental participants was not able to attend post-testing due to time constraints and therefore his pre-test data was not included for analysis. Thus, a total of 21 participants (11 control; 10 experimental) were used for final statistical analysis.

B. DESCRIPTIVE CHARACTERISTICS

1. Training characteristics

No significant differences were found between experimental (EXP) and control (CONT) groups for any training or age characteristics (P > 0.05) (Table 5.1). However, the EXP group had slightly higher weekly training mileage and frequency, as well as higher estimated barefoot experience during childhood versus the CONT group.

Table 5.1. Participant training characteristics, data represented as mean ± SD

Characteristic	**CONT (n = 11)**	**EXP (n = 10)**	**P value**
Age (yrs.)	24.00 ± 2.18	24.10 ± 1.74	0.87
Shod running experience (yrs.)	4.89 ± 2.65	5.15 ± 4.57	0.87
Weekly training (km)	24.90 ± 3.30	29.36 ± 8.51	0.12
Training sessions/week	3.64 ± 0.71	4.27 ± 0.79	0.06
Barefoot running experience (%)	4.73 ± 3.98	5.10 ± 5.99	0.73
Barefoot sports experience (%)	7.91 ± 8.61	9.00 ± 11.97	0.81
Barefoot childhood experience (%)	39.55 ± 24.74	60.00 ± 23.09	0.07

CONT: control group; EXP: experimental group; n: number of participants.

2. Anthropometric characteristics

Several anthropometric measurements were taken to model the pelvis, hips, knees, and ankles of each participant. No significant differences were found between experimental (EXP) and control (CONT) groups for any anthropometric characteristics (P > 0.05) (Table 5.2).

Table 5.2. Participant anthropometric measures. Data are mean ± SD

Parameter	Side	CONT	EXP	P value
Height (cm)		181.95 ± 6.06	182.56 ± 8.46	0.77
Body weight (kg)		78.75 ± 6.36	76.11 ± 9.19	0.90
BMI (kg/m^2)		23.78 ± 6.12	22.83 ± 8.55	0.84
Leg length (cm)	Left	94.70 ± 4.21	95.15 ± 5.10	0.81
	Right	94.86 ± 4.65	95.47 ± 4.70	0.77
Knee width (cm)	Left	10.28 ± 0.32	10.26 ± 0.42	0.99
	Right	10.21 ± 0.30	10.23 ± 0.48	0.99
Ankle width (cm)	Left	7.64 ± 0.26	7.78 ± 0.45	0.85
	Right	7.63 ± 0.28	7.73 ± 0.45	0.93

CONT: control group; EXP: experimental group.

3. Control shoe characteristics

The participants' own shoes were used in this study. Shoes varied across many brands and models, and thus it was necessary to report specific shoe characteristics and their association with various outcome variables. Own shoes were used as a control shoe to distinguish between minimalist and barefoot running conditions. Table 5.3 shows that no significant differences were found between experimental and control groups with respect to heel cushioning height, age, or size (p > 0.05). However, small, large, and medium effect sizes were seen for the control group having higher cushioning, older, and larger shoes compared to the experimental group respectively (ES = 0.26; 0.76; 0.60).

Table 5.3. Control shoe characteristics between control (CONT) and experimental (EXP) group determined by independent T-tests. Data represented as mean ± SD. Level of statistical and practical significance is provided by P values and Effect sizes (ES) respectively.

Characteristic	**CONT**	**EXP**	**P (ES)**	**Qual.**
Heel cushioning height (mm)	26.09 ± 5.59	24.60 ± 6.29	0.57 (0.26)	S
Age (months)	20.27 ± 19.80	9.60 ± 5.02	0.11 (0.76)	L
Size (UK)	10.50 ± 1.61	9.70 ±1.09	0.20 (0.60)	M

CONT: control group; EXP: experimental group; P value; ES: effect size; Qual: qualitative outcome; S: small; M; medium; L: large.UK: United Kingdom.

Correlations for all shod running trials (n = 252) were performed to determine the effect of individual control shoe cushioning height (mm) on relevant lower limb kinetic and kinematic outcome variables (Table 5.4.). For the spatio-temporal parameters, running speed and step frequency were positively moderately associated with control shoe cushioning thickness. Step time and contact time showed a negative moderate, and negative moderate to good associations with control shoe cushioning thickness. Flight time, however, showed only a weak correlation with control shoe cushioning. In terms of vertical ground reaction force parameters, vertical average loading rate (VALR) was negatively moderately associated with control shoe cushioning thickness. However, vertical impact peak (VIP) was only weakly (negatively) associated with control shoe cushioning thickness. Vertical propulsive peak and ankle plantarflexion moment (PFM) peak were positively moderately associated with control shoe cushioning thickness. Ankle dorsiflexion at contact was weakly positively associated with control shoe cushioning thickness

Table 5.4. Correlations of control shoe cushioning height with relevant outcome variables.

Parameter	**r**	**P**	**Qual.**
Running speed (m/s)	0.36	0.002	M
Step frequency (steps/min)	0.44	0.151	M
Step length (m/s)	0.09	0.001	W
Step time (m/s)	-0.45	0.0002	M
Contact time (m/s)	-0.56	0.0001	MG
Flight time (m/s)	0.04	0.603	W
VIP (BW)	-0.12	0.072	W
VALR (BW/s)	-0.34	0.002	M
VPP (BW)	0.47	0.0001	M
Ankle dorsiflexion angle at contact (degrees)	0.22	0.001	W
Ankle plantarflexion moment (PFM) peak (Nm/kg.m)	0.32	0.002	M

r: Pearson’s correlation coefficient; P value. VIP: vertical impact peak; VALR: vertical average loading rate; VPP; vertical propulsive peak. W: weak correlation; M: moderate correlation; MG; Moderate to good correlation.

4. Minimalist shoe comfort

Participants wore the minimalist shoes over a seven-day familiarisation period to investigate changes in perceived footwear comfort ratings. All participants (n = 21) abided by the guidelines set out pertaining to the familiarisation period.

Table 5.5 shows data pertaining to the various minimalist shoe comfort rating items before and after the familiarisation period, as well as the level of meaningful and statistical change. The total comfort score for all comfort items collectively showed a statistically significant improvement (P = 0.006; ES = 0.19). This may have been primarily due to the item being fit for individual toe pockets, which showed a statistically significant and large effect on improvement of comfort (P = 0.01; ES = 0.88). All except one of the other footwear comfort items showed a non-statistically significant trend towards improved perceived comfort, with negligible to small effects on perceived comfort. Only the item "forefoot cushioning" showed a non-statistically significant decrease in comfort rating (P = 0.24; ES = 0.21). Figure 5.1 represents relative positive or negative changes in footwear comfort across the various comfort items.

Table 5.5. Mean vas analogue scale (VAS) ratings of perceived footwear comfort for all (n=21) participants at pre- and post-familiarisation period, determined by dependent T-test. Data are represented as mean ± SD. Level of statistical and practical significance is provided by P values and Effect sizes (ES) respectively.

Footwear comfort item	**VAS pre**	**VAS post**	**P (ES)**	**Qual.**
Overall comfort (mm)	116.59 ± 20.08	120.27 ± 10.30	0.49 (0.24)	S
Fit for individual toe pockets (mm)	89.71 ± 34.28	113.55 ± 19.24	0.01 (0.88)*	L
Heel cushioning (mm)	105.18 ± 26.37	108.60 ± 29.62	0.52 (0.12)	N
Arch cushioning (mm)	107.08 ± 26.43	109.68 ± 29.88	0.65 (0.09)	N
Forefoot cushioning (mm)	110 ± 31.93	107.21 ± 26.47	0.61 (0.10)	N
Arch support (mm)	105.56 ± 26.45	109.43 ± 27.03	0.29 (0.15)	S
Flexibility (mm)	124.32 ± 17.53	125.21 ± 11.49	0.82 (0.06)	N
Fit around top of foot (mm)	113.80 ± 33.62	118.11 ± 22.40	0.44 (0.15)	S
Forefoot width (mm)	111.58 ± 26.76	116.40 ± 19.77	0.24 (0.21)	S
Length (mm)	117.10 ± 22.19	119.19 ± 19.86	0.68 (0.10)	N
Total comfort score	110.09 ± 27.65	114.76 ± 22.57	0.006 (0.19)*	S

CONT: control group; EXP: experimental group; P value; ES: effect size; Qual: qualitative outcome; N: negligible; M; medium; L: large; *Significant difference between pre- and post-familiarisation period (P < 0.05)

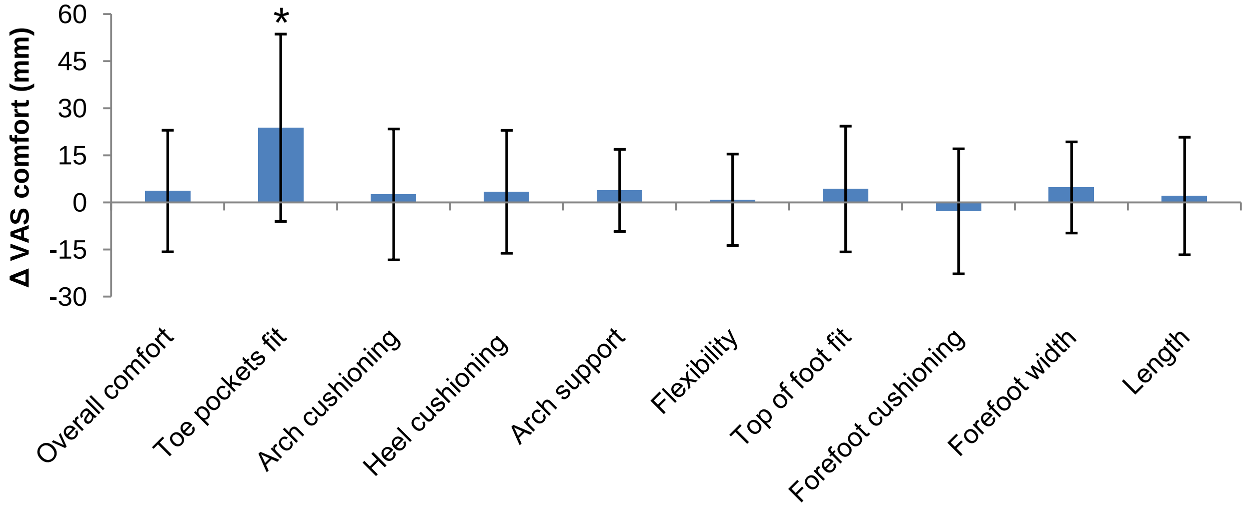


Figure 5.1. Absolute mean difference in footwear comfort items according to the vas analogue scale (VAS) at the start and end of the familiarisation period. Positive mean difference indicated improvement in comfort, while negative mean difference indicates a decline in comfort. * Indicates significant difference between pre- and post-familiarisation period ($p < 0.05$).

C. INTERVENTION CHARACTERISTICS

1. Training characteristics

The average total distance covered, duration, speed, and the number of rest days are provided in Table 5.6. As a group, participants completed 98% of minimalist shoe training sessions.

Table 5.6. Group averages for minimalist shoe training characteristic of experimental group. Data are mean ± SD

Sessions (n)	Distance (km)	Duration (hrs.)	Speed (m/s)	Rest (days)
17.7 ± 1.70	77.43 ± 14.39	6.37 ± 1.38	3.46 ± 0.28	2.38 ± 1.41

Descriptive training data on how participants from the experimental group progressed during the intervention period is illustrated (Figure 5.2) and quantified (Table 5.7). VF training distances and duration increased proportionally. Average speed showed to increase from first to third training session, then decreased gradually to the seventeenth session, then increased slightly in the last VF session. The amount of rest between VF training sessions varied between 1.46 days and 3.11 days, depending on the expected factor of lower limb comfort, or confounding factors such as poor weather, weekends versus week days, or public holidays.

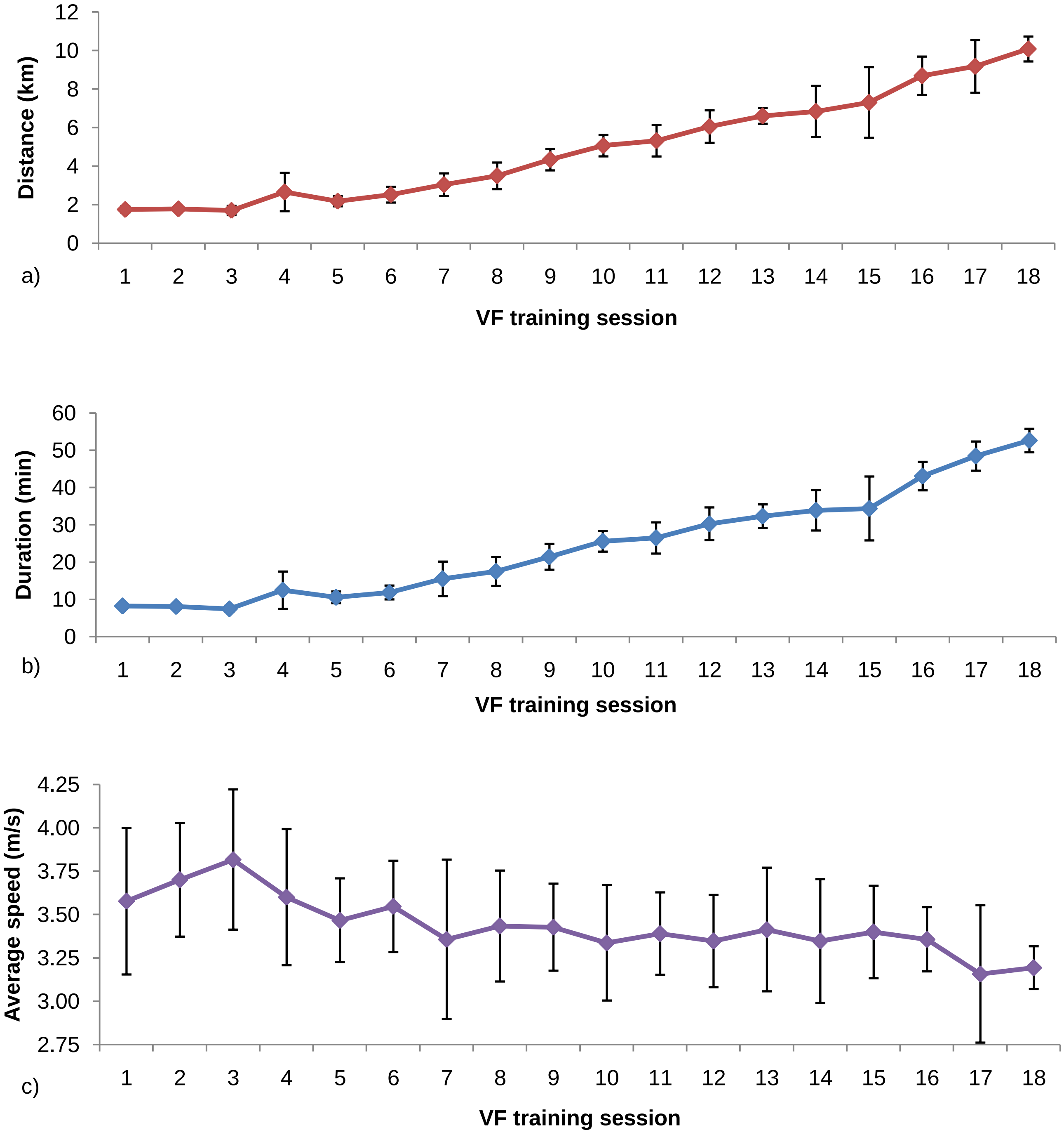


Figure 5.2**.** Mean ± SD representation of minimalist shoe training session characteristics for EXP group: a) distance (min); b) duration; c) speed.

Table 5.7. Group minimalist shoe training descriptive data distributed from session number one through to 18. Data are mean ± SD.

Session	Participants (n)	Distance (km)	Duration (min)	Speed (m/s)	Rest (days)
1	10	1.75 ± 0.17	8.17 ± 0.66	3.58 ± 0.42	
2	18	1.78 ± 0.11	8.07 ± 0.71	3.70 ± 0.33	1.46 ± 0.65
3	10	1.70 ± 0.24	7.42 ± 0.85	3.82 ± 0.40	1.77 ± 1.00
4	10	2.65 ± 1.00	12.45 ± 0.50	3.60 ± 0.39	3.11 ± 1.03
5	10	2.18 ± 0.26	10.53 ± 1.56	3.47 ± 0.24)	2.05 ± 1.46
6	10	2.52 ± 0.41	11.83 ± 1.86	3.55 ± 0.26	2.24 ± 0.94
7	10	3.03 ± 0.59	15.48 ± 4.63	3.36 ± 0.46	2.88 ± 1.10
8	10	3.49 ± 0.69	17.48 ± 3.91	3.43 ± 0.32	1.83 ± 0.88
9	10	4.34 ± 0.56	21.39 ± 3.47	3.43 ± 0.25	1.88 ± 0.67
10	10	5.06 ± 0.56	25.55 ± 2.78	3.34 ± 0.33	2.58 ± 1.53
11	10	5.32 ± 0.82	26.45 ± 4.19	3.39 ± 0.24	1.97 ± 1.82
12	10	6.05 ± 0.84	30.26 ± 4.40	3.35 ± 0.27	2.32 ± 1.42
13	10	6.61 ± 0.41	32.28 ± 3.18	3.41 ± 0.36	2.76 ± 1.29
14	10	6.84 ± 1.33	33.88 ± 5.43	3.35 ± 0.36	2.39 ± 1.72
15	9	7.31 ± 1.84	34.37 ± 8.58	3.40 ± 0.27	1.61 ± 0.70
16	7	8.69 ± 1.00	43.06 ± 3.82	3.36 ± 0.19	2.58 ± 0.85
17	7	9.18 ± 1.37	48.41 ± 3.92	3.16 ± 0.40	2.54 ± 1.54
18	6	10.08 ± 0.65	52.59 ± 3.16	3.19 ± 0.12	2.98 ± 0.98

Participants ran ~ 11% to 22% of their usual SH training distance on their first VF training session (Table 5.8). By the end of the intervention, participants were running 52% - 132% of their usual SH training distance in the VF condition. Five participants completed a VF mileage of more than their usual shod mileage by the end of the intervention.

Table 5.8. Descriptive training data of the experimental group. Data represents training performed only in the minimalist shoes during the intervention period. Data are mean ± SD for inter-session rest and speed respectively.

Participant	Percentage of usual shod mileage ran	
	First session (%)	Last session (%)
1	10.73	99.84
2	17.45	107.04
3	14.29	81.18
4	18.74	131.77
5	10.90	60.89
6	21.74	87.36
7	20.31	111.25
8	18.24	110.71
9	14.07	108.75
10	14.82	52.00
Group (mean ± SD)	16.13 (3.77)	95.08 (24.68)

2. Lower limb comfort

Lower limb comfort was recorded using the lower limb comfort index (LLCI) immediately prior to every training session. Individual means were averaged to form group means for each item. ANOVA's showed that the calf-Achilles was significantly lower than all other LLCI items (P < 0.05) (Figure 5.3). No statistical differences were seen between any of the other LLCI items (P > 0.05).

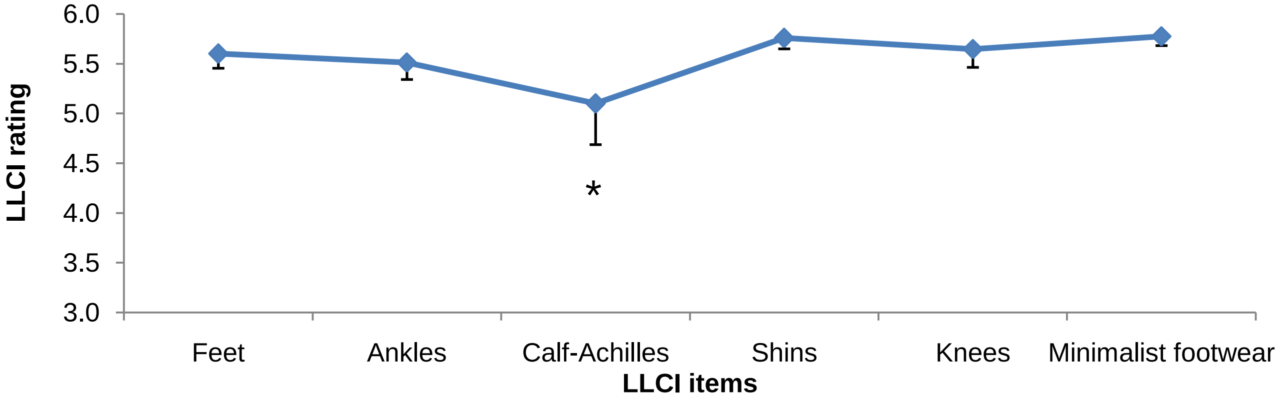


Figure 5.3. Comparison of LLCI items over entire minimalist shoe intervention period. Data represented as group mean (-SD).

Table 5.9. Lower limb comfort index (LLCI) rating at start and end of intervention period. Level of statistical and practical significance is provided by P values and Effect sizes (ES) respectively.

LLCI item	LLCI rating start	LLCI rating end	P values (ES)	Qual.
Feet	5.50 ± 0.71	5.40 ± 1.35	0.83 (0.10)	N
Ankles	5.50 ± 0.71	5.60 ± 0.52	0.68 (0.17)	S
Calf-Achilles	4.40 ± 1.43	5.40 ± 0.67	0.07 (0.94)	L
Shins	5.50 ± 0.53	5.90 ± 0.32	0.04 (0.96)*	L
Knees	5.50 ± 0.52	5.50 ± 0.97	1.00 (0.00)	N
Minimalist footwear	5.80 ± 0.42	5.90 ± 0.32	0.34 (0.28)	S
Total (average)	5.37 ± 0.51	5.62 ± 0.44	0.14 (0.55)	M

CONT: control group; EXP: experimental group; P value; ES: effect size; Qual: qualitative outcome; N: negligible; S: small; M; medium; L: large;.* indicated significant difference between start and end of intervention.

Dependant t-tests compared the LLCI ratings at the first LLCI recording (beginning of the second VF training session) to the last LLCI ratings (at the beginning of the last VF training session) (Table 5.9). Of all the various LLCI items, only the shins item improved statistically and practically (P = 0.04; ES = 0.96) in perceived comfort. While not statistically significant, the calf-Achilles item had a large practical increase in perceived comfort (ES = 0.96). The rest of the LLCI items (feet, ankles, knees, and minimalist footwear) had negligible to small practical improvements in perceived comfort. All LLCI items were averaged to determine the total comfort score. A medium practical effect was seen for an improvement in total comfort score (ES = 0.55).

Descriptive data of LLLCI ratings for feet and ankles are shown in Figure 5.4. Feet and ankle comfort appeared to keep in a 5.5 – 6.0 range throughout most of the intervention. Feet comfort dropped below the 5.0 level only on session 18. It should be noted that higher within group variation could have occurred due to low participant numbers (n = 5) at the eighteenth session, as observed by the increased standard deviation. Ankle comfort temporarily dropped to ~ 5.0 by the fourteenth training session, but steadily increased back to the 5.5 – 6 range by session 18.

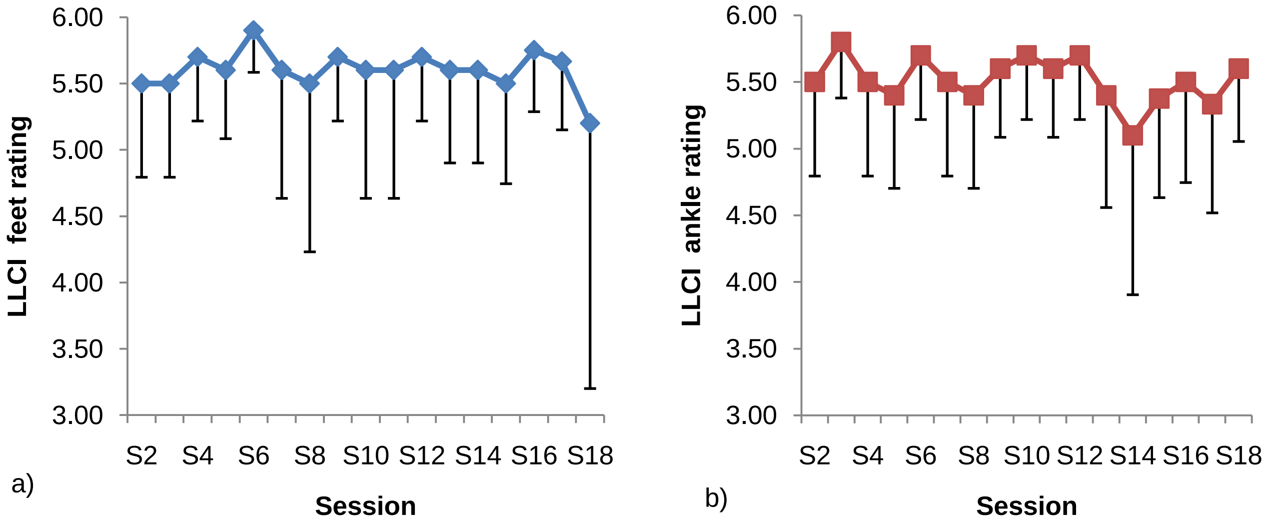


Figure 5.4. LLCI ratings for: a) feet; b) ankle items across training sessions two through to eighteen (S2 – S18). Data represented as group mean (-SD).

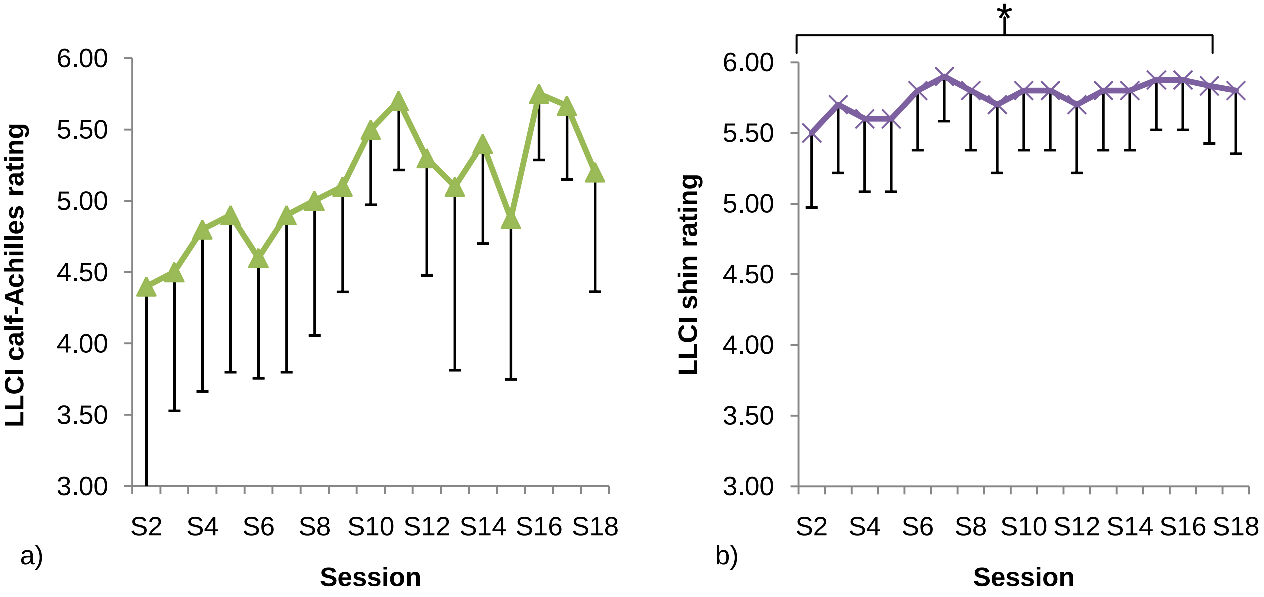


Figure 5.5. LLCI ratings for: a) calf-Achilles; b) shin items across training sessions two through to eighteen (S2 – S18). Data represented as group mean (-SD). *indicates significant difference between start and end of intervention.

LLCI comfort ratings for the calf-Achilles and shin items are illustrated in Figure 5.5. Calf-Achilles comfort dropped immediately at session two to below the 4.5 level and gradually increased through to session 11 to a level in the 5.5 – 6.0 range. Thereafter, calf-Achilles comfort decreased to the 4.5 – 5.0 range by session 15, before increasing again to the 5.5 – 6.0 range again by session 16 and 17. Participants who completed the final session (n = 6) dropped their calf-Achilles comfort again in the final session 18 to the 5.0 – 5.5 range. Shins and minimalist shoe comfort fluctuated minimally and were maintained between the 5.5 – 6.0 ranges across all training sessions. LLCI comfort ratings for the knee and total comfort items are represented in Figure 5.6. Knee comfort followed a similar trend to shins comfort, but dropped to the 5.0 – 6.0 range in the final two sessions. Total LLCI comfort increased gradually during the intervention.

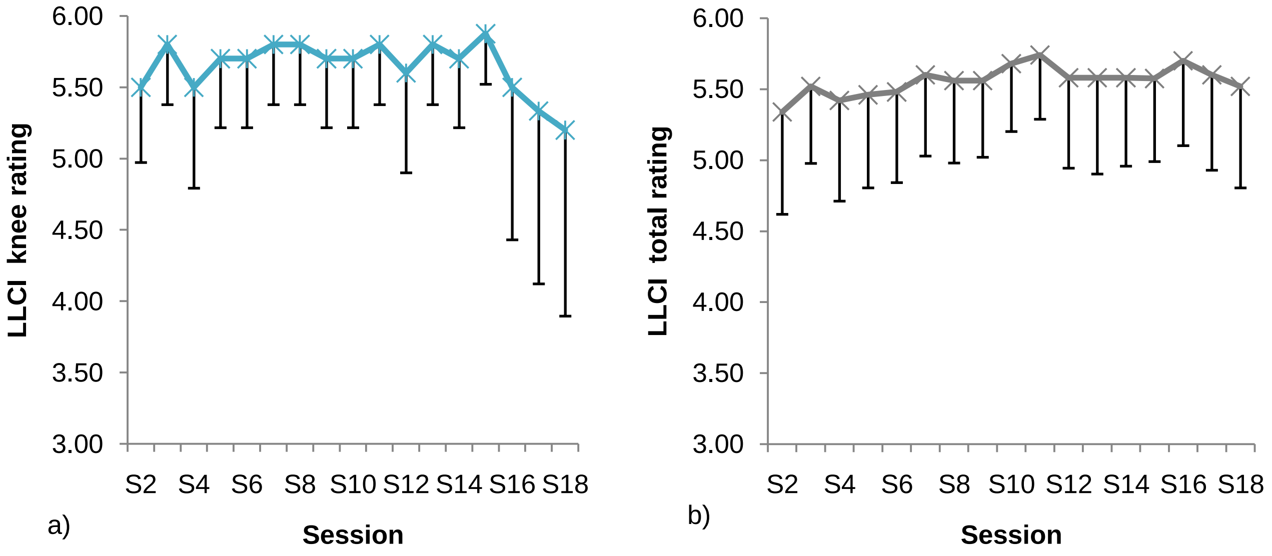


Figure 5.6. LLCI ratings for: a) knee and b) total comfort items across training sessions two through to eighteen (S2 – S18). Data represented as group mean (-SD).

3. Adverse reactions

After each minimalist shoe training session, participants were asked to give verbal feedback of any sort regarding pain or adverse reactions that occurred during the run. Table 5.10 provides a list of verbal reports regarding how up-hills and down-hills were perceived, while Table 5.11 lists reports of adverse reactions experienced by the participants. Plantar callous formation was the adverse reaction that occurred most frequent.

Table 5.10. List of participant reports regarding uphill and downhill running in minimalist shoes.

Incline	**Participant report**
Up-hill	Felt calves work more than with level running
Down-hill	Can’t lengthen my stride as I usually do in my running shoes
	Had to slow myself down and couldn’t use momentum as I would with my usual shoes
	Landing with my usual longer strides with extended leg on the downhill became tiring in my calves, so could no longer land on my forefoot. To avoid my calves from over-working, I tried to land more with my heels. This provided immediate relief in my calves, but then my heels began to pain

Table 5.11. List of adverse reactions reported during minimalist shoe intervention along with frequency of complaint.

Week	Number of participants with same adverse reaction	Participant report of adverse reaction
1	2	Achilles stiffness
2		-
3	5	Plantar callous formation
	1	Lateral aspect of great toe abrasion with toe pocket
4		-
5	1	Bruising stiffness under second metatarsal head
	1	Bruising pain under lateral aspect of heel
	1	Medial longitudinal arch ache
		Cracking of the fifth phalange toe-nail
6	1	Temporary sharp pain ± 3 sec under foot arch
	1	Medial knee pain
	1	Tibialis posterior stiffness

4. Surface characteristics

Participants' verbal reports of how they perceived running on the various surfaces (asphalt, tartan athletic track, grass, and gravel/dirt road/trail) is listed in Table 5.12.

