Transitioning to minimal running footwear; Implications for performance and running related injury when compared to conventional running shoes.

Joe P. Warne

For the award of PhD.

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For the award of PhD

Dublin City University

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of PhD is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Table of Contents

Abstract

Transitioning to minimal running footwear; Implications for performance and running related injury when compared to conventional running shoes. AIM: To investigate any changes in running economy or factors related to injury before and after a minimalist footwear (MFW) transition with gait-retraining when compared with conventional running shoes (CRS). **INTRODUCTION**: Recent interest in barefoot running has resulted in the development of a new footwear type which incorporates minimal cushioning and structural properties, in contrast with CRS. These MFW have been suggested to influence running kinetics and kinematics and may have a positive impact on performance and injury risk. However there is currently a dearth of scientific evidence available to support this theory. Of the limited research available the vast majority has only used acute comparisons between CRS and MFW, and has not considered the effect of "transitioning" into MFW over a period of time, with or without "barefoot" gait-retraining. **METHODS:** In all studies, effects for time (pre to post intervention), and condition (MFW vs. CRS) were evaluated, where participants were required to familiarise with MFW during the intervention. Study one examined changes in running economy (RE) with no feedback or gait-retraining, in contrast study two examined RE with deliberate gait-retraining included to the MFW transition. Study three investigated changes to plantar pressures and forces. Finally, study four evaluated kinetics and kinematics associated with injury. **RESULTS:** Following a MFW intervention, RE was found to improve 8.09% in MFW but not in CRS. However, when gait-retraining was included, no significant change in RE was observed over time. RE was significantly better in MFW compared to CRS irrespective of time (approx. 2.9% better in MFW). A MFW transition with gait-retraining was found to reduce plantar forces by 17.6%, loading rate by 33%, and the impact peak by 9%, which was not observed to the same degree in CRS. However, significantly higher plantar pressures and loading rates were observed in MFW when directly compared to CRS throughout testing. **CONCLUSION**: A MFW transition was found to significantly improve RE when gait-retraining was not included. However, gait-retraining may have a negative influence on RE. MFW and gait-retraining reduced impact variables over time. In addition, there was a reduction in plantar pressures under the heel, and no significant increase in pressures in the forefoot as a result of the intervention. With respect to condition, RE was better in MFW, but higher plantar pressures and loading rates were noted in MFW vs. CRS that may increase injury risk during this transition period.

List of Tables

List of Figures

Glossary of Terms

Minimalist Footwear – Shoes that advertise “minimal” conventional features, including lighter mass, greater sole flexibility, lower profile and a lower heel-toe drop.

Conventional Running Shoes – Footwear designed for running that include cushioning, heel elevation and pronation control technology.

Barefoot Running – Running with nothing whatsoever on the foot.

Storage and Recovery of Elastic Energy – A phenomenon occuring during the stretch-shortening cycle in running. Elastic structures store energy during the eccentric phase of movement and this energy is subsequently released during the concentric phase, contributing to the muscle shortening action.

Vertical Stiffness – The resistance of the CoM to changes in height when an exernal vertical force is being applied.

Joint Stiffness – The resisitance of the joint to changes angular displacement when an external force is applied.

Foot Strike Pattern – The point of initial contact of the foot with the ground. A forefoot strike pattern occurs when the ball of the foot contacts before the heel and vice versa for a rearfoot strike pattern. A midfoot strike pattern occurs when both the ball of the foot and the heel contact simultaneusly.

List of Abbreviations

CoM –	Centre of mass
vGRF –	The vertical component of the ground reaction force
CRS –	Conventional running shoes
MFW –	Minimal footwear
PCECH –	Pronation control, elevated cushioned heel running shoes
Fz1 –	The impact peak of the vertical ground reaction force
Fz2 -	The active peak of the vertical ground reaction force
VFF -	Vibram "Five Fingers"®
RE -	Running economy ($\dot{V}0_{2sub\text{-}max}$)
SSC -	Stretch shortening cycle
FSP -	Foot striking pattern
RFS -	Rear-foot strike
MFS -	Mid-foot strike
FFS -	Fore-foot strike
SF -	Stride frequency
SBR -	Simulated barefoot running
BF -	Barefoot
BR –	Barefoot running
$_{rev}$SF -	Reversed stride frequency from the opposite footwear condition
RPE -	Rated perceived exertion
$\dot{V}0_{2max}$ -	Maximal oxygen consumption during exercise
MS -	Mid-stance
IC -	Initial contact
GRT -	Gait-retraining
COMBINED -	Minimal footwear and gait-retraining intervention combined
K_{vert} –	Vertical stiffness
K_{leg} –	Leg stiffness
K_{Ankle} –	Ankle stiffness
K_{Knee} –	Knee stiffness
$\overline{\mathbf{MF}}$ -	Mean maximal force
$\overline{\mathbf{MP}}$ -	Mean maximal pressure
$\theta IC_{Ankle/Knee}$ -	Angle at initial contact for the ankle/knee
$\theta MS_{Ankle/Knee}$ –	Angle at mid-stance for the ankle/knee

List of Publications and Communications

- "Four-week habituation to simulated barefoot running improves running economy when compared with shod running" – Scand J Med Sci 2013 - http://www.ncbi.nlm.nih.gov/pubmed/23252417.

- "A 4-week instructed minimalist running transition and gait-retraining changes plantar pressure and force" – Scand J Med Sci 2013 - http://www.ncbi.nlm.nih.gov/pubmed/24004458

- "Eight weeks gait-retraining in minimalist footwear has no effect on running economy" – IN REVIEW. *Human Movement Science*.

- "Kinetic and kinematic changes during a six week minimal footwear and gait-retraining intervention in runners." - IN REVIEW. *American Journal of Sports Medicine.*

- Poster and Abstract publication –American College of Sports Medicine 2012, San Francisco Conference – "Four Weeks Familiarisation To Simulated Barefoot Running Significantly Improves Running Economy Compared To Shod Running".

- The author has been involved in an expert consensus Delphi study in collaboration with the Laval University, Canada for development of a "minimalist index" that will be used to determine the degree of minimalism in footwear. IN REVIEW.

Conflicts of Interest

The author received a once-off donation of footwear for the present study from Vibram® (Milan, Italy). No honoraria or conditions have been attached to this donation, and the company has no direction or involvement in the research. No professional relationship exists between the company and the author.

Thesis Overview and Guidelines

This thesis has been formatted using the PhD by publication guidelines. Therefore each study has been presented within its own section in the format of a journal paper. Where additional data has been collected for each individual study but not reported in the paper, an Additional Data section has been attached to each study with the relevant information. These results are then discussed in the Global Discussion (Chapter Eight) in which the study findings have been tied together with respect to the aims and objectives of this research project (Chapter One). Because of this publication format, the review of literature (Chapter Two) has been restricted to a brief summary of the relevant areas. Chapter Three outlines the proposal of a familiarisation programme that has been designed during this research, in addition to the individual aims and objectives of each study following a review of the literature. Finally, chapters Four, Five, Six and Seven are the individual studies in a publication format with the relevant journal information attached. The overall conclusion to the research can be observed in Chapter Nine, as well as future recommendations.

CHAPTER ONE

Introduction, Aims and Objectives

1. Introduction

1.1 Background and Justification

The popularity of distance running as a sport and recreational activity is increasing worldwide. Recent data from the USA suggests that those regularly participating in running as a physical activity has increased by 10% since 2010 and now is in excess of 35million (Rothschild, 2012a). For competitive distance runners from club level to international athletes, the primary considerations of training are usually associated with improving performance and cardio-respiratory health. However, it has also been noted that running injury represents a major problem in these groups (Van Gent et al, 2007) and this has a major influence on training design.

Many of these athletes participate in endurance running. Endurance running has been classified as persisting at a sub-maximal intensity for prolonged periods of time over at least 5km but anywhere up to 200km (Noakes, 1988). Performance in endurance running can be quantified in a laboratory setting using physiological profiling, such as $\dot{V}0_{2max}$ testing, lactate profiling, fractional utilisation of $\dot{V}0_{2max}$, and running economy (Lucia et al, 2008). Of these, $\dot{V}0_{2max}$, fractional utilisation of $\dot{V}0_{2max}$, and running economy (RE) have been considered the largest predictors of endurance running performance (Daniels and Daniels, 1992; Astorino, 2008; Bassett and Howley, 2000). Likewise, the successful prevention of injury will ultimately decrease missed training time and has a direct effect on performance thus making it an important consideration in any training routine. Athletes adopt multiple strategies in order to run injury free, such as compression clothing, ice baths, footwear, periodised strength and conditioning programmes etc., but despite the numerous technological advances and investment in research, running related injury remains a significant problem (19.4 to 79.3% of runners are injured every year; Van Gent et al, 2007).

Over recent years, the most abundant product marketed and sold to both prevent injury and improve performance is the conventional running shoe (CRS). Perhaps the most common “selling point” of CRS is the cushioning properties, since the foot comes into contact with the floor over 600 times per km and this generates a noticeable impact (Lieberman et al, 2010). These repeated impacts are believed to be involved in running related injury (Hall et al, 2013; Milner, Hamill and Davis, 2006; Pohl, Hamill and

Davis, 2009; Cheung and Davis, 2011; Davis, Milner and Hamill, 2004). Several authors have suggested that increasing the cushioning of running shoes and surfaces would reduce these impact forces (Cavanagh and Lafortune, 1980; Theisen et al, 2013). However, the ability of cushioned running shoes to reduce impact forces on runners has been found to be inconclusive, with no difference or even higher impact peaks being observed in CRS compared to barefoot or harder midsole footwear (Nigg, 2010; Schwellnus, Jordaan and Noakes, 1990; Squadrone and Gallozzi, 2009; Lohman et al, 2011; Aguinaldo and Mahar, 2003; Shorten, 2002). This may be largely dependent on the foot strike pattern adopted by runners (Lieberman et al, 2010), and it has been suggested that runners have a tendency to rearfoot strike in CRS due to reduced proprioceptive feedback from the foot that induces impact attenuation behaviours compared to barefoot running (Lieberman et al, 2010; Robbins and Hanna, 1987; Robbins, Hanna and Jones, 1988; De Wit, De Clerq and Aerts, 2000). This rearfoot strike pattern may be a cause of higher impact forces in runners (Lieberman et al, 2010).

In addition, the role of CRS in improving performance is not supported by a review of the literature (Richards, Magin and Callister, 2009). Previous to the running boom of the 1970’s, sports shoes were mainly constructed of flexible uppers attached to a thin rubber outsole, but have gained mass and structure over the years (Altman and Davis, 2012a). As early as 1979 researchers suggested that shoe mass had a detrimental effect on running economy and ultimately performance (Caitlin and Dressendorfer, 1979). Running economy, defined as the oxygen cost of running at a fixed steady state exercise intensity, has been considered a strong predictor of endurance performance in a homogenous group of runners (Lucia et al, 2008), and presents a feasible measure for determining differences in the metabolic cost of transport with running footwear. There are potential elastic elements of the foot and ankle that may not be fully utilised during CRS running with a rearfoot strike pattern (Perl, Daoud and Lieberman, 2012), but in contrast there may be a metabolic cost to cushion the body when shoe cushioning is absent (Franz, Wierzbinski and Kram, 2012).

Thus, in addition to the high incidence of reported injury in runners (Van Gent et al, 2007), there is a distinct lack of evidence that CRS footwear can reduce the risk of injury or improve performance (Richards, Magin and Callister, 2009). Furthermore the publication of the internationally acclaimed bestselling book "*Born to Run*" by Christopher McDougall in 2009 increased public awareness of the issue and created a worldwide interest in barefoot running which has grown exponentially over the last 4-5 years. This "barefoot running theory" became widespread, centred around three proposed benefits of barefoot running (Gallant and Pierrynowski, 2014); 1) a decrease in foot atrophy and increased foot function (e.g. Robbins and Hanna, 1987), 2) increased proprioceptive feedback (e.g. Robbins et al, 1997), and 3) a running gait that is more "natural" compared to that in CRS (e.g. Lieberman et al, 2010). Whilst many of these claims are anecdotal, "*the correct null hypothesis is that running barefoot is less injurious than running in a shoe unless proven otherwise*" (Lieberman, 2012, pp65). As a result, a study by Rothschild (2012a) identified that among 785 runners using an online questionnaire, 76% had an interest in barefoot running, and 22% have already implemented some kind of barefoot activity into their training. In response to this increase in interest worldwide, footwear manufacturers began producing "minimal" footwear (MFW) that claimed to have all the benefits of running barefoot whilst providing some degree of protection for the foot on modern surfaces (Jenkins and Cauthon, 2011; Lohman et al, 2011). MFW are shoes with a smaller mass, greater sole flexibility, lower profile, and lower heel-to-toe drop than CRS (Lussiana et al, 2013). MFW have been described as a "barefoot" alternative, however they are not the same as barefoot (Squadrone and Gallozzi, 2009; Willy and Davis, 2014; Bonacci et al, 2013), and so require consideration as a different shoe modality than barefoot or CRS (Sinclair et al, 2013; Bonacci et al, 2013).

With an increase in runner's interest in MFW running in habitually shod populations, runners are now attempting to switch to a "more natural" running condition, and therefore have to undergo a period of familiarisation to this footwear type that lacks conventional protection. Runners attempting to transition to MFW must either adapt their running kinematics to suit a novel footwear condition and/or adapt the musculoskeletal system in order to accommodate different forces acting on the body due to changes in leg geometry/loading and footwear protection. How well runners in the developed world can transition to MFW remains to be determined, and is leading into an area that lacks evidence based research. This "transition" phase to more minimal running footwear may pose a greater risk of injury for runners (Cauthon, Langer and Coniglione, 2013; Ryan et al, 2013). Already there is evidence of an increased rate of metatarsal stress fractures in the MFW condition during this transition period (Giuliani et al, 2011; Cauthon, Langer and Coniglione, 2013; Ridge et al, 2013), due to higher localised plantar pressures in MFW compared to CRS (Qiu and Gu, 2011; Squadrone and Gallozzi, 2009). Also, a high injury rate in minimalist shoes during a 12 week transition has been observed (Ryan et al, 2013), due to potentially higher rates of impact (Willy and Davis, 2014), increased peak plantar pressures (Squadrone and Gallozzi, 2009), and triceps surae soreness (Willson et al, 2014) in the MFW runner.

Advocates of MFW (or barefoot) running have suggested that the running gait is more important than what is worn on the feet (Lieberman, 2012), however many runners do not seemingly adopt a "barefoot style" gait when running in MFW. This "barefoot" running style (such as a prevalence of non-rearfoot striking and shorter strides) has been modelled using habitually barefoot Kenyans (Lieberman et al, 2010). This has led to the resurgence of "natural" gait-retraining elements being suggested to reduce the risk of running related injury and potentially improve RE (Crowell and Davis 2011; Goss and Gross, 2013; Gouttebarge and Boschman, 2013; Perl, Daoud and Lieberman, 2012). These ideas come from preliminary research suggesting changes in posture (Lieberman et al, 2010), foot strike pattern (e.g. Lieberman et al, 2010; Daoud et al, 2012) or stride frequency (e.g. Hobara et al, 2012) are the most important gait elements to successful running. Gait-retraining for runners may be important during this transition to MFW, because some runners have been found not to adopt "barefoot style" kinematics in MFW (Bonacci et al, 2013) and may be at increased risk of loading injuries (Willy and Davis, 2014). These runners may benefit from added instruction during this transition, however despite runners now adopting MFW running in combination with gait-retraining in the general public, no academic research has investigated both of these elements together with regard to performance or running related injury.

In addition, very little research has examined the differences between running in CRS and MFW, both before and after a familiarisation period to MFW, in order to determine which footwear may be more beneficial to reduce running related injury or improve performance. Whilst studies have examined this difference during acute measures, the understanding of differences between footwear types (MFW and CRS) when participants are familiar with both footwear types and not just one is important for future footwear prescription.

There is clearly a need to better our understanding of this familiarisation to a novel footwear type, and a significant number of researchers are now calling for habituation studies (e.g. Sinclair et al, 2013; Hall et al, 2013; Rothschild, 2012b; Jenkins and Cauthon 2011; Lieberman, 2012). There are three important questions for this transition that demand attention in the literature; 1) is there any change in performance or factors related to injury as the result of this transition to MFW (with or without additional gait-retraining)?, 2) what are the differences in performance or factors related to injury between running in MFW and CRS? Both at the acute stage but also following a familiarisation to MFW, and 3) what is the best approach to a transition to MFW to reduce the risk of injury?

1.2 Aim and Objectives

Study Aim:

To investigate any change in running economy or factors related to injury before and after a MFW transition with gait-retraining, when comparing both CRS and MFW.

Objectives:

1. To investigate the influence of a MFW transition and gait-retraining on;
    - Running economy
    - Plantar pressures
    - Impact forces
    - Running Kinematics
2. To determine differences in any of these variables between MFW and CRS, irrespective of this familiarisation period.
3. To establish a safe and reasonable transition schedule in order to provide some guidelines for future prescription of MFW running.

CHAPTER TWO

Review of literature

2. Review of Literature

The purpose of this literature review is to provide the background literature in the relevant areas to this study. This section has been divided into two main sections; the first half is concerned with running performance, with particular attention to how changes in footwear and the adoption of gait-retraining elements can influence running economy. The remaining half of the section will consider running related injury, with respect to the current rate of injuries experienced today, the kinetic and kinematic factors associated with injury, and how the use of footwear and gait-retraining can influence these factors.

2.1 Factors Related to Performance in Endurance Running

Endurance running, characterised by any event above 5,000m, has been strongly associated with aerobic metabolism (Noakes, 1988). In addition, when considering the evolutionary theory that early bipedal activity was dictated by the need to "persistent hunt" (Lieberman, 2012), it has been suggested that the majority of this activity was conducted at very low velocities (Hatala et al, 2013), and therefore this submaximal "aerobic" intensity should be examined with respect to footwear._ Aerobic factors related to performance have been related to 1) the maximal aerobic capacity of an individual ($\dot{V}0_{2max}$), 2) how much of this maximal capacity can be utilised for a prolonged period of time (fractional utilisation of $\dot{V}0_{2max}$), 3) the lactate threshold, and 4) the 0_2 cost of transporting the body at any given speed under steady state conditions (Running economy - RE) (Lucia et al, 2008; Midgley, McNaughton and Jones, 2007). Of these, $\dot{V}0_{2max}$, fractional utilisation of $\dot{V}0_{2max}$, and RE have been considered the strongest predictors of endurance running performance (Daniels and Daniels, 1992; Astorino, 2008; Bassett and Howley, 2000). Factors that can influence these performance measures include but are not limited to; muscle fibre type, mitochondrial density, red blood cell profile, stroke volume, aerobic enzyme activity, and buffering capacity (Astorino, 2008; Coyle, 1999), as well as central governor mediated fatigue (Noakes, Gibson and Lambert, 2005).