Table 5.12. List of minimalist shoe training surfaces and related reports from participants.

Surface	Participant report
Asphalt	Hardest and smooth
Tartan	Softer
Grass	Early morning dew made my feet cold
Gravel/dirt road/trail	More awareness of my feet
	uncomfortable and had to watch for stones
	had to relax my feet more
	Strides are shorter
	Changed my step length often
	Much less grip
	Less grip, so I had to shorten my strides to avoid slipping
	Occasional stone hurt but pain subsided immediately and was able to carry on running
	Pulled my toes up to avoid them from hitting stones
	Felt stone under heel so shifted to land on forefoot to avoid pain
	Could feel stones under feet but did not hurt
	Had to focus on the right path, whereas usually I don't worry which line I run.
	I was aware of stones in the beginning of run but got used to them by end of run

D. OUTCOME VARIABLES

Three of the six running trials recorded bilaterally for each running condition were used for analysis. This was due to some running trials where participants' toes slightly over-stepped the force plate area, or where reflective markers were unclear in the visual field of the cameras. The mean for left and right legs were taken for all outcome measures.

Running speed did not differ significantly between the three shoe conditions (P > 0.05) (Table 5.13*).* In addition, the variance of the standard deviation within each shoe condition was in an acceptable range of 10 - 11%. However, post hoc analysis revealed that the experimental (EXP) group had significantly different running speeds at pre–testing, with the barefoot (BF) condition being faster than the minimalist shoe (VF) (P = 0.04) and shod (SH) (P = 0.03) conditions respectively. Thus, running speed was included as a covariant, and all kinetic and kinematic outcome variables were adjusted accordingly. **Error! Reference source not found.** shows how running speed decreased from pre-post n the EXP group with a medium effect (P > 0.05; ES = 0.46). Running speed differences pre-post were negligible for VF and SH running conditions (P > 0.05; ES: 0.04 – 0.13).

Table 5.13. Mean (± SD) running speed for shoe conditions.

Parameter	**BF**	**VF**	**SH**
Speed (m/s)	3.51 ± 0.40 (11%)	3.50 ± 0.36 (10%)	3.48 ± 0.39 (11%)

1. Lower limb kinetics

External vertical ground reaction force

The vertical ground reaction (vGRF)-time curves of the three footwear conditions for all running trials are depicted in Figure 5.7*.* For vertical impact peak (VIP), both barefoot and minimalist shoe (VF) conditions were significantly lower than the shod (SH) condition (BF: P = 0.00004; VF: P = 0.0002) (Table 5.14). However, VIP did not differ statistically between BF and VF (P > 0.05). Significant differences were seen among all footwear conditions in terms of time to VIP (TVIP), with VF being longer than BF by 7 ms (P = 0.0001), yet quicker than shod by 23 ms (P = 0.00001). VF had a VALR that was on average 20% lower compared to BF (P = 0.009), yet was still 53% higher than SH (P = 0.00003). For vertical propulsive peak (VPP), the magnitude was significantly lower in the BF condition compared to SH (P = 0.02). VF did not differ significantly with VPP compared to either BF or SH conditions respectively (P > 0.05).

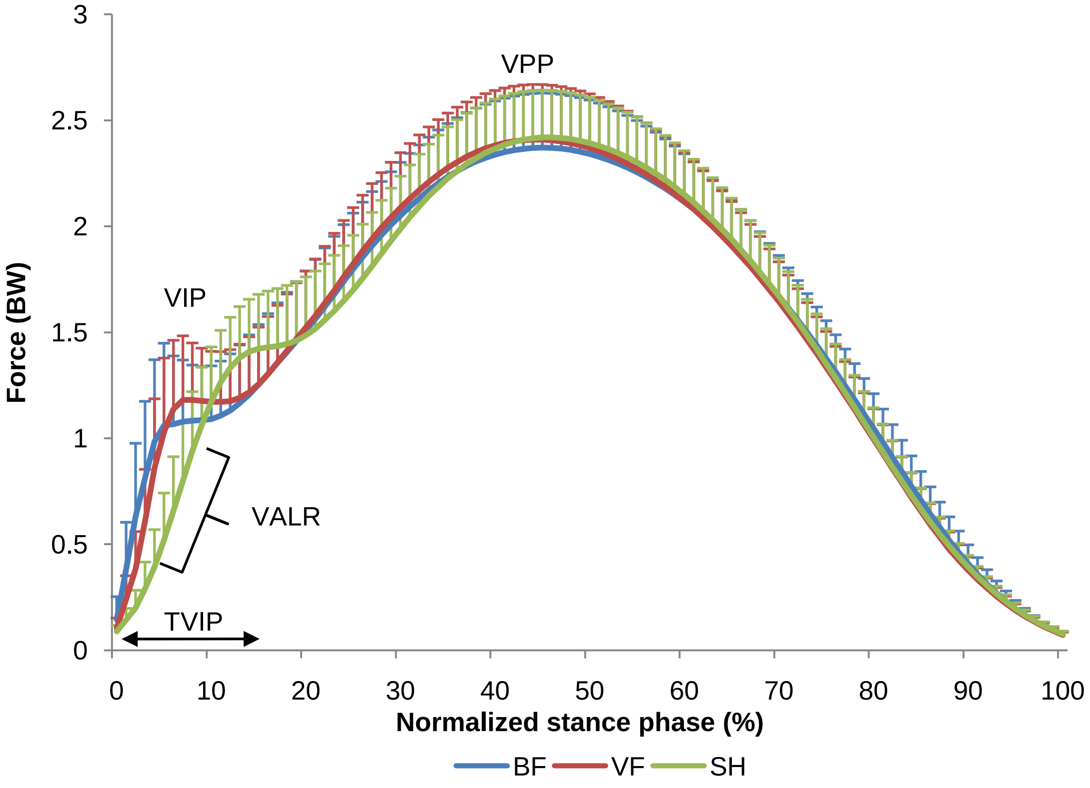


Figure 5.7. Mean + SD vertical ground reaction force (vGRF) curve normalised by stance phase (0 – 100%) between three footwear conditions: barefoot (BF); minimalist shoes (VF); and shod (SH) respectively. VIP: Vertical impact peak; VPP: Vertical propulsive peak; TVIP: Time to vertical impact peak; and VALR: vertical average loading rate.

VALR according to shoe condition as well as footstrike pattern is depicted in

Figure 5.8*.* Footstrike pattern was classified according to strike index (SI)% (Cavanagh & Lafortune, 1980). A frequency distribution (Figure 5.9) showed that footstrike patterns are not normally distributed (percentage forefoot strike runners were lower in comparison to rearfoot or midfoot strikers), and thus

comparisons in VALR between footstrike patterns are made by effect size and percentage change. A comparison between shoe conditions and footstrike patterns is highlighted in Table 5.15. VALR was the highest for rearfoot strikers (RFS), having a huge and very large practical difference compared to forefoot strikers (FFS) (ES: 2.76) and midfoot strikers (MFS) respectively (ES: 1.17). However the locus of this difference was primarily due to the higher VALR in BF and VF conditions, in comparison to the lower VALR seen in the SH condition. VALR was consistently higher in the BF condition across all footstrike patterns. However, the VF condition did not follow the same trend. The VF condition had the lowest VALR for a MFS landing. Landing with a FFS resulted in the lowest VALR for all conditions. VALR was the lowest in the SH condition with a FFS.

Table 5.14. Mean (± SD) vertical ground reaction force and centre of pressure parameters for shoe conditions.

Parameter	**BF**	**VF**	**SH**
VIP (BW)	1.30 ± 0.39 ^{c}	1.32 ± 0.30 ^{c}	1.48 ± 0.27 $^{a, b}$
TVIP (ms)	26.47 ± 11.52 $^{c, b}$	33.73 ± 9.60 $^{c, a}$	56.77 ± 8.51 $^{a, b}$
VALR (BW/s)	72.61 ± 31.92 $^{c, b}$	60.31 ± 25.95 $^{c, a}$	39.33 ± 12.44 $^{a, b}$
VPP (BW)	2.39 ± 0.26 ^{c}	2.43 ± 0.26	2.44 ± 0.22 ^{a}

VIP: vertical impact peak; TVIP; time to vertical impact peak; VALR: vertical average loading rate; VPP: vertical propulsive peak; $^{a, b, c}$ significantly different ($P < 0.05$) from barefoot (BF) ^{a}; minimalist shoes (VF) ^{b}; and shod (SH) ^{c}.

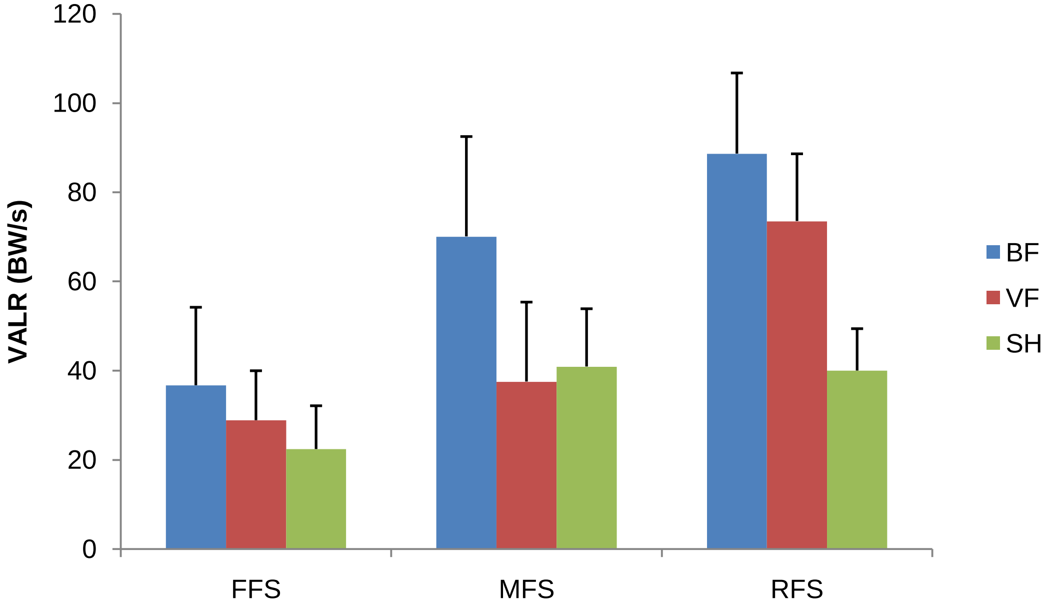


Figure 5.8. Vertical average loading rate (VALR): a) distributed among forefoot strikers (FFS), midfoot strikers (MFS), and rearfoot strikers (RFS) for barefoot (BF), minimalist shoes (VF), and shod (SH) conditions;

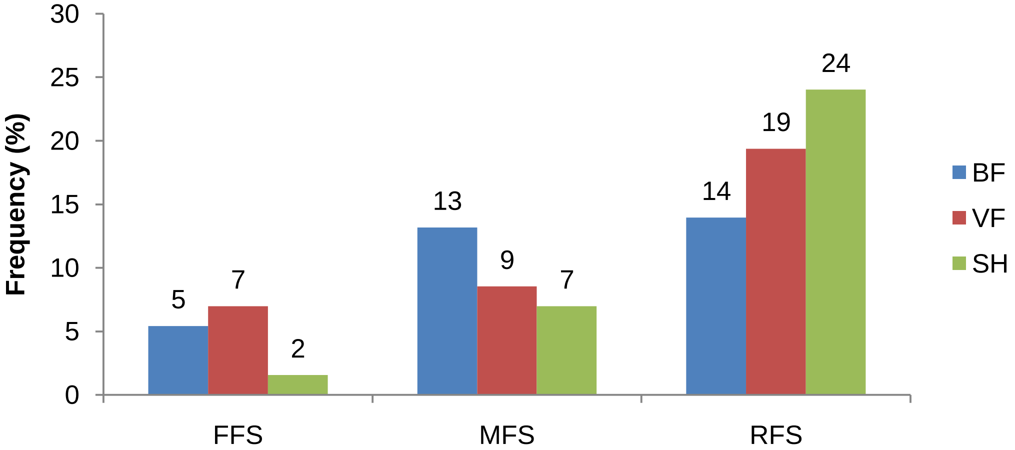


Figure 5.9. Frequency distribution of footstrike patterns according to shoe condition, classified by strike index (%).

Table 5.15. Vertical average loading rate (VALR) among shoe conditions and footstrike patterns.

Shoe	**VALR mean ± SD**			**Δ VALR:% and (ES)**		
	FFS	**MFS**	**RFS**	**FFS-RFS**	**MFS-RFS**	**FFS-MFS**
BF	36.67 ± 17.49	70.05 ± 22.39	88.62 ± 18.07	141.63 (2.99)	26.51 (0.94)	91.00 (1.65)
VF	28.84 ± 11.09	37.51 ± 17.81	73.50 ± 15.06	154.82 (3.26)	95.92 (2.32)	30.06 (0.6)
SH	22.37 ± 9.71	40.88 ± 12.95	39.97 ± 9.39	78.66 (1.93)	-2.22 (0.09)	82.71 (1.62)
All	29.30 ±12.76	49.48 ± 17.72	67.36 ± 14.18	129.93 (2.76)	36.14 (1.17)	68.89 (0.5)

VALR: vertical average loading rate; BF: barefoot; VF: minimalist shoes; SH: shod; RFS: rearfoot strike; MFS: midfoot strike; FFS: forefoot strike; ES; effect size;%: percentage difference; SD: standard deviation.

Figure 5.10 and Figure 5.11 illustrate the absolute mean differences pre-post for vGRF parameters. Level of statistical and practical significance (with qualitative outcome) for mean differences in footwear conditions between experimental and control group is represented in Table 5.16. VIP increased for all shoe conditions and groups by 0.02 BW to 0.1 BW from pre- to post-test. Although not statistically significant, there was a medium practical significance in VIP between groups for the VF condition (P > 0.05; ES = 0.40).

Table 5.16. Absolute change (pre-post) in vertical ground reaction force (vGRF) parameters. Comparisons are between-group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	**CON vs. EXP (BF)**			**CON vs. EXP (VF)**			**CON vs. EXP (SH)**		
Parameter	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**
Δ VIP (BW)	0.99	0.00	N	0.40	0.40	M	0.25	0.35	S
Δ TVIP (ms)	0.61	0.14	N	0.10	0.30	S	0.95	0.02	N
Δ VALR (BW/s)	0.61	0.16	S	0.36	0.24	S	0.48	0.23	S
Δ VPP (BW)	0.44	0.14	N	0.74	0.07	N	0.35	0.21	S

VIP: vertical impact peak; TVIP; time to vertical impact peak; VALR: vertical average loading rate; VPP: vertical propulsive peak; BF: barefoot; VF: minimalist shoes; SH: shod; P Value; ES: Effect size; Qual: qualitative outcome; N: negligible; S; small.

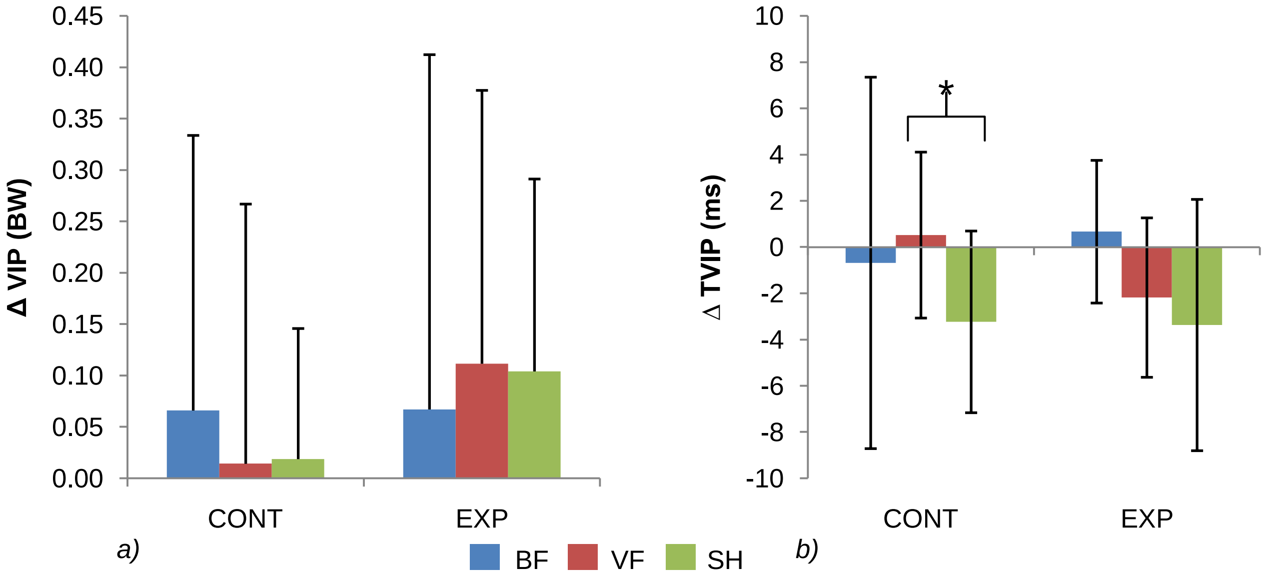


Figure 5.10. Absolute mean differences pre-post for vGRF parameters among all conditions and both groups: a) VIP (vertical impact peak); and b) TVIP (time to vertical impact peak); * indicates significant difference within group (between shoe conditions) ($P < 0.05$).

TVIP showed a trend only with the SH condition decreasing in both groups by ~ 3 ms from pre- to post-test. TVIP showed a statistical difference between VF and SH for the control group ($P < 0.05$; ES = 0.25). In terms of VALR, and increase across all shoe conditions and groups from pre to post ranged from 2 BW/s to 10 BW/s. VIP, TVIP, VALR, and VPP did not have any between-group statistical differences with negligible to small practical effects ($P > 0.05$; ES = 0.02 - 0.36). VPP increased the most in the SH condition in the EXP group by ~ 0.05 BW.

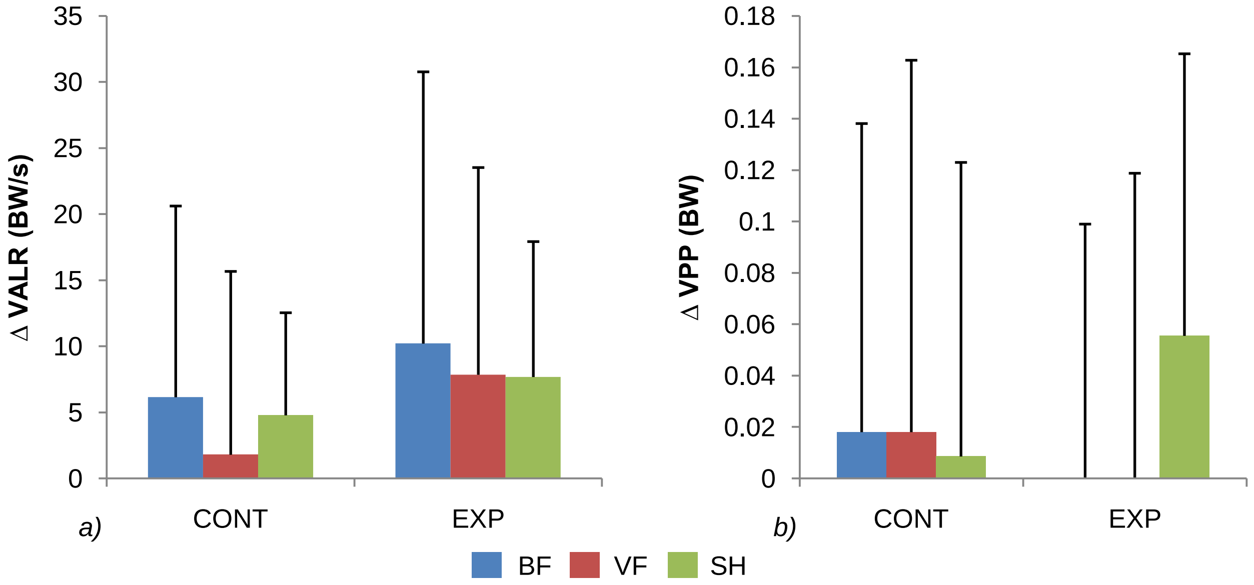


Figure 5.11. Absolute mean differences pre-post for vGRF parameters among all conditions and both groups: VALR (vertical average loading rate); VPP (vertical propulsive peak).

External joint moments

Graphical representations of the sagittal plane joint moments during stance phase are provided in Figure 5.12. For the ankle in the sagittal plane, the initial dorsiflexion moment (DM) peak during early stance was significantly decreased in both BF and VF conditions compared to SH (BF: P = 0.00005; VF: P = 0.02) (Table 5.17). In contrast, ankle plantarflexion moment (PM) peak was significantly higher in BF and VF conditions compared to SH (BF: P = 0.008; VF: P = 0.008). Peak ankle inversion moment (AIM) in the frontal plane during mid-stance was significantly higher in the VF condition compared to BF (P = 0.03).

Initial knee flexion moment peak (KFM) was significantly reduced for BF and VF compared to SH (BF: P = 0.006; VF: P = 0.04), but further into stance phase there were no significant differences in knee extensor moment (KEM) peak between any conditions (P > 0.05). Peak knee abduction moment (KAM) around mid-stance was significantly lower for BF compared to SH (P = 0.01). No statistical differences were seen at the hip for any of the joint moment peaks in all three planes of motion (P > 0.05).

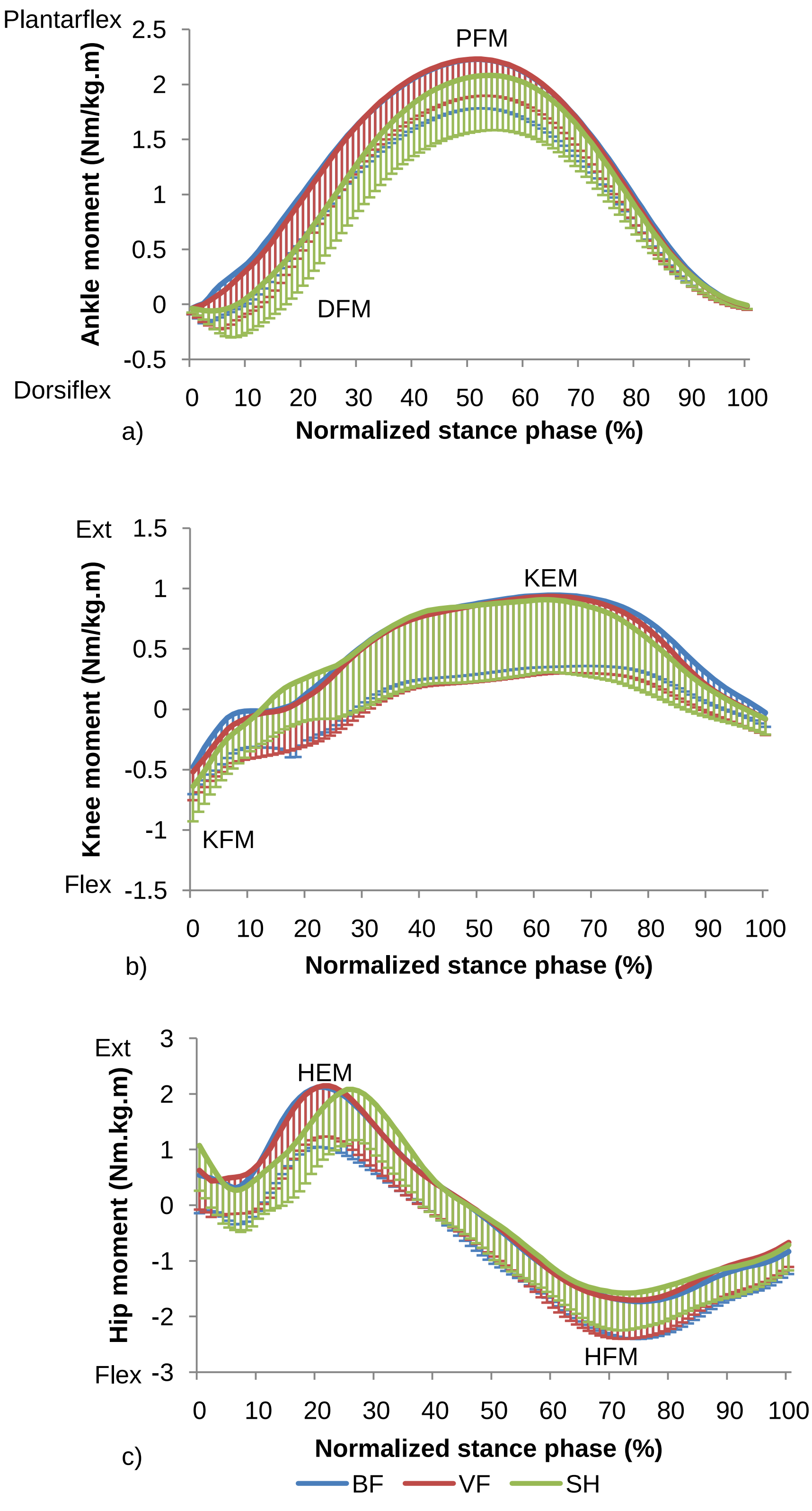


Figure 5.12. Mean (-SD) sagittal plane lower limb joint moment curves normalised to stance phase for all shoe conditions at: a) ankle; b) knee; c) hip normalised to stance phase for shoe conditions: DFM, PFM, KFM, KEM, HEM, and HFM are dorsiflexion, plantarflexion, knee flexion, knee extension, hip extension, and hip flexion moment peaks respectively.

Table 5.17. Mean (± SD) joint moment peaks for shoe conditions.

Joint moment peak (Nm/kg.m)	BF	VF	SH
Dorsiflexion moment (DFM)	0.10 ± 0.13 [c]	0.13 ± 0.15 [c]	0.17 ± 0.14 [a, b]
Plantarflexion moment (PFM)	2.27 ± 0.52 [c]	2.26 ± 0.54 [c]	2.15 ± 0.60 [a, b]
Ankle inversion moment (AIM)	0.65 ± 0.75 [b]	0.77 ± 0.82 [a]	0.71 ± 0.75
Knee flexion moment (KFM)	0.58 ± 0.28 [c]	0.60 ± 0.26 [c]	0.68 ± 0.28 [a, b]
Knee extension moment (KEM)	1.23 ± 0.57	1.20 ± 0.63	1.24 ± 0.57
Knee abduction moment (KAM)	0.09 ± 0.15 [c]	0.10 ± 0.14	0.13 ± 0.15 [a]
Hip flexion moment (HFM)	2.01 ± 0.91	1.94 ± 0.98	1.92 ± 0.92
Hip extension moment (HEM)	2.57 ± 1.05	2.52 ± 1.91	2.55 ± 1.92
Hip abduction moment (HAM)	0.39 ± 35	0.41 ± 41	0.39 ± 0.37

[a, b, c] Significantly different ($P < 0.05$) from barefoot (BF) [a]; minimalist shoes (VF) [b]; and shod (SH) [c].

Ankle dorsiflexion moment (DFM) peak showed a trend to increase in the both groups, but more so in the CONT group (Figure 5.13). Increases in DFM peak were of small to medium practical significance in the CONT group compared to EXP group for all running conditions (Table 5.18). Differences between footwear conditions for DFM peak were negligible ($P > 0.05$; ES = 0.03-0.11). Ankle plantarflexion moment (PFM) for the EXP group decreased significantly in the VF condition compared to the CONT group ($P = 0.04$; ES = 0.56). Both groups tended to increase PFM peak in the SH condition but no groups were practically different to the others (ES = 0.17). Ankle inversion moment (AIM) peaks increased by ~ 129%, 125%, and 118% for BF, VF and SH conditions. This percentage increase was similar between the two groups, and greatest for the VF condition.

Table 5.18. Absolute change (pre-post) in peak ankle joint moments. Comparisons are between group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	CON vs. EXP (BF)			CON vs. EXP (VF)			CON vs. EXP (SH)		
Parameter	P	ES	Qual.	P	ES	Qual.	P	ES	Qual.
Δ Dorsiflexion moment (DFM)	0.24	0.37	S	0.20	0.32	S	0.31	0.43	M
Δ Plantarflexion moment (PFM)	0.26	0.24	S	0.04	0.56	M	0.58	0.17	S
Δ Ankle inversion moment (AIM)	0.97	0.02	N	0.84	0.10	N	0.79	0.13	N

BF: barefoot; VF: minimalist shoes; SH: shod; P Value; ES: Effect size; Qual: qualitative outcome; N: negligible; S; small; M: medium.

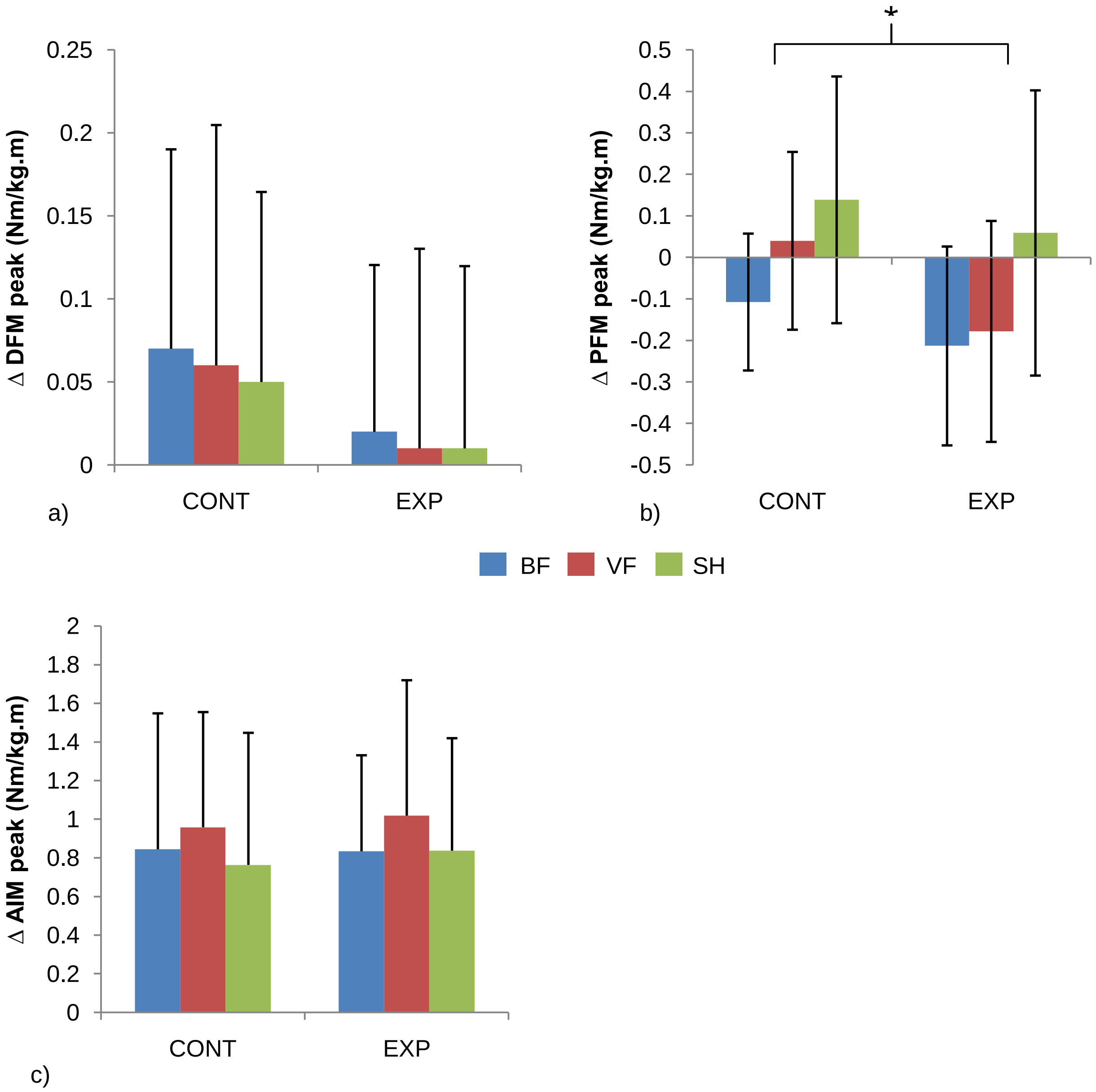


Figure 5.13. Absolute mean differences pre-post for: a) ankle dorsiflexion moment (DFM) peak; b) ankle plantarflexion moment (PFM) peak; c) ankle inversion moment (AIM) peak among all conditions and both groups. * indicates significantly different between-groups for each shoe condition ($P < 0.05$).

Knee flexion moment (KFM) peak increased in both groups for all shoe conditions (Figure 5.14). Within the EXP group, KFM peak decrease was the greatest for the BF condition and had a medium practical difference to VF ($P > 0.05$; ES = 0.67) (Table 5.19). Within the CONT group KFM peak decrease was greatest for the SH condition with a medium practical significance (P > 0.05; ES = 0.51). Knee extension moment (KEM) peak decreased in both groups and all conditions. However, KEM decreased significantly more in the EXP group for the BF condition (P = 0.02), with a very large practical significance (ES = 1.10) and VF (P = 0.04; ES = 0.90). The EXP compared to the CONT group also showed a large and medium effect for a decrease in KEM for SH (P = 0.20; ES = 0.54). Knee abduction moment (KAM) tended to increase from pre to post for shoe conditions in both groups. The increases in KAM were the largest for VF condition for both groups, although only small practical significances were detected (ES = 0.12).

Table 5.19. Absolute change (pre-post) in peak knee joint moments. Comparisons are between group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	**CON vs. EXP (BF)**			**CON vs. EXP (VF)**			**CON vs. EXP (SH)**		
Δ Joint torque (Nm/kg.m)	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**
Δ Knee flexion moment	0.51	0.29	S	0.84	0.10	N	0.57	0.23	S
Δ Knee extension moment (KEM) peak	0.02	1.10	VL	0.04	0.90	L	0.20	0.54	M
Δ Knee abduction moment (KAM)	0.92	0.04	N	0.84	0.12	N	0.69	0.19	S

BF: barefoot; VF: minimalist shoes; SH: shod; P Value; ES: Effect size; Qual: qualitative outcome; S; small; M: medium

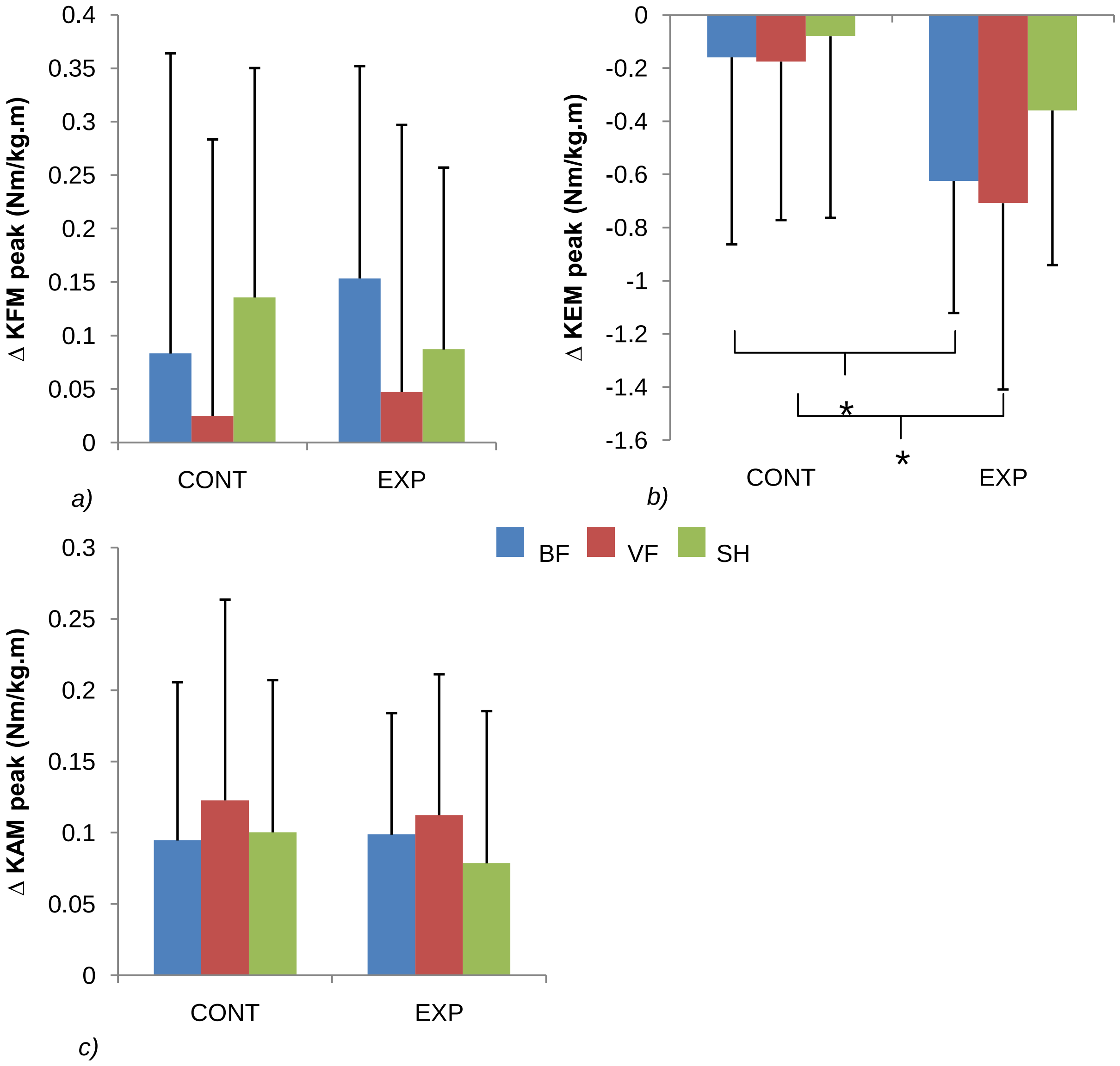


Figure 5.14. Absolute mean differences pre-post for: a) knee flexion moment (KFM) peak; b) knee extension moment (KEM) peak; c) knee abduction moment (KAM) peak. * Indicates significantly different ($P < 0.05$) between-groups for each shoe condition.

Hip flexion moment (HFM) peak increased for both groups and all conditions from pre- to post-test (Figure 5.15). In contrast to HFM, hip extension moment (HEM) peak decreased for both groups and for all shoe conditions. The EXP group decreased the most in the BF condition. Hip abduction moment (HAM) peak increased to a larger extent in the EXP group compared to the CONT group. The greatest between groups difference was localised in the BF condition, as indicated by the medium effect size ($P > 0.05$; ES = 0.51).

Table 5.20. Absolute change (pre-post) in peak hip joint moments. Comparisons are between group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	**CON vs. EXP (BF)**			**CON vs. EXP (VF)**			**CON vs. EXP (SH)**		
Parameter	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**
Δ Hip flexion moment (HFM)	0.27	0.59	M	0.52	0.33	S	0.63	0.22	S
Δ Hip extension moment (HEM)	0.73	0.16	S	0.45	0.38	M	0.40	0.38	M
Δ Hip abduction moment (HAM)	0.40	0.51	M	0.82	0.11	N	0.50	0.38	M

BF: barefoot; VF: minimalist shoes; SH: shod; P Value; ES: Effect size; Qual: qualitative outcome; S; small; M: medium

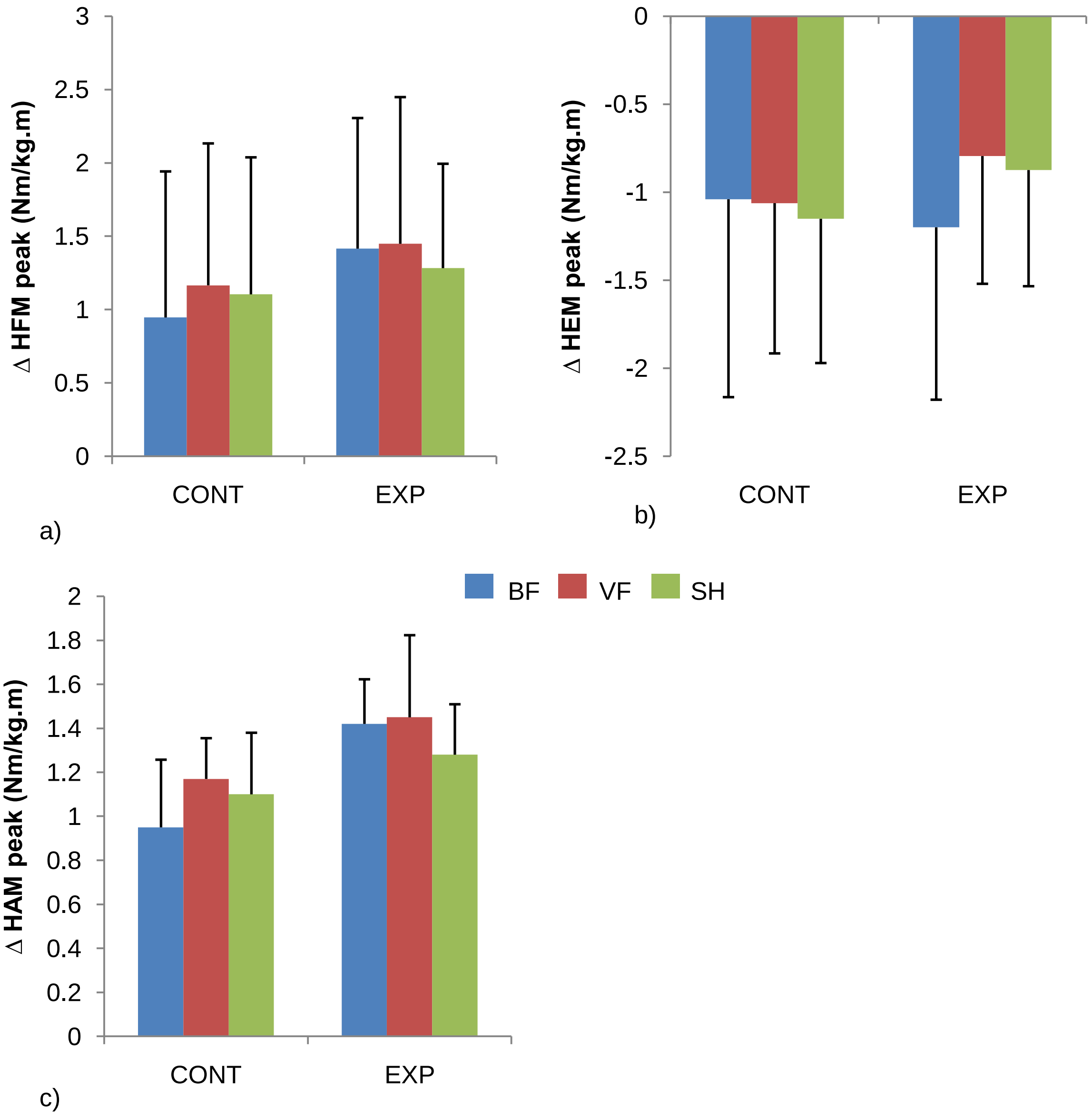


Figure 5.15. Absolute mean differences pre-post for: a) hip extension moment (HEM) peak; b) hip flexion moment (HFM) peak; c) hip adduction moment (HAM) peak.

2. Lower limb kinematics

Spatio-temporal characteristics

Running speed did not differ significantly among BF, VF, and SH conditions ($P > 0.05$) (Table 5.21) Step frequency, step length, step time, contact time, and flight time were all significantly different between all three shoe conditions. Specifically, step frequency in the VF condition was 2.5% lower than BF ($P = 0.00004$), but 2.9% higher than SH ($P = 0.00001$). Step length for VF was 3 cm longer than BF ($P = 0.00001$), but 3 cm shorter than SH ($P = 0.00001$). Step time for VF was 8 ms slower than BF ($P = 0.00002$), but 10 ms quicker ($P = 0.000001$). Contact time for VF was 3 ms slower than BF ($P = 0.004$), yet 7 ms quicker than SH ($P = 0.00005$). Flight time was 5 ms longer than BF ($P = 0.002$), although 4 ms slower than SH ($P = 0.01$).

Table 5.21. Mean (± SD) spatio-temporal parameters for shoe conditions.

Parameter	**BF**	**VF**	**SH**
Speed (m/s)	3.51 ± 0.40	3.50 ± 0.36	3.48 ± 0.39
Step frequency (steps/min)	162 ± 9.35 $^{b, c}$	158 ± 9.17 $^{a, c}$	153 ± 9.51 $^{a, b}$
Step length (m)	1.31 ± 0.15 $^{b, c}$	1.34 ± 0.14 $^{a, c}$	1.36 ± 0.14 $^{a, b}$
Step time (ms)	373 ± 22 $^{b, c}$	382 ± 22 $^{a, c}$	392 ± 24 $^{a, b}$
Contact time ms)	229 ± 21 $^{b, c}$	232 ± 20 $^{a, c}$	239 ± 22 $^{a, b}$
Flight time (ms)	144 ± 23 $^{b, c}$	150 ± 22 $^{a, c}$	154 ± 23 $^{a, b}$

$^{a, b, c}$ Significantly different ($P < 0.05$) from barefoot (BF) ^{a}; minimalist shoes (VF) ^{b}; and shod (SH) ^{c}.

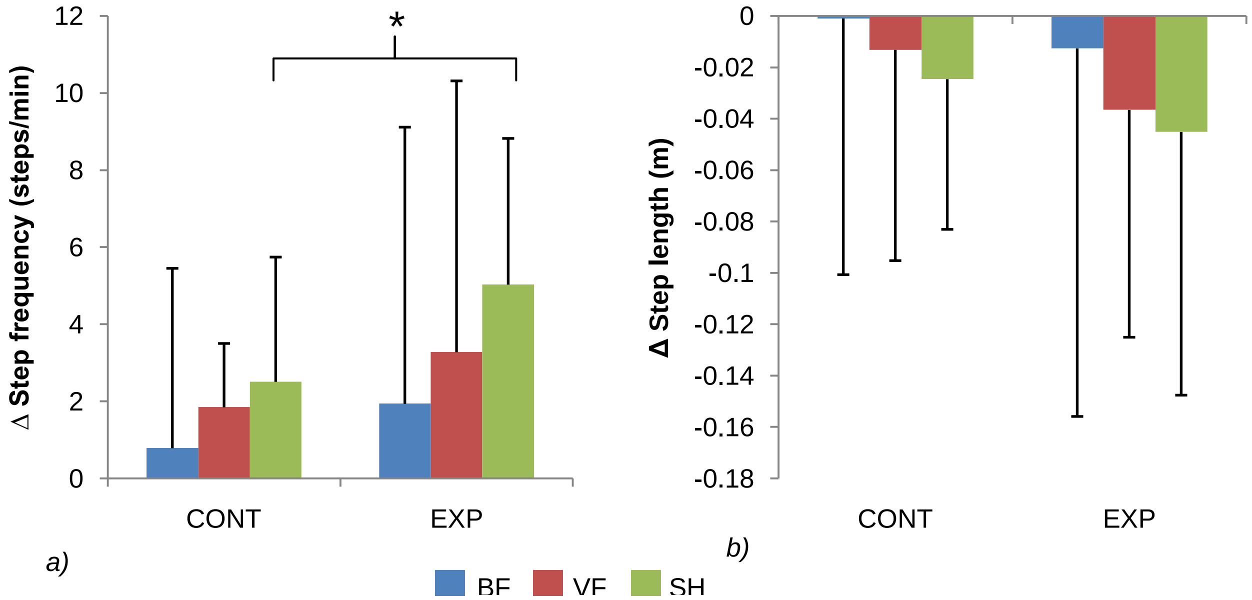


Figure 5.16. Mean differences for: a) step frequency; and b) step length. * Indicates significantly different (P < 0.05) between-groups for each shoe condition.

The absolute changes from pre- and post-test for EXP and CONT group in step frequency and step length are depicted in Figure 5.16. Step frequency in the CONT group increased by ~ 1-2 steps/min for the three shoe conditions. The EXP group compared to the CONT group increased step frequency in the SH condition by five steps/min (P = 0.04; ES = 0.76) (Table 5.22). Step frequency also increased pre- to post-test in the EXP group compared to the CONT group for the VF condition (~ 3 steps/min) and BF condition (~ 2 step/min), but were not statistically significant (P > 0.05). Step length decreased more so in the EXP group compared to CONT, with the SH condition prevailing but not statistically significant (P > 0.05).

Step time showed negligible decreases in the CONT group by around 3 - 6 ms (ES = 0.02 – 0.14), as seen in Figure 5.17 Step time within the EXP group decreased more than in the CONT group, with the biggest decrease in the SH condition by ~ 13 ms. Negligible to small differences in contact time were seen across all other conditions in both groups (P > 0.05: ES: 0.02 – 0.28). There was, however, a trend for CONT to increase and EXP to decrease contact time. Decreases in flight time were not significantly different between groups for all conditions (P > 0.05; ES = 0.09 – 0.11). Flight time decreased by ~ 4 – 8 ms in the CONT group, and by 3 ms – 10 ms in the EXP group.

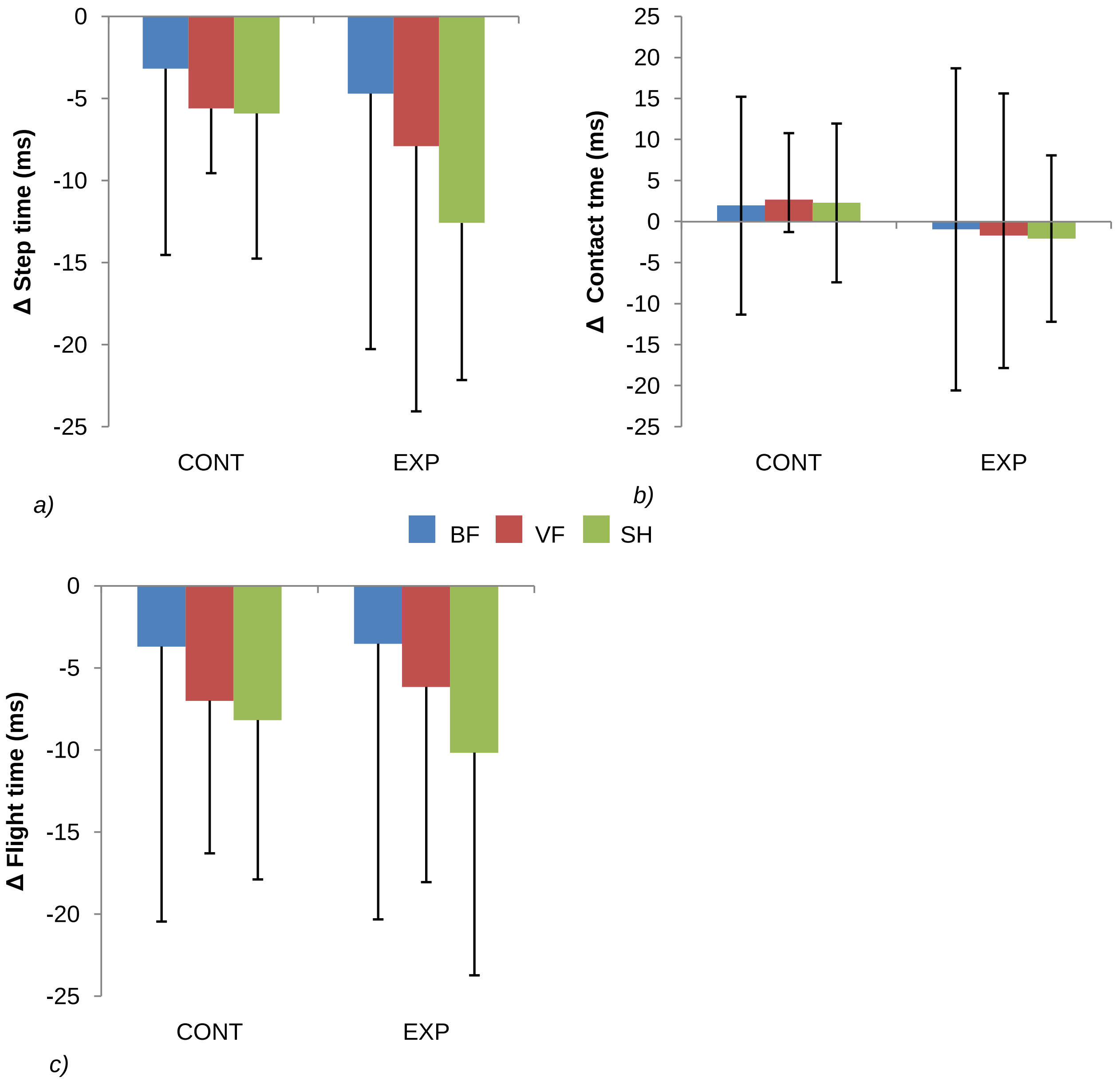


Figure 5.17. Absolute mean differences pre-post for: a) step time, b) contact time, c) flight time. * indicates significantly different between-groups for each shoe condition ($P < 0.05$).

Table 5.22. Absolute change (pre-post) in spatio-temporal parameters. Comparisons are between group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	**CON vs. EXP (BF)**			**CON vs. EXP (VF)**			**CON vs. EXP (SH)**		
Spatio-temporal parameter	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**
Δ Step frequency (steps/min)	0.41	0.27	S	0.90	0.03	N	0.04	0.76	L
Δ Step length (m)	0.42	0.30	S	0.54	0.17	S	0.09	0.36	M
Δ Step time (ms)	0.40	0.27	S	0.94	0.02	N	0.12	0.28	S
Δ Contact time ms)	0.82	0.07	N	0.62	0.14	N	0.29	0.20	S
Δ Flight time (ms)	0.74	0.11	N	0.73	0.08	N	0.71	0.09	N

P Value; ES: Effect size; Qual: qualitative outcome; S; small; M: medium; L; large.

Joint angles

Sagittal plane joint angles normalised to stance phase curved are depicted in Figure 5.18. Significantly more plantarflexed ankle angles at contact were found for BF (P = 0.00001) and VF (P = 0.00008) in comparison with SH (Table 5.23). Specifically, BF and VF running had 8.75 degrees and 4.21 degrees more ankle plantarflexion at contact compared to SH, indicating a MFS (midfoot strike). Ankle dorsi-plantarflexion angle was also significantly different between BF and VF, with BF having 4.54 degrees more plantarflexion (P = 0.0008). In the frontal plane, significant differences were seen between all conditions, with ankles at contact during BF (P = 0.00001) and VF (P = 0.00006) being in a more inverted position compared to SH. BF also landed with a more inverted ankle in comparison to VF (P = 0.01). Differences in the transverse plane were evident with BF (P = 0.000001) and VF (P = 0.0002) having ankles that were landing in a more externally rotated position compared to SH. Ankle external rotation angle and footstrike did not differ between BF and VF (P > 0.05).

Knee flexion angle was significantly greater for BF (P = 0.00008) and VF (P = 0.0008) versus SH. Similarly, knee abduction angle was significantly greater for BF (P = 0.000002) and VF (P = 0.00006) versus SH. Both BF and VF conditions landed with a more internally rotated knee compared to SH, yet statistically only BF was different (P = 0.005). At the hip, BF and VF landed with significantly less flexion (BF: P = 0.00004; VF: P = 0.0002), more abduction (BF: P = 0.0002; P = 0.02), and more internal rotation (BF: P = 0.002; VF: P = 0.002). None of the knee or hip angles at contact differed between BF and VF conditions (P > 0.05).

Table 5.23. Mean (± SD) lower limb joint footstrike angles (FSA) for shoe conditions.

Footstrike angle (degrees)	**BF**	**VF**	**SH**
Ankle dorsi (+) / plantar (-) flexion	2.40 ± 6.87 $^{b, c}$	6.94 ± 7.45 $^{a, c}$	11.15 ± 6.12 $^{a, b}$
Ankle inversion (+) / eversion (-)	3.23 ± 3.19 $^{b, c}$	1.78 ± 7.45 $^{a, c}$	-0.09 ± 3.32 $^{a, b}$
Ankle internal (+) / external (-) rotation	-4.12 ± 8.76 ^{c}	-1.30 ± 7.59 ^{c}	4.77 ± 10.41 $^{a, b}$
Knee flexion	18.38 ± 5.56 ^{c}	17.48 ± 5.37 ^{c}	16.26 ± 5.14 $^{a, b}$
Knee adduction (+) / abduction (-)	5.74 ± 4.34 ^{c}	5.25 ± 4.52 ^{c}	3.39 ± 3.75 $^{a, b}$
Knee internal (+) / external (-) rotation	3.97 ± 7.19 ^{c}	2.36 ± 8.33	-0.04 ± 7.99 ^{a}
Hip flexion	39.75 ± 5.85 ^{c}	39.65 ± 5.43 ^{c}	40.72 ± 5.49 $^{a, b}$
Hip adducton (+) / abduction (-)	4.32 ± 3.44 ^{c}	4.43 ± 3.12 ^{c}	4.84 ± 3.32 $^{a, b}$
Hip internal (+) / external (-) rotation	7.26 ± 10.72 ^{c}	7.04 ± 10.49 ^{c}	3.92 ± 10.23 $^{a, b}$

$^{a, b, c}$ Significantly different ($P < 0.05$) from barefoot (BF) ^{a}; minimalist shoes (VF) ^{b}; and shod (SH) ^{c}.

The amount of sagittal plane range of motion from footstrike to vertical propulsive peak (VPP) is represented in Table 5.24. Ankle dorsiflexion range of motion (ROM) increased significantly during SH compared to both VF (~7 degrees; P = 0.0002) and BF (~8 degrees P = 0.0001). In contrast the knee flexion ROM decreased significantly during SH compared to both VF (~ 3 degrees; P = 0.006) and BF (~5 degrees; P = 0.003). More proximal, the hip extension ROM showed a trend to increase from SH to VF and BF, but was not statistically significant (P > 0.05).

Table 5.24. Sagittal plane joint range of motion (degrees) from contact to vertical propulsive peak (VPP).

Range of motion (degrees)	**BF**	**VF**	**SH**
Ankle dorsiflexion ROM	26.19 ± 9.79 ^{c}	25.24 ± 7.46 ^{c}	18.84 ± 9.03 $^{a, b}$
Knee flexion ROM	21.30 ± 3.92 $^{b, c}$	23.23 ± 5.37$^{a, c}$	26.52 ± 6.23 $^{a, b}$
Hip extension ROM	13.14 ± 3.92	12.64 ± 4.20	11.87 ± 3.82

$^{a, b, c}$ Significantly different ($P < 0.05$) from barefoot (BF) ^{a}; minimalist shoes (VF) ^{b}; and shod (SH) ^{c}. ROM: range of motion.

Table 5.25. Absolute change (pre-post) in footstrike angle (FSA) parameters. Comparisons are between group for each shoe condition with statistical significance, practical significance, and qualitative outcome.

Pre-post	**CON vs. EXP (BF)**			**CON vs. EXP (VF)**			**CON vs. EXP (SH)**		
FSA (degrees)	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**	**P**	**ES**	**Qual.**
Δ Ankle dorsi (+)/ plantar (-) flexion	0.32	0.17	S	0.54	0.15	S	0.85	0.05	N
Δ Ankle inversion (+)/ eversion (-)	0.04	0.88	L	0.06	0.90	L	0.08	0.77	L
Δ Ankle internal (+)/ external (-) rotation	0.82	0.13	N	0.61	0.20	S	0.01	0.87	L
Δ Knee flexion	0.06	0.97	L	0.67	0.15	S	0.48	0.20	S
Δ Knee adduction (+) abduction (-)	0.12	0.76	L	0.13	0.80	L	0.12	0.64	M
Δ Knee internal (+)/ external (-) rotation	0.55	0.24	S	0.67	0.24	S	0.61	0.22	S
Δ Hip flexion	0.34	0.24	S	0.81	0.06	S	0.60	0.12	S
Δ Hip adducton (+)/ abduction (-)	0.13	0.23	S	0.38	0.25	S	0.24	0.19	S
Δ Hip internal (+) / external (-) rotation	0.009	1.38	VL	0.07	0.97	L	0.10	0.84	L

P: P Value; ES: Effect size; Qual: qualitative outcome; N: negligible; S; small; M: medium; L; large.

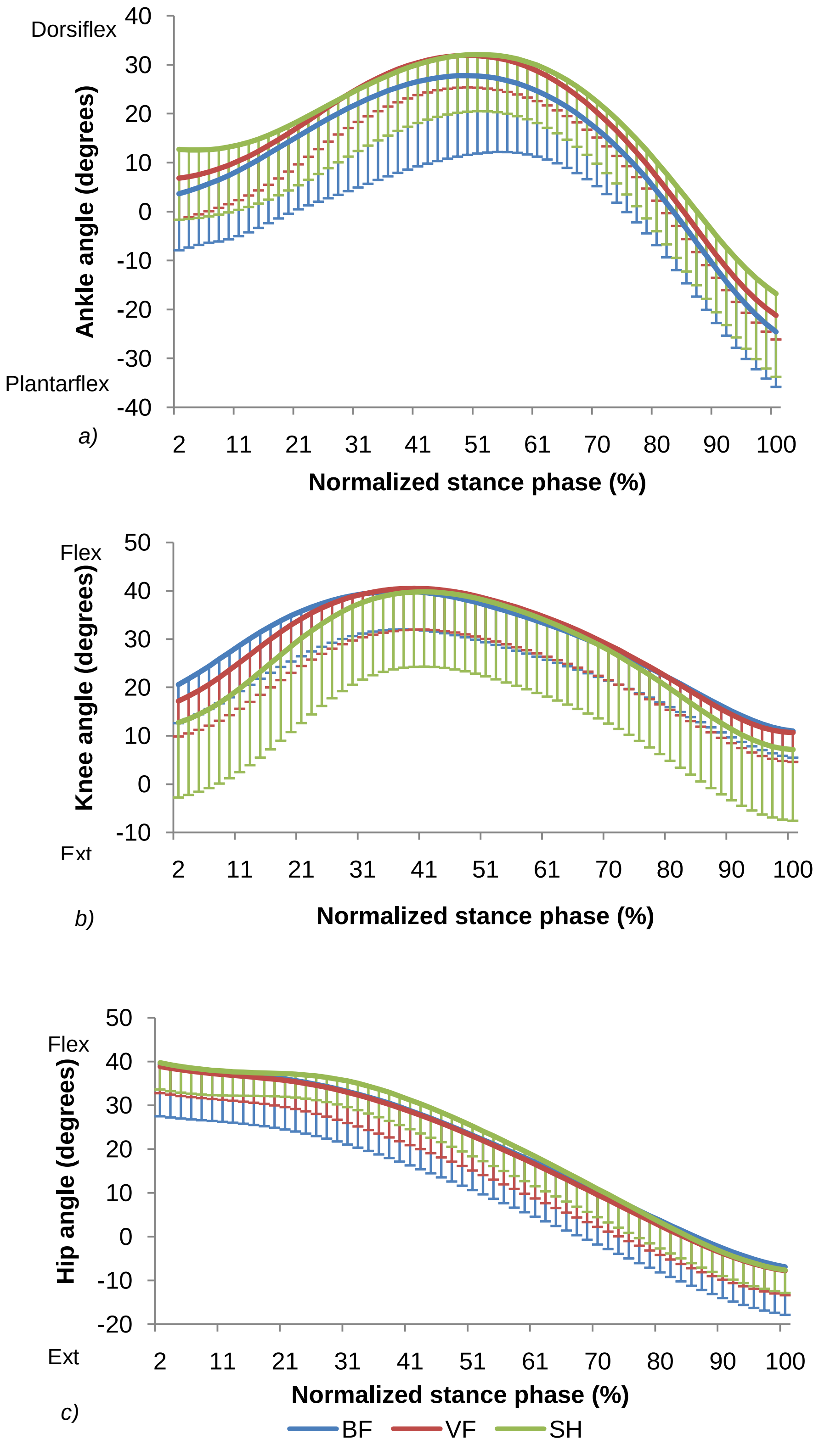


Figure 5.18. Mean (-SD) sagittal plane lower limb joint angle curves normalised to stance phase for all shoe conditions: a) ankle, b) knee, c) hip.