During this review, many of these factors cannot be influenced by changes in footwear and will not be discussed further. In fact, of the determinants of endurance performance listed above, only RE has been found to be sensitive to changes in footwear to this date (See section 2.3). Also, RE has been shown to be the most reliable indicator of endurance performance in a similarly trained group of runners (Lucia et al, 2006; Daniels, 1985; Di Prampero et al, 1993; Kyrolainen, Belli and Komi, 2001). It has been suggested that RE may explain up to 65% of race performance over 10km ($\dot{V}0_{2max}$ r=-0.12, RE r=0.8; Conley and Krahenbuhl, 1980) and was negatively correlated with 5km race performance in 10 athletes who improved run performance and RE following a 9 week explosive strength training programme (r=-0.54; Paavolainen et al, 1999a). RE has been associated with performance through comparison between trained and untrained athletes, where trained athletes have an improved RE and can thus operate at the same intensity using a lower fractional utilisation of $\dot{V}0_{2max}$ (Astorino, 2008). Chronic changes to both $\dot{V}0_{2max}$ and RE have been observed with endurance training, however elite male and female athletes were not found to improve $\dot{V}0_{2max}$ over three years despite improvements in performance. This improvement in performance was primarily attributed to improvements in RE (Arrese et al, 2005). Finally, a better RE and fractional utilisation of $\dot{V}0_{2max}$ was observed in African elite runners versus elite Caucasian runners, which was suggested to explain the African dominance of endurance running (Weston, Mbambo and Myburgh, 2000). These factors combined suggest a strong relationship between RE and performance.

Running economy represents a feasible and stable measure for determining the metabolic cost associated with exercise, since 1) the steady state measurement does not take into account contribution from anaerobic metabolism that could influence the 0_2 cost of the exercise, and 2) daily variation in RE has been found to be very stable in moderate and well-trained endurance athletes (less than 2 $ml \cdot kg \cdot min^{-1}$ variation; Williams, Krahenbuhl and Morgan, 1991; Saunders et al, 2004a). There are several important factors that should be controlled when examining RE, these include but are not limited to; time of day, day of the week, fatigue, training status, treadmill accommodation, running surface, gender, age, temperature, nutritional status, and footwear (Saunders et al, 2004b; Williams, Krahenbuhl and Morgan, 1991; Morgan, Martin and Krahenbuhl, 1989).

The magnitude of any change in RE has also been specifically related to performance, with a 5% improvement reported to relate to a 3.8% increase in run performance (Di

Prampero et al, 1993), however the smallest worthwhile change has been suggested to be 2.4% (Saunders et al, 2004a). Therefore, RE may be a suitable measure for determining if footwear can influence performance in endurance running if any change exceeds 2.4%. Indeed "*if it is assumed that an individual's race pace is one that maximally taxes his/her physiological capacities, then changes that allow a runner to use less energy at a given speed of running should prove advantageous , since they would allow a faster pace with the same relative effect on physiological capacities*" (Williams and Cavanagh, 1987, pp 1239).

Factors associated with changes in RE that are related to the present work are restricted to footwear effects, in this case, it is important to remember that footwear influences several important parameters that may have a measureable influence on RE. In particular running biomechanics and neuromuscular factors such as leg stiffness, these will be discussed in the next section.

2.2 Running Biomechanics and Running Economy

Running differs from walking in that a period of "double float" occurs in running where there is no point of contact with the ground as the runner "bounds" through the air (Figure 2.2a). The gait cycle begins and ends with the same foot contact with the floor. This initial contact has been the source of much scientific interest, since the foot-ground collision has been suggested to play a role in running related injury (Lieberman et al, 2010). Following initial contact, the leg undergoes a period of absorption, in which the body centre of mass (CoM) is lowered and decelerated until the leg reaches maximal compression (mid-stance). The leg and hip musculature then undergo a propulsion phase in which the CoM is pushed upwards and forwards as the leg extends until the point that the toe leaves the ground (toe-off). During the following flight phase, the leg is brought under the hips and anteriorly to prepare once again for initial contact (Ounpuu, 1994). During this running action, the numerous muscle-tendon units of the leg are used to store elastic energy during the absorption phase, and recoil during the propulsion phase (Lohman et al, 2011; Alexander, 1991). This results in a greater force being produced and reduced expected cost of transport when running (See “The stretch shortening cycle explained”, Figure 2.2b).

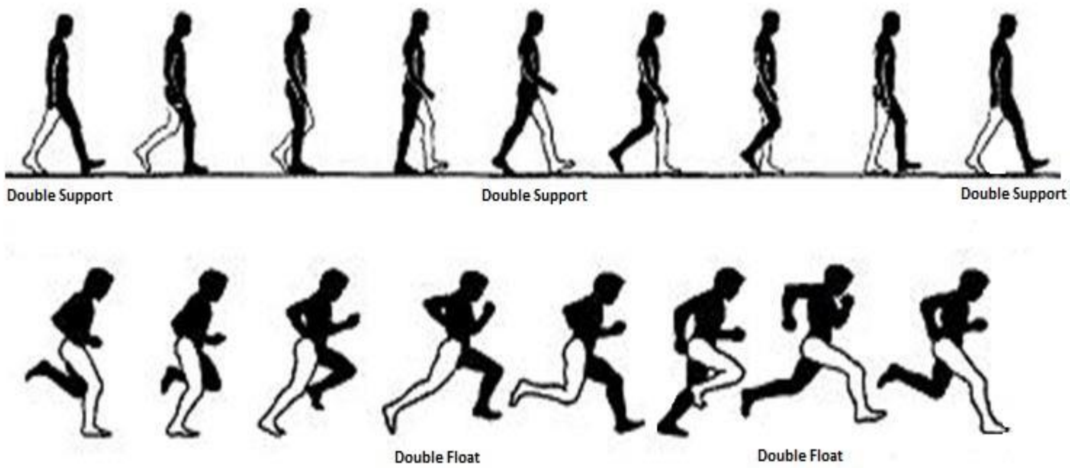


Figure 2.2a. *The walking (top) and running (bottom) gait cycle. During walking, one foot is always in contact with the floor; in contrast running involves a period of “double float” in which the body is airborne.*

The numerous springs of the lower leg (Achilles tendon, medial longitudinal arch, illiotibial band, quadriceps femoris) are suggested to reduce the metabolic cost of transport by as much as 50% (Alexander, 1991). The majority of this “metabolic saving” is thought to be due to the foot longitudinal arch (17%; Ker et al, 1987), and the Achilles tendon (35%; Alexander, 1991). Thus, running can be considered to be moving along the ground in a bouncing fashion, where energy is constantly stored and returned in the musculoskeletal system. This has been modelled like a single linear spring, in which compression of the leg and centre of mass during the first half of stance represents absorption of energy into the spring, and this energy is released during the recoil and extension of the leg up until the point the body leaves the floor (Cavagna, 1977; Bishop et al, 2006).

Figure 2.2b. The stretch shortening cycle explained

The combination of an eccentric muscle contraction immediately followed by a concentric muscle contraction is known as the stretch-shortening cycle (SSC) (Van Ingen, Bobbert and Haan, 1997). A SSC muscle action has been shown to enhance the maximum work output during the concentric phase (Asmussen and Bonde-Petersen, 1974). The SSC utilises both the recoil of elastic tissue and reactive properties of the muscle to generate this increased force production when compared to a simple concentric movement (Wilk et al, 1993). When a muscle is loaded during an eccentric muscle action, this load is transferred to the series elastic component of the muscle tendon complex and stored as elastic energy. When this eccentric muscle action is immediately followed by a concentric muscle action, this stored elastic energy is released causing an increase in force production (Baechle and Earle 2008; Asmussen and Bonde-Petersen, 1974). With regard to the reactive properties of muscle, during an eccentric muscle action, muscle spindles, which are proprioceptive organs within the muscle, detect a rapid stretch. This results in a reflexive muscle action, which causes an increase in the activity of the agonist muscle groups, increasing the force production of that muscle (Wilk et al, 1993).

There are three distinct phases in the SSC; The eccentric phase, the amortization phase and the concentric phase. The amortization phase, also known as the coupling phase is the time delay period between the end of the eccentric muscle action and the beginning of the concentric muscle action. The important features needed for an effective SSC function include well timed pre-activation of the muscles before the eccentric phase, a short and fast eccentric phase and a short amortization phase (Komi and Nicol, 2000). When there is no time delay between eccentric and concentric muscle action, there is a greater force potentiation during the concentric phase. When there is a longer time delay between eccentric and concentric muscle action, there is a significant reduction in the force potentiation effect during the concentric phase, due to energy being lost as heat. In the context of the gait cycle in running, the amortization period has been associated with ground contact time. Therefore it may be suggested that a shorter ground contact time during running may elicit a greater force potentiation during the concentric or propulsion phase of stance (Komi, 1984). Hence, increasing the neuromuscular control of running may exhibit a reduction in ground contact time and increase in the SCC function. This increase in the potential for force production as well as a reduction in the contractile demand of the muscle resulting in greater efficiency has been correlated with running performance (Bonacci et al, 2009; Divert et al, 2005b; Spurrs et al, 2003).

The metabolic cost of running therefore is not only a cost of the muscular action required to decelerate the CoM and propel the body forwards, but is also largely influenced by the action of the stretch shortening cycle (SSC) contributing to the mechanical energy cost of this movement. This can be influenced to a certain extent by biomechanical factors, as discussed in the next section.

2.2.1 Biomechanics Factors Associated with Running Economy

The understanding of the relationship between biomechanics and RE is still in its infancy, in fact a global explanation of RE may be too complex to be associated with individual factors such as running kinematics. When considering the factors influencing RE, biomechanical variables are not believed to be as considerable as physiological factors (Williams and Cavanagh, 1987). Furthermore, it has been suggested that RE may not be related to kinematic characteristics of running at all (Arampatzis et al, 2006). However it has also been suggested that runners optimise the running gait based on O_2 consumption and not for shock attenuation (Hamill, Derrick and Holt, 1995; Moore, Jones and Dixon, 2013), and some limited correlations between running biomechanics and RE have been observed (Saunders et al, 2004b; Williams and Cavanagh, 1987; Heise and Martin, 2001).

One example of how changes in running mechanics are suggested to improve RE is through more effective use of the SSC. This storage and restitution of elastic energy is dependent on the leg geometry during stance, for example the leg spring mechanics will be different with a forefoot strike pattern than a rearfoot strike pattern (Perl, Daoud and Lieberman, 2012). The Achilles tendon is believed to recover as much as 35% of energy through elastic recoil (Alexander, 1991) that can only occur with an initial eccentric action on this structure that does not occur with a rearfoot strike pattern (Perl, Daoud and Lieberman, 2012). This improved elastic recoil with a forefoot strike pattern may however be at the cost of increased mechanical work as the triceps surae attempt to control the dorsiflexion moment with eccentric contraction (Perl, Daoud and Lieberman, 2012).

A comparison of athletes who exhibit better RE than others may provide some important information on the kinematic variables associated with more economical running. However, large inter and intra-individual variation reported in RE and kinematics among runners (e.g. Tung, Franz and Kram, 2014) has resulted in some conflicting findings between these factors. There are numerous factors which may explain this variation; Firstly, a lower ground contact time has been suggested to improve RE (Kram and Taylor, 1990; Nummela, Keranen and Mikkelsson, 2007) as less time is available for force production (Kram and Taylor, 1990), and the amortization phase of the SSC is reduced thus resulting in increased elastic energy contribution (Nummela, Keranen and Mikkelsson, 2007). Indeed faster runners were observed to have a smaller contact time in an elite half marathon (Hasegawa, Yamauchi and Kraemer, 2007), and reducing contact time with explosive training significantly improved RE (Paavolianen et al, 1999a). However in an early study, Williams and Cavanagh (1986) found that a better RE was correlated to longer contact time. Finally, several studies have found no relationships between RE and contact time (Kyrolainen, Belli and Komi, 2001; Storen, Helgerud and Hoff, 2011). Therefore, the role of contact time with respect to the stretch shortening action requires further investigation.

Second, runners with a good RE were observed to take longer strides with a more dorsi-flexed foot strike pattern than matched runners with a RE that was worse (Williams and Cavanagh, 1987). This contradicts earlier work by Cavanagh, Pollock and Landa (1977) who observed that increased stride frequency (and therefore a shorter stride length) was correlated to better RE. Likewise, more recent work investigating how foot strike patterns can influence RE has been inconclusive (Section 2.2.2.2), that does not support the concept that a rearfoot strike pattern is any more efficient than a forefoot strike pattern. Also, several authors have suggested that runners self-select a stride frequency that is most economical (Hogberg, 1952; Cavanagh and Williams, 1982; Moore, Jones and Dixon, 2013).

To further confound matters, a study by Kyrolainen, Belli and Komi (2001) found that contact time and stride frequency did not correlate with RE. Instead, the authors found that increased braking forces and higher muscle activation were the only factors in that could help explain differences in RE, but this was not conclusive. In addition a lower vertical impact peak (Fz1) has been correlated with improved RE elsewhere (Williams and Cavanagh, 1987; Heise and Martin, 2001) and so both the braking force and peak impact force may be related to RE (Kyrolainen, Belli and Komi, 2001; Williams and Cavanagh, 1987; Heise and Martin, 2001). However, in both Kyrolainen, Belli and Komi (2001) and Williams and Cavanagh (1987), the authors conclude that no predominant factors became obvious as predictors of running economy. This would support Arampatzis et al (2006), who suggests RE is not influenced by kinematic factors. This area demands future research comparing groups who adopt different styles, as most research in this regard today uses deliberate changes to technique in running and this may not be appropriate for measuring how kinematics influence RE (Williams and Cavanagh, 1987).

Other biomechanical factors that have been examined with regard to RE can be observed in Table 2.2.1 (Saunders et al, 2004b). From this table it appears as though the upper body can also influence RE and this has received very little attention in the literature to this date. However, we have no evidence that footwear can influence arm movements and therefore this factor is not considered further. A lower vertical oscillation of the CoM (vertical oscillation) (Williams and Cavanagh, 1987; Cavanagh, Pollock and Landa, 1977; Saunders et al, 2004b), greater trunk angle, increased knee flexion during stance (Williams and Cavanagh, 1987), less plantar-flexion at toe-off, and increased knee flexion (Moore, Jones and Dixon, 2007) may be associated with a better RE but require further investigation also.

Table 2.2.1. Biomechanical factors that may influence RE. Adapted from a review by Saunders et al (2004b).

Factor	Description for better RE
Stride length	Freely chosen over considerable training time
Vertical oscillation of the CoM	Lower
Arm motion	Not excessive
Plantar-flexion at toe-off	Less range of movement but greater angular velocity
Transverse plane shoulder rotation	Lower
Vertical impact peak (Fz1)	Lower
Elastic energy	More effective use of SSC

It is believed that runners adopt their most economical running style over time (Nelson and Gregor, 1976), and so it will be important to examine how deliberate changes to the running gait can influence RE in the literature. This is discussed in the next section.

2.2.2 Gait Changes and their Relationship to Running Economy

It has been suggested as early as 1952 that the self-selected running kinematics (such as freely chosen stride length) is the most economical for human movement and is worsened with deliberate changes (Hogberg, 1952; Morgan et al, 1994). Indeed, "*it is reasonable to predict that during a training programme runners use a self-optimisation process to develop movement patterns that minimise energy cost and stresses on the body*" (Lake and Cavanagh, 1996, pp 860). Therefore, it may be appropriate to suggest that runners who attempt to deliberately manipulate the running gait could experience a decline in RE, and indeed this appears to be the case in the literature (e.g. Tseh, Caputo and Morgan, 2008). If deliberate changes in running technique resulted in increases in the metabolic cost of running, then it is possible that the onset of fatigue would occur sooner in these athletes, potentially increasing the likelihood of injury and reducing performance. One study has demonstrated negative changes to RE with largely exaggerated changes to running technique (Tseh, Caputo and Morgan, 2008), but no studies have clearly demonstrated improved RE with any gait changes. In an early study by Williams and Cavanagh (1987) it is stated that "*it is possible that changing one [biomechanical] variable would lead to a myriad of changes in others, and the effects of such a change [on RE] could be unpredictable*" (Williams and Cavanagh, 1987, pp 1244). However, there is a paucity of evidence suggesting that changes in biomechanical variables with training have any influence on RE over time (Lake and Cavanagh, 1996).

The popular use of gait-retraining packages such as "POSE" running has recently been assessed with regard to RE, which characterises a "midfoot to forefoot strike pattern, minimal ground contact time, and a picking up of the feet with no pushing forcefully off the floor" (Goss and Gross, 2012b, pp 63). This method attempts to teach athletes to run "more efficiently" by falling forward using gravity whilst simply pulling the trail leg up underneath the hips. However, this intervention was found to result in a decline in RE (Dallam et al, 2005), or have no effect (Fletcher, Esau and MacIntosh, 2008). Likewise a novel "midstance to midstance" running class was found to have no significant effect on RE over 8 weeks (Craighead, Lehecka and King, 2014). The use of verbal and visual feedback for gait-retraining over 5 weeks was also found to have no effect on RE (Messier and Cirillo, 1989).

As discussed in the introduction section, several simple kinematic changes that runners are now adopting as a means to run "more naturally" include increasing stride frequency and adopting a mid or forefoot strike pattern. However the impact of these modifications to the running gait on RE are mixed;

2.2.2.1 Stride Frequency and Running Economy

Increasing stride frequency to +10% of self-selected has been found to be detrimental to RE, but anything less than or equal to 10% has had minimal effect on metabolic cost (Cavanagh and Williams, 1982). Stride length will also influence stride frequency, and in one study it was suggested that a 10% reduction in stride length does not change 0_2 consumption and heart rate when compared to the preferred rate (Hamill, Derrick and Holt, 1995). In contrast, Connick and Li (2014) have suggested that a 2.9% decrease in stride length was found to promote vastus lateralis and biceps femoris pre-activation and was more economical than the freely chosen stride length (Connick and Li, 2014). Likewise when 9 uneconomical runners underwent a 3 week biofeedback programme to reduce stride length by 10%, a marked reduction in freely chosen stride length as well as an improvement in RE was observed (Morgan et al, 1994). This suggests that uneconomical runners have not adapted to their most economical running pattern and may benefit from some kinematic intervention, although this requires further research. Increased stride frequency has been found to increase K_{leg}, but this was not compared to a change in RE (Giandolini et al, 2013a; Farley and Gonzales, 1996).

2.2.2.2 The Foot Strike Pattern and Running Economy

The foot striking pattern has been categorised into three distinct movements – a rearfoot strike pattern in which the heel contacts the ground first, a forefoot strike pattern in which the anterior plantar surface of the foot is the first to contact the floor, and a midfoot strike pattern, characterised by a simultaneous contact of the heel and forefoot at the same time, with the foot flat (Lieberman et al, 2010). Adopting a forefoot strike pattern has been found to reduce ground contact time (Kulmala et al, 2013), and this may play a role in improving the SSC as discussed above. Also, a midfoot or forefoot strike pattern has been suggested to implement more elastic recoil of the lower leg (Ardigo et al, 1995; Perl, Daoud and Lieberman, 2012). However, making athletes adopt either a rearfoot or forefoot strike pattern was found to have no effect on RE (Ardigo et al, 1995; Perl, Daoud and Lieberman, 2012; Cunningham et al, 2010; Gruber et al, 2013a). Whilst one might assume this means there is no difference in the energy cost of adopting either a rearfoot or forefoot strike pattern, it is important to remember that this could be interpreted as a forefoot strike pattern being more efficient. This is because a forefoot strike pattern requires more mechanical work than a rearfoot strike pattern due to higher contractile activity during the initial phase of ground contact, and so the increased metabolic cost may be counteracted by a better SSC (Ardigo et al, 1995; Perl, Daoud and Lieberman, 2012). In comparison, a rearfoot strike pattern uses passive structures to a higher degree in order to decelerate the body during initial contact, and this requires less muscular activity (Williams and Cavanagh, 1987), although potentially at the risk of higher patellofemoral forces and loading on the lower extremity (See section 2.6.2.3). The lack of any difference in RE between a rearfoot and forefoot strike pattern was true for habitual forefoot and rearfoot strikers (Perl, Daoud and Lieberman, 2012; Gruber et al, 2013a), and novice forefoot and rearfoot strike runners (Gruber, Russell and Hamill, 2009). However, one study that did not compare the same participants adopting different foot strike patterns but instead compared a rearfoot strike pattern versus a midfoot strike pattern in different groups, found the rearfoot striking group to be more economical runners (Ogueta-Alday et al, 2013).

The understanding of how the foot strike pattern can influence RE is still in its infancy, and if runners aim to prioritise metabolic cost or impact attenuation with subconscious kinematic patterns is a much debated topic, largely due to the lack of studies examining this specific question. Hardin et al (2004) found that runners adopt a more extended knee and potentially higher impact shock in favour of a better RE when running on a hard surface. Likewise it has been observed that runners self-select a stride length to enhance RE rather than impact (Hamill, Derrick and Holt, 1995). However, numerous kinematic changes have been observed with changes in footwear and surface hardness that are clearly influenced by the need to attenuate impact (see section 2.7).

An important element of the running gait that needs to be considered is neuromuscular control as this can significantly influence running kinematics and muscular action. For example, the storage and restitution of elastic energy will be significantly influenced by neuromuscular control of lower body stiffness (Arampatzis et al, 2006; Spurrs et al, 2003). This is discussed in the next section.

2.2.3 Neuromuscular Factors Associated with Running Economy

Strength and endurance training combined has been found to improve RE and distance running performance, but have no effect on $\dot{V}0_{2max}$ (Paavolainen et al, 1999a). This change in RE without subsequent improvements in $\dot{V}0_{2max}$ may be largely due to improved neuromuscular factors (Nummela, Keranen and Mikkelsson, 2007) that result in a reduction in contact time, increased muscle pre-activation and increases in leg stiffness etc. (Paavolainen et al, 1999b).

Differences in neuromuscular control have been observed between novice and trained athletes in running (Chapman et al, 2008b). These differences relate to higher individual and population variance in the novice group that is not observed in the trained athletes. In addition, novice cyclists were found to display higher, longer and a more random sequence of muscle activity when compared to trained cyclists (Chapman et al, 2008a). These differences between groups suggest that training experience may result in improved neuromuscular control and this has been linked to improved RE (Bonacci et al, 2009; Morgan et al, 1995) and control of leg stiffness which may influence injury (Butler, Crowell and Davis, 2003). In addition, it has been noted that age can also play a role in neuromuscular control; older athletes were found to display higher muscular activity (Madhavan et al, 2009; Hoffren, Ishikawa and Komi, 2007), less utilisation of tendious tissue for elastic energy return (Legramandi, Schepens and Cavagna, 2013; Hoffren, Ishikawa and Komi, 2007), and a greater delay in closed-loop feedback mechanisms (Collins et al, 1995) when compared to younger individuals. Therefore is appears that both training status and age can influence neuromuscular control during running.

Of particular interest with regard to RE is lower body stiffness. Stiffness can be described as the relationship between the deformation of a body and a given force (Butler, Crowell and Davis, 2003) With regard to human movement, stiffness is a combination of all the individual stiffness values of the muscle, tendon, ligaments, cartilage and bone (Latash and Zatsiorsky, 1993). The leg, and stiffness (or compliance) of this structure, has traditionally been modelled on the behaviour of a single mechanical spring (Ferris, Louie and Farley, 1998). In order to maintain a constant vertical position and prevent collapse during the weight bearing portion of stance during running, leg stiffness (K_{leg}) is optimised based on surface characteristics and running velocity (Kuitunen, Komi and Kyrolainen, 2002; Kerdok et al, 2002). Any change in K_{leg} has been related to limiting local heel pressures, attenuating impact, and minimising metabolic cost of movement (Kong, Candelaria and Smith, 2009), mostly as a result of co-contraction of the agonist/antagonist muscles of the leg (Kuitunen, Komi and Kyrolainen, 2002). There are several measures of stiffness in the lower body (Table 2.2.3) and multiple ways of determining each, which has led to some degree of variation in results in this area (Butler, Crowell and Davis, 2003). For a review of methods for determining stiffness, see Brughelli and Cronin (2008). K_{leg} has been reported as reasonably constant during running irrespective of surface or footwear, but vertical stiffness (K_{vert}) can be sensitive to these factors (Butler, Crowell and Davis, 2003; Kerdok et al, 2002). This suggests that the body is sensitive to changes in surface hardness and modulates stiffness to maintain an overall value that is optimal for the task at hand (Lohman et al, 2011; Kerdok et al, 2002). Indeed, Ferris, Louie and Farley (1998) found that runners optimised K_{leg} during the first step on a new surface to maintain a constant leg-surface interaction (Ferris, Louie and Farley, 1998).

Table 2.2.3. *Different measures for lower body stiffness and their calculations (Butler, Crowell and Davis, 2003)*

Stiffness measure	Method of calculation
Leg stiffness (K_{leg})	$K_{leg} = F\text{max}/\ \Delta L$
Vertical stiffness (K_{vert})	$K_{vert} = Fmax\ /\ \Delta y$
Joint stiffness (K_{joint}; ankle, knee, hip)	$K_{joint} = \Delta M\ /\ \Delta\theta$

Where $Fmax$ = maximal vertical force, ΔL = change in vertical leg length, Δy = maximum vertical displacement of the CoM, ΔM = change in joint moment, and $\Delta\theta$ = change in joint angle. (It is important to differentiate between K_{vert} and K_{leg}. K_{vert} represents overall body stiffness defined by the relationship between the vertical ground reaction force (vGRF) and vertical displacement of the CoM, K_{leg} represents the stiffness of the lower extremity complex (foot, ankle, knee, and hip) calculated as the ratio between the vGRF and deformation in leg length. $K_{vert} > K_{leg}$ always in running because the leg compresses more than the CoM. They are related, but not synonymous (Lussiana et al, 2013).

With regard to RE, Heise and Martin (1998) found that a decrease in K_{vert} negatively correlated with O_2 consumption (r=-0.48), although the authors found no relationship between K_{leg} and $\dot{V}0_2$. Butler, Crowell and Davis (2003) identified that during running, increases in lower extremity stiffness was associated with increases in running velocity, decreases in stride length, and improved RE (Butler, Crowell and Davis, 2003). Likewise, increased K_{leg} has been associated with improved RE in a review by Kyrolainen, Belli and Komi (2001), and lowering K_{vert} increased 0_2 costs by as much as 50% in McMahon, Valiant and Frederick (1987). High muscle and leg stiffness has been related to increased utilisation of the SSC in the musculo-tendon unit, which may explain this relationship between increase stiffness and RE (Kyrolainen, Belli and Komi, 2001; Heise and Martin, 1998). Therefore it appears that any increase in stiffness would be advantageous to RE.

How and why runners adopt particular kinematics is currently poorly understood, but it may be that humans have a “preferred movement pathway” that will determine particular movements (Nigg, 2010). Footwear has been found to influence the running pattern and may have an effect on self-selected running kinematics and neuromuscular control. In addition, there are also mass and cushioning characteristics of footwear that may influence RE. These are now discussed.

2.3 The Influence of Footwear on Running Economy

CRS footwear exhibits some important differences to MFW or barefoot that can potentially influence RE. These include the cushioned sole which reduces the surface hardness on which the foot interacts, and a typically higher mass than MFW or barefoot (Figure 2.3). Other factors that should be taken into account are the degree of habituation to footwear or barefoot running, since longer term adaptations are as yet poorly understood with changes in footwear. Finally, the kinematic changes associated with CRS that can hypothetically influence the potential to implement the SSC should be considered. These will be discussed in the following sections.

Figure 2.3. A) The Vibram "FiveFinger"® model used as the MFW in the present work, and B) the Asics *"Cumulus"® model used as the CRS in the present work. Note the difference in mass and cushioning between these models.*

2.3.1 The Influence of Surface Hardness on Running Economy

The interaction of the foot and leg with a hard or soft surface will have important implications for RE. Running economy has been found to decline on softer surfaces and improve with increased surface stiffness (Hardin et al, 2004; Roy and Stefanyshyn, 2006; Kerdok et al, 2002). This effect may be highly variable with changes in shoe hardness resulting in very individual effects on RE. In a study by Nigg et al (2003), some runners were found to be more economical in soft shoes, and some in hard shoes. Simple changes to footwear design have been found to have an effect on RE; for example increases in shoe midsole stiffness was found to improve RE by 1% (Roy and Stefanyshyn, 2006).

The changes associated with surface hardness may be measured through K_{leg} changes. It seems reasonable to assume that increases in K_{leg} with softer footwear (Smith and Watanatada, 2002) occur in the same manner as increases in leg stiffness on compliant running surfaces (Ferris, Louie and Farley, 1998; Kerdok et al, 2002). However, both K_{leg} and K_{vert} were higher in the barefoot (harder surface) condition when compared to CRS in Divert et al (2005a). This finding of increased stiffness in the barefoot condition when compared to CRS has been consistently reported during running (De Wit, De Clerq and Aerts, 2000; Divert et al, 2005a, Divert et al, 2008). The reason that stiffness is higher barefoot is possibly due to shoe compression when in CRS that will be included in the CoM calculation (Butler, Crowell and Davis, 2013). Stiffness has been found to decrease on a very hard surface when footwear changes are not considered (Hardin et al, 2004). Therefore, it is important to remember that most stiffness calculations comparing barefoot/MFW to CRS includes shoe deformation and this will be a key factor in the SSC during running (Divert et al, 2005a).

Several authors have attempted to determine the joint stiffness values and their respective changes when running in the barefoot condition compared to CRS. Coyles et al (2001) found that participants who ran barefoot increased ankle stiffness and decreased knee stiffness when compared to CRS. The authors noted that it was essentially an equal trade off, where reductions in knee stiffness were matched with similar increases in the ankle to maintain constant leg stiffness. Hamill et al (2012a) also compared barefoot and CRS where inclusion was dictated only if participants adopted a forefoot strike pattern when running barefoot, and a rearfoot strike pattern in CRS. The authors found that only an increase in ankle stiffness was observed when barefoot, with no difference in knee stiffness between the two footwear conditions in both old and young runners. In contrast, when participants were asked to adopt a forefoot or rearfoot strike pattern in CRS, a similar crossover effect was observed but with the forefoot strike group adopting lower ankle stiffness values and higher knee stiffness (Hamill, Gruber and Derrick, 2012b). Since no foot strike pattern analysis or classification was observed in Coyles et al (2001), it is difficult to compare the results, but it may be reasonable to suggest that both footwear and the foot strike pattern influence stiffness. Most of these studies have calculated joint stiffness for the knee and ankle with the same methods, however the ankle is very likely to both dorsiflex and plantarflex with a rearfoot strike pattern during the first half of stance and the methods employed may overestimate ankle stiffness with this foot strike pattern. In contrast, a forefoot strike pattern will only experience dorsiflexion in the first half of stance and thus this overall change in joint angle will be higher. It may therefore be pertinent to measure ankle stiffness from the point at which the ankle beings to dorsiflex until midstance and thus measure "plantarflexion stiffness" in a manner that is universal to all foot striking patterns. A second limitation to the present work is that none of these studies examined these stiffness changes in relation to RE. The relationship between these variables is poorly understood in running, or may just be highly variable (Nigg and Enders, 2013). To elaborate, Arampatzis et al (2001) found that forefoot strike running increased knee stiffness and reduced ankle stiffness, and that the relationship was reversed with a rearfoot strike pattern. In contrast, in an earlier study by Hamill et al (2011), the authors noted an increase in ankle stiffness, and no change in knee stiffness when comparing 4/0mm drop shoes to 12/8mm and 20/16mm shoes, and suggested that the increased ankle stiffness was in order to mid-foot strike and prevent localised heel pressures. However the same author subsequently found a decrease in ankle stiffness with a more anterior foot strike pattern, which contradicts their own previous work (Hamill, Gruber and Derrick, 2012b).

Regardless of how this interaction occurs with changes in surface stiffness, if the overall lower body stiffness increases as a consequence of changes in footwear, it may result in optimised storage and reutilisation of elastic energy. This will reduce the mechanical work performed by the muscle and potentially improve RE (Latash and Zatsiorsky, 1993; Ferris, Louie and Farley, 1998; Kubo et al, 2007). "*Mammals use the elastic components of their legs (principally tendons, ligaments and muscles) to run economically, whilst maintaining consistent support mechanics across various surfaces*" (Kerdok et al, 2002, p1). Any decrease in surface stiffness will reduce the opportunity to implement elastic recoil despite concomitant increases in leg stiffness and support mechanics. However, a surface that allowed "rebound" with a 12.5% reduction in surface stiffness was associated with a 12% decrease in runner's metabolic rate (Kerdok et al, 2002) and therefore may have contributed to the return of elastic energy during the running action. Again, this has not been examined as a result of a footwear intervention, and so interactions between long term changes in leg and joint stiffness with changes in footwear type remain unexplored.

2.3.2. The Influence of Shoe Mass and Shoe Cushioning on Running Economy

The effect of carrying various masses on the foot has been examined with regard to RE. Once again, the current research in this area is conflicting and inconclusive. Several studies have concluded that for every 100g added to the foot, RE increases by 1% (Frederick, Daniels and Hayes 1984; Divert et al, 2008; Franz, Wierzbinski and Kram, 2012), although this may represent a spectrum and not a definitive value, with heavier shoes resulting in greater changes to RE than lighter footwear (Franz, Wierzbinski and Kram, 2012). Whilst it has been suggested in a number of studies comparing barefoot and CRS running that 100g of shoe mass adds 1% to running economy (Burkett, Kohrt and Buchbinder, 1985; Divert et al, 2008; Flaherty, 1994; Frederick, Daniels and Hayes, 1984; Hanson et al, 2011; Franz, Wierzbinski and Kram, 2012; Pugh, 1970), few have found a statistically significant difference in RE between these conditions due to mass (Burkett, Kohrt and Buchbinder, 1985; Divert et al, 2008; Flaherty, 1994). Furthermore, no significant difference was observed in barefoot running compared to CRS with a shoe mass difference of +150g (Divert et al, 2008), +250g (Pugh, 1970), and +300g (Frederick, Daniels and Hayes, 1983) respectively. Hanson et al (2011) did find a significant difference in RE for barefoot and CRS running, but the methods of this study have been suggested to be erroneous resulting in barefoot running being slower than CRS running (Kram and Franz, 2012). This is because the authors attempted to control running velocity using a Nike+® system that ascertained this value from step frequency, and the difference in stride length and frequency between barefoot and CRS running was not accounted for. Thus the 5.7% lower 0_2 cost when running over ground barefoot vs CRS should be interpreted with caution.

In contrast to the mass theory, barefoot running may offer no extra metabolic savings compared to a lightweight cushioned running shoe (Franz, Wierzbinski and Kram, 2012; Tung, Franz and Kram, 2014), due to a “cost of cushioning” effect when using a slightly cushioned (10mm) surface or ultra-lightweight footwear. The “cost of cushioning” theory by Franz, Wierzbinski and Kram (2012) suggests that there is an increased mechanical cost in actively attempting to attenuate impact when no cushioning is present. However, this was not true for a 20mm soft surface in which no significant difference in metabolic cost compared to 10mm was observed (Tung, Franz and Kram, 2014). This is in contrast to studies that have found a higher metabolic cost with decreases in treadmill surface stiffness (Hardin et al, 2004), but this treadmill may have had excessive damping properties that resulted in this effect and may need to be controlled for (Tung, Franz and Kram, 2014).

Current evidence appears to suggest that any positive RE changes with cushioning seems to counteract the additional cost of the cushioning mass. For example, a lightweight cushioned MFW of 210g offered a -1.63% metabolic saving compared to barefoot (Tung, Franz and Kram, 2014), that should have resulted in an extra +2.1% metabolic cost due to mass (Divert et al, 2008). Likewise Franz, Wierzbinski and Kram (2012) did not find a statistically significant difference in RE cost comparing barefoot and CRS despite a mass difference, but when mass was controlled for a lightweight CRS resulted in a 3.4% lower RE (Franz, Wierzbinski and Kram, 2012). Interestingly, an early study by Williams and Cavanagh (1987) alluded to the cost of cushioning hypothesis stating “*lower energy costs might be related to the cushioning that takes place immediately following contact. Extreme rearfoot strikers might be able to let footwear and [passive] skeletal structures take more of the load, reducing necessary muscular forces to provide cushioning*” (Williams and Cavanagh 1987, pp 1242). This model does not however take into account elastic energy, and changes in footwear may influence this factor.

2.3.3 Elastic Energy Utilisation with Footwear

In a major study comparing habitually shod vs. unshod American and Kenyan runners, Lieberman et al (2010) hypothesised that habitually barefoot runners are much better suited to use elastic recoil of the lower leg than shod runners. The research group later confirmed this hypothesis by controlling foot strike pattern, shoe mass and stride frequency in habitually barefoot and MFW runners and observing a ~3% better RE in the habitually barefoot and MFW runners compared to CRS (Perl, Daoud and Lieberman, 2012). It was suggested that footwear limit the ability of the longitudinal arch to store and recoil elastic energy, as well as reducing knee stiffness and the potential to implement the SSC via the quadriceps. Interestingly the authors found a rearfoot strike pattern to be non-significantly more economical than a forefoot strike pattern (Perl, Daoud and Lieberman, 2012). This would support the earlier hypothesis that the use of passive structures in decelerating the leg upon impact demands less mechanical energy than a more active deceleration via eccentric loads in a forefoot strike pattern. However there are still "energy saving" opportunities in running that should be taken into account. For example, wearing CRS has been found to reduce the ability to sense joint position at the ankle (Squadrone and Gallozzi, 2009), which may reduce pre-contraction and the activity of increasing stiffness to enhance the SSC (Lussiana et al, 2013). Secondly, higher pre-activation of the plantar flexors and the reduction on contact time observed when barefoot has been suggested to be an important mechanism for improving the SSC during running (Divert et al, 2005b). Given that the majority of research examining the effect of footwear on RE use acute studies, it becomes very difficult to interpret how these factors will relate to RE over time. This is because acute changes to footwear may not identify how long term barefoot or MFW use adapts the body to better implement the SSC. In support of this, a study by Robbins and Hanna (1987) that found a significant shortening of the medial longitudinal arch of the foot with increased barefoot activity. This improvement in arch function and stiffness could hypothetically influence the SSC in the foot to the elastic energy opportunities in the medial longitudinal arch (Ker et al, 1987), which will not be observed in acute studies or novice barefoot/MFW runners.