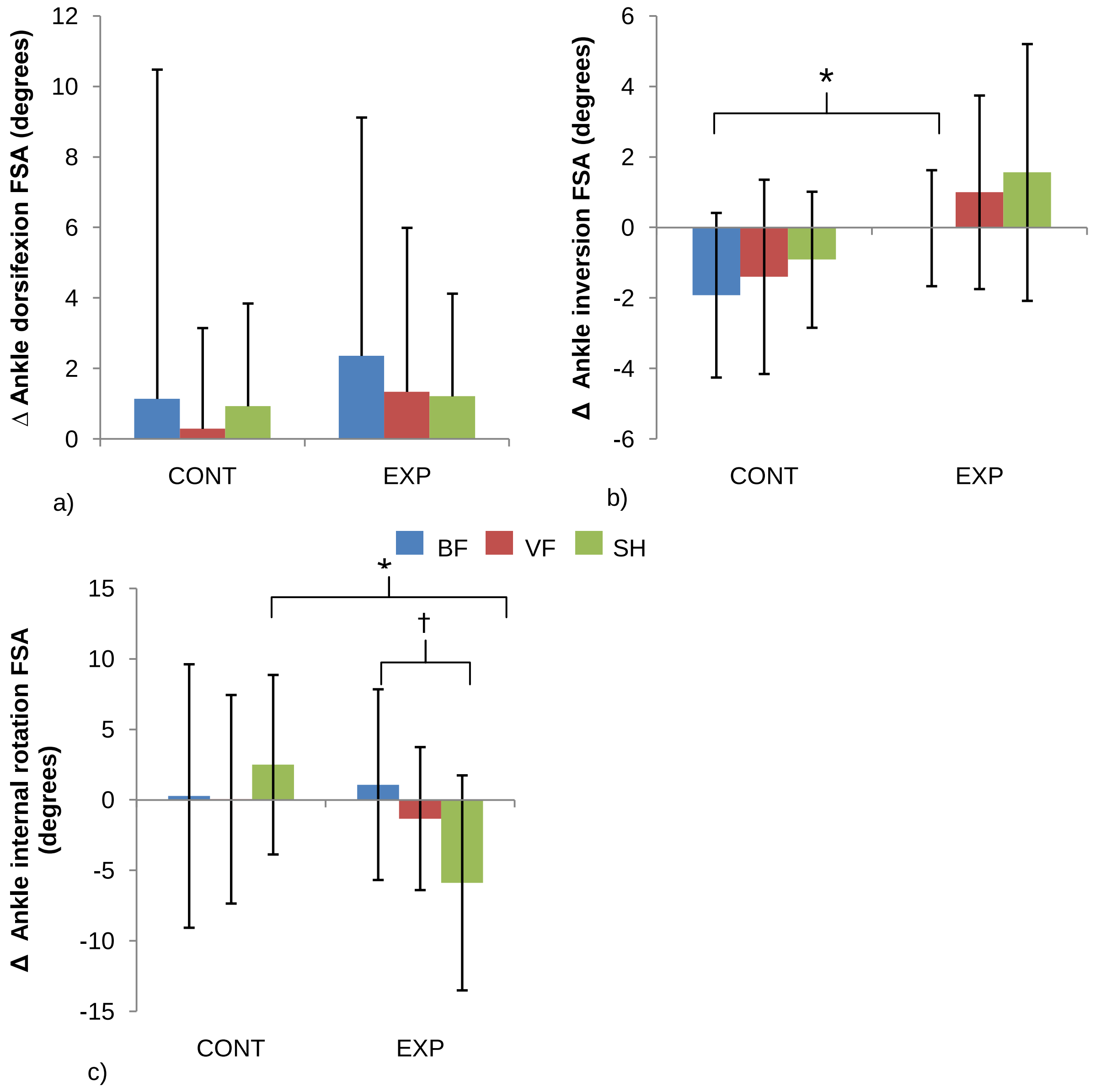


Figure 5.19. Absolute mean differences pre-post for ankle footstrike angle (FSA) parameters. Positive increases (pre-post) indicate increases in: a) dorsiflexion; b) inversion; c) internal rotation. † indicates significant difference with group (between shoe conditions) ($P < 0.05$). * indicates significantly different ($P < 0.05$) between-groups for each shoe condition.

Absolute mean differences (degrees) for ankle dorsiflexion, inversion, and internal rotation are shown in Figure 5.19. Both groups increased their ankle dorsiflexion angles pre to post, indicating a shift towards a rearfoot strike (RFS). This shift towards a RFS was consistent for all shoe conditions, with increase dorsiflexion angles of ~ 1 – 2 degrees. The greatest increase in ankle dorsiflexion angle at contact was seen in the EXP group for the BF condition, but maintained a small practical significance

(P > 0.05; ES = 0.17) compared to the CONT group (Table 5.25). In the frontal plane, the EXP group showed to increase their ankle inversion angles at contact from pre to post in the VF and SH condition, whilst the BF condition remained unchanged. In contrast, the CONT group showed a trend to decrease their ankle inversion angles at contact (more everted position) from pre- to post-intervention. Large practical significance in ankle inversion at contact was found between CONT and EXP groups for all three shoe conditions (ES = 0.77 – 0.90), with the BF condition having statistical significance (P = 0.04). For the transverse plane, the CONT showed negligible changes in ankle rotation at contact. However, the EXP group showed a trend to decrease their ankle internal rotation at contact (more externally rotated position). Ankle rotation for SH condition was significantly different between groups, with a more externally rotated ankle at contact in the EXP group (P = 0.01; ES = 0.87).

Knee flexion at contact showed to increase from pre to post by ~ 2 – 3 degrees in all conditions for both groups, with exception to the barefoot condition in the EXP group which showed a negligible decrease of less than 1 degree (Figure 5.20). Small practical significances were found between groups for VF and SH conditions for knee flexion angle at contact (P > 0.05; ES = 0.15 – 0.20). Knee adduction angle consistently decreased (more knee abduction) from pre to post for shoe conditions in the CONT group. However, these decreases were negligible (ES = 0.02 – 0.23) and all within 2 degrees. Negligible changes in knee adduction angle for all shoe conditions were also seen in the EXP group. However, in contrast to the CONT group, these differences were in a positive direction thus indicating a tendency towards more knee adduction angle in at ground contact.

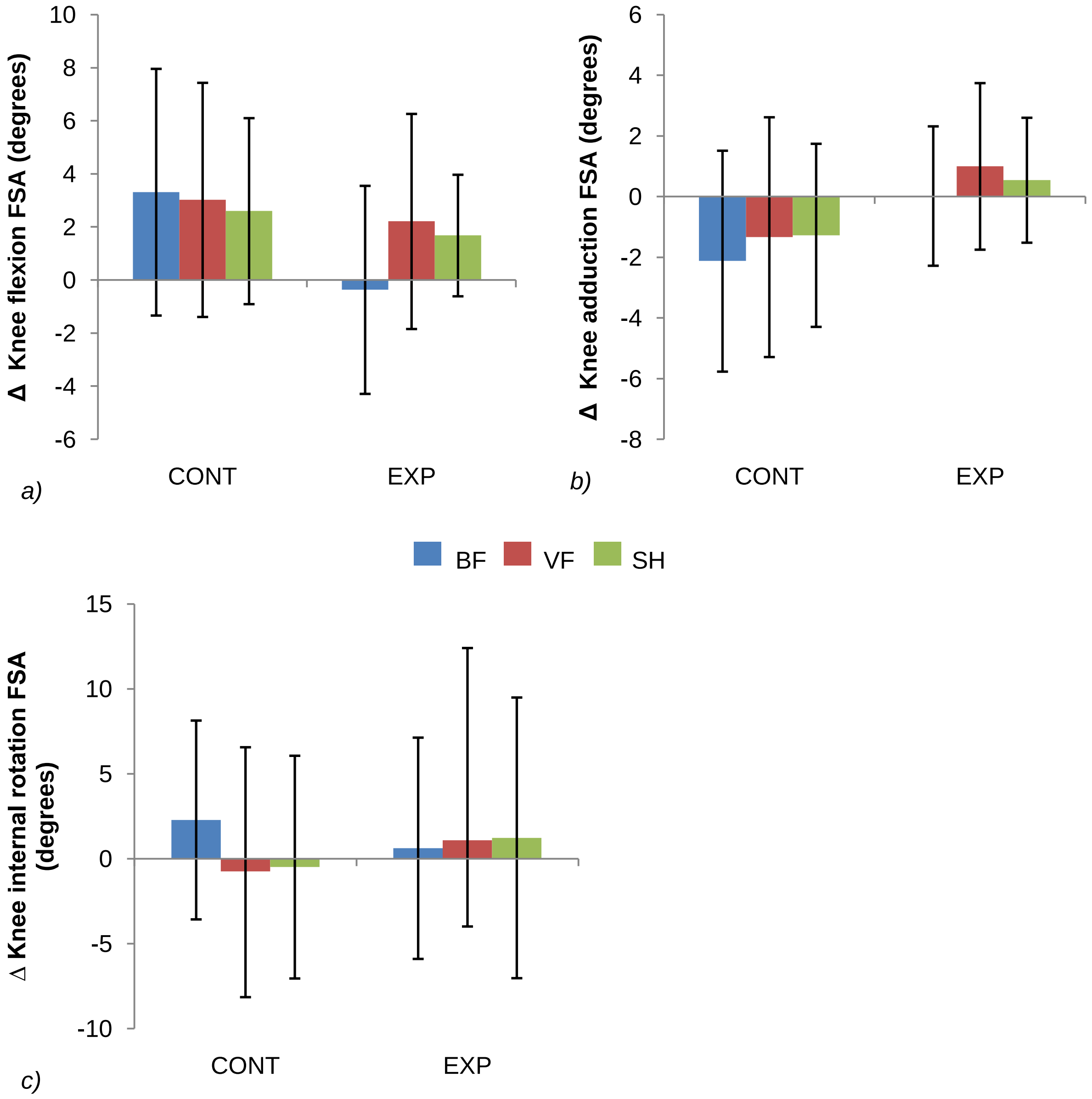


Figure 5.20. Absolute mean difference pre-post for knee footstrike angle (FSA) parameters. Positive increases pre-post indicate increases in: a) flexion; b) adduction; c) internal rotation.

Hip flexion angle at contact followed a similar trend to the knee flexion angle at contact. Both groups had negligible increases (ES = 0.02 – 0.08) in hip flexion at contact by ~ 1 degree across all shoe conditions, with one exception to the BF condition in the EXP group which decreased by 0.4 degrees. The frontal plane at the hip showed negligible increases in hip adduction across all conditions and groups (ES = 0.01 – 0.07). These increases were higher in the EXP group, thus resulting in small practical significances between groups (ES = 0.17 – 0.23).

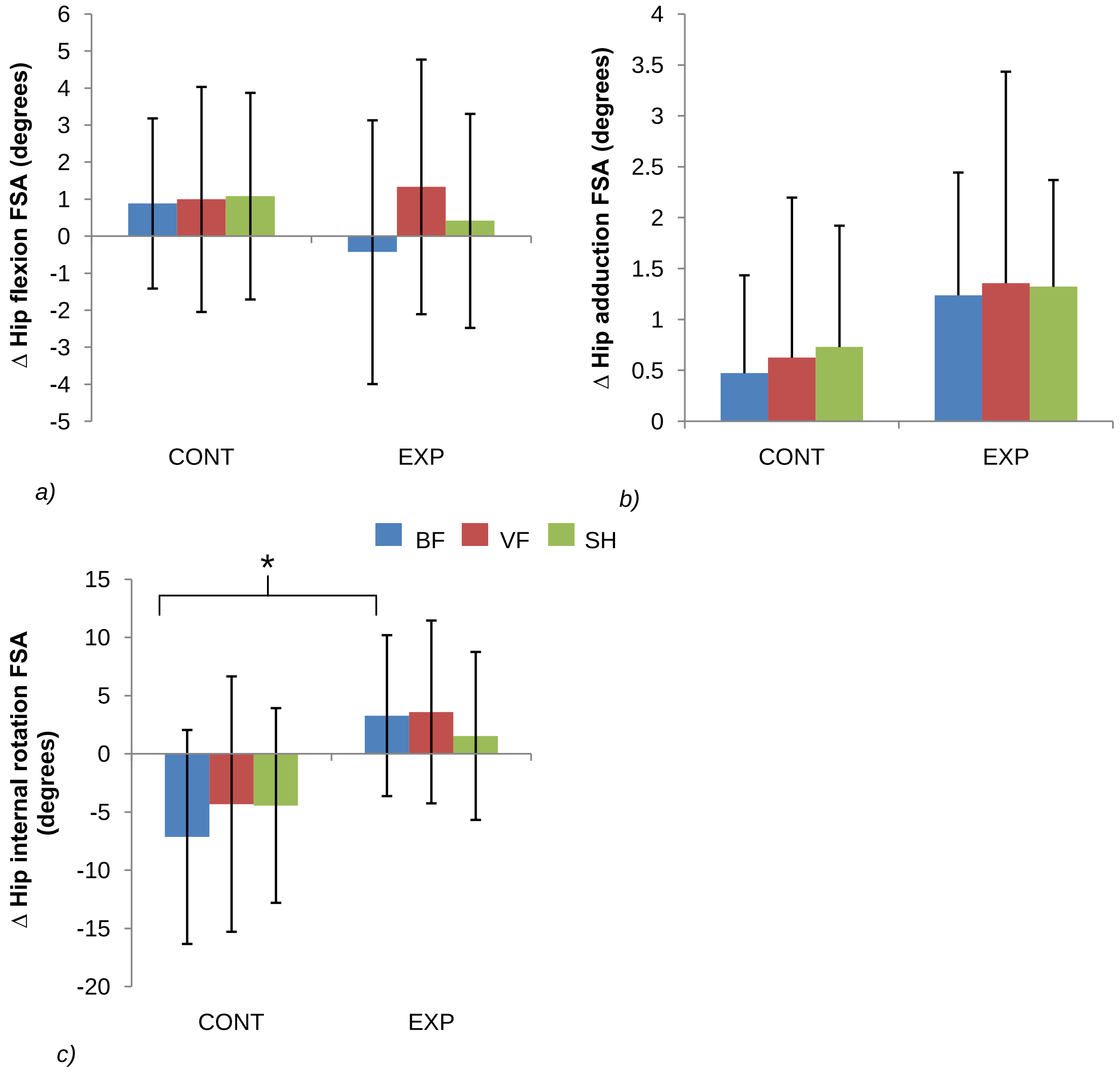


Figure 5.21. Absolute mean differences pre-post for hip footstrike angle (FSA) parameters. Positive increases (pre-post) indicate increases in: a) flexion; b) adduction; c) internal rotation.

Hip transverse plane motion showed that the CONT group decreased their hip internal rotation contact angle (more external rotation) at contact by ~ 7 degrees in the BF condition, and 4 degrees in the VF and SH condition. In contrast, the EXP group increased their hip internal rotation angles by 2 – 4 degrees, with the greatest increase found in the BF condition. A significant difference in hip rotation angle was found between groups for the BF condition, with a very large practical significance (P = 0.009; ES = 1.38). For hip rotation angle at contact, close to significant differences with large practical significance were also seen between groups for the VF (P = 0.07; ES = 0.97) and SH (P = 0.09; ES = 0.84) conditions respectively.

Strike index

Strike index (SI) was significantly higher for both VF (P = 0.001) and BF (P = 0.0004) compared to SH (Table 5.26). SI did however not differ between BF and VF conditions (P > 0.05). SI mean for BF and VF indicated a midfoot strike landing (SI > 33% but < 66), while the SI mean for SH indicated that landing occurred as a rearfoot strike (RFS) (SI < 33%). SI showed strong negative correlations with ankle dorsiflexion-plantarflexion at footstrike in the BF condition (r = - 0.76; P = 0.0002), a strong negative correlation in the VF condition (r = -0.78; P = 0.0001), and moderate to good negative correlation in the SH condition (r = - 0.53; P = 0.001). SI thus confirms the ankle plantarflexion angles seen at foot strike, as discussed in the previous section

Table 5.26. Mean (± SD) centre of pressure at landing for shoe conditions.

COP trajectory parameter	**BF**	**VF**	**SH**
SI (%)	38.48 ± 23.94 ^{c}	37.52 ± 24.85 ^{c}	27.22 ± 18.52 $^{a, b}$

COP: Centre of pressure; SI: strike index; $^{a, b, c}$ Significantly different (P < 0.05) from barefoot (BF) ^{a}; minimalist shoes (VF) ^{b}; and shod (SH) ^{c}.

Distribution of footstrike patterns according to groups and pre-post intervention are illustrated in Figure 5.22. A trend towards a rearfoot strike (RFS) was seen for the BF and SH conditions from pre to post in both the CONT and EXP group. Footstrike pattern distribution remained unchanged in the VF condition for the CONT group from pre to post. However, in the EXP group during VF, a trend from a forefoot strike (FFS) to a midfoot strike (MFS) pattern was evident pre to post, with the percentage of RFS landings being unchanged. During pre- and post-tests for both groups, SH running condition was associated the most with a RFS pattern (60% - 91%), followed by MFS pattern (9% - 30%) and lastly FFS (0 – 10%). VF running condition was also associated mostly with a RFS pattern (50% - 70%), followed by both MFS pattern (9% - 40%) and FFS (10% - 40%). Lastly, the BF running condition was also mostly associated with a RFS (20 - 64%), followed by MFS (27% - 36%), and then by FFS (9% - 30%).

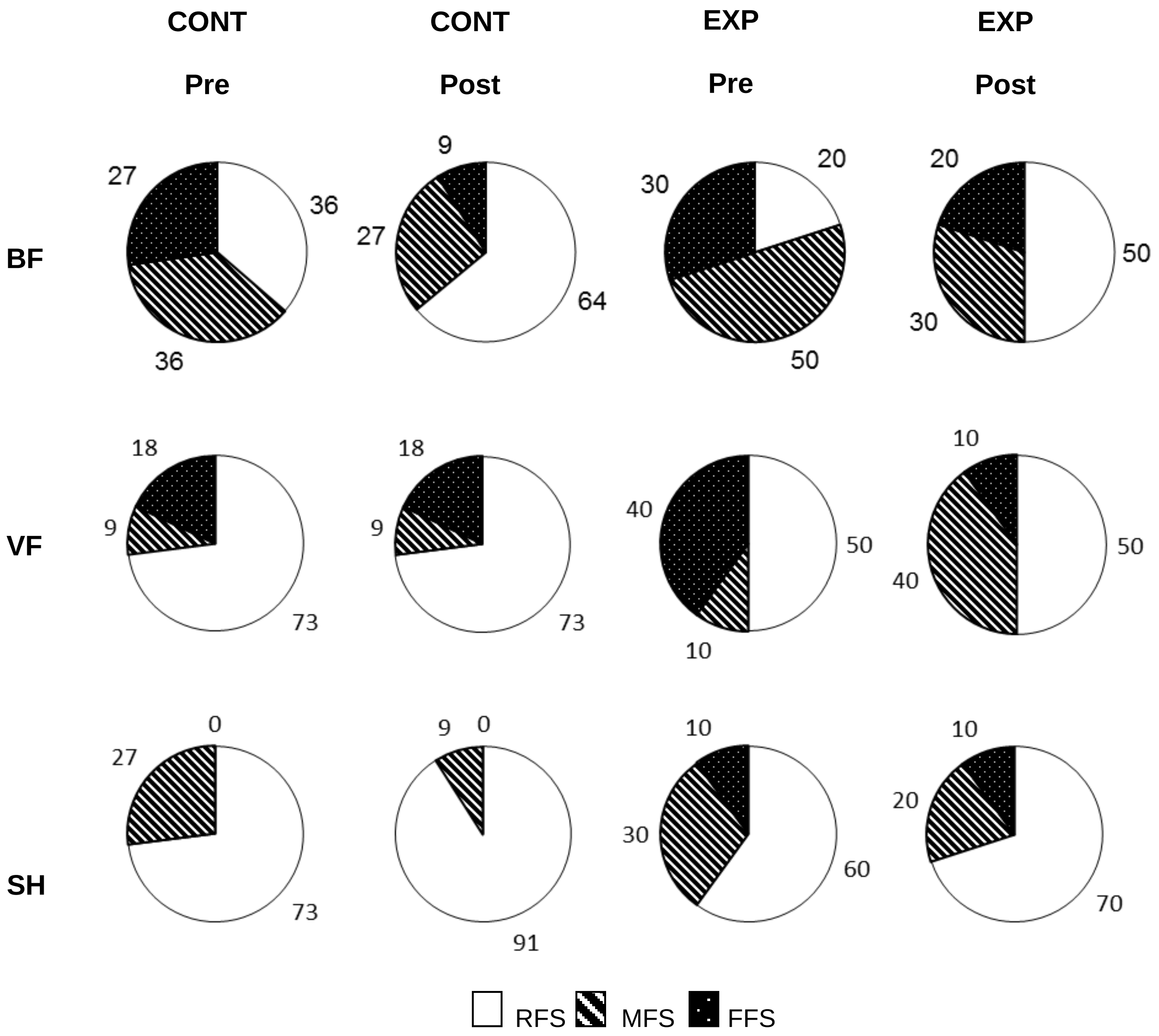


Figure 5.22. Footstrike pattern distribution (%): rearfoot strike (RFS); midfoot strike (MFS); and forefoot strike (FFS) among CONT and EXP groups for pre- and post- intervention. Footstrike patterns are categorized horizontally by shoe condition: barefoot (BF); minimalist shoes (VF); and shod (SH). Footstrike patterns are categorized vertically by group and pre- or post- intervention.

3. Correlations

Correlations were performed to find relationships between certain kinematic parameters and vertical impact force parameters (Table 5.27). Higher strike index (SI) (more towards a forefoot strike) was moderately associated with a smaller vertical impact peak (VIP) in the VF condition only. Higher SI showed a moderate to good association with a lower VALR in the BF condition (r = - 0.56) and VF condition (r = -0.65), but was only weekly associated in the SH condition (r = 0.22). Figure 5.23 represents scatter plots of the correlations between SI and VALR for all three shoe conditions. The scatter plots are divided into thirds to illustrate the criteria of the three different footstrike patterns, namely forefoot strike (FFS), midfoot strike (MFS), and rearfoot strike (RFS) respectively. For BF running (Figure 5.23a), a trend can be seen that the more the participants landed with a FFS, the lower the VALR. However, it can also be seen that that data points are also spread over a large range of VALR (25.25 – 158.60 BW/s). For VF running (Figure 5.23b), a steeper trend may be seen between footstrike pattern and VALR. Even though the range for VALR is spread over a large distribution (11.4 – 162.4 BW/s), most data points fall under100 BW/s. The predominant clusters of data points seem to be for RFS and FFS patterns, with some data points indicating MFS in between. Lastly, for the SH condition (Figure 5.23c), the trend between footstrike pattern and VALR is much weaker than either the BF or VF conditions. The range for VALR is also less (14.6 – 85.4 BW/s), with most of the data points clustered around the MFS region.

Step frequency was weakly associated with both VIP and VALR for all shoe conditions. For all shoe conditions longer step lengths were moderately associated with higher VIP, and weakly associated with lower VALR. A larger knee flexion footstrike angle (FSA) was moderately associated with reduced VALR in the VF condition only. Moderate to good associations were found for a more plantarflexed ankle with reduced VALR in BF and VF conditions respectively. Moderate and moderate to good associations were found for a more inverted ankle with reduced VALR in BF and VF conditions respectively.

Table 5.27. Pearson correlation coefficients between various kinematic parameters with impact force parameters.

Parameter	**Shoe**	**VIP (BW)**			**VALR (BW/s)**		
		r	**P**	**Qual.**	**r**	**P**	**Qual.**
Strike index (%)	BF	-0.09	0.181	-W	-0.56	0.0002	-MG
	VF	-0.29	0.003	-M	-0.65	0.0001	-MG
	SH	0.03	0.62	W	-0.22	0.001	-W
Step frequency (steps/min)	BF	-0.22	0.006	-W	-0.15	0.03	W
	VF	-0.19	0.003	-W	0.00	0.94	W
	SH	-0.14	0.04	-W	-0.14	0.03	W
Step length (m)	BF	0.33	0.001	M	-0.13	0.1	None
	VF	0.28	0.002	M	0.06	0.34	W
	SH	0.39	0.0004	M	0.03	0.61	W
Knee flexion FSA	BF	0.02	0.70	W	-0.19	0.004	-W
	VF	-0.18	0.005	-W	-0.34	0.0004	-M
	SH	0.03	0.6	W	-0.09	0.43	-W
Ankle dorsiflexion FSA	BF	0.20	0.006	W	0.59	0.0001	MG
	VF	0.17	0.009	W	0.55	0.0002	MG
	SH	0.05	0.41	W	0.05	0.44	W
Ankle inversion FSA	BF	0.02	0.751	W	-0.30	0.0004	-M
	VF	0.17	0.009	W	-0.55	0.0003	-MG
	SH	0.20	0.01	W	0.12	0.07	W

r: Pearson's correlation coefficient; P value. VIP: vertical impact peak; VALR: vertical average loading rate; BF: barefoot; VF: minimalist shoes; SH; shod; W: weak correlation; M: moderate correlation; MG: Moderate to good correlation.

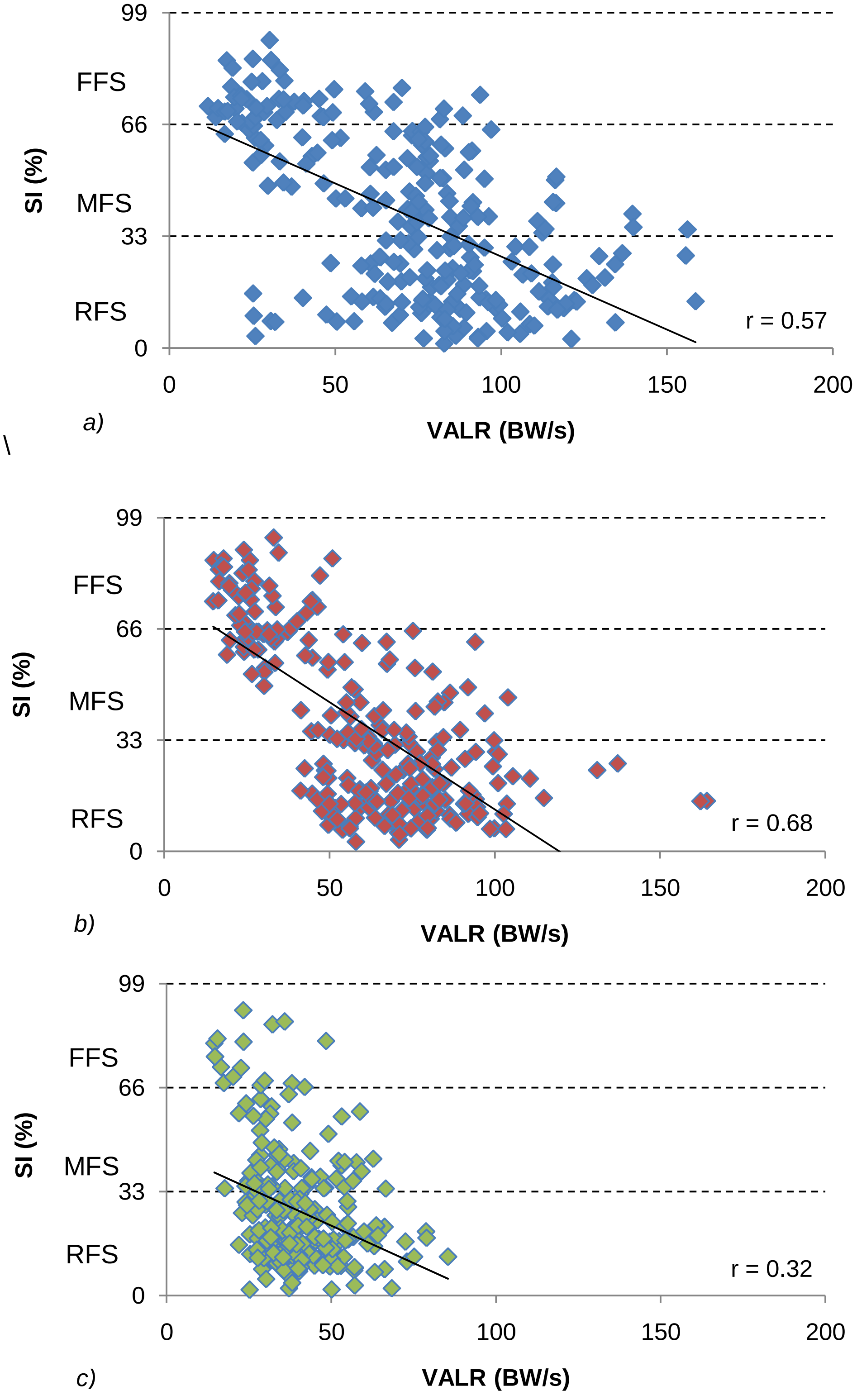


Figure 5.23. Scatter plots of Pearson correlations between change in strike index (SI) (%) and change in vertical average loading rate (VALR) (BW/s) for a) barefoot (BF); b) minimalist shoes (VF); c) shod (SH). Footstrike patterns are divided by horizontally dotted gridlines: FFS: forefoot strike; MFS: midfoot strike; and RFS: rearfoot strike.

4. Lower limb circumferences

Figure 5.24 shows the absolute mean change in left and right maximum calf circumferences (MCC) between the EXP and CONT group. A statistically significant increase in left calf circumference (P = 0.04; ES = 0.47), but not for the right MCC (P = 0.16; ES = 0.34) was observed in the EXP group. Absolute mean increases in MCC for the EXP groups were 0.77 cm and 0.52 cm for the left and right respectively. In comparison, the control (CONT) group had negligible increases between pre- and post-sessions: 0.08 cm (ES = 0.05) left and 0.06 cm

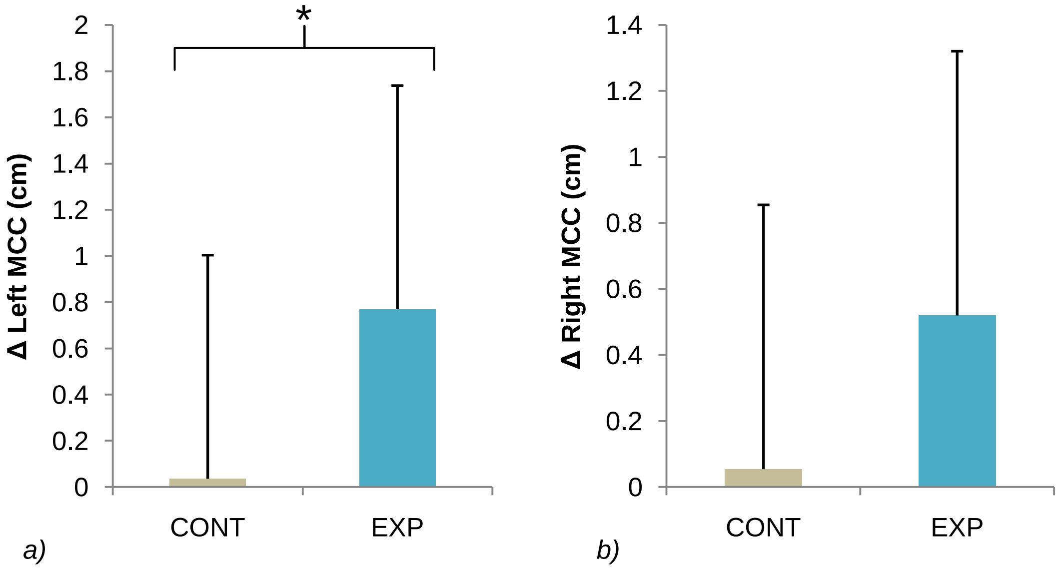
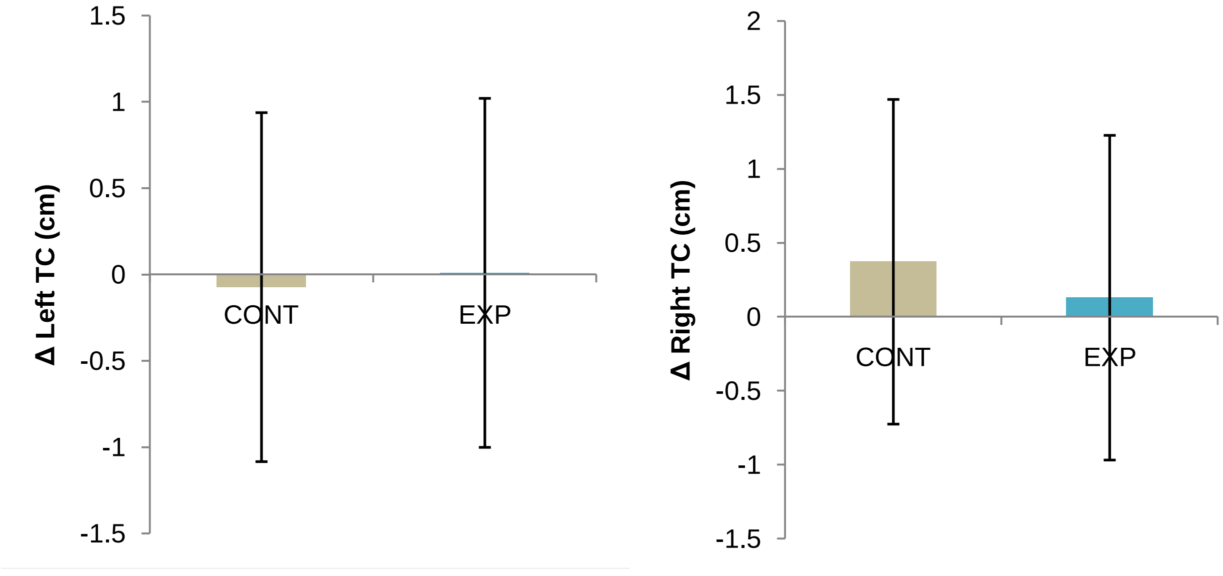


Figure 5.24. Absolute mean differences in: a) left; b) right maximum calf circumferences (MCC) for CONT and EXP groups at pre- and post-testing. * indicates significantly different between EXP and CONT group (P < 0.05).