2.3.4 Habituation to Footwear

The degree of habituation to barefoot or MFW running is an important factor in understanding the energy cost of running. In this regard, the findings of the existing literature is varied, with some studies using habituated barefoot or MFW participants (Squadrone and Gallozzi, 2009; Perl, Daoud and Lieberman, 2012; Franz, Wierzbinski and Kram, 2012), some with no experience (Burkett, Kohrt and Buchbinder, 1985; Flaherty, 1994; Divert et al, 2008), and some with irregular amounts of barefoot experience (Hanson et al, 2011). Perhaps the most robust study design in this regard is the study Perl, Daoud and Lieberman (2012), who used experienced barefoot runners with several controlled factors. The authors found that irrespective of foot strike pattern, habituated barefoot and MFW runners were more economical than habituated CRS runners (Perl, Daoud and Lieberman, 2012). Whilst this study is good, it does raise into question an interesting consideration; the study controlled for shoe weight and stride frequency, and also asked participants to deliberately adopt different foot strike patterns. However, these “effects” are an integral part of the difference between footwear, and so controlling for them may take away from the global difference between CRS and barefoot/MFW running. It may be feasible to suggest that more studies need to examine RE without any controlling factors to first determine these global effects, as they may have a more applied outcome to the current running generation. To elaborate, novice forefoot strike runners (who would normally rearfoot strike) have been found to increase the 0_2 cost and amount of carbohydrate contribution to total energy expenditure when compared to a habitual forefoot striking group (Gruber et al, 2013a). Therefore, asking runners to deliberately adopt a certain foot strike pattern may “contaminate” the observed effect with regard to RE.

2.3.5 MFW Research with Regard to Running Economy

Whilst many studies have compared CRS with barefoot running, only limited research has investigated how various MFW can influence running economy. MFW footwear exhibit varied designs and degrees of “minimalism” and so should not be grouped into one footwear sub-section necessarily. Instead these shoes should be each given individual scrutiny and considered separately.

Several studies have used the Vibram “FiveFinger”® (VFF) footwear when examining RE in runners. Perl, Daoud and Lieberman (2012) found a mean improvement in RE of 3.32% and 2.41% when rearfoot striking and forefoot striking respectively in the VFF condition when compared to a CRS. This footwear was also examined in Squadrone and Gallozzi (2009) and was found to be more economical than both barefoot and CRS running, that may support the “cost of cushioning” theory, despite being only a 3mm hard outsole. The shoe was also found to display some similarities to barefoot running with regard to kinematics and kinetics (for further details see section 2.8). Likewise Perl, Daoud and Lieberman (2012) suggest that improved energy storage and recoil in the longitudinal arch of the foot during VFF running may be very similar to barefoot running, since shoe longitudinal bending stiffness is much higher in CRS than in VFF's. The VFF is also the only shoe to simply offer a "skin" of protection for the foot whilst not impeding normal barefoot movement (Squadrone and Gallozzi, 2009), potentially making this the closest shoe available to being barefoot.

With regards to other commercially available MFW footwear, Lussiana et al (2013) found that RE was 1.9% better in MFW than CRS (Merrell "Trail Glove"® 187g vs 333g CRS). In a further study, running in a MFW (Merrell "Pace Glove"®) was 1.1% more economical than a CRS, but this was not found to be significant (CRS 541 vs. MFW 321g mass) (Sobhani et al, 2014). When considering the difference between these studies, the "Pace Glove" (Sobhani et al, 2014) was a heavier shoe than the "Trail Glove" used in Lussiana et al (2013), and therefore the mass difference to CRS was not as substantial in Sobhani et al (2014).

The Nike "Free (3.0)"® received attention in Tung, Franz and Kram (2014) with regard evaluating the effects of MFW on performance. The authors found no significant difference in metabolic cost when compared to barefoot. Likewise the ultra-lightweight Nike "Mayfly"® was found to offer no metabolic advantage over barefoot (Franz, Wierzbinski and Kram, 2012). Both of these shoes are lightweight (~150-250g) but offer at least 10mm of cushioning. Given that the difference in metabolic cost should be ~1.5-2.5% due to mass, the lack of any difference lends support to the "cost of cushioning" hypothesis outlined above. Why the Merrell and VFF footwear resulted in significantly better RE than the Nike shoes warrants further investigation. The Merrell and VFF footwear both exhibit hard thin outsoles, and so it may be the case that increases in proprioceptive feedback in these conditions mediate a greater kinematic change (see section 2.7) that improves RE when running in these shoes. This requires further examination.

2.4 Conclusion – Running Economy, Biomechanics, and Footwear

Based on the current scientific research, the metabolic cost of running barefoot vs MFW vs CRS appears to be highly varied. There may be several influencing factors including shoe mass, a metabolic cost of cushioning, or implementation of the SSC involved. The lack of any consensus may be due to a large degree of inter and intra-subject variation in this area (Nigg and Enders, 2013; Tung, Franz and Kram, 2014) and suggests that the individual effects of footwear on runners is highly variable. There may be a metabolic cost of transport associated with shoe cushioning due to higher muscular activity required to "cushion" the impact during foot contact when compared to barefoot, but this has not been observed in Merrell and VFF MFW. As a general rule, it has been suggested that there is a +1% metabolic cost for each 100g of mass added to a shoe, but this may only be true with heavier shoes. Lower body stiffness appears to change with footwear, and this may influence the SSC but has not been investigated over a familiarisation period. Popular gait changes such as increases in stride frequency and adoption of a mid or forefoot strike pattern do not seem to influence RE. Further, interventions that deliberately change natural gait parameters can be detrimental to RE but have not been considered over a very long habituation period (years).

2.5 Running Related Injury

Overuse injury of the musculoskeletal system is thought to occur when the bodily structures are exposed to a large number of repetitive forces, such as the cyclical action of the foot coming in contact with the ground during running (Lopes et al, 2012). These forces can cause micro damage and fatigue over time, even if the forces are well below the threshold for acute injury (Hreljac, Marshall and Hume, 2000). In the case of running, it has been suggested that 56% of recreational runners and 90% of marathoners will sustain a running related injury every year. Half of these will affect the patellofemoral joint (Taunton et al, 2002). Running related injuries have been used to classify the incidence of injury rates and the exposure to injury as a result of training hours (per 1000hours) or the amount of injuries experienced per 100 runners (Buist et al, 2010). Results vary in the literature from 30% to 79% of running related injuries per 100 runners, and injury incidence from 7 to 59 injuries per 1000 hours of training (Buist et al, 2010). The most common sites for injury and their prevalence have been summarised in Table 2.5a.

Table 2.5a. *Running related injury locations and their prevalence, a summary of the relevant literature.*

Author(s)	Description	Injury	Injury prevalence
Taunton et al, 2002	Retrospective analysis of 2002 running injuries	• Patellofemoral pain syndrome • Illiotibial band friction syndrome • Plantar fasciitis • Meniscal injuries • Tibial stress syndrome	Knee – 42.1% Foot/Ankle – 16.9% Lower leg – 12.8% Hip/Pelvis – 10.9% Achilles/Calf – 6.4%
Buist et al, 2010	8 week prospective study in 629 novice runners		30.1 injuries per 1000h of running
Theisen et al, 2013	5 month prospective study with hard and soft midsole shoes		12.1 injuries per 1000h of running
Bennett, Reinking and Rauh, 2012	Relationships between plantar flexor endurance, navicular drop, and leg pain.	Only measured “exercise related leg pain”	44.1% injured during a cross country season
Hespanhol et al, 2012	Injury questionnaire in 200 recreational runners	Knee most affected region (27.3%). In general main reported injuries were tendinopathies (17.3%), and muscle injuries (15.5%)	55% of runners in the last 12 months
Astorino, 2008	15 cross-country runners over a single season	• Shin Splints • Ankle Sprains • Stress fractures • Groin pulls • Back pain	50% of athletes in a competitive season
Schwellnus, Jordaan and Noakes, 1990	Shock absorbing insoles (n=237) vs. controls (n=1151)	Over 80% of injuries in the leg or knee. Tibial stress syndrome	22.8% injured in insoles, 31.9% injured in control group.

	over 9 weeks	and patellofemoral pain most common.	
Alonso et al, 2010	Injury rates at the IAAF World Athletics Championships	80% of injuries in the lower extremity – thigh strain was most common (13.8%)	135.4 injuries per 1000 athletes during the event.
Van Middelkoop et al, 2008	694 male marathon runners leading into a marathon	• Knee (28.7%) • Calf (27.2%) • Thigh (15.9%)	28% (before or during the marathon)
Knobloch et al, 2008	291 elite masters athletes	• Achilles tendinopathies (0.02/1000km) • Anterior knee pain (0.01/1000km) • Shin splints (0.01/1000km)	0.07 injuries per 1000km of running.
Tonoli et al, 2010	Systematic review	• Achilles tendinopathies • Illiotibial band friction syndrome • Medial Tibial stress syndrome	Between 0.1 and 2.6% in long distance runners
Van Gent et al, 2007	Systematic review	• Knee (7.2 - 50%) • Lower leg (9.0 - 32.2%) • Foot (5.7 - 39.3%) • Upper leg (3.4 - 38.1%) • Ankle (3.9 - 16.6%) • Hip/pelvis (3.3 – 11.5%)	Lower extremity: 19.4 – 79.3%. Whole body: 19.4 – 92.4%
Nielsen et al, 2014	Prospective study in 927 novice runners		253 of 927 runners sustained a running related injury in 1 year (26%).
Lopes et al, 2012	Systematic Review	• Medial Tibial Stress Syndrome • Achilles Tendinopathies • Plantar fasciitis • Patellofemoral pain syndrome	
Daoud et al, 2012	6 months of injury data in collegiate cross country runners comparing foot strike patterns - retrospective	• Muscle strains (21.5%) • Medial tibial stress syndrome (13.8%) • Patellofemoral pain syndrome (7.7%)	84% of runners sustained a repetitive injury. running related injury: 8.66 per 1000 miles with a rearfoot strike

		• Illiotibial band friction syndrome (7.2%) • Achilles tendinopathies (6.6%)	/ 5.00 per 1000 miles with a non-rearfoot strike pattern
Willems et al, 2006	3 year prospective study looking at gait abnormalities	"exercise related lower leg pain"	11.5% injuries over the three years (18% in women, 7% in men)
Malisoux et al, 2013	A review of injury risk in runners who use different pairs of running shoes		33% of 264 participants were injured over 22 weeks.

Despite long term research being undertaken in the area of musculoskeletal injury, the cause of many running related injuries are not fully understood. The numerous risk factors for injury suggested in the literature have been summarised in Table 2.5b. However, whilst it is apparent that there are some consistencies and "common sense" factors included, many of these factors, when individually analysed, are inconsistently correlated with injury (Murphy, Conolly and Beynnon, 2003: Van Gent et al, 2007). Hreljac and colleagues (2000) suggest that factors related to injury can be classified into three areas; training (excessive distance or intensity, rapid increases in training, surface, footwear), anatomical (arch height, ankle range of motion, alignment abnormalities) and biomechanical (Fz1, loading rate, magnitude of the vertical ground reaction force [Fz2], rearfoot control). However the authors found considerable evidence to both support and dispute the majority of these factors, suggesting that no strong evidence exists to support any of these contentions with the exception of training volume, intensity, and rate of progression, with over 60% of running injuries attributed to training error (Hreljac, Marshall and Hume, 2000; Nielsen et al, 2012). It appears that the manifestation of particular injuries is a multifactorial anomaly largely determined by a number of factors (Nielsen et al, 2012), but duration, frequency or running distance, as well as previous injury, are the main factors involved in running related injury (Yeung and Yeung, 2001; Van Gent et al ,2007).

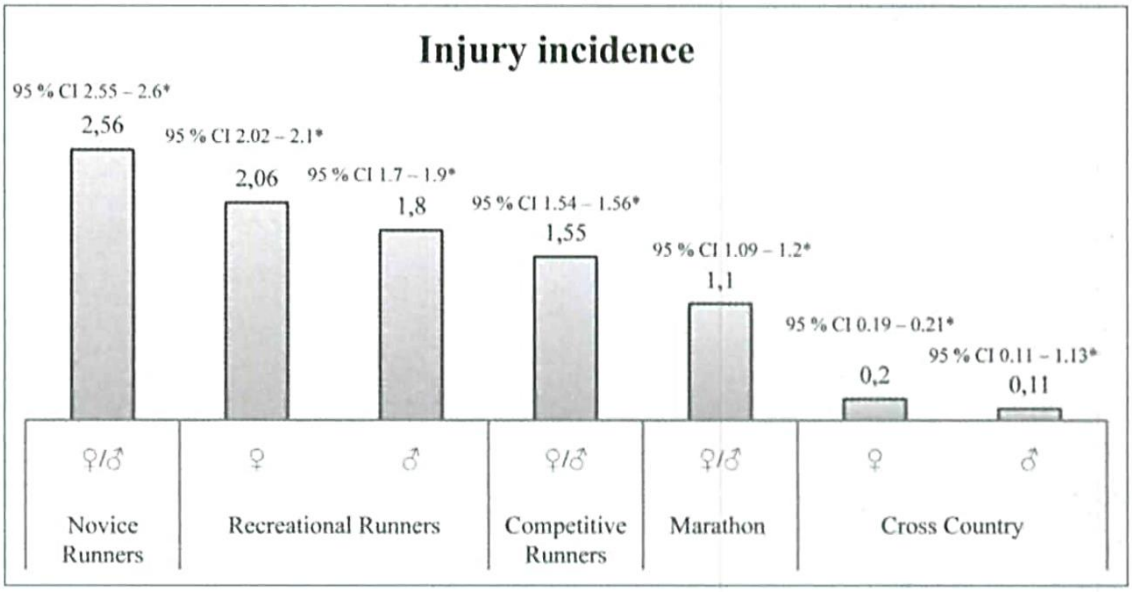
Table 2.5b. *Factors associated with injury, a summary of the relevant literature.*

Author(s)	Description	Injury Factor	Factors investigated directly?
Nigg, 2001	Proposal of a new muscle tuning paradigm	Excessive soft tissue vibration	Yes
Zadpoor and Nikooyan, 2011	Impact related variables between previous stress fracture group and control	Loading rate and <u>not</u> Fz1	Meta-analysis
Buist et al, 2010	8 week prospective study in 629 novice runners	Male Being younger Females with higher BMI Less previous running experience	Yes
Van Mechelen, 1992	Review	Only four factors have consistent evidence: Running inexperience Previous injury Running to compete Excessive distance /wk	Review
Taunton et al, 2002	Retrospective analysis of 2002 running injuries	Being less than 34 years old Less than 8.5 years of activity BMI less than 21 in women	Yes
Verrelst et al, 2013	Prospective kinematic factors related to exertional medial tibial pain in 86 females over 2 years	Increased range of movement in transverse plane of hip and thorax in stance phase	Yes
Edwards et al, 2009	Determining effect of stride length and mileage as risk factors for stress fractures	Increased mileage Decreased stride length by 10%	Yes
Daoud et al, 2012	6 months of injury data in collegiate cross country runners comparing foot strike patterns - retrospective	Rearfoot striking Female Longer race distance Higher weekly mileage	Yes
Theisen et al, 2013	5 month prospective study with hard and soft midsole shoes	High BMI Previous injury Mean session intensity (other sports participation was a protective factor)	Yes
Hreljac, Marshall and Hume, 2000	Injury free and injury prone groups compared	Poor sit and reach test Increased loading rate Increased Fz1	Yes
Pohl et al, 2008	30 females with tibial	Peak hip adduction	Yes

	stress fracture history compared to controls	Absolute free moment Rearfoot eversion	
Bennett, Reinking and Rauh, 2012	Relationships between plantar flexor endurance, navicular drop, and leg pain	Navicular drop > 10mm (x7 more likely to experience leg pain) Previous leg pain (x12 more likely to experience leg pain)	Yes
Hespanhol et al, 2012	Injury questionnaire in 200 recreational runners	Running experience less than 5-15 years	Yes
Milner, Hamill and Davis, 2006	Female RFS participants comparing stress fracture and non-stress fracture group	Increased loading rate Increased tibial shock	Yes
Pohl, Hamill and Davis, 2009	Male participants with and without plantar fasciitis history	High loading rate Low medial longitudinal arch	Yes
Schwellnus, Jordaan and Noakes, 1990	Shock absorbing insoles (n=237) vs. controls (n=1151) over 9 weeks	Shock absorbing insoles were a protective factor	Yes
Knapik et al, 2010	Assigning shoes based on foot shape in military recruits over 1 year.	Low aerobic fitness Smoking	Yes
Van Middelkoop et al, 2008	694 male marathon runners leading into a marathon	More than 6 races in 12 months Previous injury High education level Daily smoking Protective factors - <40km/week for calf, more intervals for knee	Yes
Tonoli et al, 2010	Systematic review	Younger Injury history Less running experience	No – review
Van Gent et al, 2007	Systematic review	**Strong evidence:** High mileage Previous injuries (BUT this was a protective factor for knee injuries) **Limited Evidence:** Older Sex differences Leg length differences Height Alcohol Poor medical history Greater knee varus Greater tubercle-sulcus angle	No - review

Yeung and Yeung, 2001	Systematic review of interventions	Mileage, Frequency of training Distance	No – review
Chuter and Janse de Jonge, 2012	Review of proximal and distal contributions to injury	Excessive foot eversion (but may be a protective factor for stress fractures) Poor "core" stabilisation	No - review
Murphy, Conolly and Beynnon, 2003	Review of lower extremity risk factors	Regular competition Artificial turf Previous injury Specific to stress fractures: High arches Foot inversion Decreased bone mineral density	No - review
Milner, Hamill and Davis, 2010	Kinematic analysis in tibial stress fracture and control groups	Peak hip adduction peak rearfoot eversion	Yes
Milner, Hamill and Davis, 2007	Kinematic analysis in tibial stress fracture and control groups	Increased knee stiffness	Yes
Willems et al, 2006	3 year prospective study looking at gait abnormalities	1) A central heel strike pattern at initial contact 2) More everted foot and lateral plantar loading 3) A higher lateral roll-off	Yes
Malisoux et al, 2013	A review of injury risk in runners who use different pairs of running shoes	Using only one pair of running shoes Previous injury No other sports participation	Yes
Goss and Gross, 2012b	Review of injury trends with different running styles	**Extrinsic:** Running shoe age High volume High frequency High intensity **Intrinsic:** Previous injury Being older Increased mass Genu valgum Pes planus Pes cavus Higher Fz1 and loading rate	No - review

With regard to specific populations, in the 2009 IAAF World Athletics Championships, more than 13% of the athletes became injured within the short period of time that they were at the competition (135.4 injuries per 1000 athletes over approx. two weeks). Furthermore, most of these injuries occurred in distance runners and multi event athletes, with overuse being the most common cause account for more than 44% of the injuries reported (Alonso et al, 2010). The study by Alonso et al (2010) was based on elite athletes, but the injury incidences have been found to be much higher in novice and recreational runners when compared to competitive, marathon or cross country athletes (Tonoli et al, 2010; see Figure 2.5;). The reduction in injury rates in more experienced runners has been suggested to be largely as a result of necessary adaptation to training stimuli over time, but has also been related to a "survival of the fittest" phenomenon. This is where athletes who are not predisposed to injury appear to move into higher levels of running and show increased participation (Hespanhol et al, 2012). Indeed running injury has been flouted as the biggest cause of dropout in novice athletes (Hespanhol et al, 2012). To support this observation, it was found that older more experienced athletes were at reduced risk of receiving a running related injury, possibly for the same reasons (Tonoli et al, 2010), but this may also be due to reductions in training volumes with age. Likewise, increases in BMI or body mass have been suggested to be protective factors for running related injury, since it is assumed that this population cannot/do not achieve high volumes of running related activity (Van Gent et al, 2007) due to anthropometric limitations. Therefore, it has been suggested that a combination of intrinsic and extrinsic risk factors predisposes runners to develop a running related injury (Buist et al, 2010).



** = P ≤ 0.05, CI = Confidence Interval.*

Figure 2.5. *Injury incidence in various levels of running for men ♂ and women ♀. Adapted from Tonoli et al (2010).*

2.6 Running Biomechanics and Running Related Injury

It is apparent in the previous section that the understanding of running related injury is still in its infancy and therefore not fully understood. Whilst most running injuries are related to training error, volume and intensity (see section 2.5), abnormalities in running biomechanics has been proposed to relate to specific injuries (Goss and Gross, 2012b). However, very few relationships of this kind have been consistently observed in the literature (Novacheck, 1998).

It has been suggested that gender can influence running mechanics. For example, during running females have been found to display lower variability in transverse plane hip, knee and ankle rotations and sagittal plane rotations at the ankle (Barrett, Noordegraaf and Morrison, 2008), greater hip adduction, hip internal rotation (Chumanov, Wall-Scheffler and Heiderscheit, 2008; Ferber, Davis and Williams, 2003) higher knee abduction angles, higher hip frontal and transverse plane negative work (Ferber, Davis and Williams, 2003), and higher gluteus maximus activity (Chumanov, Wall-Scheffler and Heiderscheit, 2008), than their male counterparts. Therefore any studies examining kinematics related to running should control for gender in order to control for these differences.

A review by Hall et al (2013) suggested that the biomechanical risk factors for injury in runners fall under kinetic, kinematic and neuromuscular factors. These are discussed in the following sections.

2.6.1 Kinetic Factors and Running Related Injury

Kinetic analysis involves evaluation of the forces and powers that cause movement, the "how and why" of kinematic changes (Novacheck, 1998). During running, the foot comes in contact with the ground over 600 times per km, and each contact results in impact forces acting on the body (Lieberman et al, 2010). This impact can be measured using the vGRF. Of significant academic interest are the first impact peak of the vGRF (Fz1) and the loading rate of the vGRF (loading rate). These measures have been used as a means to determine soft tissue loading and associated with injury (Hreljac, 2004). Both Fz1 and loading rate can be observed in Figure 2.6.1. The peak Fz1 in runners can be 1.5 to 3.5 times body weight, and is dependent on running speed, foot strike pattern and stride length (Goss and Gross, 2012b). The Fz1 has been proposed to be a significant factor in the development of running injuries (Hall et al, 2013). However this may only be the case for bony injuries (Milner, Hamill and Davis, 2006), as the repetitive loading on cartilage and soft tissue have been found to be within an acceptable window for soft tissue remodelling and management (Nigg and Wakeling, 2001). Also, plantar pressures measurements have been used to measure direct loading on the foot and may be linked to foot and ankle injuries (Shorten, 2002).

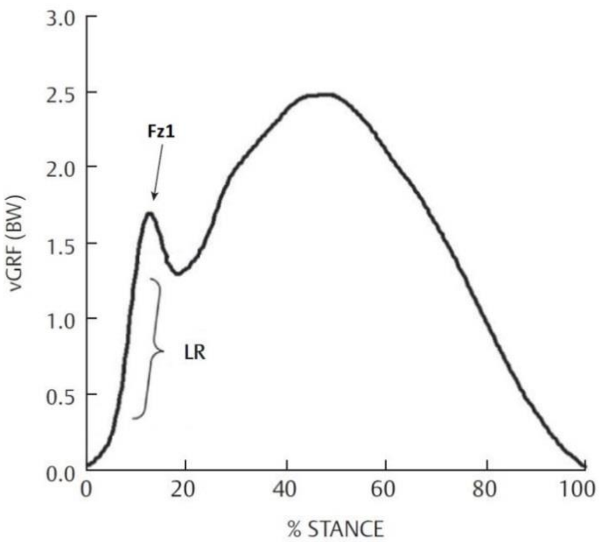


Figure 2.6.1. *The* vGRF during the stance period of running expressed at body weights (BW). The Fz1 and loading rate are determined in the early part of stance. Not listed is the active peak (Fz2), characterised *by the second, larger peak of the vGRF. Adapted from Hobara et al (2012).*

2.6.1.1 Impact Forces

Impact forces are characterised by high frequency forces transmitted through the foot and lower leg over a short duration (Shorten and Mienjtes, 2011). The suggestion that impact is related to injury is supported by the reported lack of lower leg injuries in cross country skiing and ice skating compared to running (Robbins and Hanna, 1987). Bony injuries are now becoming more synonymous with impact characteristics (Giandolini et al, 2013b). Increased Fz1 and loading rate are believed to be harmful and have been suggested as the primary etiological factor for several injuries including plantar fasciitis (Pohl, Hamill and Davis, 2009), patellofemoral pain (Cheung and Davis, 2011), stress fractures (Milner, Hamill and Davis, 2006; Crowell and Davis, 2011) and Osteoarthritis (Hreljac, 2004). However, these relationships are not strong and require further research, with perhaps the exception of loading rate and stress fracture risk (Zadpoor and Nikooyan, 2011).

Despite leading authors such as Benno Nigg questioning the association between impact and injury (Nigg, 2001; Nigg, 2011; Nigg and Enders, 2013), there is some evidence that impact forces are a likely cause of tissue damage. For example, Hreljac, Marshall and Hume (2000) found that injury free runners had a lower Fz1 and loading rate than injured runners. Likewise, increased impact forces have been related to increased injuries in female runners (Zifchock, Davis and Hamill, 2006). However, many of the studies in this area are retrospective and there is a lack of high level prospective data with respect to the vGRF and injury. One important consideration for impact during running is surface hardness, and sporting surfaces have been the attention of much development and research for reducing injury. Interestingly, peak impact forces have been found to be maintained at regular levels when running on surfaces with different mechanical properties (Van Mechelen, 1992; Kerdok et al, 2002; Nigg and Yeadon, 1987), most likely due to leg stiffness adaptations to maintain the leg-surface system constant (see section 2.2.3 and 2.6.4). Indeed, a review by Van Mechelen (1992) found that surface hardness was not linked to running injuries. Whilst this may appear to suggest that changes in forces acting on the lower extremity will be different with changes in shoe or surface hardness, it has been noted that runners optimise their leg stiffness based on this hardness and therefore maintain a leg-surface system constant (see section 2.6.4). Therefore the examination of impact forces with respect to surface hardness may not be appropriate.

One kinetic variable that has been associated with the development of stress fractures is loading rate which are predominantly of the tibia (about 33-55% of all stress fractures), with metatarsal stress fractures accounting for about 15.6% (Milner, Hamill and Davis, 2006; Zadpoor and Nikooyan, 2011). Furthermore, runners with a history of stress fracture or stress reactions were found to display higher loading rate than controls (Davis, Milner and Hamill, 2004). A prospective study by Gallant and Pierrynowski (2014) also associated injuries in female runners to higher loading rate over a two year period. It is important to note that sub maximal forces on bone do not result in bone damage, and can in fact increase bone density and strength via increases in cortical bone density, cross sectional area, and bone marrow metabolism (Nigg, 2010). However, cyclical loading at high rates of force development can result on micro-cracks in the bone that will fracture given insufficient time for remodelling (Nigg, 2010; Zadpoor and Nikooyan, 2011). The ability of bone to resist this cyclical fatigue has been found to be significantly reduced at higher loading rates. This would support the meta-analysis of Zadpoor and Nikooyan (2011), that suggested loading rate, and not Fz1, are related to stress fractures.

2.6.1.2 Plantar Pressures

Plantar pressure measurements have become an increasingly popular source of data analysis for foot biomechanics and pathologies (Giacomozzi, 2011). This measure can provide detailed regional loading properties of the foot, and the region of this loading can also influence movement of the entire lower extremity (Rosenbaum and Becker, 1997). Unnatural or localised pressures underfoot have been related to stress fractures, plantar fasciitis, heel spurs, and metatarsalgia (Hennig and Milani, 1995). Whilst the GRF is typically used as a measure of impact, this method may be insensitive to localised forces (Miller, 1990). Indeed when comparing shoes of various midsole hardness, there was no difference in the vGRF variables, but significant changes for plantar pressures between footwear types. Harder shoes were found to result in reduced heel pressures but increased forefoot loading (Gross and Bunch, 1989; Hennig, Valiant and Liu, 1996). However, Hennig and Milani (1995) also found correlations between heel pressures and Fz1 ($r=0.52$), as well as tibial acceleration ($r=0.76$). In addition, plantar pressure measurements with insoles were significantly correlated with vGRF data from a force plate, which suggest this is a valid measure of "impact" (Cordero et al, 2004). In any case, the importance of measuring plantar pressures in injury studies is merited either to correlate with other impact data or to determine specific foot loading profiles.

Increases in plantar pressure have been observed as a result of walking barefoot, walking at a greater velocity (Burnfield et al, 2004), fatigue following a marathon (Nagel et al, 2008), in rigid high arched feet (Chuckpaiwong et al, 2008), but not following a submaximal 10km run (Alfuth and Rosenbaum, 2011). Increases in pressure as a result of barefoot activity have been related to a reduction in the contact surface area (Burnfield et al, 2004). Treadmill running has been associated with lower plantar pressures and forces than overground running, and this has important implications for dictating results from treadmill research (Hong et al, 2012; Lafortune et al, 1994). Hong et al (2012) also found that grass and concrete running resulted in comparable plantar values.

2.6.1.3 Does Impact Cause Injury?

A novel paradigm for injury has been presented by Nigg (2001) in which the author questions the association between impact and injury. This comprehensive review noted that running injures did not decline when running on softer versus harder running surfaces, and even suggested that in one case participants with a higher loading rate experienced less injuries than those with a low loading rate (Nigg, 1997). Nigg (2001) suggested that impact forces may be important for bony development. There is a need for higher bone loading in order to maintain or improve bone mass. For example the frequency of loads may be important to influence a stress response; a low 1Hz signal was not sufficient to maintain bone mass over an 8-week period, but loading experienced at 15Hz resulted in substantial new bone development (Nigg, 2001). Increases in bone mass could be explained to 68-81% by the loading rate applied; suggesting that impact stimuli can improve bone integrity and that not all impact related behaviour should be seen in a negative fashion (Nigg, 2001). Also, the impact peak is actually 3-5 times smaller than the active peak, and thus impact forces may not be a large factor in running injuries, as opposed to the larger forces experienced during the active phase of running on internal joint structures (Nigg, 2001, Nigg and Wakeling, 2001; Nigg and Enders, 2013). Whilst the impact period of stance can expose the passive structures to high forces, the period is relatively short and the forces acting internally during the remaining 66% of stance are actually much higher. This may cause more soft tissue damage, in contrast to bony injuries observed in the "collision" period of stance (Novacheck, 1998; Nigg, 2010). In this regard it has been suggested that peak forces on the Achilles tendon complex do not occur during the initial contact but during mid-to late stance where the powerful contraction of the gastrocnemius applies active tensile forces on the tendon (Nigg, 2010). Thus, active and not passive forces are much higher for soft tissue compartments and may be a large cause of injury (Novacheck, 1998; Nigg, 2010). Finally, it has been suggested that "excessive" impact is not an injury related factor in running, since running yields impact forces well below any dangerous threshold. Instead, the cyclical loading at a high frequency with insufficient recovery periods is more important, which would explain the high relationship of volume and frequency of training with injury (Nigg, 2010).

The lack of understanding for the biomechanical mechanisms associated with running related injury remains unclear, with no single biomechanical variable identified with strong consistent evidence for prediction of running related injury (Tam et al, 2013). However, the relationship between impact and injury is not non-existent, with several authors' identifying factors such as loading rate and the Fz1 in particular having an association with injury in runners. In a review by Hreljac (2005) it was observed that at least four published studies have linked higher vertical forces to injured runners compared to non-injured runners (Hreljac, 2004). In addition to kinetic forces acting on the body, it has been suggested that abnormal kinematics may predispose a runner to injury and this is discussed in the next section.

2.6.2 Kinematic Factors and Running Related Injury

Kinematic analysis considers the description of movement and does not take into account the forces that cause the movement (Novacheck, 1998). There is limited evidence for any kinematic factors being related to injury directly; however consideration should be given to the influence of kinematics on kinetic factors, such as an increase in stride frequency resulting in reduced vGRF for example (Hobara et al, 2012). With respect to running many of these changes are related to gait parameters that have been influenced and studied in the literature and these will be examined in this section.

2.6.2.1 Gait Changes and their Relationship to Running Related Injury

Making changes to running technique (gait-retraining) has become a popular intervention for runners attempting to reduce the risk of receiving a running related injury, with many programmes offering "natural running techniques" (running form inspired by barefoot movement) as part of this retraining (Gouttebarge and Boschman, 2013; Lieberman, 2012; Goss and Gross, 2012b). Whilst there is insufficient evidence that any "natural running" techniques or simple gait-retraining can reduce the risk of running related injury (Gouttebarge and Boschman, 2013; Goss and Gross, 2012b; Crowell and Davis, 2011), there are significant changes to kinetics and kinematics that may have some influence on injury risk. These should be examined in light of the mechanics associated with injury discussed above. Crowell and Davis (2011) identify an important point in that any running technique changes will have no meaning unless they persist beyond the intervention or training sessions. The retention of the motor skill indicates learning and the potential for long term adoption, but based on a thorough review of the scientific literature, it is evident that the understanding of long term changes to motor skills lacks methodological guidance and will change with each specific skill being undertaken. Also, very few retraining studies have investigated retention as part of their methodology (Crowell and Davis, 2011). One potential method for increasing retention is a graded feedback method, in which participants learn to rely on internal queues with less feedback provided each week. This approach was used in a study by Crowell and Davis (2011). However, the majority of runners do not have a personal coach or access to this kind of expertise or bio-feedback, and so this may not apply to the general population. This population may only be provided a once off tutorial before attempting to incorporate long term changes. This in itself is an important consideration, as these are the runners that may be more susceptible to injury.

Gait-retraining can be broken down into simple popular kinematic changes such as increased stride frequency or changes in foot strike patterns, as well as gait-retraining “packages” such as “POSE” or “Chi” running that attempt to globally alter running mechanics to a more “natural” pattern. Gait-retraining has also been implemented in athletes with specific injuries who used biofeedback to “correct” or reduce certain movements. It is important to remember that kinematic changes to gait are largely interrelated, for example a forefoot strike pattern will result in an increased plantarflexion angle, reduced horizontal distance from foot contact to CoM, increased stride frequency, decreased stride length, increased knee flexion, and higher triceps surae activation (Rothschild, 2012b). Therefore whilst these factors can be considered individually, they are very likely to influence one another. The various popular interventions are discussed below.

2.6.2.2 Stride Frequency and Running Related Injury

Perhaps one of the most common acute interventions in runners is an increased stride frequency (Heidersheit et al, 2011; Hobara et al, 2012; Lenhart et al, 2014; Burkett, Kohrt and Buchbinder, 1985). Increasing stride frequency has been suggested to reduce the impact forces on the musculoskeletal system (Burkett, Kohrt and Buchbinder, 1985). However increasing stride frequency will increase the accumulated load due to more ground contacts per unit time which may be a secondary injury mechanism (Hall et al, 2013). It has been suggested that the reduction in impact variables associated with increases in stride frequency are; 1) changes in the foot striking pattern, since an increased stride frequency will reduce step length and result in a flatter foot placement; 2) a change in joint angles at initial contact, such as increased knee flexion that will reduce the effective mass of these segments; or 3) a reduction in the perpendicular distance of foot contact to the CoM, as a result of the reduced step length, that may reduce braking forces and the moment arm of the vGRF relative to the hip and knee (Hobara et al, 2012).

It would appear as though a reduction in loading variables with increases in stride frequency is consistent in the literature; when frequency was increased to 180-185 steps per minute, there was a reduction in the peak vGRF, a decrease in joint moments, and a reduced ground contact time (Heidersheit et al, 2011). Also, tibial acceleration was reduced when participants ran at +20% stride frequency, but not at +10% (Hamill, Derrick and Holt, 1995). Similarly, Hobara et al (2012) identified through regression analysis that the Fz1 and loading rate during running is minimal at 117-118% of self-selected stride frequency. Schubert, Kempf and Heiderscheit (2013) in a review identified a reduction in peak vGRF, vertical oscillation, and tibial accelerations with increases in stride frequency. Increases in stride frequency will also reduce stride length, reducing the distance from the CoM to the point of foot contact, and this can reduce levers and internal forces acting on joints during running (Nigg and Enders, 2013).

A simulation study found that the risk of tibial stress fracture increased with running mileage, but a +10% stride frequency can significantly reduce this risk (Edwards et al, 2009). This result rejected the hypothesis that increases in stride frequency would increase impacts per unit time potentially increasing the risk of developing a running related injury. This was however a simulation model and requires further examination *in vivo.*

Lenhart et al (2014) recently compared leg internal muscle forces and joint loads during 90, 100, and 110% preferred step rate, the authors found that adopting a 110% stride frequency reduced peak patellofemoral joint forces by 14%, as a result of a reduction in peak stance knee flexion. Likewise a +10% stride frequency was found to increase energy absorption at the knee and hip (Heiderscheit et al, 2011). Hip, knee, and ankle extensor forces, as well as hip adduction force was also significantly lower at the higher stride rate (Lenhart et al, 2014). Muscle activation patterns have been found to increase in late swing with a higher stride frequency, suggesting an actively induced muscle contraction sequence to bring the foot back under the centre of mass with higher step frequencies (Chumanov et al, 2012). This strategy also increases activation of gluteus Maximus and Medius that may be important for treatment of anterior knee pain (Chumanov et al, 2012). This section highlights the potential for increases in stride frequency to influence loading of the lower extremity and this should be examined with respect to changes related to footwear.

2.6.2.3 Foot Strike Patterns and Running Related Injury

The landing pattern during running has been the subject of much debate in the literature with regards to injury. The foot strike pattern is dependent on multiple factors not limited to footwear type, surface hardness, velocity, inter-individual subject variation (Nigg and Enders, 2013), and environmental habituation (Lieberman et al, 2012). The majority of today's shod endurance runners have been found to implement a rearfoot strike pattern during running (75% - Hasegawa, Yamauchi and Kraemer, 2007; 89% - Larson et al, 2011; 98% - Bertelsen et al, 2012; 95% - De Almeida et al, 2014), and so most data on injury rates in runners should take this into account. This is particularly relevant since the vast majority or runners today wear CRS. Before examining how changes in foot strike pattern can influence injury in runners, one must first understand why different foot strike patterns occur;

The foot striking pattern has been found to be influenced by a number of factors including;

1) Running velocity – There appears to be a higher prevalence of forefoot or midfoot strikers in faster runners (Hasegawa, Yamauchi and Kraemer, 2007; Kasmer et al, 2013; McCallion et al, 2014).

2) Shoe/surface hardness - Harder surfaces have been found to result in runners adapting their foot strike pattern to a higher prevalence of mid or forefoot striking compared to a soft surface (Gruber et al, 2013b). This may be a means to reduce localised pressures as the heel in order to prevent direct impact to the calcaneus and reduce high localised pressures in this area (De Wit, De Clerq and Aerts, 2000; Hennig and Milani, 1995; Squadrone and Gallozzi, 2009; Hennig, Valiant and Liu, 1996) or to change the leg geometry to attenuate higher impact transients observed with a rearfoot strike pattern on hard surfaces (Lieberman et al, 2010).

Examples of this effect are clear when barefoot and CRS running are compared. Barefoot runners have been found to rearfoot strike on a soft surface and adopt a forefoot strike pattern on a hard surface (Hamill et al 2011b; Gruber et al, 2013b). The reason runners may adopt a rearfoot strike pattern on soft surfaces may be to reduce metabolic cost as discussed earlier (see section 2.2.2.2). Likewise a different group of runners did not change their foot strike pattern on a harder surface when in CRS, but consistently adopted a forefoot strike pattern when barefoot (Hamill et al, 2011a). The same was apparent in Kurz and Stergiou (2004), in which all shod rearfoot striking participants adopted a forefoot strike pattern when barefoot on a hard surface.