With regard to left thigh circumference (TC), negligible effect sizes were found between CONT and EXP group for left (P = 0.97; ES = 0.01). However, a small practical increase was found for the right TC in the CONT group compared to the EXP group (P = 0.65; ES = 0.30).



a) *b)*

Figure 5.25. Absolute mean differences in: a) left; b) right thigh circumferences (TC) for CONT and EXP groups at pre- and post-testing.

Table 5.28**.** Means (±SD) for lower limb circumferences. Data are mean ± SD.

Parameter	**Side**	**CONT**		**EXP**	
		Pre	**Post**	**Pre**	**Post**
TC (cm)	L	46.22 ± 1.47	46.15 ± 1.41	45.72 ± 3.03	45.73 ± 1.41
	R	46.65 ± 1.69	47.12 ± 1.61	46.40 ± 2.86	46.53 ± 2.81
MCC (cm)	L	37.77 ± 1.47	37.85 ± 1.62	37.46 ± 1.63	38.23 ± 1.81
	R	38.06 ± 1.68	38.12 ± 1.61	37.70 ± 1.62	38.22 ± 1.61

TC: thigh circumference; MCC: Max calf circumference; L: Left leg; R: Right leg;

CHAPTER SIX

DISCUSSION

A. INTRODUCTION

The present study investigated the effects of minimalist shoes (VF) on lower limb kinematics and kinetics under both acute conditions as well as after seven-weeks of VF training. The primary aim of this study was thus to determine whether lower limb kinematics can be adapted, whether vertical impact loading rate (VALR) can be attenuated, and whether lower limb joint moments can be altered by either novice or short-term (seven-week) minimalist shoe training..

Before reporting the main findings of the study, descriptive results regarding participant training characteristics and anthropometric characteristic will be discussed. The literature (Acut *et al.,* 2009; Squadrone & Gallozzi, 2009), as well as anecdotal suggestions from coaches (Robillard, 2010; Sandler & Lee, 2010; Wallack & Saxton, 2011), suggest that previous barefoot experience plays a role in the ability to adapt kinematics to barefoot running. Participants of this study were asked to estimate the amount of barefoot running experience (specific to endurance running only), barefoot sports experience (barefoot touch rugby, soccer, etc.) and barefoot experience during childhood and adolescence (amount of time barefoot or with shoes). These characteristic differences, as well as their influence on outcome parameters, are now discussed.

A section on the specifics of the conventionally cushioned control shoes and how they could influenced the relevant outcome variables will be discussed. A control shoe was used in this study to serve as comparison to both minimalist shoe and barefoot running conditions. This study followed the protocols of studies which had participants run in their own shoes (Dickinson *et al.,* 1980; Dixon *et al.,* 2000; Lieberman *et al.,* 2010). While the use of participants' own shoes may

Stellenbosch University http://scholar.sun.ac.za

provide more insight into a realistic running condition (Dixon *et al.,* 2000), the possible loss of consistency and standardisation among shoe type, brand, and model should be noted. Nevertheless, all the participants in this study had shoes which had significant heel cushioning and arch support.

Comfort has been mentioned as an important factor for footwear in recreational physical activities (Mündermann *et al.,* 2002). A previous study made use of a familiarisation period to improve comfort when investigating athletic footwear (Squadrone & Gallozzi, 2009). However, to the knowledge of this author, this is the first study to have specifically quantified the effect of a familiarisation period on perceived footwear comfort and is original in that respect. Findings with respect to the familiarisation period in VF shoes and its associated role on the perceived shoe comfort will also be discussed.

The main findings of this study will be discussed according to the research objectives set out in chapter three. Thereafter, specific conclusions pertaining to these research questions will be made. Limitations to the present study will be identified along with a list of recommendations for future studies.

B. DESCRIPTIVE CHARACTERISTICS

1. Training characteristics

No significant differences were found between the randomised control (CONT) and experimental (EXP) groups with regard to any training characteristics (Table 5.1). Both groups had adequate shod running experience of ~ 5 yrs. There was, however, a tendency in the EXP group for participants to have higher weekly training mileage and frequency. There are no studies to suggest how this tendency may have influenced the primary research objectives of this study. However, half marathon runners who finish with faster times have been shown to have a footstrike pattern that is more directed towards the forefoot at the 15 km mark, compared to runners who finish with

Stellenbosch University http://scholar.sun.ac.za

slower times and who have a more rearfoot strike (Hasegawa *et al.* 2007). According to Robillard (2010), runners who adopt a more mid- to forefoot-strike pattern when running in conventional shoes are more likely to be able to transition to barefoot running successfully.

Both groups in this study had little barefoot running experience or barefoot sports experience, and did not differ significantly or practically from one another. However, the EXP group did have a propensity for a larger barefoot experience during childhood and adolescence. Lieberman *et al.* (2010) showed that 14 adult Kenyan shod runners who grew up barefoot for the most part of their childhood and adolescence were mostly midfoot strikers (MFS 18%) or forefoot strikers (FFS 54%) when running in conventional shoes. In addition, these Kenyan runners landed 91% of the time with a FFS while running barefoot. One could thus speculate that the EXP group of this could have adapted their kinematics more towards the mid- or forefoot in either shod, barefoot, or minimalist shoes condition based on practically higher barefoot experience. More research is needed to establish a relationship between barefoot experience and footstrike patterns.

2. Anthropometric characteristics

The relevant anthropometric measurements taken in this study were neither statistically nor practically significant (ES = 0.09 – 0.35) (Table 5.2). Body weight and height were measured to normalise ground reaction forces and joint moments to each individual. Body weight was taken at both pre- and post-testing sessions to account for any changes. Knee and ankle width were measured to more accurately determine the lower limb joint centres of the each participant, thus allowing for more accurate determination of the linear velocity and acceleration of the lower limb segments which were used to calculated the joint moments. Anthropometric factors such as body weight, leg length, height, etc. may have an influence on running kinematics and kinetics. However, it was not within the scope of this study to determine such relationships.

3. Control shoe cushioning effects

No significant differences were seen between experimental and control groups with regard to the heel cushioning height, age, or size (Table 5.3). It should be noted that although not statistically significant, shoes of the CONT group were 10.67 months older on average (ES = 0.76). However, Kong, Candelaria and Smith (2009) found no differences in lower limb joint angles or external vertical ground reaction force before and after 24 runners (14 men) ran 320 km in conventional cushioned running shoes. These investigators did, however, notice a 2% increase in stance time with the older shoes compared to the new shoes. Further studies are needed to confirm any effect shoe age has on running kinematics and kinetics.

The thickness of shoe cushioning of the control shoes were correlated with various outcome variables (Table 5.4). Participants who wore thicker shoes did not have significant changes in vertical impact peak (VIP), but did have a lower vertical average loading rate (VALR). These conclusions are drawn on the basis that shoe cushioning showed a weak association with VIP (r = - 0.12), yet a moderated association with VALR (r = - 0.34). These results may be due to what Shorten and Mientjes (2011: 41) explained as the “impact peak anomaly”. According to these authors, the magnitude of VIP during running does not quantify the effect of shoe cushioning *in vivo*. It was explained that the magnitude of the VIP consists of the sum of both high and lower frequency components. Shoes with more cushioning or that are more compliant attenuate the initial impact by reducing the high frequency component (delayed time to VIP and reduced average rate of impact loading). However, the fraction of attenuated high frequency component that is attenuated is then summated with the low frequency impact component. The overall magnitude of the VIP thus varies minimally due to this shift from high to low frequency impact components (Shorten & Mientjes, 2011).

The hypothesis that the typical rearfoot strike (RFS) with dorsiflexed ankle position is a function of shoe cushioning height (Lieberman *et al.,* 2010) is partially supported. Ankle dorsiflexion showed a weak relationship with shoe cushioning height (r = 0.22). This indicates that there is a tendency for thicker shoe cushioning to promote a more dorsiflexed ankle at footstrike.

Running shoe cushioning was also correlated with spatio-temporal parameters. Step time was also moderately and negatively associated with thicker shoe cushioning. Step time is the sum of both contact and flight times. Here, it was shown that contact time was responsible for this relationship (r = -0.56), while flight time was not (r = 0.04). Shorter contact times were thus observed with more cushioning. The reason that runners with thicker cushioned shoes have shorter contact times is unclear and contradicts previous findings. Racing flats and spikes are shoes that are designed with less cushioning under the heel compared to that of conventional running shoes. Logan, Hunter, Hopkins, Feland, and Parcell (2010) found that contact time was significantly reduced in men and slightly reduced in women runners when running in either racing flats or spikes compared to conventional shoes. One possible reason to why the results of this study were different is that runners with thicker shoe cushioning tended to run at faster speeds, as shown by the moderate positive association (r = 0.36). Running speed is a function of both step frequency and step length. It appears that the increase in running speed observed among those with thicker cushioning was due to higher step frequency (r = 0.44) and not due to step length (r = 0.09). A finding that may help explain this is that the maximum vertical propulsive peak (VPP) of the ground reaction force, as well as the maximum plantarflexion moment (PFM), was moderately associated with thicker cushioning (VPP: r = 0.47; PFM: r = 0.32). One can speculate that more cushioning under the heel promotes more comfortable running (Lieberman, 2012; Shorten, 2002) that allows runners to push off with a greater VPP force.

4. Minimalist shoe comfort

As hypothesized, the familiarisation period had a statistically significant positive effect on total footwear comfort (P < 0.05). It is important to note, however, that only one of the ten footwear comfort items (fit for individual toe pockets) had a significant improvement in comfort from pre- to post-familiarisation period (Figure 5.1). For the rest of the comfort items, the familiarisation period

Stellenbosch University http://scholar.sun.ac.za

had a negligible to small effect in comfort ratings, as indicated by the effect sizes (ES = 0.09 - 0.24). Several reasons may account for this. The construction of footwear, along with specific design and physical properties, have been shown to affect comfort (Hennig *et al.* 1996). The particular brand of minimalist shoes used in this study is designed to fit the shape of the foot, and lacks various features of conventional shoes such as cushioning and arch support. This being said, the structure of the minimalist shoes used in this study had pockets designed to accommodate each individual toe. One particular participant commented: “My second and third toes feel like they don’t fill up their entire pockets”, while another participant stated “my toes need some getting used to the feeling of the pockets”. It has also been mentioned that participants tend to base their perceived comfort on stimuli received previously (Mündermann *et al.,* 2002). None of the participants had previously worn shoes with individual toe pockets, and thus lack of previous experience with this item could account for why such a large improvement in the fit for individual toe pockets item was observed.

Negligible improvements in heel cushioning comfort (ES = 0.12) and arch cushioning comfort (ES = 0.09) may be due to the fact that minimalist shoes are designed without cushioning. Conventional running shoes are subject to cushioning material degradation (Kong *et al.,* 2009). It could thus be speculated that changes in perceived cushioning comfort may be more visible in conventional shoes where compression or degradation of cushioning material is more probable. Cushioning items may therefore be less relevant when investigating perceived comfort in minimalist shoes.

According to Mündermann *et al.* (2002), a control shoe condition should always be included for footwear comfort studies to improve reliability measures. A control shoe condition was not administered in this study and may explain why many of the minimalist shoe comfort items did not improve significantly. However, participants were asked to rate their perceived comfort items in comparison to their own, usual shoes. The measuring of perceived comfort items of their own shoes would have been beneficial, and should be incorporated into future studies that aim to measure comfort changes.

C. RESEARCH OBJECTIVE ONE

To determine active kinematic predictors of average vertical loading rate (VALR) attenuation and joint moments for minimalist shoe (VF) running compared to barefoot (BF) and shod (SH) running.

The present study is the first to identify three-dimensional kinematic and kinetic adaptations of the lower limbs due to minimalist shoe running. H 1: It was hypothesized that VF running would depend on active kinematic methods to attenuate VALR; and b) alter joint moments lower than compared to both BF and SH conditions. Significant changes in lower limb kinematics occurred from SH to VF condition, leading to attenuated vertical impact peak (VIP) but not VALR. The first part of this hypothesis is therefore only partially confirmed. Joint moments were altered from SH to both VF and BF conditions, thus substantiating this second part of this hypothesis. Main findings will be discussed according to attenuation of impact force and adaptation in external joint moments. Kinematic results will be used to justify changes in kinetics where relevant.

1. Effect on impact force attenuation

The vertical impact peak (VIP) was significantly attenuated in barefoot (BF) running compared to shod running (SH) (Figure 5.8). The BF condition specifically had a mean difference in VIP that was 0.18 BW lower than SH. Divert *et al.* (2005) similarly reported that VIP was 0.22 BW lower for novice barefoot BF running compared to SH running. In addition, Hamill *et al.* (2011a) showed that VIP decreased by 0.19 BW – 0.31 BW during novice BF running at both self-selected and fixed running speeds. Some studies have reported no differences in VIP between BF and SH running (De Clercq *et al.,* 1994; De Wit *et al.,* 2000; Oakley & Pratt, 1988). One study by Dickinson *et al.* (1980) found 0.46 BW higher in BF compared to SH. However, these particular researchers instructed their participants to land on their heel while barefoot and it is therefore inappropriate to make comparisons with studies that allow their participants to naturally select or self-select their footstrike pattern.

Stellenbosch University http://scholar.sun.ac.za

Decreased VIP for BF running in the current study could be due to step length adaptations. For the BF condition, shorter step lengths were moderately associated with lower magnitude of VIP (r = 0.33) (Table 5.27). Step length was 3.8% shorter while BF compared to SH running. De Wit *et al.* (2000) found almost identical results, with novice BF running step lengths being 3.9% shorter than SH running at a similar speed of 3.5 (m/s), but found that VIP did not change. With experienced barefoot runners, Squadrone and Gallozzi (2009) found that barefoot runners had 6.8% shorter step lengths and dereased their VIP by 0.1 BW. Edwards *et al.* (2009) modelled the effects of reduction in step length and showed that a 10% reduction in step length resulted in a 0.7 BW decrease in axial tibial (contact) force. Heiderscheit *et al.* (2011) also showed that a 5% reduction in step length reduced the occurance of the VIP. Changes in step length could thus have accounted for the decreased VIP magnitude observed while BF at post-test in this study.

It is difficult to determine whether footstrike pattern played a role with with the decrease in VIP magnitude for the BF condition. According to Nigg (2010), a more forefoot landing decreases the amount of body mass that needed decelerated at impact - known as the effective mass - which either decreases or completely eliminates the VIP. Both strike index (SI) and ankle dorsiflexion angles were used to determine footstike pattern in this study. SI was statistically higher for BF compared to SH running (38.48 ± 23.94 vs. 27.22 ± 18.52), indicating a more midfoot strike (MFS) pattern. SI was weakly correlated with VIP magnitude in BF (r = -0.09) and SH (r = 0.03) runing. This negative relationship for the BF condition indicates that there is a tendency for a rearfoot striker to have a higher VIP than a forefoot striker with a lower VIP. Ankle dorsiflexion angle was also shown to have a week association with VIP for the BF runing (r = 0.20). These relations also suggest a tendency towards a lower VIP for a FFS landing. Indeed, the relationship between footstrike patterns and VIP may have been stronger if a greater percentage of runners in this study employed a forefoot strike landing. Over the entire study, forefoot landings (FFS) accounted for between 9% to 30% of all footstrike patterns. This same reasoning may be applied/transposed to the SH condition, as FFS landings accounted for only 0% - 10% of total footstrike patten distribution.

Increased knee flexion footstrike angle (FSA) was not associated with a reduced VIP while barefoot (r = 0.02) or SH (r = 0.03). This may partially contend the theory of adaptation to external environment proposed by Derrick (2004), who alleges that higher knee flexion angles at contact will decrease VIP. Overall, BF running resulted in a significantly more knee flexion footstrike angle compared to shod (18.38 ± 5.56 vs. 16.26 ± 5.14), which is in agreement with previous investigations (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006; De Wit *et al.,* 2000; Lieberman *et al.,* 2010; McCarthy *et al.,* 2011; Squadrone & Gallozzi, 2009). The mean difference between BF and SH running was ~ 2 degrees. A mean difference of 7 degrees more knee flexion footstrike angle has been observed in experienced barefoot runners (Squadrone & Gallozzi, 2009). This indicates that greater knee flexion FSA may increase even more as a runner becomes more experienced with the BF condition. Derrick (2004) states that 5 degrees more knee flexion FSA was necessary to achieve a decreased VIP. If 5 degrees is viewed as a critical threshold for VIP attenuation, then the participants of this study needed to increase their knee flexion FSA by a further 3 degrees.

VF running similarly had significantly lower VIP magnitude compared to SH running (Table 5.14). The approximate decrease in VIP from SH to VF was 0.16 BW. From a VIP magnitude standpoint, VF running imitated BF running. VIP differed by only 0.02 BW between VF and BF running, with the former being higher. To the knowledge of this author, no other study has reported or quantified VIP for novice minimalist shoe runners. One study (Squadrone & Gallozzi, 2009), however, found smaller VIP magnitude of 0.13 BW in experienced barefoot runners using the same brand of minimalist shoes (Vibram Fivefingers ®). Thus, it appears that this particular brand of minimalist shoes promotes a reduced VIP compared to conventional shoes in both experienced and novice minimalist shoes running. Kinematic parameters that moderately predicted VIP for VF running were strike index (SI) (r = -0.29), and step length (r = 0.28). It follows that a more plantarflexed positioned ankle with a shorter step length attests to the decrease in VIP evidenced.

While the magnitude of the VIP has often been a primary kinetic parameter in footwear research, the clinical relevance of the VIP may be superfluous. A systematic review found that stress

Stellenbosch University http://scholar.sun.ac.za

fractures of the lower extremity were in fact not related to the magnitude of the VIP, but rather the rate at which the impact force occurs Zadpoor and Nikooyan (2011).

Vertical average loading rate (VALR) did not follow the same trend to that of VIP. Barefoot running overall increased VALR by 85% more than SH running. This higher VALR was primarily a function of the significantly quicker time to VIP (TVIP), with BF being 30 ms quicker on average compared to SH (Table 5.14). From this result one could infer that, as a whole, barefoot running does not attenuate more VALR compared to shod, and that the innate impact moderating behaviour theory proposed Robbins and Gouw (1991) can be rejected. The two reasons purposed for these results are firstly that the lack of cushioning resulted in less passive attenuation of VALR for BF running, and secondly that the participants were unable to adapt their kinematics for active attenuation of VALR. In support of the former reason, VF delayed the TVIP by ~ 5 ms compared to the barefoot condition, but was delayed by another 26 ms in the shod condition. This corresponds with previous studies showing that more compliant shoes delay TVIP (Shorten & Mientjes, 2011; Snel, 1985; de Wit *et al*., 1995). VF running overall significantly attenuated the VALR by 17% compared to BF running, but still remained with 35% less VALR attenuation compared to SH running. Thus, this author is of the opinion that the overall decrease in VALR from BF, to VF, to SH, was primarily due to the increase in progressive amounts of shoe cushioning, as well as a lack of sufficient active kinematic adaptation.

There may be a minimum threshold of ankle plantarflexion adaptation required to attenuate VALR while barefoot. De Wit *et al.* (2000) found loading rates that were higher in the novice BF runner by 290% compared to the SH condition, even though their runners adapted landed with ~ 8 degrees more ankle plantarflexion at contact. This is similar to the runners in the present study, who landed with ~ 9 degrees more ankle plantarflexion on average when BF compared to SH. In contrast, a study by Hamill *et al.* (2011a) showed that novice BF runners attenuated VALR by 215% more than SH runners, but also reported that their participants had ~ 18 degrees more ankle plantarflexion while BF. While there is uncertainty as to why these novice BF runners had such greater magnitudes of plantarflexion adaptation compared to this study or to that undertaken by de

Stellenbosch University http://scholar.sun.ac.za

Wit *et al.* (2000), there is a clear indication that there may be a critical level of ankle plantarflexion adaptation required to attenuate VALR. The magnitudes of this adaptation are unknown, but may be in the range of that reported by Hamill *et al.* (2011a).

The hypothesis that VALR is a function of footstrike pattern was supported for BF and VF running, but not for SH running. Figure 5.23a and Figure 5.23b show the moderate to good relationship between VALR and strike index for BF (r = -0.56) and VF (r = -0.65) running exists. The relationship for both of these is negative, indicating that runners who adapted their footstrike patterns more towards the forefoot were able to successfully attenuate VALR. In contrast, SH was much less influenced by footstrike pattern (r = -0.22) (Figure 5.23c), yet the same negative relationship existed as found with the BF and VF conditions. If running with a FFS or even a MFS were successful active methods of attenuating VALR, then one would expect that most of the participants of this study would naturally selected these footstrike patterns. Indeed, strike index (SI) overall was higher for both BF and VF running in comparison to SH running (BF 38.48 ± 23.94%; VF: 37.52 ± 24.85%; SH: 27.22 ± 18.52%). This shows that this study population of runners overall *did* adapt their footstrike pattern while BF or with VF in response to these high VALR. However, upon closer inspection the variation around the mean was especially high, especially when compared to the SI of experienced barefoot runners who ran in the same conditions as this study (BF 58.6 ± 6; VF: 56.5 ± 5; SH: 40 ± 6) (Squadrone & Gallozzi, 2009). The larger standard deviation in SI observed in the current study may be due to unfamiliarity with BF or VF running, and that further training may diminish differences seen to that of more experienced BF runners.

The notion (Nigg, 2010) that some runners may be incapable of sensing higher VALR and consequently reduce VALR was somewhat supported for BF running, and mostly supported for VF running. Overall, the percentage of participants who continued to use a RFS while BF averaged 45% (range 20 – 36%), and while VF averaged 62% (range 50 – 73%). These runners who rearfoot struck while BF and/or VF could be classified as adaptation-failures from a footstrike pattern perspective. Previous studies have found the number of footstrike adaptation-failures in

Stellenbosch University http://scholar.sun.ac.za

experienced shod participants to be as high as 83% for novice barefoot running (Lieberman *et al.,* 2010), and 100% for novice VF running (Reenalda *et al.,* 2011).

In this study, VALR was the highest for adaptation-failures (RFS) in the BF condition, and second highest in the VF condition across all footstrike patterns and shoe conditions (Figure 5.8). Specifically, the participants who maintained a RFS landing while BF had 222% higher VALR compared to a typical shod RFS landing (Table 5.15). This would agree with other investigations that found similar differences of ± 200% (McCarthy *et al.,* 2011), or even higher differences of 445% (De Clercq *et al.,* 1994), 615% (Dickinson *et al.,* 1980), or 720% (Lieberman *et al.,* 2010).

For the participants who maintained a RFS pattern in the VF condition, VALR was 84% higher than landing with the typical SH RFS pattern. This difference is of similar magnitude to what McCarthy *et al.* (2011) found (~ 77%) using minimalist shoes of the same brand (Vibram Fivefingers ®), as depicted earlier in Figure 2.10. Thus, the tenet that runners will immediately learn to avoid landing on the heels to avoid local deformations through coordinated movements (Robbins & Gouw, 1991) should be interpreted cautiously.

The idea that VALR may be reduced by shifting from a RFS to a FFS is supported. VALR was the lowest for a FFS landing compared to a RFS landing for all three conditions, with 129% more VALR attenuation (Table 5.15). Oakley and Pratt (1988) reported that VALR was attenuated by up to 760% when their 18 participants ran with a FFS compared to a RFS, irrespective of whether they ran barefoot or with three types of insoles inside their socks. McCarthy *et al.* (2011) also showed that FFS landings were consistently lower compared to RFS landings for BF, minimalist shoes, and SH running. These investigators showed that VALR was attenuated by 268% when a FFS landing was utilized instead of a RFS pattern. Thus, these results all agree with the idea that VALR will be attenuated when converting from a RFS to a FFS, irrespective of shoe condition or being barefoot or not.

Midfoot strike (MFS) landing showed the lowest VALR for minimalist shoe running. The studies previously mentioned (McCarthy *et al.,* 2011; Oakley & Pratt, 1988) divided footstrike patterns into either a FFS or RFS. It is the opinion of this author that a MFS pattern should also be included, as from a practical standpoint some runners may want to find the medium between the extremes of either a FFS or RFS. MFS landings in this study were overall lowest for the VF condition (Figure 5.8). A decrease from ~ 87% in VALR was seen for midfoot striking while BF to midfoot striking while VF. This decrease was sufficient to drop a further 9% below the SH condition. As speculated by Altman and Davis (2009), using a MFS could be a good compromise to reduce the susceptibility of impact related injury found on the extremes of footstrike patterns. Based on the findings of this study, SH running with a MFS would not be a good compromise (VALR showed a negligible increase of 2.2% from a RFS to a MFS). It is noteworthy that two of the five participants in the study by Altman and Davis (2009) showed the same trend. Altman and Davis (2009) attributed this finding to the fact that these two participants felt uncomfortable using a MFS condition while SH. This reasoning cannot be applied to the present study as all of the SH midfoot strikers in this study did so naturally without instruction. Thus, the exact mechanism to this phenomenon remains unclear. Moreover, why exactly the VF condition had the lowest VALR with a MFS pattern is also debatable. It could be speculated that landing with a MFS with VF shoes promotes an ideal combination of both active and passive impact attenuation that is neither seen in BF, nor SH conditions.

The theory of adaptation of knee flexion to external environment (Derrick, 2004) was to an extent supported with regard to VALR. Greater knee flexion footstrike angles (FSA) were moderately associated with reduced VALR for VF running only (r = -0.34) and not for BF (r = -0.19) or SH (r = -0.09). Thus, increasing one's knee flexion FSA may be a primary factor for VALR attenuation in VF running, and that BF running is dependant more on other kinematics adaptations. Derrick (2004) explained that landing with a more flexed knee FSA changes the line of action of the vGRF component to fall posterior to the knee joint centre, thus allowing for greater eccentric muscular absorption and maximisation of elastic stretching of the muscular components (Figure 2.5).

An unexpected and potentially novel finding of this study was the relationship between ankle inversion angle and VALR attenuation. A moderate negative relationship was found between ankle inversion angle and VALR for the BF condition (r = -0.30), a moderate to good negative relationship for the VF condition (r = -0.55), with only a weak positive relationship in the SH condition (r = 0.12). These relationships suggest that with the elimination of cushioned shoes, the ankle may use not only sagittal plane movement to attenuate VALR, but also frontal plane movement. The average inversion footstrike angle (FSA) was in the region of 3 degrees more for BF versus SH, and ~ 2 degrees more for VF versus SH. Even with large variation around the mean for BF and VF, both of these results were statistically significant (P < 0.05) compared to SH. To the knowledge of this author, only a few studies have taken frontal plane motion of the ankle into account when comparing BF and SH running. Samawarawickrame *et al.* (2011) found their novice barefoot runners to have around 5 degrees more inversion at contact when running VF than when running in conventional shoes. However, these investigators found the peak eversion angle at mid-stance to be similar, indicating that the primary differences between BF and SH were determined at or immediately prior to footstrike, and not during stance. Stacoff, Nigg, Reinschmidt, van den Bogert, and Lundberg (2000) concluded that at the skeletal level, ankle movements of the frontal plane do not differ significantly between BF and SH running.

Vertical propulsive peak (VPP) was significantly lower while BF (0.05 BW less) compared to the SH condition (Table 5.14). Other studies using novice barefoot runners have found no difference (De Wit *et al.,* 2000), 0.05 BW smaller BF (Divert *et al.,* 2008), 0.09 BW smaller BF (Kerrigan *et al.,* 2009), and 0.13 BW smaller BF (Divert *et al.,* 2005) compared to SH. A study with experienced barefoot runners showed the same trend, with VPP being 0.03 smaller BF (Squadrone & Gallozzi, 2009). Therefore, there appear to be no studies showing that barefoot running promotes a higher VPP in comparison to SH running. However, while running with VF the participants had VPPs that were of similar magnitude to that of SH (VF: 2.43 ± 0.26 BW vs. SH: 2.44 ± 0.22 BW), but not statistically higher than BF (2.39 ± 0.26 BW).

Other studies using the same brand of minimalist shoes have observed similar trends. Paquette *et al.* (2011) found that both minimalist shoes and conventional shoes have equally higher VPP's than BF. Experienced runners had a VPP for minimalist shoe running that even surpassed that of

Stellenbosch University http://scholar.sun.ac.za

conventional shoes (2.49 ± 0.50 BW vs. 2.46 ± 0.60 BW) (Squadrone & Gallozzi, 2009), which the authors attributed to a more vigorous push off allowed by the thin rubber sole of the Vibram Fivefingers ® shoe. Squadrone and Gallozzi (2009) hypothesized that the longer step lengths observed from BF to VF, and from VF to SH were due to higher push-off peaks. The same significant trend in step length increase was observed in this study, with VF being ~ 3 cm on average longer than BF, and SH being ~ 2 cm longer on average than VF. Squadrone and Gallozzi (2009) speculated that this thin rubber sole is sufficient to allow plantar sensations to be detected, which was seen in the reduced step length from SH to VF. However, because step length is still significantly higher in VF than BF, the thin rubber sole provided by the minimalist may still provide a greater perceived comfortable landing. Step length was weakly correlated with VALR for all shoe conditions (r = 0.3 – 0.13). Thus, the reduction in step length when running BF may not be to foster attenuation or absorption of VALR during initial-stance.

On the whole, BF and VF running attenuated VIP compared to SH, which could be attributed to decreased step lengths. Conversely, VALR was attenuated the least in BF and VF compared to SH, indicating the overall inability of the participants to have sufficient active (kinematic) adaptation. The better VALR in VF compared to BF could merely have been due to the minimal but greater cushioning effects of the shoes compared to the bare feet. It is important to note, however, that certain kinematic parameters were associated with decreased VALR in BF and VF conditions, such as higher strike index, greater ankle plantarflexion, greater ankle inversion and greater knee flexion. Taking these associations into consideration, it is confounding that all of the participants did not adapt their kinematics to sufficiently attenuate VALR. The ability to sense higher VALR and adapt kinematics sufficiently may require additional time, practice, or strengthening of the lower extremity musculature to develop.

Stellenbosch University http://scholar.sun.ac.za

2. Effect on external joint moments

This study normalised all joint moments to individual body weight and height, as has been done with other studies (Kerrigan *et al.,* 2009; Moisio *et al.,* 2003; Riley *et al.,* 2008). Existing studies have only normalised joint moments to body weight (Samawarawickrame *et al.,* 2011; Schache *et al.,* 2011; Stefanyshyn *et al.,* 2006). Comparisons between studies for joint moments will therefore be made with percentage difference and not with absolute difference.

Ankle dorsiflexion moment (DFM) peak at initial stance was significantly lower for barefoot (BF) and minimalist shoes (VF) compared to shod (SH) (Table 5.17). An increase of 30% was seen from BF to VF, and a further 31% from VF to SH. Figure 5.12a illustrates how ankle DFM peak is attenuated during initial-stance by BF and VF. The curve that represents the SH condition is consistent with previous literature, with an initial dorsiflexion curve followed by a longer plantarflexion curve (McClay & Manal, 1998; Novacheck, 1998; Samawarawickrame *et al.,* 2011). The initial DFM peak is related to the posterior line of action of the vertical ground reaction force (vGRF) relative to the ankle joint at contact (McClay & Manal, 1998). As the ankle begins to plantarflex the tibialis anterior must contract eccentrically to control the landing and prevent the foot from slapping (Hamill & Knutzen, 1995; McClay & Manal, 1998). The reduction in ankle DFM from SH to VF and BF may have been primarily due to a more plantarflexed ankle at contact, as was found in this study (Table 5.17). Samawarawickrame *et al.* (2011) attribute their findings of a completely eliminated DFM peak in novice BF running to a more plantarflexed ankle. However, their study was preliminary and included only three habitually shod participants. The present study thus confirms this trend over a larger study population. Novacheck (1998) similarly reported a parallel trend with sprinters who have also eliminated ankle DFM peaks due to their preferred forefoot contacts, indicating a more plantarflexed ankle position.

A lower ankle DFM peak also indicates that the work done by the dorsiflexion muscles on the anterior side on the shank during initial stance may be decreased. In support of this hypothesis, von Tscharner, Goepfert and Nigg (2003) reported decreased activity of the tibialis anterior muscle

Stellenbosch University http://scholar.sun.ac.za

immediately prior to footstrike when their participants performed novice barefoot running. These investigators attributed their findings to either the altered running style (more towards the forefoot) observed while barefoot, or to the decreased mass of the shoe, which is needed to decelerate. The minimalist shoes used in the present study were lightweight (~ 170 g, depending on size), and subjectively lighter than any of the conventional shoes that belonged to the participants of the study. Therefore, the 31% reduction in ankle DFM peak from SH to VF, or conversely, the 30% increase in ankle DFM from BF to SH, could have been due to additional shoe mass. To the knowledge of this author, no other studies have reported ankle DFM peak for the minimalist shoe brand used in this study or for any other minimalist shoe brands, and thus no comparisons are possible.