It is important to note that whilst most runners will adopt a mid or forefoot strike pattern when barefoot on a hard surface, this does not happen as a rule and often runners will continue to rearfoot strike on hard surfaces (Lieberman et al, 2010; Williams et al, 2012). If runners do not adopt a non-rearfoot strike pattern when barefoot or in MFW they may experience higher impact forces (Lieberman et al, 2010). Several authors have found runners to not change their foot striking pattern when running in MFW. Willson et al (2014) found only 3 participants changed their foot strike pattern to a non-rearfoot strike following a two week training period in MFW. The majority of participants (14 out of 17) simply kept the same foot strike pattern as observed at pre-tests (rearfoot strike pattern = 71%) which was similar to those reported in McCarthy et al (2013). Researchers have suggested that pervious shod running experience was the primary determinant of the foot striking pattern (Willson et al, 2014) since this pattern may be a learned effect engrained in the neuromuscular system over years of running activity (Sinnatamby, 2011). In a study by Lieberman et al (2010), 12% of habitual barefoot runners from Kenya were found to adopt a rearfoot strike pattern in Lieberman et al (2010) and 33% habitually shod participants were found to display a non-rearfoot strike pattern when running barefoot for the first time (Cheung, 2013). Likewise, 77% of runners adopted their shod rearfoot strike pattern to a non-rearfoot strike when running barefoot in Nunns et al (2013) and 100% did so in Hein and Grau (2014). In a review, Hall et al (2013) found varied responses to changes in foot strike patterns between barefoot and CRS running, and this factor seems to be largely determined by habituation to the footwear condition prior to testing that remains to be examined in depth.

3) Long term environmental factors - Lieberman et al (2010) found a significantly greater prevalence of forefoot striking in a group of habitual barefoot Kenyans when compared to habitually shod matched runners. The authors suggested that this presented a chronic tactic for reducing impact forces that is characterised by experience running barefoot over a number of years (Lieberman et al, 2010). This history of running activity may be an important mediator in selection of a foot strike pattern due to surface and footwear. This may be true in running populations, however Hatala et al (2013) investigated a habitually barefoot Daasanach tribe in Kenya who are not known runners and observed a large proportion of rear foot striking on a clay surface (72%). The authors did note however that their running velocity was much slower than that of Lieberman et al (2010). This higher velocity in Lieberman et al (2010) may have influenced the results, resulting in a higher prevalence of forefoot striking (Hasegawa, Yamauchi and Kraemer, 2007).

Different foot strike patterns have been suggested to load the lower body joints in different ways, and may not always be a positive change to kinematics (Lieberman et al, 2010; Kirby and McDermott, 1983; Almonroeder, Willson and Kernozek, 2013; Kulmala et al, 2013). One must consider the impact forces acting on the body but also the internal joint forces with changes in the foot strike pattern.

Impact Forces and the Foot Strike Pattern

Changes in the foot strike pattern have been recognised as an important factor in the attenuation of the Fz1 and loading rate during foot contact with the floor. This is because a forefoot strike pattern will reduce effective mass and lengthen the time it takes to decelerate the body to zero by increased ankle excursion (Nigg, 2010). Indeed, much of the research looking at vGRF variables has confirmed this theory. Adopting a forefoot or mid foot strike pattern has been found to decrease the Fz1, as well as loading rate by between 15-33% (Lieberman et al, 2010; Divert et al, 2005b; De Wit, De Clerq and Aerts, 2000). Likewise Fz1 was found to be 26% lower, and loading rate was 47% lower when adopting a forefoot strike pattern in Kulmala et al (2013). In some cases, a non-rearfoot strike pattern has also resulted in the complete absence of an impact peak (Altman and Davis, 2011a; Dickinson et al, 1985; Lieberman et al, 2010; Giandolini et al, 2013a; Nilsson and Thorstensson, 1989; Cavanagh and Lafortune, 1980). However for the many participants that do not adopt a forefoot or midfoot strike pattern with changes in shoe or surface hardness, a significant increase in loading rate can occur, particularly when barefoot or in MFW (Willson et al, 2014; Shih, Lin and Shiang, 2013; De Wit, De Clerq and Aerts, 2000). This has been illustrated in Figure 2.6.2.3. How the impact forces are changed with respect to familiarisation to footwear remains to be determined and will be an important element of this research project.

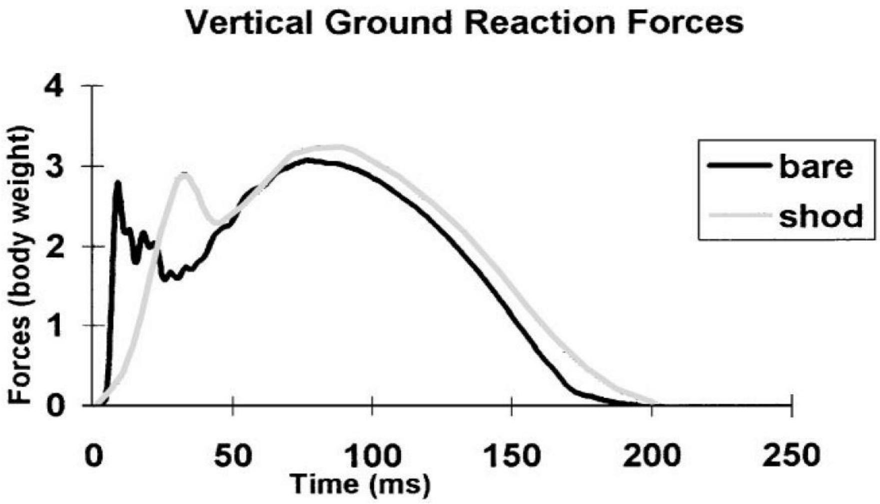


Figure 2.6.2.3. *The vertical ground reaction force when adopting a rearfoot strike* pattern *with the foot bare, and the foot shod. Adapted from De Wit, De Clerq and Aerts (2000).*

Internal Forces and the Foot Strike Pattern.

It is important to remember that any changes to running technique will result in a shift of internal loads to different structures that may present a risk for injury (Nigg, 2010). For example, internal ankle joint forces remain the same in both a forefoot and rearfoot strike pattern (3.0BWs), but there is an increased Achilles tendon force with a forefoot strike pattern (+2.5BWs), and increased tibialis anterior force with a rearfoot strike pattern (+1.5BWs; Nigg, 2010).

It would appear as though adopting a rearfoot strike pattern can have implications for increased risk of knee injuries, and adopting a forefoot strike pattern can potentially increase the risk of ankle and Achilles tendon injuries; A rearfoot strike pattern has been found to increase knee external work (Arendse et al, 2004), patellofemoral and tibio-femoral compressive forces (Kerrigan et al, 2009; Braunstein et al, 2010), patellofemoral stress and knee frontal plane moments (Kulmala et al, 2013). Arendse et al (2004) also demonstrated that a forefoot strike pattern resulted in lower eccentric quadriceps work during the braking phase compared to a rearfoot strike pattern, suggesting that a rearfoot strike pattern is a potentially dangerous movement for knee load. In contrast, a forefoot strike pattern has been suggested to increase the plantar-flexor moment and Achilles tendon load and may predispose forefoot strike runners to Achilles tendinopathies (Kirby and McDermott, 1983; Almonroeder, Willson and Kernozek, 2013; Kulmala et al, 2013). Almonroeder, Willson and Kernozek (2013) examined Achilles tendon load during running with the adoption of a forefoot and rearfoot strike pattern and found that there was a 15% increase in Achilles tendon loading rate, 11% greater Achilles tendon impulse per step, and 47.7 BW's of load for each mile ran when adopting a forefoot strike pattern in the bare feet compared to a rearfoot strike pattern (Almonroeder, Willson and Kernozek, 2013), although these differences were not statistically significant. In further support of this notion, Kulmala et al (2013) found increased ankle plantar flexor and Achilles tendon loading in an experienced forefoot striking group when compared to an experienced rearfoot striking group (Kulmala et al, 2013).

To further elaborate, Shih, Lin and Shiang (2013) observed a higher degree of pre-activation and stance phase activity of gastrocnemius when runners adopted a FFS irrespective of whether the runners were shod or in their bare feet, that suggests higher mechanical work on this muscle group. This could be considered beneficial in the long term due to higher musculo-skeletal strength, but dangerous in the short term (Shih, Lin and Shiang, 2013). As a further note, outside of considerations for the knee and ankle, arch strain was higher with a forefoot strike pattern than a rearfoot strike pattern when barefoot (Perl, Daoud and Lieberman, 2012), and this may have implications for foot injuries during any transition to a forefoot strike pattern in runners. However to date this relationship has not been examined in the scientific literature.

The "Toe Strike" Pattern, a Fourth Foot Striking Pattern.

Whilst most researchers discuss the differences in three different types of foot strike pattern (rearfoot, midfoot, forefoot), there is also a distinct fourth strike type, the toe strike pattern, in which runners heels do not contact the ground following initial contact on the forefoot (Nunns et al, 2013). This style was also described in Lieberman (2012) but has yet to receive significant attention in the literature. A recent large military study (n=1065) examined foot strike pattern type in habitually shod runners when running barefoot and clearly identified these four different strike patterns. The groups where then randomly balanced to have the same numbers in each before the researchers examined kinematic and kinetic parameters (Nunns et al, 2013). There was a significantly higher plantar flexor moment observed in toe strike pattern group compared to all others, which gives credibility to the suggestion that a toe strike pattern is important to differentiate from a forefoot strike pattern. As one might expect, significantly higher regional pressures were observed in the first and second metatarsal heads during a forefoot and toe strike pattern, with higher heel pressures in the rearfoot strike group compared to the other strike pattern types. The reason that the toe strike pattern may not be considered in many other studies is the rarity of this occurring (Daoud et al, 2012). It is also possible that some runners adopt an asymmetrical foot strike pattern, which has been observed in 1.8% of novice male runners (Bertelsen et al, 2013).

The Foot Strike Pattern and Running Related Injury

Whilst several authors have suggested that the change into a forefoot strike pattern can increase joint forces (see above), Daoud et al (2012) did not find any increase in Achilles tendinopathies, foot pain or metatarsal stress fractures in collegiate distance runners who ran with a forefoot strike pattern when compared to rearfoot striking teammates. The authors did however find more “impact” related injuries in the rearfoot strike pattern group (Daoud et al, 2012). In fact, the adoption of a forefoot strike pattern in cross country runners during a competitive season was found to significantly reduce injury risk as much as 2.5 times (Daoud et al, 2012), and significantly reduce the risk of developing a running related injury in a separate study (Goss and Gross, 2012a). Likewise, adopting a forefoot strike pattern has resulted in decreased anterior compartment pressures when compared to a rearfoot strike pattern (Diebal et al, 2012). In this study, forefoot strike running dramatically reduced pain and disability associated with chronic exertional compartment syndrome. The authors used a six week training period of adopting a forefoot strike pattern and observed reduced impact kinetics, increased running distance (by over 300%), reduced pain and most significantly, they prevented all of the participants receiving a surgical intervention for the injury. Clearly in this case, anterior lower leg injuries will benefit significantly from this type of intervention. It is also worth noting that whilst most studies suggest a forefoot strike increases the plantar flexor moment and Achilles tendon loads (Kirby and McDermott, 1983; Almonroeder, Willson and Kernozek, 2013;

Kulmala et al, 2013), no prospective studies have identified an increase in Achilles tendon or triceps surae injuries as a result of this modification.

2.6.3 Gait-retraining Models

One popular gait-retraining method is "Pose" running, which characterises a "*midfoot to forefoot strike pattern, minimal ground contact time, and a picking up of the feet with no pushing forcefully off the floor*" (Goss and Gross, 2012b, pp 63). "Pose" running has been found to increase stride frequency and knee flexion at initial contact, as well as reduce stride length, knee eccentric work, vertical oscillation, ground contact time, and horizontal distance from the CoM to the point of foot contact with the floor ("over striding") (Dallam et al, 2005; Fletcher, Esau and MacIntosh, 2008; Arendse et al, 2004). Loading rate and Fz1 were also reduced with a "Pose" running intervention (Arendse et al, 2004) However the same intervention was found to increase eccentric work at the ankle (Dallam et al, 2005).

Similar to "Pose" Running, "Chi" running, based on theories of movement from Tai Chi (incorporating "*a midfoot strike pattern, a forward lean and shorter more relaxed strides*"; Goss and Gross 2012b, pp 63) is also popular with runners. A "Chi" running intervention was compared to a normal group of rearfoot striking runners by Goss and Gross (2013). Again, stride frequency was found to increase (180 in the RFS group vs. 185 in Chi runners), as was the degree of plantar-flexion at initial contact. With regard to impact characteristics, braking forces (the horizontal component) and loading rate were found to be lower (62% and 37% respectively) in the Chi running group. Joint work was also examined, and the "Chi" group displayed minimal knee extensor eccentric work but an increase in ankle negative work compared to the control. Thus, this method of gait re-training may reduce load in the quadriceps and tibialis anterior, but increase the workload of the triceps surae (Goss and Gross, 2013). However, whilst these changes with both "Pose" and "Chi" running suggest a potential reduction for injury, there is as yet no strong scientific evidence that this is the case (Goss and Gross, 2012b).

Other methods have been adopted in the research. Gait-retraining using a feedback method of instructing participants to "run softer" and "quieter", as well as keeping tibial accelerations low with visual feedback was found to be effective at reducing loading rate, Fz1 and tibial acceleration (Crowell and Davis, 2011). This “bio-feedback” method (that involves runners receiving real time feedback on a specific parameter that they are trying to change), resulted in greater independence within participants and as a result the 4 week follow up also displayed the same reduced values. This may be important for future prescription of gait-retraining, modelled around creating an environment in which the participant can actively work on correcting their own technique in combination with a faded feedback method to increase retention. Interestingly in this study, the bio-feedback was found to be more successful in reducing these loading variables than changing footwear, using orthoses or shock absorbing insoles (Crowell and Davis, 2011). Verbal and visual feedback using pre-recorded instructions and visual aids was also found to be a feasible method of influencing the running pattern, but kinetics and kinematics were not measured in this study (Eriksson, Halvorsen and Gullstrand, 2011). Other gait-retraining studies specifically looking at changing parameters suspected to be related to running related injury can be found in Table 2.6.3. These studies highlight the success of gait-retraining for the improvement in pain and function of specific injuries using simple gait-retraining.

Table 2.6.3. *Gait-retraining interventions for treatment of specific injuries in running.*

Author(s)	Description	Injury	Kinematic change	Result
Willy, Scholz and Davis, 2012	Mirror and verbal gait-retraining for hip mechanics – 8 graded sessions	Patellofemoral pain syndrome	Reduced hip adduction, pelvic drop, hip adduction moment.	Improvements in pain and function
Noehren, Scholz and Davis, 2011	Real time feedback for hip adduction – 8 graded sessions	Patellofemoral pain syndrome	Reduced hip adduction, hip internal rotation, NB- ~20% reduction in loading rate also.	Improvements in pain and function
Cheung and Davis, 2011	Modification of a rearfoot strike to a non-rearfoot strike pattern over 8 sessions	Patellofemoral pain syndrome	Between 10 and 35% reductions in Fz1 and loading rate	Improvements in pain and function
Davis, 2005	Case studies advocating the use of gait-retraining to reduce injury	Plantar fasciitis, Patellofemoral pain syndrome (PFPS) High tibial shock	**Plantar fasciitis** – reduced hip internal rotation and adduction. Reduced knee abduction. **PFPS –** reduction in hip internal rotation **High tibial shock -** reduced with biofeedback of tibial acceleration	All symptoms reduced

A novel intervention implementing the use of a lightweight racing flat, increased stride frequency (+10%) and a midfoot strike pattern was undertaken by Giandolini et al (2012) in order to examine impact characteristics (loading rate, Fz1, time to Fz1). Only a midfoot strike pattern and the combination of all three factors were found to completely eliminate the impact peak, in contrast to just the racing flat, +10% stride frequency, or the participant's normal running gait in CRS. Likewise loading rate was reduced in both the midfoot strike pattern and with all factors combined, but was not significantly affected by the racing flat or the +10% stride frequency. These results support the notion that a non-rearfoot strike pattern is the most effective way of reducing impact variables during running (Lieberman et al, 2010). However, a further study by Giandolini (2013) implementing a low drop footwear (4mm) or a midfoot strike pattern over three months was found to have no effect on loading rate. The authors concluded that the attempt to change from a rearfoot to a midfoot strike pattern had no effect on impact characteristics, or magnitude of acceleration at the heel, metatarsals and tibia. The low drop footwear did result in a reduction in heel acceleration and shock wave propagation between the heel and the tibia after three months suggesting that a low drop shoe is more effective than attempting to midfoot strike in this case. However, a major limitation to this study is that the participants had limited feedback for the adoption of the midfoot strike pattern and both groups actually retained a rearfoot strike pattern for the duration of the testing. This would explain the differences in this study compared to their previous work.

A review by Gouttebarge and Boschman (2013) identified only seven studies that focused on enhancement of the running technique. These studies adopted the use of increased stride frequency, a non-rearfoot strike pattern, the "Pose" and "Chi" method of running, visual feedback of tibial accelerations, and visual and verbal feedback on technique, as we have discussed above. However, none of these studies examined if the relevant changes were maintained over a prolonged period of time (more than a month). More importantly, none of these gait-retraining elements have been examined prospectively in regard to running related injury. Therefore, there is no evidence that gait-retraining can reduce injury in runners. Gouttebarge and Boschman (2013) also highlight potential barriers with the uptake of these methods over time, including "*lack of patience, self- discipline, motivation, or concentration, and the running technique being too extensive to learn*" (Gouttebarge and Boschman, 2013, pp 16), that need to be taken into account when considering the long term application of gait-retraining.

Again, changes to the running gait are controlled by the neuromuscular system and this should be discussed with respect to injury.

2.6.4 Neuromuscular Control and Running Related Injury

Whilst a high loading rate has been implicated in the development of bony injuries, the understanding of soft tissue injury, or impact in general still remains to be determined (Nigg, 1997). It is clear from the literature review above that overuse and biomechanical misalignment may be important in soft tissue injury, but key variables related to injury in these tissues is unclear and warrants further investigation. Nigg and Wakeling (2001) proposed a muscle tuning paradigm, in which soft tissue vibrations may be involved in tissue injury, and muscle co-contraction or pre-contraction is a self-optimising tactic to limit soft tissue vibration during impact. Tissue vibrations have been associated with muscle necrosis (Nigg, 2010), but this theory lacks considerable evidence for soft tissue injury. Enders, Von Tscharner and Nigg (2013) examined tissue vibration properties in runners utilising different foot strike patterns, and concluded that the preferred movement pattern exhibited the lowest damping coefficient, and that preferred movement patterns should play a much more important role in the debate about what is "correct" for human movement and injury (Enders, Von Tscharner and Nigg, 2013). This is an important concept, because self-optimisation of biological systems could be independent of foot strike pattern and/or footwear, and instead be due to neuromuscular control.