BF and VF running generated a significantly greater ankle plantarflexion moment (PFM) peak than SH running, being ~ 5-6% higher. Ankle joint moments are also influenced by shoes during mid-stance, where the role of the lower limb muscles shifts from eccentric force absorption to concentric force generation. In contrast to initial stance, the latter part of stance causes the line of action of the vGRF to pass anterior to the ankle joint, thus allowing a plantarflexion moment to prevail (McClay & Manal, 1998). The present results would suggest that a greater contribution from the calf musculature, ankle plantarflexors and perhaps Achilles-tendon are used to push off while running BF or VF. Samawarawickrame *et al.* (2011) also noticed this tendency, but did not quantify the differences. Forefoot running is said to actively absorb and store work via eccentric contraction of the triceps surae (Oakley & Pratt, 1988). According to Hof, Zandwijk and Bobbert (2002), running involves an eccentric-concentric contraction of the triceps surae: work that is performed by the triceps surae muscle-tendon complex is stored as elastic energy, which can be released at speeds that significantly exceed the maximum shortening speed. It can be concluded that that BF and VF conditions allow for a greater elastic recoil of the Achilles tendon (Perl *et al.,* 2012) and thus promote faster release of concentric contraction of the triceps surae, which translates into higher ankle PFM at mid-stance.

Stellenbosch University http://scholar.sun.ac.za

Ankle inversion moment (AIM) peak was significantly higher for VF compared to BF (~ 18%), but moderately higher compared to SH (~8%) condition. McClay (2000) suggested that higher ankle AIM peaks were due to excessive foot eversion and could be related to running-related injury. During initial stance, the foot and ankle begin to evert as a result of the lateral position of the vertical ground reaction force (vGRF) (McClay & Manal, 1998). The eversion range of motion created is known as passive eversion, as it is created by the weight of the body and not by activating peronei muscles (McClay & Manal, 1998). However, the tibialis posterior muscle is needed to eccentrically control this eversion movement, which is responsible for controlling the inversion (AIM) moment (McClay & Manal, 1998). Based on this mechanism, it may be that the VF condition facilitates more eccentric work of the tibialis posterior muscle. This may be due to the construction of the minimalist shoe used in this study which has been designed without arch support. Theoretically, BF running should introduce larger ankle AIM peak considering the lack of shoe material between the foot and the ground. As this was not the case in this study, one could infer that the BF condition allows other mechanisms to potentially reduce the work needed by the tibialis posterior muscle to eccentrically absorb the vGRF. As Nigg (2010) points out, the arch of the foot cannot possibly function as an shock absorber, as postulated by Robbins and Hanna (1987). Nigg (2010) argues that VIP usually occurs around 30 ms – 50 ms after contact, while maximum arch deflexion occurs much later (~ 200 ms) during mid-stance, which is too late to act as a shock absorber. However, considering that the peak ankle AIM occurs around 40 – 50% of stance (McClay & Manal, 1998), it could be that greater arch deformation occurs during BF compared to VF, which allows for more passive elastic recoil of the foot arch (Ker *et al.,* 1987), and thus reduces the eccentric load necessary by the tibialis posterior. The thin rubber sole of the Vibram Fivefingers ® as well as the cushioning provided in the SH running condition likely reduce the full elastic recoil of the foot arch relative to that of BF, and thus requires greater eccentric load of the tibialis posterior.

Knee abduction moment (KAM) peak for SH running were substantially higher than BF (44%) and VF (30%) running. In agreement, Kerrigan *et al.* (2009) found SH running to have 38% higher KAM

Stellenbosch University http://scholar.sun.ac.za

than BF. McClay and Manal (1998a) explained that a knee abduction moment is required during the first half of stance to control the abduction that occurs at the knee joint. The iliotibial band, other non-contractile structures, as well as the lateral hamstrings allcontribute to the KAM peak (McClay & Manal, 1998a). Participants were in more knee abduction at the time of landing for the shod conditions by ~ 2 degrees more than VF and BF (Table 5.23). Stefanyshyn *et al.* (2006) found that a higher hip abduction angle could also contribute to KAM peak, as it increases the distance between the line of action of the vertical ground reaction force (vGRF) and the knee joint centre. In accordance with this theory, the runners in this study had significantly higher hip abduction angles at contact for SH compared to both BF and VF, which may explain for differences in KAD.

Knee flexion moment (KFM) peak was also highest for SH running, being 16% and 13% higher than BF and VF respectively (Table 5.17). Results from Kerrigan *et al.* (2009) found even larger differences, with SH being 36% higher than BF. During the second half of the swing phase of running, the hamstring muscles become dominant to prepare for footstrike and produce a knee flexor moment. At footstrike the quadriceps muscles contract eccentrically as the knee flexes during initial stance (Novacheck, 1998). Reilly and Martens (1972) state that abnormally high KFM at terminal stance would require a greater eccentric counteraction moment by the quadriceps. Reilly and Martens (1972) further explains that strain through the patella tendon occurs from such a large eccentric counteraction, which could result in Patellofemoralpain (PFP).

No significant differences were seen between shoe conditions with respect to peak knee extensor moment (KEM). This result is unexpected and does not support the sparse literature available. Paquette *et al.* (2011) found contrasting results, with the SH condition having significantly higher knee extension moments compared to VF (Vibram Fivefingers ®) and BF. However, their conference paper did not provide quantitative data and it is therefore difficult to compare results. The quadriceps muscles are said to dominate over the hamstring muscles during the first 75% of stance phase which causes the net positive moment (McClay & Manal, 1998a). The quadriceps contract eccentrically to produce knee flexion during the first half of stace, and then contract eccentrically to produce knee extension during the second half of stance (McClay & Manal, 1998a). According to Novacheck (1998), peak KEM tends to be greater in running than in sprinting as KEM is related to the maximum degree of knee flexion range of motion (ROM) as the stance leg is eccentrically loaded. However, SH running resulted in significantly more knee flexion ROM compared to VF (~3 degrees) and BF (~5 degrees) (Table 5.24). The similar KEM peaks between shoe conditions can thus not be attributed to varying degrees of knee flexion ROM. Other factors may play a more significant role in determining KEM peak.

The statistically less flexed (~1 degree), less abducted (~0.4 degree), and more internally rotated (~ 4 degrees) hip at footstrike for BF running compared to SH running were most likely not practically sufficient to alter hip joint moments. This assumption is supported by the fact that no significant differences for either sagittal or frontal plane hip joint moments were observed.

To conclude, BF and VF running attenuated ankle dorsiflexion moment (DFM) peak, knee flexor moment (KFM) peak, and knee abduction moment (KAM) peak. According to Stefanyshyn *et al.* (2006), both shoes and running style can have an influence on knee joint moments, which could ultimately serve as preventative treatment for running injury. In terms of this study, the reduction in ankle dorsiflexion moment (DFM) could partially explain why others have found decreased chronic exertional compartmental syndrome symptoms associated with forefoot training (Diebal *et al.,* 2012). In addition, the decreased knee KAM peak (Stefanyshyn *et al.,* 2006) and KFM peak (Reilly & Martens 1972) would suggest a reduced risk of running–related pattelofemoral pain (PFP).

In contrast, higher ankle plantarflexion moment (PFM) suggests that novice BF and VF runners should be cautioned due to possible increased work done by the calf musculature and Achilles tendon (Williams *et al.,* 2000). VF running also showed to increase ankle inverter moment (AIM) peak, which could lead to greater eccentric work and perhaps injury to the tibialis posterior tendon (McClay & Manal 1998). For the hip joint, no significant differences were observed in joint moments for any of the planes of motion. This suggests that changes that occur from BF and VF running are more distally located towards the knee and ankle.

Stellenbosch University http://scholar.sun.ac.za

D. RESEARCH OBJECTIVE TWO

To determine the effect seven-weeks of VF training has on kinematic adaptation, VALR attenuation, lower limb joint moments and circumferences.

This study is novel in the sense that it is the first to examine the longitudinal effects of minimalist shoes (VF) on lower limb biomechanics. The hypothesis (H2) contends that seven weeks of minimalist shoe training would a) promote a learning effect of active VALR attenuation; b) alter lower limb joint moments; and c) increase calf circumference, with thigh circumference to remain unchanged. Impact force attenuation did not change statistically after VF training, and the first part of this hypothesis can thus be rejected. The main findings for joint moments, however, revealed changes in both sagittal and frontal planes at the ankle, knee, and hip, thereby confirming the second part of the hypothesis. Furthermore, maximal calf circumference (MCC) increased statistically for the left, and practically for the right leg, thus confirming the last part of the hypothesis.

1. Effect on impact force attenuation

The changes in external vertical ground reaction force (vGRF) are somewhat contradictory to the original hypothesised set. Vertical impact peak (VIP) and vertical average loading rate (VALR) did not statistically change from pre- to post-intervention for either control (CONT) or experimental group (EXP) (Table 5.16). Over all conditions, the CONT group increased VIP on average by ~ 2% (0.03 BW), showing high consistency between testing days. VIP increased on average by ~ 8% (0.10 BW) for the EXP group. As was seen with the VIP, the EXP group showed a trend to increase their VALR more than the CONT group (Figure 5.12a). VALR among the EXP group increased over all shoe conditions by ~10 BW/s (20%) compared to the CONT group which increased by only 4 BW/s (7.7%). According to Milner *et al.* (2006), a change of 15% in VALR can be termed clinically relevant to a higher predisposition of running-related injury. Although not particularly comparable to the design of this study, Crowell and Davis (2011) investigated the

Stellenbosch University http://scholar.sun.ac.za

effects of a two-week (eight session) gait retraining programme on external GRF and tibial acceleration. These investigators instructed their participants to “run softer”, to “make their footfalls quieter”, and to “keep their acceleration peaks below the line” that was visible on a monitor. Their study achieved the overall aim of decreasing VIP (19% VALR (32%) and tibial acceleration.

Increased VALR from pre to post found in this study can be attributed to the inclination to a more rearfoot strike (RFS) positioned ankle from pre to post. On first look, this higher increase in the EXP for BF is anomalous, considering that decreased running speed should have subsequently decreased VALR (De Wit *et al.,* 2000). However, on closer inspection, Figure 5.22 illustrates how the EXP group shifted their footstrike patterns towards their heels while BF (RFS pre: 20%; RFS post: 50%). Speed did not have a significant effect for any other condition or between group comparisons, and thus can be excluded as possible confounding factor. This same trend for BF footstrike pattern to increase towards the heel was seen for the CONT group (RFS pre: 36%; RFS post: 64%). This observation is contrary to the innate impact moderating theory proposed by Robbins and Gouw (1991), who state that the barefoot runner would instinctively sense and learn to avoid local plantar discomfort and deformations under the heel, and consequently make behavioural adjustments towards the forefoot (Figure 2.8). The fact that the EXP showed the same trend implies that seven weeks of minimalist shoe training would not alter footstrike coordination in the manner hypothesized by Robbins and Gouw (1991), and that the percentage of footstrike adaptation-failures increased in the barefoot condition. This is slightly in contrast to one other study (Lieberman *et al*., 2010), where longitudinal changes in footstrike pattern were found after six weeks of minimalist shoe training. Lieberman *et al.* (2010) found that of the 72% of rearfoot strike adaptation-failures under acute BF running, half remained so (36%) after six-weeks of training in minimalist shoes.

Footstrike pattern could account for pre-post differences in VALR observed in the VF condition. The CONT group showed on average a negligible increase in VALR of 2.5% for VF running pre-post, with an overall identical footstrike distribution pattern for both testing occasions (FFS: 18%; MFS: 9%; and RFS: 73%). Thus, the negligible change for the CONT group was most likely due to

Stellenbosch University http://scholar.sun.ac.za

factors other than footstrike pattern. For the EXP group, VALR increased by 18% for VF running pre-post. The EXP group's footstrike distribution showed that this increase may be due to a higher percentage of participants shifting from the forefoot to the midfoot (FFS pre: 10%; FFS post: 40%), as the percentage of rearfoot strikes remained unchanged.

Step length was probably less related to the increases seen in VALR. Decreased step length has previously been associated with decreased axial loads of the tibia (Edwards *et al.,* 2009) and decreased frequency of VIPs (Chumanov, Wille, Michalski, & Heiderscheit, 2012). Step lengths decreased (Table 5.22), but not significantly pre-post for both groups (although there was a larger decrease with the EXP group) and for all shoe conditions. Step lengths were also poorly correlated with VALR, and thus were most likely not the primary determinant for apparent changes pre-post for VALR. Step frequency increased of both groups, although differences were the greatest for the SH condition in the EXP group. This could serve as the first sign as kinematic adaptation to VF training.

From pre-to-post, the EXP group participants decreased their step lengths by ~ 2 cm for BF, ~2 cm for VF, and ~5 cm for SH. Even after accounting for decreases in step length due to the use of a treadmill (4.23% shorter compared to over-ground; Riley *et al.,* 2008), the participants of this study would had to have decreased their step lengths by ~ 27 cm for BF, ~ 24 cm for VF, and ~ 25 cm for SH to meet the appropriate step lengths recorded in experienced barefoot runners under the same shoe conditions (Squadrone & Gallozzi, 2009). There is thus an indication that the participants of this study did not adapt their step lengths enough to be comparable with an exerienced BF runner.

Significant increases in step frequency (~ 5 steps/min) were observed in the SH condition for the EXP group. Subsequently, step time decreased by ~ 13 ms which was a mainly function of a decrease in flight time. These results indicate that kinematic adaptation could have started in the form of spatio-temporal parameters. However, these adaptations appear to be not sufficient to have had an effect on impact force attenuation. As mentioned earlier, there may be a critical threshold for step length and/or step frequency adaptation to have an attenuating effect on impact force.

In conclusion, impact force magnitude and rate of loading was attenuated less after the EXP group performed the VF shoe training. There was thus a negative learning effect due to VF training, which is in contast to the hypothesis set and to previous theories present in both the literature and the media. This could be attributed either to an inability to sense higher impact while running in VF, to insufficient time permitted for kinematic habits to develop and/or musculoskeletal adaptation comparable to that of an experienced barefoot runner (Lieberman 2012). Nonetheless, these adaptation-failures may have aquired other forms of adaptation. Nigg (2010) suggests that runners may maintain similar kinematics (preferred movement path) through metabolic or muscular adaptations.

2. Effect on external joint moments

While not statistically significant, the CONT group did show large practical increases in ankle dorsiflexion moment (DFM) of 87% for BF, 54% for VF, and 40% for SH running conditions. An increase in peak ankle DFM would suggest that there was an increased eccentric load placed on the tibialis anterior muscle (McClay & Manal, 1998a; Novacheck, 1998; von Tscharner *et al.,* 2003). While this result may be confounding, it can be partially explained by the shift in footstrike pattern towards the heel as mentioned earlier. However, this reason does not suffice for the VF condition, which showed no changes in footstrike pattern pre-post. Some of the participants of CONT group claimed that they increased their normal SH mileage to prepare for the half marathon races that occurred during the course of the study. It could therefore be that the additional SH mileage resulted in greater eccentric loading of their dorsiflexors and resulted in the higher ankle DFM peak. The EXP group negligibly increased its ankle DFM peak for all three shoe conditions, which may have been due to the shift from the mid-forefoot to rearfoot as seen pre-post.

Stellenbosch University http://scholar.sun.ac.za

The EXP group reduced ankle plantarflexion moment (PFM) peak from pre-post by ~ 9% for BF, and ~ 8% for VF running. Considering the fact that the CONT group did not change ankle PFM peak for the VF condition, this may be evidence of the lack of change in footstrike pattern as mentioned earlier. The changes in ankle PFM observed in the EXP group are consistent with the changes in vertical propulsive peaks (VPP). As stated by Williams *et al.* (2000), the ankle PFM peak is synchronous with the VPP at around 45% of stance. From a clinical perspective, although the participants of the EXP group were well rested for post-testing, some of them still complained that their calf musculature was in some discomfort. The author is uncertain as to how this may have affected the joint moments as a whole. However, allowance could be made for the notion that these runners may have attempted to avoid the concentric loading of their calf musculature as a compensation to avoid discomfort, which may have ultimately resulted in decreased ankle PFM peak. Williams *et al.* (2000) found that the only biomechanical differences to the parameters they investigated between habitual forefoot strike (FFS) and immediately converted forefoot strikers was the reduced ankle PFM in the latter study population. These authors mentioned that a newly adopted forefoot striker would require further training to be able to improve the ability to push-off using the calf musculature.

The decreased knee extensor moment (KEM) peak is consistent with the decreased vertical propulsive peaks (VPP) seen in the BF and VF conditions, but not those in the SH condition. This suggests that other kinematic adjustments might have accounted for this discrepancy, perhaps in the frontal and sagittal planes. Nevertheless, the EXP showed large decreases in knee KEM peak for BF (67%), VF (90%), and including SH (35%). In contrast, the CONT group showed negligible decreases in knee KEM peak for BF (14%), VF (15%) and SH (6%). These results imply that the seven-week minimalist shoe training performed by the EXP group could have promoted a running style that uses their quadriceps muscles less during mid-stance. Higher step frequencies could clarify why knee KEM peak decreased. Heiderscheit *et al.* (2011) found that knee KEM peak reduced slightly when step frequency was increased by 5%, and knee KEM peak reduced significantly when step rate increased by 10%. Additionally, these investigators found that the

Stellenbosch University http://scholar.sun.ac.za

amount of energy absorbed and generated at the knee decreased by increasing step frequency by 5%. Step frequency from pre to post decreased for all conditions in the EXP group. However, the largest of these decreases was only ~ 3% for the SH condition and thus might not be able to justify such large decreases in knee KEM peaks.

Contrary to the sagittal plane, joint moments of the ankle and knee in the frontal plane increased substantially. Ankle inversion moment (AIM) peak increased in both groups across all shoe conditions. The ankle inversion angles at footstrike increased for the EXP group across shoe conditions, yet decreased for the CONT group for all shoe conditions. The fact that these differences did not influence the changes in ankle AIM peak indicates other parameters such as peak ankle inversion angle which occurs at a similar percent of stance may warrant investigation. For the knee in the frontal plane, knee abduction moment (KAM) peak was similarly increased for both groups and all shoe conditions. As mentioned above, the hip frontal plane motion plays a primary role in determining knee KAM peak (McClay & Manal, 1998). Therefore, increased knee KAD may have been influenced by motion of the hip joint, as hip adduction FSA was shown to increase.

The decreases in knee extension moment could have been compensated for by the increases in knee flexion moment (KFM) peak at terminal-stance, or by increases in hip flexor moment (HFM) observed peak during mid-stance. However, increases in these variables were seen for both groups, and there appears to be no literature to account for these changes. Changes in joint moments that occurred at the hip are confounding, and require further investigation that is beyond the scope of this study.

In summary, pre-post alterations in joint moments were seen for both CONT and EXP group. Specifically, ankle dorsiflexion moment (DFM) increased significantly in the CONT group, while ankle PFM decreased significantly for the EXP group. Some of the results pertaining to the hip joint were confounding and should therefore be treated with caution.

Stellenbosch University http://scholar.sun.ac.za

3. Effect on lower limb circumferences

The hypothesis that calf size would increase due to minimalist shoe training was partially substantiated. Left maximum calf circumference (MCC) significantly increased from pre- to post-interventions for participants who underwent the minimalist shoe transition programme. Mean increases in the EXP group were of medium practical significance. Left and right calves increased by 0.77 cm (ES = 0.47) and 0.52 cm (ES = 0.34) respectively (Figure 5.25).

There are no studies of similar protocols that allow for accurate comparison to other research to be made. However, one particular study showed that maximum calf circumference or calf circumference 30 cm from the floor did not improve statistically when their 10 female netball players (mean age 20 ± 2 yrs) underwent a barefoot training programme (Du Plessis, 2011). The study did however report that the left calf circumference 30 cm from the floor showed a small improvement in calf circumference (ES = 0.2). Bennell *et al.* (1999: 107) state that “measurements of muscle size can be indicative of the ability of that muscle to generate force”. Du Plessis (2011) mentions that one cannot assume that improvements in calf muscle size from barefoot training did not lead to muscles strength benefits. Isometric plantarflexion strength has been moderately correlated to calf circumference (r = 0.41) in 30 military recruits (mean age 21.1) (Damholt & Termansen, 1978). It may not be appropriate to use isometric strength as a correlate of calf circumference as calf muscles during barefoot running undergo eccentric contraction during impact (Divert *et al.,* 2005). Nevertheless, muscle strength tests of the calf muscles were not performed by Du Plessis (2011) or in this current study, and thus increases in calf muscle strength due to either barefoot or minimalist shoe training remain mere speculation. Future studies should investigate the possible relationship between eccentric calf strength and calf circumference in barefoot or minimalist runners.

A longer minimalist shoe intervention period may have allowed for greater increases in calf muscle size. The barefoot training programme provided by Du Plessis (2011) consisted of twenty sessions, while this study consisted of eighteen sessions. According to Wallack and Saxton

Stellenbosch University http://scholar.sun.ac.za

(2011), typical rearfoot striking shod runners have underused and underdeveloped calf muscles that may result in pain during the initial phase of a barefoot running programme. As will be discussed in a further section, many of the experimental participants still had a certain degree of calf-Achilles discomfort at the end of the seven-week intervention period. Persisting calf-Achilles discomfort and delayed onset muscle soreness would suggest that their calf muscles require more time to adequately adapt to the minimalist shoe training.

Improvements in calf size may have clinical benefits. Bennell *et al.* (1999) are of the opinion that the calf muscles may be able to oppose large bending moments by applying a backward moment as they contract to control both tibial rotation as well as the lowering of the foot to the ground. Bennell *et al.* (1999) also speculated that that stress fractures could result when the triceps surae are unable to produce adequate eccentric force to counteract the loading at ground contact and excessive bone strain. There is one study that supports this notion. Bennell *et al.* (1996) conducted a 12-month prospective study on a cohort of 53 female track and field athletes (age 17 to 26 yrs) and found that every 1 cm increase in calf girth was associated with a four-fold reduced risk of incurring a running-related tibial stress fracture. Participants of this study would thus be expected to decrease their risk of incurring a tibial stress fracture by a factor/magnitude of three for the left and two for right tibias respectively. The author acknowledges that gender differences may distort this relationship between calf size and stress fracture risk. Women have been shown to have different calf morphology than men, with calves that are bigger and with higher points of maximum calf circumference (Wunderlich & Cavanagh, 2001). One prospective study found that 38 male military recruits who sustained stress fractures had calf circumferences that were 6% smaller when compared to 487 uninjured counterparts (Beck *et al.,* 2000). The calf size-tibial stress fracture risk for injury relationship may then apply to both genders. Mean calf size increases of the EXP group of this study were of ~ 2%. This difference may not have been great enough to play a role in development of stress fractures.

Increased calf size may have physiological implications. Assuming all other factors remain constant (e.g. speed, body mass, running style, etc.), a runner that has a proportionally smaller

Stellenbosch University http://scholar.sun.ac.za

amount of body mass concentrated in the lower extremities would perform less work to move the body segments (Meyers & Steudel, 1985). In support, greater VO_2 cost has been strongly associated with higher calf circumferences in 7 elite black Eritrean shod endurance runners ($r = 0.55$) at 5.83 m/s (Lucia *et al.,* 2006).

The hypothesis that thigh circumference would not be influenced by minimalist shoe training was confirmed. Although there is no apparent supporting literature, the researcher acknowledges that skin-fold thickness was not measured and could have affected both calf and thigh circumferences. Other researchers have factored in skin-fold thickness when measuring calf circumferences (Bennell *et al.,* 1996). Factors such as diet and exercise intensity were unaccounted for in this study and all could potentially have affected calf skin-fold thickness and thus calf girth circumference. Future studies should include skin-fold thickness measurements to eliminate it as a potential source for error.

E. INTERVENTION CHARACTERISTICS

Another goal of this study is to document, evaluate and report on the implementation of a plausible seven-week minimalist shoe transition programme according to a) training characteristics, b) lower-limb comfort, c) adverse reactions experienced, and d) surface selection.

Until now, most theories surrounding the minimalist shoe transition programme have been calculated speculation, presented either as scientific hypothesis or media-driven dogma. This is the first study to scientifically address practical issues concerning the minimalist shoe transition process. Training characteristics is discussed, followed by information regarding lower limb comfort as well as adverse reactions that occurred during the intervention. Thereafter, the variances in running surface are briefly explained.

Stellenbosch University http://scholar.sun.ac.za

1. Training characteristics

A steady progression in running distance and time permitted the participants of this study to run ~ 52 – 131% of their usual daily shod (SH) mileage in their new minimalist shoes. The criteria proposed to classify as a minimalist runner require running a) a mileage of at least 66% or more in minimalist shoes relative to conventional running shoes, and b) for a period of at least six months (24 weeks) (Lieberman *et al.,* 2010). Concerning the first criterion, two participants did not achieve this criterion (52.00% and 60.89% respectively). Thus, the remaining eight of the ten runners could be termed minimalist runners under. However, considering the intervention was only seven weeks, none of these runners may officially be termed minimalist runners. With regard to specific running distances, it took the participants approximately nine to ten VF training sessions to achieve a distance of 5 km (~ 26 min). All of the participants were able to achieve 7 km (~ 34 min) of VF running after 13 – 14 VF training sessions. Six of the participants were able to achieve 10 km (~ 53 min) after 17- 18 VF training sessions.

A post-study questionnaire revealed that seven of the participants thought that the running distances (relevant to VF training) set by the researcher were appropriate. The remaining three participants reported that training distances could have been longer. As the primary objective relating to training distance was to be conservative, these results give confidence to saying that the training distanced were not beyond the limits or threshold of what the participants could handle.

According to Wallack and Saxton (2011), minimalist shoes may lead to a false sense of security that could in turn lead to wanting to run faster than would occur if barefoot. This notion may be partially supported, as a rise in running speed occurred from VF training session one to three. However, after session three, running speed decreased gradually throughout the intervention, indicating that running speed was moderated as distances were increased. No restraints were made regarding how fast the participants should run. Rather, the participants were instructed to select a comfortable training pace. The average drop in running speed between first and last VF training session was ~ 0.39 m/s. Running speed decrease may have been primarily determined by pacing strategies as distances became further and durations became longer, although it could also be speculated that running speed was reduced as a form of adaptation to the comfort of minimalist shoe running. The gradually improved calf-Achilles lower limb comfort index (LLCI) would support this idea. Thus, the inverse relationship between calf-Achilles comfort and running speed would refute the hypothesis that runners slowed their speed due to discomfort experienced in the calf-Achilles.

2. Lower limb comfort

Although originally designed for elite soccer players (Kinchington *et al.,* 2010), the lower limb comfort index (LLCI) showed to be a quick and useful tool to monitor the health condition of the lower limbs of the runners partaking in the minimalist shoe transition programme. The post-study questionnaire revealed that nine of the ten participants regarded the regular comfort monitoring provided by the primary researcher as a necessary procedure. The theory behind the LLCI posits that pain (discomfort) is a neural stimulus due to the interaction of nociceptive stimulation and the cerebral cortex (Kinchington *et al.,* 2010). When pain or discomfort is experienced, it serves as the stimulus for information that is sent via the neural networks and thus provides information regarding the state of comfort or homeostatis (Kinchington *et al.,* 2010). The feedback circuit model of innate impact moderation proposed by Robbins and Gouw (1991) abides by the same principle.

Calf-Achilles injury is one of the most frequently reported adverse reactions to runners who attempt either barefoot (BF) or minimalist shoe (VF) training (Robillard, 2010; Sandler & Lee, 2010; Wallack & Saxton, 2011). The calf-Achilles item of the LLCI was found to have a significantly lower perceived comfort rating over the entire intervention period compared to all other LLCI items. In addition, the drop in calf-Achilles comfort was observed from as early as the second VF training session. Most of the participants who underwent the transition programme complained of calf discomfort upon awakening the day after a VF training session. Some participants stated that the initial part of each VF training session was the most uncomfortable for the calves and Achilles, but

Stellenbosch University http://scholar.sun.ac.za

that after a few minutes' running they felt warmed-up and the discomfort subsided. Over the course of the intervention period, the calf-Achilles LLCI rating generally improved. This could indicate that a) the participants' calf-Achilles were adapting to the new stimuli, and b) adequate rest was given to enable positive adaptation to the new mechanical loads placed on the calf-Achilles.

The LLCI revealed that other areas of the lower limb are less affected by the minimalist shoe transition programme. Even considering the small scale the LLCI offers, the feet, ankles, shins, and knees comfort items fluctuated much less than the calf-Achilles item. This suggests that passive structures were less affected by the change in mechanical loads offered by the VF training. A noteworthy finding was the significant improvement in perceived shin comfort from the start to the end of the intervention programme. Diebal *et al.* (2012) found that six weeks' of forefoot strike (FFS) training reduced pain and discomfort in those who had chronic exertional compartmental syndrome (CECS). These investigators speculated that the change in footstrike pattern most likely reduced loads on the anterior shin and tibialis anterior muscle, which allowed for the CECS-related symptoms to subside.

3. Adverse reactions

The hazards and risks during the transition process are mentioned on countless websites and books (Sandler & Lee, 2010; Wallack & Saxton, 2011). Most of the advice provided on either preventing or managing these new injuries is given by barefoot running books or websites (Rothschild, 2011). However, there is not one scientifically-based study on which to base these suggestions. A lack of progressive accommodation to such greater demands placed on the lower extremity musculoskeletal system could potentially enhance risk of injury such as tendonitis or even stress fractures (Neumann, 2010). In addition, each runner has his or her individual threshold for attaining a running-related injury (Hreljac, 2004). Thus it is imperative to discuss the individual adverse reactions that were witnessed over the course of the minimalist shoe intervention.

Stellenbosch University http://scholar.sun.ac.za

An adverse reaction reported was the callous formation under the plantar surface of the foot, as well as under the medial aspect of the second phalange. A photo is provided in Figure 6.1. Callous formations under the plantar surface of the skin has been observed in habitual barefoot populations from both Kenya (Lieberman *et al.,* 2010) and India (Acut *et al.,* 2009). Thus, although the minimalist shoes used in this study have a protective surface, they appear to allow enough stimulation for skin abrasion and subsequent callous formation. For some participants, callous formation was apparent from as early as the third training week, indicating that the plantar skin readily adapted to the stimulus provided while running in minimalist shoes. Other investigators have shown that the minimalist shoes used in this study did not blunt their participants' perception of slope while running on a treadmill (Squadrone & Gallozzi, 2011). Therefore, it appears that this particular brand of minimalist shoes allow for plantar-sensation. As will be discussed on the section on running surface, all of the participants reported higher plantar sensations when training on the rough off-road surface.

Figure 6.1. Adverse skin reaction in response to minimalist shoes: plantar surface second phalange blister and calloused epidermis of the plantar surface of the forefoot. (Photo by ??)

Excessive downhill running may be a risk factor during the minimalist shoe transition. One participant verbally explained that "landing with my usual longer strides with extended leg on the downhill became tiring in my calves, so I could no longer land on my forefoot. To avoid my calves from over-working, I tried to land more with my heels. This provided immediate relief in my calves, but then my heels began to pain" (Table 5.10). According to Noakes (2003), over-striding is usually more common during downhill running, which increases loading of the calf muscles, having to give

Stellenbosch University http://scholar.sun.ac.za

additional eccentric work and thereby increasing the propensity for muscle damage. Shortly prior to the downhill descent, the participant had completed the same distance in the opposite direction (uphill). It can be speculated that uphill running puts the calf musculature and Achilles tendon at additional stretch (Noakes, 2003). As was reported during testing in this study, the dorsiflexion range of motion was significantly higher during VF running than compared to SH running by ~7 degrees. The Achilles tendon as such may be placed at even additional stretch compared to normal cushioned running shoes while running uphill. Therefore it is plausible that the fatigue in the calf muscles caused by the uphill running, combined with the increased eccentric work on the downhill resulted in mechanical fatigue of the calf musculature that exceeded the threshold for this individual. It is speculated that the participant had to compensate for this calf fatigue by reverting to a rearfoot strike pattern, which ultimately resulted in the heel bruising and pain.

Excessive speed may also play a role in development of adverse effects. The participant who complained of heel bruising ran on average 1.6 m/s faster when compared to all other participants in the intervention group. Increasing one’s running speed typically requires greater movement amplitude, movement velocity, and generation of forces (Neumann, 2010).

It is possible that there is a safe range of ankle dorsi-plantar-flexion in the middle of extreme rearfoot or forefoot landings which should be adopted when attempting to run in minimalist shoes. Rothschild (2012: 3) declared that “reducing the rearfoot strike component is fundamental in the transition process to barefoot-minimalist running”. The vertical ground reaction force (vGRF) results of this study support this declaration, as strike index was the highest correlating factor with VALR for the VF condition (r - -0.65) (Table 5.27). This indicates that the closer to FFS, the lower the VALR. However, strong caution should be exercised by those who also attempt to land with a FFS. One participant who constantly adopted a significant forefoot strike (FFS) pattern (on visual inspection and verbal communication) during the intervention complained of a mild bruising pain under the second to third metatarsalgia head at week five. Rest was provided until the participant was able to complete the rest of the intervention without pain or discomfort.

The present study also found that for a midfoot strike (MFS) landing, VALR attenuation is the greatest while running in VF, even surpassing conventional shoe running. Based on differences found in frequency components, Gruber *et al.* (2011) proposed that FFS running may lead to the reliance and injury of active structures (eccentric muscular contractions), while RFS running may lead to the reliance on and injury of passive type structures (bone and articular cartilage). It is the opinion of this author that adopting a MFS during the minimalist shoe transition will minimise the risk of possible injury associated at the footstrike pattern extremes.

4. Surface selection

Several surfaces were chosen to run on, including asphalt, grass, and off-road/gravel trails. Surface selection was generally rotated during the week from session to session. Several issues regarding surface selection must be addressed. Firstly, previous experience on different surfaces was not controlled for. Some of the participants had rarely, if ever, performed off-road (dirt track/trail) running. Runners accustomed to trail running have dealt with greater amounts of surface variance and irregularity with respect to camber, hardness, incline, friction, protrusions, and lose debris (stones, rocks, roots). Road runners on the other hand, who usually train on asphalt/concrete, must deal with less surface variance and irregularity. Based on the verbal reports by the participants, running on off-road or gravel forced them to make adjustments to their running line of path, technique and lower limb kinematics. A list of verbal reports regarding each training surface specific to VF training is provided in Table 5.12.

Some participants reported feeling more comfortable on the grass than on the asphalt, which may have promoted a tendency to land with a rearfoot strike pattern (Hamill *et al.,* 2011b; Nigg, 2010). .Figure 6.2 illustrates that some runners may keep a FFS pattern even when running on more compliant surfaces such as grass. In the post-study questionnaire, runners were asked if running surface would alter their choice of whether or not to continue running in VF. Six of the participants reported that they would only choose to run on grass or on asphalt for VF training, and that they

Stellenbosch University http://scholar.sun.ac.za

would keep running in their conventional running shoes for off-road trails. The remaining four participants stated that VF training would not depend on surface.

[redacted] [redacted]

.Figure 6.2. Photographs of two experimental participants during a minimalist shoe training session on grass surface: a) rearfoot striker on soft surface; b) forefoot striker on soft surface. (Photographs by K Schütte).

The post-study questionnaire found that overall, eight of the ten participants preferred their VF shoes compared to their conventional running shoes. In addition, nine of the ten participants indicated that they were going to incorporate VF training into their future schedule, while four of the ten indicated that they would use VF for competitions and races.

Stellenbosch University http://scholar.sun.ac.za

F. CONCLUSION

Running with minimalist shoes (VF) introduced changes similar to those of barefoot running in all three planes of motion that have previously been neglected in the literature. This study found that for VF running, there are significant changes that occur at the ankle and the knee, but not at the hip with regard to joint moments of the sagittal and frontal plane. Where most studies have only focused on the external ground reaction force, this study adds value to the literature by providing an understanding of how these forces are distributed further up the kinetic chain with respect to joint moments.

This study adds to the paucity of literature available on the minimalist shoe transition, and is the only study to date that scientifically documents this process. Although limited to young male runners, the training characteristics (e.g. mileage, duration, rest periods, etc.) used in this study may be used as guidelines to those habitually shod runners who wish to transition to minimalist shoe running. While some limitations were listed, the lower limb comfort index (LLCI) was an effective monitoring tool for monitoring the comfort of the lower limb prior to each VF training session.

Participants who underwent the transition program showed a learning effect for higher step frequency in the SH condition. However, this had no apparent positive effect on impact force attenuation, or the altering of joint moments. Contrary to what was hypothesized, a tendency to adapt towards the rearfoot was seen after seven weeks of minimalsit shoe training. This could be attributed either to an inability to sense higher impact while running in VF, or due to insufficient time permitted for kinematic habits to develop and/or musculoskeletal adaptation comparable to that of an experienced barefoot runner. Calf-Achilles discomfort played a significant role in the progression of the adaptation process, and may account for why runners reverted to a RFS landing strategy. Runners may also expect calf circumference to increase after seven weeks of minimalist running.

Stellenbosch University http://scholar.sun.ac.za

G. LIMITATIONS AND FUTURE DIRECTIONS

Numerous limitations to the testing protocol merit mention. There are often inconsistencies in modelling techniques used between gait laboratories which make comparisons to previous studies difficult. Although the Vicon ® Plug-in-Gait model used in this study is one of the few standardised models for gait analysis, the manner in which joint moments are calculated are based on several assumption, namely/such as seven proximal passive markers from the hip down are used to determine the ankle joint centre, and thus any errors that occur proximally are transferred distally to the ankle in larger quantities. In addition the model used to calculate joint moments may be sensitive to running speed, as most laboratories used this model for walking and not running. A literature search could not find a study reporting on the reliability of this model used for running analysis. Nevertheless, an attempt was made to minimise any form of measurement error that could influence the estimation of joint moments (the same researcher was used for multiple marker placement and anthropometric measurements).

Several other parameters were not analysed because they were not within the scope of the study: for kinematics, i.e. joint coupling, for external ground reaction force (anterior-posterior, and medio-lateral directions), and kinetics (power absorption and generation calculations). Joint moments in the transverse plane had a considerable amount of variation, and were thus not analysed.

The reflective markers for the foot and heel were not placed directly on the skin for VF and SH conditions by cutting out areas of the shoes, as has been performed previously (Altman & Davis, 2011; Braunstein *et al.,* 2010). Nevertheless, careful attention was given to accurate toe and heel marker placement.

Some limitations regarding the minimalist shoe intervention period warrant mentioning. Firstly, physiological measures e.g. heart rate or oxygen consumption, or subjective indicators of physiological measures e.g. rating of perceived exertion, were not attained in this study. The addition of at least some of these parameters would have aided in interpreting the exercise intensities of the VF training sessions.

The potential changes in running kinematics that occurred during the intervention were not accounted for. As seen in .Figure 6.2, footstrike patterns varied between participants on different surfaces. A method for viewing landing kinematics in the outdoors would permit more precise session to session monitoring, that also may have more accurately resembled between session or week to week adaptations.

Experimental participants were asked to provide an average of lower limb comfort index (LLCI) scores for the left and right limbs, and thus unilateral comfort data were not provided. Participants often reported more discomfort on one side. The use of unilateral LLCI data could also have helped explain for why maximal calf circumference (MCC) increase was greater for the left leg than the right leg. One could speculate that improvement of the left MCC would mean that the non-dominant calf is required to perform more mechanical work (whether it be eccentric power absorption or concentric power generation). It is imperative that future studies distinguish left and right limbs, as well as dominant and non-dominant limbs.

A major limitation with the LLCI is that it fails to take into account other areas of the lower limb where active muscle absorption occurs, e.g. the quadriceps, hamstrings, gluteals, etc. The present LLCI incorporates only one such active shock absorber (calf musculature). It is advisable that the anatomical areas of the LLCI be adapted for future protocols relating to either minimalist shoe or barefoot running protocols. On occasion, calf discomfort was more distally-posteriorly positioned (Achilles Tendon insertion), or distally-medially positioned (tibialis posterior), and other times discomfort was more proximal (belly of gastrochnemius-soleus), thus making it difficult to distinguish between (potential) discomforts. Adapting the LLCI to somehow account for these differences while still having a questionnaire that is time-efficient is advisable.

Stellenbosch University http://scholar.sun.ac.za

Another limitation to the LLCI in respect of mentioning was that discomfort was not established prior to the start of the study. The ability to prospectively track LLCI for several weeks prior to the minimalist shoe intervention would have allowed for a normative base to compare to.

Lower limb comfort was not monitored before the intervention and thus the effects of the minimalist shoes lower limb comfort are difficult to compare with lower limb comfort that would be experienced in their conventional running shoes.

With the lack of significant effects of the intervention on various lower limb kinetic and kinematic parameters, it would be interesting to investigate the effect that specific barefoot technique and training drills have on these parameters, if included in a similar intervention.

It would surely be beneficial to conduct a similar study over a much longer period of time (at least six months or more) and prospectively monitor changes in lower limb biomechanics, as well as record the frequency, type, and location of injury.

Stellenbosch University http://scholar.sun.ac.za

REFERENCES

ALTMAN, A. R., & DAVIS, I. S. (2009). Is midfoot striking during running advantageous over rearfoot or forefoot running? *American Society of Biomechanics Congress*, 2–3.

ALTMAN, A. R., & DAVIS, I. S. (2011). A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait & posture*, *35*(2), 298–300.

ARDIGO', L. P., LAFORTUNA, C., MINETTI, A. E., MOGNONI, P., & SAIBENE, F. (1995). Metabolic and mechanical aspects of foot landing type, forefoot and rearfoot strike, in human running. *Acta Physiologica Scandinavica*, *155*(1), 17–22.

ARENDSE, R. E., NOAKES, T. D., AZEVEDO, L. B., ROMANOV, N., SCHWELLNUS, M. P., & FLETCHER, G. (2004). Reduced eccentric loading of the knee with the pose running method. *Medicine and Science in Sports and Exercise*, *36*(2), 272–7.

BACON, N. T., GENDLE, S. C., & BISHOP, P. A. (2010). A cross-sectional survey of why shod runners do not run barefoot. *Medicine and Science in Sports and Exercise*. S30.

BAHLSEN, A. (1989). *The etiology of running injuries: A longitudinal prospective study*. University of Calgary.

BALIUNIS, A. J., & RYALS, A, B. (2002). Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis Cartilage*, *10*, 573–579.

BECK, T. J., RUFF, C. B., SHAFFER, R. A, BETSINGER, K., TRONE, D. W., & BRODINE, S. K. (2000). Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors. *Bone*, *27*(3), 437–44.

Stellenbosch University http://scholar.sun.ac.za

BECKER, J., SINSURIN, K., PISCIOTTA, E., JAMES, S., OSTERNIG, L., & CHOU, L. (2011). Foot strike pattern does not predict loading rates during shod or barefoot running. *International Society of Biomechanics Congress*.

BENNELL, K., CROSSLEY, K., JAVARAJAN, J., WALTON, E., WARDEN, S., & KISS, Z. S. (2004). Ground reaction forces and bone parameters in females with tibial stress fractures. *Medicine and Science in Sports and Exercise*, *36*, 397–404.

BENNELL, K. L., MALCOLM, S. A., THOMAS, S. A., REID, S. J., BRUKNER, P. D., EBELING, P. R., & WARK, J. D. (1996). Risk factors for stress fractures in track and field athletes: A twelve-month prospective study. *The American Journal of Sports Medicine*, *24*(6), 810–818.

BENNELL, K., MATHESON, G., MEEUWISSE, W., & BRUKNER, P. (1999). Risk factors for stress fractures. *Sports Medicine*, *28*(2), 91–122.

BERGMANN, G., KNIGGENDORF, H., GRAICHEN, F., & ROHLMANN, A. (1995). Influence of shoes and heel strike on the loading of the hip joint. *Journal of Biomechanics*, *28*(7), 817–27.

BISHOP, M., FIOLKOWSKI, P., CONRAD, B., BRUNT, D., & HORODYSKI, M. (2006). Athletic footwear, leg stiffness, and running kinematics. *Journal of Athletic Training*, *41*(4), 387–392.

BLOOM, M. (1997). Judging a Path by it’s Cover. *Runner’s World*.

BRAUNSTEIN, B., ARAMPATZIS, A., EYSEL, P., & BRÜGGEMANN, G.P. (2010). Footwear affects the gearing at the ankle and knee joints during running. *Journal of Biomechanics*, *43*(11), 2120–5.

BUIST, I., BREDEWEG, S. W., LEMMINK, K. P. M., VAN MECHELEN, W., & DIERCKS, R. L. (2010). Predictors of running-related injuries in novice runners enrolled in a systematic training program: a prospective cohort study. *The American journal of Sports Medicine*, *38*(2), 273–80.

Stellenbosch University http://scholar.sun.ac.za

BURR, D. B., MARTIN, R. B., SCHAFFER, M. B., & RADIN, E. L. (1985). Bone remodelling in response to in vivo fatigue microdamage. *Journal of Biomechanics*, *18*(3), 189–200.

CAVANAGH, P. R., & LAFORTUNE, M. A. (1980). Ground reaction forces in distance running. *Journal of Biomechanics*, *13*(5), 397–406.

CHAMBERS. (1993). *Chambers handy dictionary* (p. 7). Edinburgh: Chambers Harrap publishers.

CHEUNG, R. T. H., & NG, G. Y. F. (2010). Motion control shoe delays fatigue of shank muscles in runners with overpronating feet. *The American Journal of Sports Medicine*, *38*(3), 486–91.

CHEUNG, R. T. H., NG, G. Y. F., & CHEN, B. F. C. (2006). Association of footwear with Patellofemoralpain syndrome in runners. *Sports Medicine*, *36*(3), 199–205.

CHUMANOV, E. S., WILLE, C. M., MICHALSKI, M. P., & HEIDERSCHEIT, B. C. (2012). Changes in muscle activation patterns when running step rate is increased. *Gait & Posture*, *36*(2), 231–5.

CLARKE, T. E., FREDERICK, E. C., & COOPER, L. B. (1983). Effects of Shoe Cushioning Upon Ground Reaction Forces in Running. *International Journal of Sports Medicine*, *4*(4), 247–251.

CLEMENT, D. B., & TAUNTON, J. E. (1981). A guide to the prevention of running injuries. *Australian Family Physician*, *10*(3), 543–548.

COLE, G. K., NIGG, B. M., FICK, G. H., & MORLOCK, M. M. (1995). Internal loading of the foot and ankle during impact in running. *Journal of Applied Biomechanics*, *11*, 25–46.

COOK, S. D., KESTER, M. A., BRUNET, M. E., & HADDAD, R. J. (1985). Biomechanics of running shoe performance. *Clinics in Sports Medicine*, *4*(4), 619–626.

CREAGH, U., REILLY, T., & LEES, A. (1998). Kinematics of running on “off-road” terrain. *Ergonomics*, *41*(7), 1029–1033.

Stellenbosch University http://scholar.sun.ac.za

CROWELL, H. P., & DAVIS, I. S. (2011). Gait retraining to reduce lower extremity loading in runners. *Clinical Biomechanics (Bristol, Avon)*, *26*(1), 78–83.

DAMHOLT, V., & TERMANSEN, N. B. (1978). Asymmetry of plantar-flexion strength in the foot. *Acta Orthopaedica Scandinavica*, *49*(2), 215–9.

DAOUD, A. I. (2009). *One strike and you' re out: Kinematics and impact forces in reverse strike running versus heel Strike running.* Harvard.

DAOUD, A. I., GEISSLER, G. J., WANG, F., SARETSKY, J., DAOUD, Y. A, & LIEBERMAN, D. E. (2012). Foot Strike and Injury Rates in Endurance Runners: a retrospective study. *Medicine and Science in Sports and Exercise* (In press).

DAVIS, J. E., & HARFMANN, B. (2012). Kinetics and kinematics of running after a six-week barefoot training programme. *Medicine and Science in Sports and Exercise*, *44*(5), S108.

DAVIS, I., MILNER, C. E., & HAMILL, J. (2004). Does increased loading during running lead totibial stress fractures? *Medicine and Science in Sports and Exercise*, *36*(5), S58.

DE CLERCQ, D., AERTS, P., & KUNNEN, M. (1994). The mechanical characteristics of the human heel pad during foot strike in running: an in vivo cineradiographic study. *Journal of Biomechanics*, *27*(10), 1213–22.

DE WIT, B., DE CLERCQ, D., & AERTS, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics*, *33*(3), 269–78.

DE WIT, B. D., CLERCQ, D. D., & LENOIR, M. (1995). The Effect of Varying Midsole Hardness on Impact Forces and Foot Motion During Foot Contact in Running. *Journal of Applied Biomechanics*, *11*, 395–406.

DENOTH, J. (1986). Load on the locomotor system and modelling. In B. M Nigg (Ed.), *Biomechanics of running shoes* (pp. 78–84). Human Kinetics.

DERRICK, T. R. (2004). The Effects of Knee Contact Angle on Impact Forces and Accelerations. *Medicine and Science in Sports and Exercise*, 36(5), 832–837.

DICKINSON, J. A., STEPHAN, S. D., & LEINHARDT, T. M. (1980). The measurement of shock waves following heel strike while running. *Journal of Biomechanics*, *18*(6), 415–422.

DIEBAL, A. R., GREGORY, R., ALITZ, C., & GERBER, J. P. (2012). Forefoot Running Improves Pain and Disability Associated With Chronic Exertional Compartment Syndrome. *The American journal of Sports Medicine*, 23–25.

DIVERT, C., MORNIEUX, G., BAUR, H., MAYER, F., & BELLI, A. (2005). Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine*, *26*(7), 593–8.

DIVERT, C., MORNIEUX, G., FREYCHAT, P., BALY, L., MAYER, F., & BELLI, A. (2008). Barefoot-shod running differences: shoe or mass effect? *International Journal of Sports Medicine*, *29*(6), 512–8.

DIXON, S. J., COLLOP, A C., & BATT, M. E. (2000). Surface effects on ground reaction forces and lower extremity kinematics in running. *Medicine and Science in Sports and Exercise*, *32*(11), 1919–26.

DU PLESSIS, E. (2011). *The effect of barefoot training on speed, agility, power and balance in netball players*. Stellenbosch University.

D' ACUT, PATAKY, T. C., DE CLERCQ, D., & AERTS, P. (2009). The effects of habitual footwear use: foot shape and function in native barefoot walkers. *Footwear Science*, *1*(2), 81–92.

EDWARDS, W. B., TAYLOR, D., RUDOLPHI, T. J., GILLETTE, J. C., & DERRICK, T. R. (2009). Effects of stride length and running mileage on a probabilistic stress fracture model. *Medicine and Science in Sports and Exercise*, *41*(12), 2177–84.

EMERY, C. A., CASSIDY, J. D., KLASSEN, T. P., ROSYCHUK, R. J., & ROWE, B. H. (2005). Effectiveness of a home-based balance –training program in reducing sports-related injuries among healthy adolescents: a cluster randomized controlled trial. *Canadian Medical Association Journal*, *172*(6), 749–754.

ESLAMI, M., DAMAVANDI, M., & ALLARD, P. (2006). Foot joints and tibial kinematic coupling patterns during stance phase of barefoot versus shod running. *Journal of Biomechanics, 39(1),* S183*.*

FARTHING, J. P., & CHILIBECK, P. D. (2003). The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *European Journal of Applied Physiology*, *89*(6), 578–86.

FERBER, R., MCCLAY DAVIS, I., HAMILL, J., POLLARD, C. D., & MCKEOWN, K. (2002). Kinetic variables in subjects with previous lower extremity stress fractures. *Medicine and Science in Sports and Exercise*, *34*, S5.

FERRIS, D. P.,LOUIE, M., & FARLY, C. T. (1998). Running in the real world: adjusting leg stiffness to different surfaces. *Proceedings of the Royal Society*, *265,* 989–994.

FREDERICK, E. C. (1984). Physiological and ergonomics factors in running shoe design. *Applied Ergonomics*, *15*, 281–287.

FREDERICK, E. C. (2011). Starting over. *Footwear Science*, *3*(2), 69–70.

FREDERICK, E. C., CLARKE, T. E., & HAMILL, J. (1984). The effect of running shoe design on shock attenuation. in E. C. Frederick (Ed.), *Sport Shoes and Playing Surfaces* (pp. 190–198). Champaign, IL: Human Kinetics.

GERRITSEN, G. M., BOGERT, A. J. V. D., & NIGG, B. M. (1995). Direct dynamics simulation of the impact phase in heel toe running. *Journal of Biomechanics*, *28*(6), 661–668.

Stellenbosch University http://scholar.sun.ac.za

GIULIANI, J., MASINI, B., ALITZ, C., & OWENS, B. D. (2011). Barefoot-simulating footwear associated with metatarsal stress injury in 2 runners. *Orthopedics*, *34*(7), 320–3.

GOK, H., ERGIN, S., & YAVUZER, G. (2002). Kinetic and Kinematic characteristics of gait in patients with medial knee arthrosis. *Acta Orthopaedica Scandinavica*, *73*, 647–652.

GRUBER, A. (2012). Kinetic and Kinematic characteristics of gait in patients with medial knee arthrosis. *Acta Orthopaedica Scandinavica*, *73*, 647–652.

HAMILL, J., DERRICK, T. R., & HOLT, K. G. (1995). Shock attenuation and stride frequency during running. *Human Movement Sciences, 14(1)*, 45–60.

HAMILL, J., GRUBER, A. H., FREEDMAN, J., BRUGGEMANN, G.P., & ROHR, E. (2011b). Are footfall patterns a function of running surface?. *Proceeding of the 10th Footwear Biomechanics Symposium, Tuebingen* (S66).

HAMILL, J., & KNUTZEN, K. M. (1995). *Biomechanical Basis of Human Movement*. Baltimore, MD: Lippincott Williams & Wilkins.

HAMILL, J., RUSSELL, E. M., GRUBER, A. H., & MILLER, R. H. (2011a). Impact characteristics in shod and barefoot running. *Footwear Science*, *3*(1), 33–40.

HAMILL, J., & SELBIE, W. S. (2004). Three-Dimensional Kinematics. In G. E. Robertson (Ed.), *Research Methods in Biomechanics* (pp. 35–53). Champaign, IL: Human Kinetics.

HANSON, N. J., BERG, K., DEKA, P., MEENDERING, J. R., & RYAN, C. (2011). Oxygen cost of running barefoot vs. running shod. *International Journal of Sports Medicine*, *32*(6), 401–6.

HARDIN, E. C., VAN DEN BOGERT, A. J., & HAMILL, J. (2004). Kinematic Adaptations during Running: Effects of Footwear, Surface, and Duration. *Medicine and Science in Sports and Exercise*, 36(5), 838–844.

Stellenbosch University http://scholar.sun.ac.za

HART, P. M., & SMITH, D. R. (2008). Preventing running injuries through barefoot activity. *Journal of Physical Education, Recreation, and Dance*, *79*(4), 50–53.

HASEGAWA, H., YAMAUCHI, T., & KRAEMER, W. J. (2007). Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *Journal of Strength and Conditioning Research*, *21*(3), 888–93.

HEIDERSCHEIT, B. C., CHUMANOV, E. S., MICHALSKI, M. P., WILLE, C. M., & RYAN, M. B. (2011). Effects of step rate manipulation on joint mechanics during running. *Medicine and Science in Sports and Exercise*, *43*(2), 296–302.

HENNIG, E. M., VALIANT, G. A., & LIU, Q. (1996). Biomechanical Variables and the Perception of Cushioning for Running in Various Types of Footwear, (1970), 143–150.

HERZOG, W. (1978). *The influence of velocity and playing surfaces on the load on the human body in running*. ETH, Zurich. (Thesis).

HIGBIE, E. J., CURETON, K. J., WARREN III, G. L. ., PRIOR, B. M., SULLIVAN, K. O., MCAULIFFE, S., DEBURCA, N., et al. (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *Journal of Applied Physiology*, *81(5)*, 2173–2181.

HOF, A. L., ZANDWIJK, J. P., & BOBBERT, M. F. (2002). Mechanics of human triceps surae muscle in walking, running and jumping. *Acta Physiologica*, *174*, 17–30.

HOPKINS, W. G. (2002). *A scale of magnitudes for effect statistics. A new view of statistics*. (Available online at: http://sportsci.org/resource/stats/effectmag.html).

HRELJAC, A. (2004). Impact and overuse injuries in runners. *Medicine and Science in Sports and Exercise*, *36*(5), 845–849.

Stellenbosch University http://scholar.sun.ac.za

JENKINS, D. W., & CAUTHON, D. J. (2011). Barefoot running claims and controversies: a review of the literature. *Journal of the American Podiatric Medical Association*, *101*(3), 231–46.

KER, R. F., BENNETT, M. B., BIBBY, S. R., KESTER, R. C., & ALEXANDER, R. M. (1987). The spring in the arch of the human foot. *Nature*, *325*(7000), 147–9.

KERRIGAN, D. C., FRANZ, J. R., KEENAN, G. S., DICHARRY, J., DELLA CROCE, U., & WILDER, R. P. (2009). The effect of running shoes on lower extremity joint torques. *The Journal of Injury, Function, and Rehabilitation*, *1*(12), 1058–63.

KINCHINGTON, M., & BALL, K. (2010). Reliability of an instrument to determine lower limb comfort in professional football. *Journal of Sports Medicine*, *1*, 77–85.

KINCHINGTON, M., BALL, K., & NAUGHTON, G. (2010). Monitoring of lower limb comfort and injury in elite football. *Journal of Sports Science and Medicine*, *9*, 652–663.

KNUDSON, D. (2010). Significant and meaningful effects in sports biomechanics research. *Sports Biomechanics*, 8(1), 96–104.

KONG, P. W, CANDELARIA, N. G., & SMITH, D. R. (2009). Running in new and worn shoes: a comparison of three types of cushioning footwear. *British Journal of Sports Medicine*, *43*(10), 745–9.

KONG, P. W, CANDELARIA, N. G., & SMITH, D. (2011). Comparison of longitudinal biomechanical adaptation to shoe degradation between the dominant and non-dominant legs during running. *Human Movement Science*, *30*(3), 606–13.

KRISTIANSLUND, E., KROSSHAUG, T., & VAN DEN BOGERT, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *Journal of Biomechanics*, *45*(4), 666–671.

KURZ, M. J., & STERGIOU, N. (2004). Does footwear affect ankle coordination strategies? *Journal of American Podiatry Medical Association*, *94*(1), 53–58.

LAKE, M. J., & CAVANAGH, P.R. (1996). Six weeks of training does not change running mechanics or improve running economy? *Medicine and Science in Sport and Exercise*, *28*(7), 860–869.

LIEBERMAN, D.E. (2012). What we can learn about running from barefoot running: an evolutionary medical perspective. *Medicine and Science in Sports and Exercise*, *40*(2), 63–72.

LIEBERMAN, D. E., VENKADESAN, M., WERBEL, W. A, DAOUD, A. I., D'ANDREA, S., DAVIS, I. S., MANG'ENI, R. O., ET AL. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. Supplementary Information. *Nature*, *463*(7280), 531–5.

LOGAN, S., HUNTER, I., HOPKINS, J. T., FELAND, J. B., & PARCELL, A. C. (2010). Ground reaction force differences between running shoes , racing flats , and distance spikes in runners, *9*, 147–153.

LORENZ, D. S., & PONTILLO, M. (2012). Is There Evidence to Support a Forefoot Strike Pattern in Barefoot Runners? : A Review. *Sports Health: A Multidisciplinary Approach*.

LUCIA, A., ESTEVE-LANAO, J., CHAMORRO-, C., JUAN, A. F. S., SANTIAGO, C., PE, M., & FOSTER, C. (2006). Physiological characteristics of the best Eritrean runners — exceptional running economy, *540*, 530–540.

LUO, G., STERGIOU, P., WOROBETS, J., NIGG, B., & STEFANYSHYN, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science*, *1*(1), 25–29.

Stellenbosch University http://scholar.sun.ac.za

MACLELLAN, G. E. (1984). Skeletal heel strike transients, measurement, implications, and modification by footwear. In E. C. Frederick (Ed.), *Sport shoes and playing surfaces* (pp. 76–81). Champaign, IL: Human Kinetics.

MACERA, C. A. (1989). Predicting lower-extremity injuries among habitual runners. *Archives of Internal Medicine*, *149*(11), 2565–2568.

MAIWALD, C., AXMANN, D., & GRAU, S. (2011). Measurement error in footwear research biomechanics. *Footwear Science*, *3*(2), 117–124.

MARFELL-JONES, M., OLDS, T., STEWART, A., & CARTER, L. (2006). *International standards for anthropometric assessment* (p. 137). Potchestroom: International Society for the Advancement of Kinanthropometry (ISAK).

MARTIN, R. B., & BURR, D. B. (1989). *Structure, function and adaptation of compact bone*. New York, Raven Press.

MCCARTHY, C., PORCARI, J. P., KERNOZEK, T., WILLSON, J., FORSTER, C., & ANDERS, M. (2011). Like barefoot, only better? *American Council of Exercise*, 8–12.

MCCLAY, I. (2000). The evolution of the study of the mechanics of running. *Journal of American Podiatry Mediacal Association*, *90*, 133–148.

MCCLAY, I., & MANAL, K. (1998). Three-dimensional kinetic analysis of running: significance of secondary planes of motion. *Medicine and Science in Sports and Exercise*, *31*(11), 1629–1637.

MCDOUGALL, C. (2010). *Born to run, the hidden tribe, the ultra-runners and the greatest race the world has ever seen* (p. 287). London: Profile Books.

MCNAIR, P. J., & MARSHALL, R. N. (1994). Kinematic and kinetic parameters associated with running in different shoes. *British Journal of Sports Medicine*, *28*(4), 256–260.

MCPOIL, T. G. (2000). Athletic footwear: Design, performance and selection issues. *Journal of Science and Medicine in Sport*, *3*(3), 260–267.

MERCER, J. A., DEVITA, P., DERRICK, T. I. M. R., & BATES, B. T. (2003). Individual Effects of Stride Length and Frequency on Shock Attenuation during Running. *Medicine and Science in Sports and Exercise*, *35*(2), 307–313.

MEYERS, M., & STEUDEL, K. (1985). Effect of limb mass and its distribution on the energetic cost of running. *Journal of Experimental biology*, *116*, 363–373.

MIENTJES, I. V., & SHORTEN, M. R. (2011). Contoured cushioning: effects of surface compressibility and curvature on heel pressure distribution. *Footwear Science*, *3*(1), 23–32.

MILNER, C. E., DAVIS, I. S., & HAMILL, J. (2006b). Free moment as a predictor of tibial stress fracture in distance runners. *Journal of Biomechanics*, *39*(15), 2819–2825.

MILNER, C. E., FERBER, R., POLLARD, C. D., HAMILL, J., & DAVIS, I. S. (2006a). Biomechanical factors associated with tibial stress fracture in female runners. *Medicine and Science in Sports and Exercise*, *38*(2), 323–328.

MILNER, C. E., HAMILL, J., & DAVIS, I. (2007). Are knee mechanics during early stance related to tibial stress fracture in runners? *Clinical Biomechanics*, *22*(6), 697–703.

MOISIO, K. C., SUMNER, D. R., SHOTT, S., & HURWITZ, D. E. (2003). Normalization of joint moments during gait: a comparison of two techniques. *Journal of Biomechanics*, *36*(4), 599–603.

MUNRO, B, MICKLE, K. J., & STEELE, J. (2011). Can Flexible shoes improve function in the older foot? *Proceeding of the 10th Footwear Biomechanics Symposium, Tuebingen*, S116.

MUNRO, BRIDGET, MICKLE, K. J., & STEELE, J. (2011). Can flexible shoes improve function in the older foot? *Footwear Science*, S116–S117.

Stellenbosch University http://scholar.sun.ac.za

MÜNDERMANN, A, STEFANYSHYN, D. J., & NIGG, B. M. (2001). Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. *Medicine and Science in Sports and Exercise*, *33*(11), 1939–1945.

MÜNDERMANN, ANNE, NIGG, B. M., HUMBLE, R. N., & STEFANYSHYN, D. J. (2003). Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. *Medicine and Science in Sports and Exercise*, *35*(10), 1710–1719.

MÜNDERMANN, ANNE, NIGG, B. M., STEFANYSHYN, D. J., & HUMBLE, R. N. (2002). Development of a reliable method to assess footwear comfort during running. *Gait & Posture*, *16*(1), 38–45.

NEUMANN, D. A. (2010). *Kinesiology of the musculoskeletal system: Foundations for rehabilitation* (p. 725). New York, Mosby Elsevier.

NIGG, B. M. (2001). The role of impact forces and foot pronation: a new paradigm. *Clinical journal of sport medicine*, *11*(1), 2–9.

NIGG, B. M. (2010). *Biomechanics of Sport Shoes*. Calgary, Alberta. Topline Printing Inc.

NIGG, B. M, COLE, G. K., & BRUGGEMANN, G.P. (1995). impact Forces During Heel-Toe Running. *Journal of Biomechanics*, *11*, 407–432.

NIGG, B. M, STERGIOU, P., COLE, G., STEFANYSHYN, D., MÜNDERMANN, A., & HUMBLE, N. (2003). Effect of shoe inserts on kinematics, center of pressure, and leg joint moments during running. *Medicine and Science in Sports and Exercise*, *35*(2), 314–319.

NOAKES, T. D. (2003). *The lore of running* (4th ed.). Champaign, IL: Human Kinetics.