As discussed previously, an important component of neuromuscular control is stiffness. In contrast to the potential benefits of higher stiffness to RE, any increase in leg stiffness will reduce the compliance of the "leg spring" and result in higher loading rate and impact accelerations, due to less limb excursion and increased effective mass (Derrick, 2004). Increased Fz1, loading rate and segment accelerations have been suggested to increase the risk of developing a bony injury (e.g., Grimston et al, 1991; Davis, Milner and Hamill, 2004). For example, knee stiffness was found to be higher in a group of tibial stress fracture participants when compared to a control, and this was believed to result in higher loading rate and tibial shock (Milner, Hamill and Davis, 2007). High arched runners who also displayed increased leg stiffness were more likely to receive bony injuries (Williams et al, 2004), that would support this concept. At the other end of the spectrum, too little stiffness will possibly increase joint movements and reduce control of the structure that may increase the chance of soft tissue injuries (Williams, McClay and Hamill, 2001). In support of this theory, Granata, Padua and Wilson (2002) suggested that the well documented increase in knee ligament injuries in women correlated with a decrease in leg stiffness in this gender. Likewise, low arched runners with lower leg stiffness suffered more soft tissue injuries than their stiffer counterparts (Williams, McClay and Hamill, 2001). Based on these findings it appears that there may be an "optimal" stiffness of the lower body that is neither excessively high nor low, but this remains to be established.

How kinematic, kinetic and neuromuscular factors can be influenced by gait-retraining can present an interesting dataset on the running gait and injury. Gait-retraining will be discussed in the next section.

2.7 The Influence of Footwear on Injury and Running Biomechanics

In the 1980's and 1990's, Steven Robbins and his research group suggested that habitually barefoot populations are less likely to experience injury than shod counterparts, based on a multitude of anecdotal personal correspondence and reports on habitually shod and barefoot humans in Haiti and north America (Robbins and Hanna, 1987). In contrast, injuries were reported by practitioners in "almost every shoe model available" (Robbins and Hanna, 1897), suggesting that variation in modern CRS was not a successful attempt to prevent running related injury. The authors did not receive any communication of a high injury frequency in barefoot populations. At this time, the "minimalist" shoe market was not in place and so comparisons cannot be made to MFW. There are several limitations to this research that should be taken into account, firstly the rural barefoot populations in question may not have access to professional injury clinics and so these injuries may not be reported. The second is the lack of any robust academic approach to the reporting of these reduced injury rates in barefoot populations. However this observation has recently been reported again with *"many authors and clinicians familiar with podiatric medicine report[ing] that the foot ailments commonly seen on the shod population are absent in barefoot populations"* (Gallant and Pierrynowski, 2014, pp 217). In addition, Aibast et al (2012) found only 8% of habitually barefoot rural Kenyan runners were injured during a one year follow-up compared to 61% weight matched shod controls in the same country, and so this early claim is not unfounded in evidence.

Robbins and colleagues (1987, 1988, 1989, 1993) went on to publish more data supporting their “plantar sensation” hypothesis, in which a reduction in feedback to the neuroreceptors of the plantar surface cause “neuropathic” behaviour, characterised by a reduction in feedback-mediated impact-attenuation tactics (Robbins and Hanna, 1987; Robbins, Hanna and Jones, 1988; 1989; 1993). This plantar sensation hypothesis is supported by the work of Magnusson et al (1990) where the authors used hypothermia of the feet to reduce feedback of the mechanoreceptors of the glabrous epithelium and observed increased body sway when sensory feedback was impaired. Thus postural control in humans is largely dictated by plantar feedback (Magnusson et al, 1990). In addition, changes in foot sensation through direct icing was found to significantly alter muscle firing patterns and plantar pressures, which would support this theory (Nurse and Nigg, 2001). Since the foot is the first and only point of contact with the floor during running, its importance in the regulation of gait cannot be ignored. Kurz and Stergiou (2003) found much greater joint variability when barefoot compared to shod, and suggested that the increased sensation when barefoot led to more specific surface responses, greater muscle activation, and increased reactions to surfaces when compared to the shod condition, of which only responded to major variations (Kurz and Stergiou, 2003). Many of these surface responses have also been noted in MFW and this can be observed in Table 2.7.3, however this will depend on the degree of “minimalist” associate with the shoe in question. Differences in landing strategies due to important proprioceptive feedback when barefoot and in MFW were identified in comparison to reduced feedback in CRS, as a result of the thick cushioned outsole (Robbins and Hanna, 1987; Robbins, Hanna and Jones, 1988; Fiolkowski et al, 2005; Squadrone and Gallozzi, 2009). Therefore it could be suggested that CRS can potentially insulate sensory feedback and motor control during running that may have a significant influence on the running pattern, and many MFW are suggested to improve this feedback through thinner outsoles and a more flexible design (Lussiana et al, 2013).

More recently, Lieberman (2010) characterised differences in landing strategies and impact forces in habitually barefoot vs habitually shod populations, and suggested that impact attenuation tactics were enhanced when the foot was bare. As an evolutionist, Lieberman speculated that the bare foot provides an optimal level of sensory feedback and landing control that is a direct result of thousands of years of barefoot activity, and that this presents a means to re-introduce more natural movement (Lieberman, 2012). According to Gallant and Pierrynowski (2014) there are three proposed benefits to the barefoot running theory: 1) a decrease in foot atrophy and increased foot function, 2) increased proprioceptive feedback, and 3) a running gait that is "natural" compared to that in CRS. These claims have also been proposed in MFW but have been widely regarded as anecdotal, and indeed much more strong evidence is required to make any substantial conclusions. However, there are several interesting pieces of research that support this "barefoot theory" and should be taken into account. For example, barefoot and minimal footwear have been found to increase foot muscles functional capacity (Robbins and Hanna, 1987; Bruggemann et al, 2005). Also, higher arch characteristics and foot strength was observed in habitually barefoot children vs. weight matched controls (Aibast et al, 2012). Likewise Zipfel and Berger (2007) examined foot morphology in four human groups (skeletal habitually shod samples from Sotho, Zulu, and European recent pre-historic samples, and habitually unshod samples from pre-pastoral Holocene people or a hunter-gatherer lifestyle) and concluded the Holocene group suffered much less ostcological modification as well as improved foot function compared to the habitually shod groups. A more recent analysis examining habitual footwear use in barefoot Indians vs. shod Indian controls and western shod participants arrived at a similar conclusion: "*current data suggests that footwear fails to respect natural foot shape and function and will ultimately alter the morphology and the biomechanical behaviour of the foot"* (D'Aout et al, 2009, pp 81). Finally, the prevalence of "flat feet" was 8.6% in habitually shod children and only 2.8% in habitually barefoot children in (Rao and Joseph, 1992). The second theory of reduced proprioceptive feedback was discussed in the previous paragraph, and with regard to the third theory, we draw your attention to the numerous kinematic differences observed between barefoot, MFW and CRS running in Table 2.7.3 (section 2.7.3). However, the lack of longitudinal data observing a difference in running related injury or performance among barefoot, MFW and CRS runners makes this data very difficult interpret as to what footwear (or lack of), it best adopted for long term use.

With regard to running related injury, according to Lieberman (2012, pp 69) "*asking whether barefoot running is more or less injurious than shod running is a naïve question given the complex, multifactorial basis for most kinds of injury*". Lieberman (2012) also suggests that the barefoot condition is the "null hypothesis" and any research examining differences in footwear should first attempt to accept or reject the null hypothesis. In this regard, the evidence for footwear as a protective factor against injuries is lacking despite the numerous anecdotal marketing strategies employed by manufacturers worldwide. This section will first examine the direct evidence for injuries in various footwear in the literature, before identifying important kinetic and kinematic differences between barefoot and CRS running. Finally, we will examine the small body of research looking specifically at MFW.

2.7.1 Injuries in Various Footwear

2.7.1.1 Conventional running shoe design and injury

Different shoe types have traditionally been prescribed based on foot type (cushioned stability shoes for high arched runners, and cushioned motion control shoes for low arched runners) (Goss and Gross, 2012a). However the evidence that pronation control, elevated cushioned heel shoes result in a reduction of running related injury has been found to lack any significant data in a systematic review (Richards, Magin and Callister, 2009).

According to Richard, Magin and Callister (2009), the idea of implementing shoes with cushioning, elevation and pronation control is based on the following assumptions:

1) That excessive impact forces whilst running are a significant cause of injury
2) That running on a hard surface is a cause of high impact forces
3) That cushioned shoes can reduce these impact forces
4) That cushioning itself will not cause any injury
5) That shoe elevation will reduce Achilles tendon strain
6) That over-pronation and over-supination cause running injury
7) That reducing pronation/supination will reduce injury risk
8) That motion control shoes effectively reduce sub-talar movement

We have discussed the various research with regard to many of these factors in this literature review both above and below. Many of these assumptions have been inconclusive. In fact strong scientific evidence supporting many of these theories is currently lacking. Indeed, the study by Richards, Magin and Callister (2009), suggests that "*the lack of evidence for [PCECH] use and their potential to cause injury has been raised by several authors, including leading authorities in the field*" (Richards, Magin and Callister, 2009, p 161). To provide some examples; In one well designed, double blind randomised control trial, no difference in running related injury was identified between soft and hard (15% greater heel stiffness) midsole cushioned shoes (Theisen et al, 2013), or between motion control, stability and neural shoes when prescribing shoes based on foot shape (Knapik et al, 2010).

It is possible that parallel use of running shoes can reduce injury risk (Malisoux et al, 2013). There is also research suggesting that cheaper, less cushioned shoes may reduce the risk of a running related injury (Robbins and Waked, 1997), and that motion control shoes resulted in more injuries and missed training days than both a neutral and stability shoe during a 13 week half marathon programme (Ryan et al, 2011). In support of this, barefoot running has been observed to reduce the eversion moment at the ankle irrespective of foot type (Hall et al, 2013) Shoes have been suggested to increase the amount of lateral ankle ligament injuries, due to the elevated profile that increased the external inversion moment when compared to barefoot (Kerr et al, 2009; De Wit, De Clerq and Aerts, 2000). The concept of "natural" anatomical alignment may be more important than any characteristic of shoes that attempts to reduce impact peaks, since most internal active forces occur late in stance and may contribute more to injury (Nigg, 2010; Novacheck, 1998). It is important to note that no amount of technological development or academic understanding of the nature of running injuries has resulted in a measureable decrease in running related injury, and all injury "theories" should perhaps be considered as a working hypothesis with no significant evidence to aid medical or sports professionals. Nevertheless, some authors have attempted to link running related injury with biomechanics as discussed previously (section 2.6).

2.7.1.2 Injury risks comparing footwear types

To date there has been very little research examining injury outcomes as the result of wearing different shoes. In a recent study Ryan et al (2009) examined pain reduction in 21 participants with plantar fasciitis over 12 weeks, and a follow up at 6 months, when implementing a rehabilitation programme either in Nike "Free"® (MFW) or CRS. Whilst there was no difference in the pain outcome between either footwear at 6 months, the Nike "Free"® group reported significantly less pain throughout the intervention than the CRS group. In contrast to this study, the Nike "Free 3.0"® was found to result in more injuries than both a CRS and VFF intervention in Ryan et al (2013). It may appear surprising that the Nike "Free"® was more injurious than the ultra-minimalist VFF, but as discussed below the Nike "Free"® may not offer enough sensory feedback through the foot to initiate some degree of impact attenuation. This shoe has reduced cushioning and lateral stiffness compared to CRS that can often result in runners maintaining a "conventional shoe running style" (Bonacci et al, 2013). As a consequence according to Lieberman et al (2010), this may be a dangerous option for runners. However these researchers did not provide direct evidence of this resulting in injury (Lieberman et al, 2010).

Research investigating injury rates in barefoot and MFW appears to be equivocal. Barefoot and MFW runners who adopted a forefoot strike pattern were significantly less likely to develop a running related injury compared to CRS runners in Goss and Gross (2012a). In contrast, in a study by Grier et al (2013) there was no significant difference between CRS and MFW users with regard to injury. To confound matters further, Daumer et al (2014) highlighted the danger associated with the transition to MFW or barefoot by reporting much higher injuries during this transition period (Table 2.7.1). Interestingly the authors observed a much lower injury risk per 10,000km of running in experienced MFW or barefoot runners compared to experienced CRS runners (Daumer et al, 2014). The study by Daumer et al (2014) involved the use of a retrospective questionnaire, but may have been biased by the questionnaire being advertised mostly to a barefoot running forum. In addition, Salzler et al (2012) identified 9 runners who presented with stress fractures within 2.8 months of moving into MFW. These runners had previously run more than 40 km per week in CRS for more than 20 years without noticeable injury (Salzler et al, 2012). Also, runners who attempted to transition to running barefoot reported with Achilles tendinopathies and metatarsal stress fractures in several case studies (Cauthon, Langer and Coniglione, 2013; Giuliani et al, 2011), as well as following a ten week VFF transition (Ridge et al, 2013).

Table 2.7.1. *Injuries per 10,000km (±SD) reported by experienced shod runners, experienced MFW/barefoot runners, and runners attempting to transition to MFW/barefoot running. Reports based on questionnaire feedback. Adapted from Daumer et al (2014).*

Injuries / 10,000km	Mean (±SD)
CRS	12.77 (±56.82)
MFW/Barefoot	5.63 (±22.42)
Transition phase	33.27 (±95.28)

Understanding of how biomechanical changes with footwear can influence factors related to injury is ongoing. These include the kinematic and kinetic factors associated with running and have been discussed with regard to footwear in the next two sections.

2.7.2 Kinetic Changes with Footwear

Studies looking at impact characteristics related to footwear have been somewhat inconclusive in the literature. Early *in-vitro* reports of shoe cushioning found that increased shoe compliance reduced Fz1 and loading rate, leading to the assumption that shoe cushioning would reduce impact forces acting on the body (Shorten and Mientjes, 2011; Theisen et al, 2013). However this was not the case with *in-vivo* measures where the inverse effect was observed (Nigg, 2010; Schwellnus, Jordaan and Noakes, 1990; Richards, Magin and Callister, 2009; Squadrone and Gallozzi, 2009; Lohman et al, 2011; Goss and Gross 2012a; Aguinaldo and Mahar, 2003; Shorten, 2002). This may be due to runners adjusting lower body stiffness and running kinematics depending on surface hardness in order to maintain a leg-surface system constant (Lohman et al, 2011; Nigg, 2001). This was confirmed in a study by Kong, Candelaria and Smith (2009), in which worn shoes resulted in no difference in force variables compared to new shoes, as a result of adaptations by the runner to maintain the leg-surface system constant as the shoe got harder. This suggests that better cushioned shoes to not reduce the impacts on the body since runners will increase stiffness on the compliant surface to counteract the shoe deformation (Dixon, Collop and Batt, 2000). Runners have also been found to adopt a more extended stride, straighter knee and a rearfoot strike pattern at initial contact when in CRS (potentially as a means to optimise economy – Moore, Dixon and Jones, 2013) and this will result in higher impact characteristics when compared to the increased knee flexion, shorter stride, and a non-rearfoot strike pattern often observed in barefoot runners (see section 2.7.3) (Lieberman et al, 2010). These changes have also been proposed to be plantar feedback mediated impact attenuation behaviours (Robbins and Hanna, 1987).

The differences in the running gait among individuals is highly variable however (Nigg and Enders, 2013), and this is reflected in the kinetic data available;

2.7.2.1 The Fz1 and Loading Rate with Respect to Footwear

Numerous studies have examined differences in the Fz1 when comparing barefoot, MFW and CRS running. However the results are equivocal, with studies observing no difference in the Fz1 between CRS, MFW and barefoot (Giandolini et al, 2013a; Divert et al, 2008; De Wit, De Clerq and Aerts, 2000; Braunstein et al, 2010: Fong Yan et al,2012; Shorten, 2002), a lower Fz1 in barefoot/MFW vs. CRS (Hamill et al, 2011; Divert et al, 2005a; Divert et al, 2005b; Squadrone and Gallozzi, 2009; Nigg, 2010; Utz-Meagher, Nulty and Holt, 2011), or a higher Fz1 in barefoot/MFW vs. CRS (Lussiana et al, 2014; Sinclair et al, 2013; Willy and Davis, 2014). This variation has been suggested to be either due to the methods employed for determination of Fz1, the degree of habituation of participants in these studies (Lussiana et al, 2014), or the limited amount of steps taken during analysis (Divert et al, 2005b). A limited step count may have counteracted any need to attenuate impact, as this may be a feedback oriented tactic that requires a high amount of ground contacts (Divert et al, 2005b).

When investigating loading rate, some studies have found loading rate to be significantly higher for barefoot/MFW vs. CRS (Sinclair et al, 2013; De Wit, De Clerq and Aerts, 2000; Fong Yan et al, 2012; Willy and Davis, 2014; Paquette, Zhang and

Baumgartner, 2010), but also to be lower when barefoot/MFW when compared to CRS, and this has largely been related to the adoption of a non-rearfoot strike pattern (Lieberman et al, 2010). With respect to this change in foot strike pattern, barefoot running was found to reduce the Fz1 and loading rate when compared to several different shoe types, as a result of adopting a non-rearfoot strike pattern in the barefoot condition, but a rearfoot strike pattern in CRS (Hamill et al, 2011). The foot strike pattern may not be the only factor involved in reducing impact forces in running with different footwear, as Cheung (2013) noted a reduced loading rate when barefoot irrespective of the foot strike pattern adopted. Therefore it is possible that other factors such as lower body stiffness and leg geometry are just as important as the foot strike pattern in mediating impact during initial contact (Nigg, 2010; Derrick, 2004), but this requires further investigation. In runners that adopt a rearfoot strike pattern, CRS have been found to reduce the loading rate due to shoe cushioning properties (Nigg and Enders, 2013). Since the majority of the shod population adopt a rearfoot strike pattern, this may have some positive influence on injury rates in this population (Shorten and Mientjes, 2011; Hreljac, 2004; Fong Yan et al, 2012; TenBroek et al, 2013). However, this association lacks any empirical evidence for long term reduction of running related injury (Richards, Magin and Callister, 2009).

In a major review of acute research comparing barefoot and CRS running, Hall et al (2013) found some evidence for a lower peak vGRF, lower Fz1, and a higher loading rate when in the barefoot condition. However the authors note that there is yet only limited evidence available in this area, and none of this research identifies changes in these variables associated with a transition to barefoot running over time.

2.7.2.2 Plantar Pressures with Respect to Footwear

A further consideration with regard to impact kinetics is plantar pressures. Footwear with varying hardness has been found to have a significant influence on foot loading (Hennig and Milani, 1995). Likewise, footwear with minimal cushioning properties has been suggested to increase the likelihood of developing metatarsal stress fractures (Giuliani et al, 2011; Nunns, Stiles and Dixon, 2012), via increased localised pressures in the anterior plantar region as a result of a more anterior foot placement and thinner shoe (Squadrone and Gallozzi, 2009; Nunns et al, 2013). This can be a result of either reducing the cushioning (or consequently the time to decelerate the foot velocity), or adopting a non-rearfoot strike pattern that will reduce contact area and localise pressures under the bony prominences of the metatarsal heads (Squadrone and Gallozzi, 2009; Guiliani et al, 2011). Indeed, minimally cushioned footwear has shown increased pressures under the body prominences of the foot as well as result in much higher rates of pressure development (Shorten, 2002). This significant increase in localised plantar pressures may be more important than the potential 15-33% reduction in Fz1 and loading rate observed when running barefoot with a more anterior foot strike pattern (Goss and Gross, 2012b; Lieberman et al, 2010; Squadrone and Gallozzi, 2009; Divert et al, 2005b). It is important to note that this data involves a sample from habitually shod modern-day runners, but native Indian barefoot populations were observed to have much wider feet and more equally distributed plantar pressures (D'Aout et al, 2009). Plantar pressures were very different between shod Indian controls and Western participants when compared to Indian barefoot populations. There were areas of high and low pressures observed in shod Indian controls and Western participants who were observed to have shorter, thinner feet with focal pressure points under the heel, metatarsals and hallux in comparison to the habitually barefoot group (D'Aout et al, 2009). Therefore, these injuries related to higher plantar pressures may be a result of long term footwear use and reduction in foot shape and function (Zipfel and Berger, 2007), that are realised with an attempt to move out of CRS.