NOVACHECK, T. (1998). The biomechanics of running. *Gait & Posture*, *7*(1), 77–95.

Stellenbosch University http://scholar.sun.ac.za

OAKLEY, T., & PRATT, D. J. (1988). Skeletal transients during heel and toe strike running and the effectiveness of some materials in their attenuation. *Clinical Biomechanics*, *3*(3), 159–165.

OGLES, B. M., & MASTERS, K. S. (2003). Older vs. Younger male marathon runners: Participative motives and training habits. *Journal of Sport Behavior*, *23*(2), 130–143.

PAQUETTE, M., BAUMGARTNER, L., & ZHANG, S. (2011). A comparitive investigation of fivefingers with barefoot and shoes in rear-foot strikers. *Medicine and Science in Sports and Exercise* (p. S718).

PERL, D. P., DAOUD, A. I., & LIEBERMAN, D. E. (2012). Effects of Footwear and Strike Type on Running Economy. *Medicine and Science in Sports and Exercise*, (In press).

POHL, M. B., HAMILL, J., & DAVIS, I. S. (2009). Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clinical Journal of Sport Medicine : official journal of the Canadian Academy of Sport Medicine*, *19*(5), 372–376.

POTTHAST, W. (2011). Impact and cushioning. *Footwear Science*, *3*(1), 1.

POTTHAST, W., BRAUNSTEIN, B., NIEHOFF, A., & BRUGGEMANN, G.-P. (2005). The choice of training footwear has an effect on changes in morphology and functon of foot and shank muscles. *International Society of Biomechanics Congress* (pp. 668–670).

POWERS, C. M. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *Journal of Orthopaedic and Sports Physical Therapy*, *40*(2), 42–51.

PULEO, J., & MILROY, P. (2010). *Running Anatomy* (pp. 157–167). Champaign, IL: Human Kinetics.

QUEEN, R. M., GROSS, M. T., & LIU, H.-Y. (2006). Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. *Gait & Posture*, *23*(3), 282–287.

Stellenbosch University http://scholar.sun.ac.za

RAO, U. B., & JOSEPH, B. (1992). The influence of footwear on the prevalence of flat foot. A survey of 2300 children. *Journal of Bone and Joint Surgery*, *74*, 535–527.

REENALDA, J., FRERIKS, B., & BUURKE, J. (2011). A comparison of ground reaction force patterns of conventional running shoes and minimalistic footwear in habitually shod runners. *Proceedings of the 10th Footwear Biomechanics Symposium, Tuebingen* (p. S130).

REILLY, T., & MARTENS, M. (1972). Experimental analysis of the quadriceps muscle force and patellofemoral joint reaction force forc various activities. *American Academy of Physical Medicine and Rehabilitation*, *1*, 1058–1063.

RICHARDS, C. E., MAGIN, P. J., & CALLISTER, R. (2009). Is your prescription of distance running shoes evidence-based? *British Journal of Sports Medicine*, *43*(3), 159–162.

RILEY, P. O., DICHARRY, J., FRANZ, J., DELLA CROCE, U., WILDER, R. P., & KERRIGAN, D. C. (2008). A kinematics and kinetic comparison of overground and treadmill running. *Medicine and Science in Sports and Exercise*, *40*(6), 1093–1100.

RIXE, J. A, GALLO, R. A, & SILVIS, M. L. (2012). The barefoot debate: can minimalist shoes reduce running-related injuries? *Current Sports Medicine reports*, *11*(3), 160–165.

ROBBINS, S. E., & GOUW, G. J. (1991). Athletic footwear: unsafe due to perceptual illusions. *Medicine and Science in Sports and Exercise*, *23*(2), 217–224.

ROBBINS, S. E., GOUW, G. J., & HANNA, A M. (1989). Running-related injury prevention through innate impact-moderating behavior. *Medicine and Science in Sports and Exercise*, *21*(2), 130–139.

ROBBINS, S. E., & HANNA, A M. (1987). Running-related injury prevention through barefoot adaptations. *Medicine and Science in Sports and Exercise*, *19*(2), 148–156.

Stellenbosch University http://scholar.sun.ac.za

ROBILLARD, J. (2010). *The Barefoot Running Book Second Edition: A Practical Guide to the Art and Science of Barefoot and Minimalist Shoe Running*. Allendale, MI: Barefoot Running University.

ROMANOV, N. (2002). *Pose method of running* (pp. 219–222). Pose Tech Press, Coral Gables, FL.

ROTHSCHILD, C. E (2012). Running barefoot or in minimalist shoes: evidence or conjecture? *Strength and Conditioning Journal*, 0(0), 1–10.

ROTHSCHILD, C. E. (2011). Primitive Running: A survey analysis of runners' interest, participation, and implementation. *Journal of strength and conditioning research,* in press.

SACHITHANANDAM, V., & JOSEPH, B. (1995). The influence of footwear on the prevalence of flat foot. *Journal of Bone and Joint Surgery*, *77*, 254–257.

SALADIN, K. S. (2007). *Anatomy and physiology: the unity of form and function* (Fourth ed., pp. 588–593). New York, McGraw-Hill.

SALE, D. G. (1988). Neural adaptation to resistance training. *Medicine and Science in Sports and Exercise*, (S135).

SAMAWARAWICKRAME, S., HASHISH, R., & SALEM, G. (2011a). Kinematic and kinetic differences between shod and barefoot running. *American Society of Biomechanics Congress* (pp. 3–4).

SANDLER, M., & LEE, J. (2010). *Barefoot running: How to run light and free by getting n touch with the earth*. Runbare company.

SAXBY, L. (2011). *Proprioception: Making Sense Of Barefoot Running* (p. 32). Vivobarefoot.

Stellenbosch University http://scholar.sun.ac.za

SCHACHE, A. G., BLANCH, P. D., DORN, T. W., BROWN, N. A T., ROSEMOND, D., & PANDY, M. G. (2011). Effect of running speed on lower limb joint kinetics. *Medicine and Science in Sports and Exercise*, *43*(7), 1260–1271.

SCHILLING, B. K. (2012). Minimalist Footwear in Strength and Conditioning. *National Strength and Conditioning Association*, 1–4.

SCHÜTTE, K. H., MILES, K. C., VENTER, R. E., & VAN NIEKERK, S.M. (2011). Acute differences in sagittal plane lower limb kinematics between barefoot, minimalistic shoes, and shod running in male athletes. *International Society of Biomechanics Congress* (pp. 8–9).

SHINOHARA, J., & GRIBBLE, P. A. (2011). Effects of Five-Toed Socks on Static Postural Control Among Physically Active Young Adults. *Athletic Training and Sports Health Care*, *3*(5), 218–225.

SHORTEN, M. R. (1993). Pressure distribution beneath the heel while running in a cushioned shoe: a sagittal plane finite element model. *XIV International Society of Biomechanics Congress*. Paris.

SHORTEN, M. R. (2002). The myth of running shoe cushioning. *IV International conference of engineering of sport* (pp. 1–6). Kyoto, Japan.

SHORTEN, M. R., & MIENTJES, I. V. (2011). The “heel impact” force peak during running is neither “heel” nor “impact” and does not quantify shoe cushioning effects. *Footwear Science*, *3*(1), 41–58.

SHROYER, J. F., ETHEREDGE, C. E., & WEIMAR, W. H. (2011). Effect of Minimalist Footwear on Arch Rigidity Index. *Medicine and Science in Sports and Exercise*, S1464.

SNEL, J. G. (1985). Shock absorbing characteristics of running shoes during actual running. In D. A. Winter, R. W. Norman, C. Hayes, & P. E. Patla (Eds.), *Biomechanics* (pp. 228–304). IL: Human Kinetics.

SQUADRONE, R., & GALLOZZI, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of Sports Medicine and Physical Fitness*, *49*, 6–13.

SQUADRONE, R., & GALLOZZI, C. (2011). Effect of a five-toed minimal protection shoe on static and dynamic ankle position sense. *The Journal of Sports Medicine and physical fitness*, *51*(3), 401–8.

STACOFF, A, NIGG, B. M., REINSCHMIDT, C., VAN DEN BOGERT, A J., & LUNDBERG, A. (2000). Tibiocalcaneal kinematics of barefoot versus shod running. *Journal of Biomechanics*, *33*(11), 1387–1395.

STANTON, R., REABURN, P. R., HUMPHRIES, B. (2004). The effect of short-term Swiss ball training on core stability and running economy. *Journal of Strength and conditioning research* *18*(3), 522–528.

STEFANYSHYN, D. J., & NIGG, B. M. (1998). Dynamic Angular Stiffness of the Ankle Joint During Running and Sprinting. *Journal of Applied Biomechanics*, *14*, 292–299.

STEFANYSHYN, D. J., STERGIOU, P., LUN, V. M. Y., MEEUWISSE, W. H., & WOROBETS, J. T. (2006). Knee angular impulse as a predictor of Patellofemoralpain in runners. *The American Journal of Sports Medicine*, *34*(11), 1844–1851.

TESSUTTI, V., TROMBINI-SOUZA, F., RIBEIRO, A. P., NUNES, A. L., & SACCO, I. D. C. N. (2010). In-shoe plantar pressure distribution during running on natural grass and asphalt in recreational runners. *Journal of Science and Medicine in Sport*, 13(1), 151–155.

Stellenbosch University http://scholar.sun.ac.za

THOMAS, J. R., NELSON, S., & SILVERMAN, J. (2005). *Research Methods in Physical Activity,* Champaign, IL: Human Kinetics.

TURNER, A. M., OWINGS, M., & SCHWANE, J. A. (2003). Improvement of running economy after six-weeks plyometric training. *Journal of Strength and Conditioning Research*, 17(1), 60–67.

VALIANT, G. A. (1990). Transmission and attenuation of heelstrike accelerations. *Biomechanics of Distance Running* (pp. 225–247). Champaign, IL: Human Kinetics.

VAN GENT, R. N., SIEM, D., VAN MIDDELKOOP, M., VAN OS, A. G., BIERMA-ZEINSTRA, S. M. A., & KOES, B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British Journal of Sports Medicine*, *41*(8), 469–80.

VAN MECHELEN, W. (1992). Running injuries. A review of the epidemiological literature. *Sports Medicine*, *14*(5), 320–335.

VON TSCHARNER, V., GOEPFERT, B., & NIGG, B. M. (2003). Changes in EMG signals for the muscle tibialis anterior while running barefoot or with shoes resolved by non-linearly scaled wavelets. *Journal of Biomechanics*, *36*(8), 1169–1176.

WALLACK, R., & SAXTON, K. B. (2011). *Barefoot Running: Step by Step* (p. 300). New York, Quayside publishers.

WARBURTON, M. (2001). Barefoot running. *Sport Science*, *5*(3).

WILLIAMS, D. S., MCCLAY, I. S., & MANAL, K. (2000). Lower extremity mechanics in runners with a converted forefoot strike pattern. *Journal of Applied Biomechanics, 16,* 210–218.

WILLY, R., POHL, M. P. T. M. B., & DAVIS, I. S. (2008). Calculation of Vertical Load Rates in the Absence of Vertical Impact Peaks. *North American Congress on Biomechanics*.

WINTER, D. A., & BISHOP, P. J. (1992). Lower extremity injury: biomedical factors associated with chronic injury to the lower extremity. *Sports Medicine*, 14, 149–156.

WUNDERLICH, R. E., & CAVANAGH, P. R. (2001). Gender differences in adult foot shape: implications for shoe design. *Medicine and Science in Sports and Exercise*, *33*(4), 605–611.

ZADPOOR, A. A., & NIKOOYAN, A. A. (2011). The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review. *Clinical Biomechanics*, *26*(1), 23–28.

ZIFCHOCK, R. A., DAVIS, I., & HAMILL, J. (2006). Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *Journal of Biomechanics*, *39*(15), 2792–2797.

Stellenbosch University http://scholar.sun.ac.za

APPENDIX A: CONSENT TO PARTICIPATE IN RESEARCH

Title of Research Project: The effect of minimalist shoe training on lower limb kinematics and kinetics in experienced shod runners.

You are asked to participate in a research study conducted by **Kurt Schütte** (enrolled for M in sport Science) under the supervision of **Dr. R. E. Venter**, from the **Department of Sport Science** at Stellenbosch University. You were selected as a possible participant in this study because you are a man between the ages of 21 and 30 years of age.

PURPOSE OF THE STUDY

The purpose of this study is to examine the alterations in lower limb kinematics and kinetics in experienced shod runners after a 7 week intervention training period with minimalist shoes.

PROCEDURES

Visit 1

You will be required to visit the Biomechanics Laboratory at the Department of Sport Science at Stellenbosch University, for an information session regarding the Study. You are expected to arrive in your athletic attire and the running shoes you usually train with. The procedures of the study will be explained to you. You will be asked to complete a questionnaire regarding your injury and training history.

A qualified Biokineticist (Kurt Schütte, BK no.0020346) registered under the Health Professions Council of South Africa (HPCSA) and Biokinetics Association of South Africa (BASA) will perform an orthopedic assessment on you. Height, weight, leg length, shoulder width, knee width, ankle width, elbow width, wrist width, hand thickness, mid-thigh circumference, maximum calf circumference, and maximum foot circumference, ankle range of motion, and foot pronation will be measured.

You will be given a new pair of minimalist shoes. You are expected to familiarize yourself in the new pair of shoes by sitting, standing or walking in them for a minimum of 1 and maximum of 2 hours per day, over a period of one week until testing begins. You are expected to refrain from any other activities (jogging, running, sprinting, jumping, skipping, climbing etc.) in your new minimalist shoes. You are expected to keep a familiarization log of the time you spend sitting, standing or walking in the minimalist shoes. You are expected to maintain your usual training sessions in your usual running shoes during the familiarization period.

Visit 2

You will be required to visit the Biomechanics Laboratory, Department of Physiotherapy, Tygerberg, Stellenbosch University. You are expected to arrive in your athletic clothes and running shoes. You are expected to refrain from competing in any races or intensive training within 48 hours prior to testing. The purpose of the visit will be verbally explained to you.

Reflective markers will be placed on specific bony landmarks. You are expected to warm-up on a 12 meter indoor runway. Three different shoe conditions will be tested, namely barefoot, your usual running shoes, and the new pair of minimalistic shoes. You will be allowed to rest when necessary between running conditions.

After the testing session, you will be requested to hand your new minimalist shoes back to the researcher. You will be randomly divided into either an experimental or control group. If you are divided into the control group, you will receive the minimalist shoes after the completion of the study. If you are divided into the experimental group, your new minimalist shoes will be provided to you before each training session (Visits 3-23). After the completion of the study, you and all other participants will be allowed to keep the minimalist shoes.

Stellenbosch University http://scholar.sun.ac.za

Visit 3-23

If you are randomly divided into the control group, you are expected to self-train and keep a training log of your daily running mileage. Relevant pages will be provided for you to complete over the 7 week intervention period.

If you are randomly divided into the experimental group, you are asked to attend 21 training sessions. You are expected to arrive in exercise apparel at the Coetzenburg athletic stadium for your training sessions. On arrival of each training session, you will receive your new pair of minimalist shoes to train in. You will be requested to complete a *questionnaire regarding your lower limb discomfort* before the commencement of each training session. You will perform a dynamic warm-up for 5 minutes at the beginning of each training session. You will then run a specific distance in their new pair of minimalist shoes. The initial weekly distance that will be run in the minimalist shoes is calculated as 10% of your usual weekly training mileage. This 10% mileage is spread over between 3 training sessions (week 1 to 3) and four training sessions (week 4 to 6) of the intervention period. This percentage will increase throughout the intervention period by 10% each week. Once you have completed the distance in your minimalist shoes, you are expected to take off the minimalist shoes and put on your usual running shoes. You are expected to run the remaining daily mileage in your usual running shoes. Your running information regarding speed, distance, and acceleration will be recorded.

POTENTIAL RISKS AND DISCOMFORTS

All measurements are **non-invasive**, and therefore minimal risk is expected. You may find the minimalist shoes to be uncomfortable around your feet and ankle whilst running. Any pain or discomfort caused by the minimalist shoes must be stated in the *questionnaire regarding your lower limb discomfort* before each training session. You running will be closely monitored and sufficient time for recovery will be provided.

Stellenbosch University http://scholar.sun.ac.za

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

You will receive interesting information on your personal running biomechanics and this may be beneficial to your future running performance and training. This study will be the first to monitor and implement the transition process from training in usual running shoes to minimalist shoes. Conclusions drawn from this study may reduce fears and remove the perceptual barriers with regards to implementing a minimalist training programme. This study may help runners, coaches, shoe companies, and biomechanists understand whether such a transition is feasible and beneficial.

PAYMENT FOR PARTICIPATION

As a participant you will not receive any financial reimbursement or payment to participate in the study and there will be no costs involved for the participation in this project. After the study is completed, you will receive a pair of minimalist shoes.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of withholding the names of the participants and only using numerical codes to represent subjects. This means that reported results will only include codes and no names at all. Recorded data will be filed and stored in a locked room and on a password protected personal computer and will only be accessed by the researcher and study leader. All information obtained in the study will not be disclosed, unless published, in which case it will be treated as not to identify anyone.

PARTICIPATION AND WITHDRAWAL

You can choose whether to take part in this study or not. If you volunteer to participate in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don’t want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. Participation will be terminated if you fail to comply with the testing protocol. Your consent to participate in this research will be indicated by your signing and dating of the consent form.

IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact the researcher Kurt Schütte (074 133 6441; kurtschutte.sa@gmail.com) or the supervisor, Dr. R. E. Venter (021 808 4915 or rev@sun.ac.za).

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

Stellenbosch University http://scholar.sun.ac.za

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me by Kurt Schütte (researcher) in English and I am in command of this language. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form

____

Name of Subject/Participant

____

Signature of participant

____

Date

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to ____________________ and he was encouraged and given ample time to ask me any questions. This conversation was conducted in English and no translator was used

_____________________________________ ______________

Signature of Investigator Date

Kurt Schütte

Stellenbosch University http://scholar.sun.ac.za

APPENDIX B: PARTICIPANT PERSONAL INFORMATION AND QUESTIONNAIRE

PERSONAL DETAILS

Name & Surname: ___________________________________

Date: ___________________________________

Date of birth: ___________________________________

City of Residence: ___________________________________

Email address: ___________________________________

Cell No: ___________________________________

PLEASE MARK THE QUESTIONS WITH AN (X), AND ELABORATE ON YOUR ANSWER IF REQUESTED:

1. In the previous three months, have you had **any injuries** that have prevented you from participating in typical training practices for more than one week? **If yes please elaborate.**

No	Yes

____

____

____

2. **If you have selected yes to question 1**. Have you received any of the following **treatments** for your injuries in the previous three months? **Please elaborate.**

Medical Treatment	Physiotherapy	Biokinetics	Alternative (Specify)	No Treatment

____

____

____

Stellenbosch University http://scholar.sun.ac.za

3. Is there any **other condition** not mentioned here that might affect your ability to exercise, or be aggravated by exercise? **If yes, please elaborate.**

No	Yes

____

____

____

4. Do you wear foot orthotics? **If yes, please elaborate.**

No	Yes

____

____

5. Have you ever trained in minimalist shoes? **If yes, please elaborate.**

No	Yes

____

____

____

6. Do you participate in any weekly physical activities, sport, or strength training (other than running)? If **yes please elaborate.**

No	Yes

____

____

____

7. What is your self-perceived running level? **Please select an option.**

Novice (beginner)	Amateur (recreational)	Elite (professional)

8. What is the longest race you have **completed** in the previous six months? **Please select an option for road and/or off-road below, and write your time to completion in the brackets provided.**

Road:

10km (................)	21km (................)	42km (................)	Ultra-marathon (................)	Other: (................)

Off-road/trail:

10km (................)	21km (................)	42km (................)	Ultra-marathon (................)	Other: (................)

9. What is the longest race you **plan** to complete in the next six months? **Please select an option for road and/or off-road below, and write your predicted time to completion in the brackets provided.**

Road:

10km (................)	21km (................)	42km (................)	Ultra-marathon (................)	Other: (................)

Off-road/trail:

10km (................)	21km (................)	42km (................)	Ultra-marathon (................)	Other: (................)

10. How many times a week do you train on average? **Please select an option. Please specify if your times per week are less than 3 and more than 7.**

<3 (................)	4	5	6	7	>7 (................)

11. What is your average weekly training mileage? **Please select an option and approximate the exact distance.**

Stellenbosch University http://scholar.sun.ac.za

<20km (................)	20-30km (................)	30-40km (................)	40-50km (................)	50-60km (................)	>60km: (................)

12. What is your estimated self-selected running pace, that would represent a pace that feels comfortable, and that you would follow in an easy training run? **Please select an option. Please specify if your pace is less than 3min/km or more than 8min/km.**

<4min/km (................)	4min/km	5min/km	6 min/km	7 min/km	8 min/km	>8 min/km (................)

13. What is your motivation to participate in this study? **Please write your answer below.**

____

____

____

14. How many years' experience of endurance running do you have? ________________Yrs.

15. Please approximate your distribution (%) of training experience according to footwear, training surface, and surface incline.

	Footwear		Surface texture				Surface incline	
	Shoes (%)	Barefoot (%)	Concrete & asphalt (%)	Off-road, trails (%)	Grass (%)	Tartan track (%)	Flat (%)	Hills (%)
Running								
Sports				-	-	-	-	-
Time during childhood & adolescence				-	-	-	-	-

SIGNATURE OF PARTICIPANT: ______________________________

SIGNITURE OF RESEARCHER: ______________________________

APPENDIX C: ETHICAL CLEARANCE

Researcher:	Mr K. H. Schütte
Research Project:	The effect of minimalist shoe training on lower limb circumferences, kinematics and kinetics in experienced shod runners
Nature of the Research Project:	M degree, Department of Sport Science, Stellenbosch University
Supervisor(s):	Dr. R. E. Venter
Reference number:	HS759/2011
Date:	02 February 2012

The research proposal and associated documentation was circulated and considered by the members of the Ethics Committee (as prescribed by Council and laid down in the SU policy framework) on 02 February 2012; the purpose being to ascertain whether there are any ethical risks associated with the proposed research project of which the researcher has to be aware of or, alternatively, whether the ethical risks are of such a nature that the research cannot continue.

Ethical clearance for the project, The effect of minimalist shoe training on lower limb circumferences, kinematics and kinetics in experienced shod runners, has been obtained from the

Ethics Committee on 2 February 2012 on condition that:

1. The researcher will remain within the procedures and protocols indicated in the proposal, particularly in terms of any undertakings made in terms of the confidentiality of the information gathered.

Stellenbosch University http://scholar.sun.ac.za

2. The research will again be submitted for ethical clearance if there is any substantial departure from the existing proposal.

3. The researcher will remain within the parameters of any applicable national legislation, institutional guidelines and scientific standards relevant to the specific field of research.

4. The researcher will consider and implement the foregoing suggestions to lower the ethical risk associated with the research.

APPENDIX D: PRETESTING DATA CAPTURING FORM

Name and Surname: ______________________________

Vicon ® file number: _______________

Date: _______________

Anthropometrical data	Left	Right
Height (m) (barefoot; own shoes)		
Weight (kg)		
Leg length (mm) standing		
Knee width (mm) standing		
Ankle width (mm) standing		
Lower limb circumferences		
Mid-thigh (10 cm supra-patella) (cm)		
Max calf (cm)		

Shoe characteristics	Minimalist shoe	Running shoe
Brand		
Model		
Size		
Age (months)	N/A	
Midsole thickness (mm)		

SIGNATURE OF PARTICIPANT: _________________________

SIGNATURE OF RESEARCHER: _________________________

Stellenbosch University http://scholar.sun.ac.za

APPENDIX E : PRETRAINING DATA CAPTURING FORM

Name & surname: ______________________

Date: ______________________ Time: ____________________

GPS No. ______________________

Training Week & Day: Week: 1; 2; 3; 4; 5; 6 Day: 1, 2 , 3

Hours since last VF training session : VF: ____________ SH: ________

Lower Limb Comfort: Rank each body area from 0-6 using the ***comfort descriptors***	**Place a score 0 to 6 in each box**						**Sum Comfort** **/36 maximum** **score**
	Foot	**Ankle**	**Calf-Achilles**	**Shin**	**Knee**	**Footwear**	

COMFORT DESCRIPTORS

0 = extremely uncomfortable (unable to run or jump);

1

2

3= neither uncomfortable or comfortable (more or less uncomfortable / comfortable)

4

5

6= zero discomfort (extremely comfortable; best ever feel)

SIGNATURE OF PARTICIPANT: ______________________

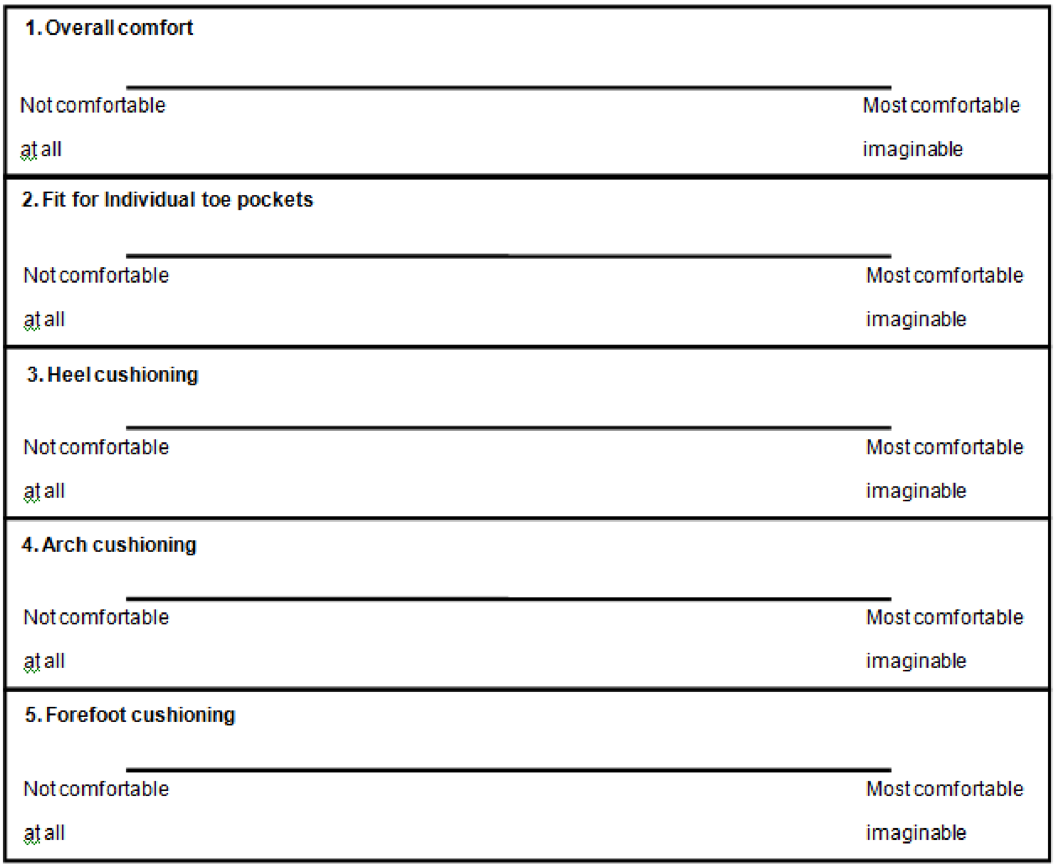
Stellenbosch University http://scholar.sun.ac.za

APPENDIX F: MINIMALIST SHOE COMFORT QUESTIONNAIRE

Name & surname: ________________________

Date: ________________________

With regard to walking in the Vibram Fivefingers, please rate the following aspects of comfort by placing a single vertical line on the scale left (lease comfort) or right (most comfort) in each scale:



1. Overall comfort

Not comfortable at all	____	Most comfortable imaginable

2. Fit for Individual toe pockets

Not comfortable at all	____	Most comfortable imaginable

3. Heel cushioning

Not comfortable at all	____	Most comfortable imaginable

4. Arch cushioning

Not comfortable at all	____	Most comfortable imaginable

5. Forefoot cushioning

Not comfortable at all	____	Most comfortable imaginable

Stellenbosch University http://scholar.sun.ac.za

6. Flexibility

Not comfortable at all ______________________________ Most comfortable imaginable

7. Fit around top of foot

Not comfortable at all ______________________________ Most comfortable imaginable

8. Support

Not comfortable at all ______________________________ Most comfortable imaginable

9. Forefoot width

Not comfortable at all ______________________________ Most comfortable imaginable

10. Length

Not comfortable at all ______________________________ Most comfortable imaginable

SIGNATURE OF PARTICIPANT: ____________________________

SIGNATURE OF RESEARCHER: ____________________________

Stellenbosch University http://scholar.sun.ac.za

APPENDIX G: FAMILIARIZATION PERIOD LOG

Name & Surname: ___________________________

Date: ___________________________

		Activities in minimalist shoes			**Activities running shoes**		
Day	**Date**	**Sit**	**Stand**	**Walk**	**Mileage (km)**	**Time (minutes)**	**Surface (road/trail)**
1							
2							
3							
4							
5							
6							
7							

SIGNATURE OF PARTICIPANT: ___________________________

SIGNATURE OF RESEARCHER: ___________________________

Stellenbosch University http://scholar.sun.ac.za

APPENDIX H: CONTROL GROUP TRAINING LOG

Name & Surname: ______________________

Date: ______________________

Session	Date	Time of day	Duration (minutes)	Mileage (km)	Surface (road, tail, etc.)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
n					

SIGNATURE OF PARTICIPANT: ______________________

SIGNATURE OF RESEARCHER: ______________________

APPENDIX I: LETTER OF REQUEST TO DONATE TO RESEARCH

Dear…………………(footwear manufacturer),

You are asked to contribute to a research study conducted by **Kurt. H. Schütte** (Masters in sport Science) under supervision of **Dr. Ranel. E. Venter**, and department chair of **Prof. Elmarie Terblanche,** from the **Department of Sport Science** at Stellenbosch University. You were selected as a possible contributor as you are a shoe company which manufactures minimalist (barefoot related) shoes. The title of research project is **"The effect of minimalist shoe training on lower limb kinematics and kinetics in experienced shod runners"** and the purpose of the study is to examine the alterations in lower limb kinematics and kinetics in experienced shod (shoe) runners after a seven-week intervention training period with minimalist shoes.

A statistical power analysis based on data from Lieberman *et al.* (2010) performed with STATISTICA Version 10 (StatSoft, Inc. Tulsa, OK, 2010) determined the minimal sample size for this study as 22 participants (11 experimental and 11 control group) to get significant ($p < 0.05$); power 80%) results. Therefore, a **minimum of 22 pairs of minimalist shoes** are required for this study. No financial assistance is required; however any number of shoes for donation towards this study will be appreciated. Any donation of minimalist shoes for this study will be acknowledged in any published data from this study.

_________________________________ _____________

Signature of Investigator Date

Kurt. H. Schütte

_________________________________ _____________

Signature of Supervisor Date

Dr. Ranel. E. Venter

_________________________________ _____________

Signature of Department Chair Date

Prof. Elmarie Terblanche

Stellenbosch University http://scholar.sun.ac.za

APPENDIX J : POST STUDY INTERVENTION QUESTIONNAIRE

Name:___________________

1. Overall, do you prefer running in the Vibram Fivefingers over running in your usual shoes? Yes/NO: please provide reason/s:____
   ____
   ____
2. Since the study started, did you change your stretching routine? Yes/No. If so, how?_______
   ____
   ____
3. Do you feel that regular monitoring (comfort, distance, etc) was necessary for the minimalist shoe transition process? Yes/No. Please provide reason/s:___________________________
   ____
   ____
   ____
4. With regards to running distances completed in the Vibram Fivefingers, do you feel:

   A: You could have ran longer distances

   B: The distances were appropriately set

   C: The distances were too far

5. What adverse effects i.e. pain, discomfort, injury, irritations, did you experience during the intervention period for the first time since you started training in the Vibram Fivefingers?
   ____
   ____
   ____

6. With regards to <u>training</u> after completion of the study, you will chose to:

   A: Carry on with my usual training in shoes only as before the study

   B: Perform some of my training in Vibram Fivefingers as to be used as a training “tool”

   C: Perform most of my training in Vibram Fivefingers

Stellenbosch University http://scholar.sun.ac.za

D: Perform all of my training in Vibram Fivefingers

7. If you decide to carry on training in the Vibram Fivefingers, will it depend on which surface you train on? Yes/No. Which surface will you chose and why?______________________________
____
____

8. With regards to <u>racing</u> after completion of the study, you will chose to:

A: Carry on racing as usual in normal shoes only, as prior to the study

B: Perform some of my races in Vibram Fivefingers

C: Perform most of my races in Vibram Fivefingers

D: Perform all of my races in Vibram Fivefingers

SIGNATURE OF PARTICIPANT: _________________________

SIGNATURE OF RESEARCHER: _________________________