Considering these plantar pressure changes further, changing to a non-rearfoot strike pattern will increase the amount of time that this region of the foot is under stress, as opposed to the "roll over" effect of a rearfoot strike pattern in which the heel, midfoot and then forefoot are under pressure. This will increase the force*time integral, which may have some implications for stress reactions in the metatarsals (Goss and Gross, 2012a). Indeed a recent study by Ridge et al (2013) investigating bone marrow edema in athletes transitioning into VFF's over a ten week period, the authors found that 11 of 16 participants had a stress response which required a reduction in training load, and two participants experienced full metatarsal stress fractures during this period. The observed increase in metatarsal pressures is potentially due to impact moderating behaviours under the heel (Squadrone and Gallozzi, 2009), indeed a flatter foot placement has been significantly correlated with maximal localised pressures under the heel when barefoot running (r=-0.7) (De Wit, De Clerq and Aerts, 2000), and in harder shoes (Hennig, Valiant and Liu, 1996). The lack of protective properties when running in MFW or barefoot is a stark difference to the heavily padded CRS; higher metatarsal pressures were observed in all regions of the foot in Qiu and Gu (2011) in barefoot vs. CRS (Figure 2.7.2.2). This study identified the importance of midfoot cushioning properties for reducing plantar pressure. Whilst there is evidence that long term CRS use may reduce foot structure and function as discussed, the protective effect of CRS must be considered when an acute change in footwear is being considered. The long term use of footwear with limited cushioning remains to be examined in this regard.

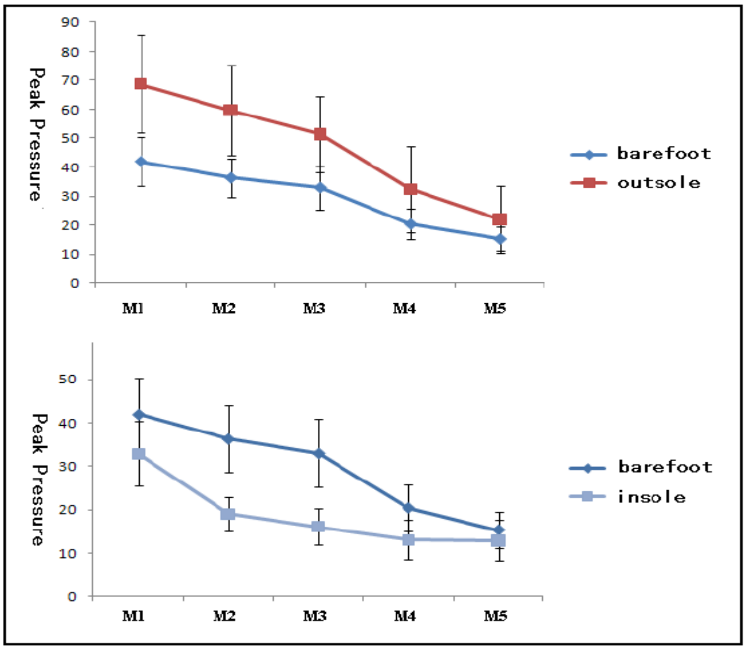


Figure 2.7.2.2. *Metatarsal peak pressures both recorded at the insole and outsole level of a CRS using pressure sensors and compared to barefoot. The figure demonstrates the reduction in localised plantar pressures with a cushioned shoe sole. Adapted from Qiu and Gu (2011).*

2.7.2.3 Internal Forces and Joint Moments with Respect to Footwear

The moments and forces acting on the body has also be different with changes in footwear; Increased knee flexion has been observed when barefoot, and this has been considered a potential impact attenuation tactic that will result in positive changes to knee loading (Braunstein et al, 2010). Indeed, running barefoot (shorter steps and shorter lever arm of the vGRF) has been found to reduce patellofemoral joint stress, knee joint moments (Bonacci et al, 2014; Kerrigan et al, 2009; Sinclair, 2014; Willwacher, Fischer and Bruggemann, 2013), lower peak extension and abduction moments as well as negative work at the knee (Bonacci et al, 2014; Williams et al, 2012). There was also a reduction in moments and forces the hip in Kerrigan et al (2009) and Bergmann et al (1995). However no difference in the moments or forces at the hip was observed in Willwacher, Fischer and Bruggemann (2013) or Bonacci et al (2014) when comparing barefoot and CRS running. In contrast to this potential reduction in knee internal work, barefoot forefoot strike pattern running may increase joint stress and mechanical work at the ankle (Olin and Gutierrez, 2013; Arendse et al, 2004; Divert et al, 2005a; Divert et al, 2008; Bonacci et al, 2014; Williams et al, 2012; Sinclair, 2014; Willwacher, Fischer and Bruggemann, 2013). The consensus in these studies is that barefoot running can have protective properties for the knee (potentially reducing the risk of injuries such as patellofemoral pain syndrome), but will increase demand on the triceps surae therefore increasing the risk of Achilles tendinopathies and associated injuries (Daoud et al, 2012; Divert et al, 2005a; Divert et al, 2008; Bonacci et al, 2014). However, more long term prospective studies are required to confirm these theories.

One study has investigated muscle activity and tibial shock during the first attempt at barefoot running (Olin and Gutierrez, 2013). This study used habitually shod rearfoot striking runners, who were required to implement a forced forefoot strike pattern in the barefoot condition, and compared to a rearfoot strike pattern when barefoot and in CRS. Gastrocnemius activity was found to be increased in the barefoot forefoot strike pattern modality. Knee flexion was increased, and average and peak tibial shock was higher during the barefoot forefoot strike pattern as a result of the lack of cushioning. The results suggest that upon the first attempt at a barefoot forefoot strike pattern, there is increased muscular demand in the gastrocnemius, as well as increased shock, both of which will have a potential for injury until the participants become accustomed to this novel activity (Olin and Gutierrez, 2013). This again highlights the potential danger of this transition period, and why it demands further research.

Whilst it appears that the evidence for reduced impact forces in difference shoes is equivocal and required investigation during a transition to barefoot or MFW, this section highlights a danger associated with barefoot and MFW running with regard to higher plantar pressures. It appears that whilst CRS to not attenuate impact forces *in vivo*, there is strong evidence that the cushioning properties reduce localised plantar pressures. In habitually barefoot populations this may not be an issue (Zipfel and Berger, 2007), but will be an important increase in load associated with modern day runner's attempting to incorporate MFW or barefoot running into their training. Indeed there is already evidence of an increased prevalence of stress fractures with a reduction in footwear (Giuliani et al, 2011; Nunns, Stiles and Dixon, 2012). Likewise the transition to barefoot or MFW could potentially result in increased risk of triceps surae injuries whilst reducing the internal forces at the knee (Bonacci et al, 2014).

2.7.3 Kinematic Changes with Footwear

There have been numerous kinematic differences associated with changes in footwear that can potentially have an impact on the risk of injury in runners and these have been discussed in section 2.7. Footwear has been shown to have a significant impact on the running gait (Lohman et al, 2011; Hennig and Milani, 1995; Bishop et al, 2006; Lieberman et al, 2010; Divert et al, 2005b). The many changes between barefoot, MFW and CRS have been summarised in Table 2.7.3. It has been suggested that the change in kinematics when barefoot running are actively prepared in free flight, suggesting an actively induced adaptation strategy for this condition compared to CRS (De Wit, De Clerq and Aerts, 2000). This may be as a result of necessary changes to leg geometry in order to counteract the reduced protective sensation of wearing shoes as previously discussed, either for economy (Moore, Jones and Dixon, 2013), impact attenuation (Nigg, 2010; Robbins and Hanna, 1987), or to limit localised pressures under the heel when barefoot (De Wit, De Clerq and Aerts, 2000). However, large individual variation has been observed when comparing footwear (Nigg and Enders, 2013).

Table 2.7.3. *Kinematic and spatiotemporal differences between CRS, barefoot and MFW running. Based on the current literature. Given that MFW are highly variable in design, the model used for the study has been listed in this category.*

Author(s)	**Variable**	**CRS**	**Barefoot (BF)**	**MFW (shoe type)**
Divert et al, 2005a; Divert et al, 2005b; De Wit, De Clerq and Aerts, 2000; Lussiana et al, 2014; McCallion et al, 2014; Bonacci et al, 2013; Hall et al, 2013; Squadrone and Gallozzi, 2009; Willy and Davis, 2014	Stride Frequency	Reduced	Increased	MFW > CRS (Merrel "Barefoot Glove"®) BF>MFW>CRS (VFF) MFW=CRS (Nike "Free 3.0"®)
Bonacci et al, 2013; De Wit, De Clerq and Aerts, 2000; Squadrone and Gallozzi, 2009; Franz, Wierzbinski and Kram, 2012	Stride Length	Longer	Shorter	CRS>MFW>BF (Nike "Free 3.0"®) CRS = MFW (Nike "Free 3.0"® and VFF)
Divert et al, 2005a; Divert et al, 2005b; Chambon et al, 2014; Lussiana et al, 2014; De Wit, De Clerq and Aerts, 2000; Hamill et al, 2011	Leg Stiffness	Reduced	Increased	MFW > CRS (Merrel "Barefoot Glove"®)
Bishop et al, 2006; Hamill et al, 2011; Chambon et al, 2014; Sinclair et al, 2013; Williams et al, 2012; Willy and Davis, 2014; Hall et al, 2013; Squadrone and Gallozzi, 2009	Ankle angle (at initial contact)	Higher dorsi-flexion	Higher plantar-flexion	MFW > CRS (Nike "Free 3.0"®) MFW = BF (VFF)
Bishop et al, 2006; Lieberman et al, 2010; De Wit, De Clerq and Aerts, 2000; Willy and Davis, 2014; Hall et al, 2013	Knee angle (at initial contact)	Decreased	Increased	MFW > CRS (Nike "Free 3.0®" MFW=BF=CRS (VFF)
Divert et al, 2005a; Divert et al, 2005b; Chambon et al, 2014; Lussiana et al, 2014; McCallion et al, 2014; Braunstein et al,	Ground contact time	Higher	Lower	CRS>MFW>BF (VFF and custom New Balance® MFW)

2010; Sinclair et al, 2013; Burkett, Kohrt and Buchbinder, 1985; De Wit, De Clerq and Aerts, 2000; Squadrone and Gallozzi, 2009; TenBroek et al, 2013; Olin and Gutierez, 2013				CRS>MFW=BF (Nike "Free 3.0"®) MFW=BF (VFF)
Chambon et al, 2014, Hamill et al, 2012	Knee Stiffness	=	=	
Lussiana et al, 2014; Divert et al, 2005a	vertical oscillation	Higher	Lower	CRS > MFW (Merrel "Barefoot Glove"®)
Divert et al, 2005a; Divert et al, 2005b; McCallion et al, 2014; Squadrone and Gallozzi, 2009	Flight time	Higher	Lower	MFW = CRS (VFF)
Bonacci et al 2013; Burkett, Kohrt and Buchbinder, 1985; Bishop et al, 2006	Knee excursion	More	Less	MFW=BF=CRS (VFF)
Bonacci et al, 2013; Williams et al, 2012; Squadrone and Gallozzi, 2009	Ankle Excursion	More	Less	MFW = BF (VFF)
Hall et al, 2013; Bishop et al, 2006; De Wit, De Clerq and Aerts, 2000; Divert et al, 2008; Lieberman et al, 2010; Squadrone and Gallozzi, 2009; Altman and Davis, 2011a; Hamill et al, 2011	Foot strike pattern	Varied but a tendency for a RFS	Varied but a tendency for a FFS	Varied
Hall et al, 2013; De Wit, De Clerq and Aerts, 2000	Eversion (initial and maximal)	Increased	Reduced – occurs earlier	
Hall et al, 2013	Knee valgus	increased	reduced	

2.7.4 MFW Design Considerations with Regard to Running Related Injury

Throughout this review we have made very little distinction between barefoot, CRS and MFW as a footwear choice. In this regard, the large variation of “minimal” features observed in MFW demand individual scrutiny and cannot be considered as one large MFW group. Likewise one must not assume that thinner footwear will induce more sensory feedback in a similar fashion to barefoot (Robbins and Waked, 1997; Robbins, Waked and McClaran, 1995). In fact, one element of footwear that has been found to have little effect on the running gait is the midsole thickness; shoes with 4mm, 12mm, and 16mm heel thickness did not influence the running pattern, but running barefoot did (Hamill et al, 2011). In a similar study, Chambon et al (2014) found that the foot strike pattern and other kinematics did not change from 0mm to 16mm of shoe stack height, but there were significant differences for the barefoot condition. The authors concluded that the presence of footwear, even with a very thin upper and sole was enough to significantly influence the running pattern (Chambon et al, 2014). Another shoe design that has been found to influence the running pattern is the heel-toe drop. A higher heel-toe drop has been found to result in a greater amount of rearfoot strikes than zero-drop footwear (Chambon et al, 2014; Hamill et al, 2011). In support of this notion, footwear with a higher heel-toe drop has been found to limit the ability to adopt a non-rearfoot strike pattern (Horvais and Samozino, 2013). These studies highlight the important difference between running barefoot vs. any type of footwear, and also highlight the need to clarify each different MFW being investigated instead of packaging them into one footwear type (Bonacci et al, 2013).

The main kinematic findings of studies comparing MFW to barefoot and/or CRS running are summarised in Table 2.7.3 above. One example of a minimal shoe that has not resulted in any clear differences to CRS (or similarities to barefoot) is the Nike “Free 3.0”® (Bonacci et al, 2013; Hein and Grau, 2014; Willy and Davis, 2014; Sinclair et al, 2013). This finding was also mirrored in a study including several different MFW (VFF, Inov-8 “Evoskin”®, Nike “Free 3.0”®) when compared to CRS and barefoot (Sinclair, 2014). The VFF and Inov-8 shoes were found to display similar reductions in patellofemoral kinetic parameters, and increases in Achilles tendon forces as barefoot, but the Nike free 3.0 was found to be similar to the CRS (Sinclair, 2014).

One shoe that has been found to have both similarities and differences to barefoot running is the VFF. As mentioned above, Sinclair (2014) identified similarities in patellofemoral and Achilles tendon work between the VFF and barefoot. Likewise, McCallion et al (2014) observed a lower contact time in VFF compared to CRS, and Squadrone and Gallozzi (2009) found similarities to barefoot for contact time, Fz1, RE, and ankle plantar-flexion angle when using the VFF footwear. In Squadrone and Gallozzi (2009) however stride frequency, stride length, the centre of pressure length, and flight time in the VFF condition more closely resembled the CRS than barefoot. Therefore, whilst the VFF has been found to have more similarities to barefoot than perhaps any other MFW, they should still be considered a separate footwear condition to barefoot.

2.7.5 The MFW Transition with Regard to Running Related Injury

To date, limited research has investigated changes in running kinetics and kinematics as a result of a transition to MFW. As a result, there is currently no “timeline” or evidenced based practice for this transition period. Giandolini et al (2013) suggested 6 hours of MFW running was enough for kinematic changes to “settle down”. In contrast, Robbins and Hanna (1987) have suggested the adaptation to barefoot running could take several weeks. With regard to short term changes, Divert et al (2005a) has suggested that 4 minutes is sufficient to optimise the foot-surface interaction with a change in footwear or surface hardness. Since there has been a large variation observed in kinematics when runners switched to barefoot running for the first time (see table 2.7.3), we suggest that individual responses to a novel footwear type will be highly dependent on the individual runner in question.

One short study over just two weeks examined kinematic and kinetic changes when training in VFF and found very little change in foot strike patterns, joint angles or kinetic parameters such as loading rate and Fz1, as well as joint moments and negative work (Willson et al, 2014). The participants were required to train in VFF’s for 20 minutes, three times a week for two weeks, and so the exposure time was limited in this study. Indeed the total time spent in the MFW in this study was 2 hours, where it has been suggested 6 hours is required to adapt to changes in footwear (Giandolini et al, 2013b). To compare this to a barefoot training intervention, a similar study over just two weeks required participants to include five minutes barefoot in the first week and ten minutes in the second week following each of their normal runs in CRS (Utz-Meagher, Nulty and Holt, 2011). The authors found a more plantar-flexed foot, reduced contact time, and a smaller peak vGRF following the training intervention. They also observed an increased plantar-flexion angle, decreased stride length, and a reduced Fz1 in the barefoot condition compared to CRS at pre-tests. These studies again highlight the difference in the effects of a familiarisation between MFW and barefoot running.

It was mentioned above that the responses to a MFW transition could be highly dependent on the runner in question. Indeed very little change was observed during a two week transition to VFFs in Willson et al (2014), but some participants on an individual basis did show similarities to barefoot movement. Those that changed displayed significantly reduced contact time and stride length, increased plantar-flexion, increased knee flexion, and less hip flexion (Willson et al, 2014). The authors concluded that most runners may require specific instruction to elicit similar changes to habitual barefoot runners, if indeed this was the desired effect. Understanding the individual responses to changes in footwear may be an important part of future research in this area.

2.8 Conclusion

The current understanding of running related injury is limited. However there is a growing body of evidence suggested that higher plantar pressures and impact characteristics during the foot-ground contact can predispose runners to bony injuries in particular. Footwear cushioning has been found to reduce localised plantar pressures on the foot, but this may be at the detriment of higher impact forces due to changes in running kinematics. Gait-retraining and simple kinematic changes to stride frequency and foot strike patterns have been found to influence these injury related factors, but no long term evidence that gait-retraining can reduce running related injury is available. Barefoot or MFW running does not have any strong evidence of injury reduction, however limited research suggests a forefoot strike pattern, shoe variation, and long term use of MFW or barefoot running may reduce injury rates in the current cohort of distance runners. The process of familiarisation has been suggested to be a high risk time for runners, as some runners don't change the running gait or leg stiffness properties in accordance with the reduced protective properties of MFW or when running barefoot. It appears as though the VFF is the only MFW that has somewhat resembled barefoot characteristics due to similarities in kinematic and kinetic variables; however there are also key differences. There may also be a large individual response in kinematics with changes in footwear that is poorly understood in running science.

From the literature review above, we have identified several important parameters with respect to performance and running related injury that should be examined with respect to a MFW transition. As a performance measure, RE has been found to be sensitive to endurance performance in a group of homogenous runners, and is also sensitive to changes in shoe mass or cushioning properties. However the smallest worthwhile change in RE has been proposed to be 2.4% (Saunders et al, 2004a) and this should be taken into account when interpreting the results. With regard to running related injury, several authors have reported metatarsal stress fractures during the transition to MFW or barefoot running, and plantar pressures have been found to be a viable measure of foot load. If so, this research project should examine how plantar pressures change during a MFW transition, particularly if changes in foot strike pattern are also observed in these runners, as this will redistribute the load on the foot considerably. Other impact measures that have been related to injury (particularly stress fractures) include the Fz1, and to a greater extent to loading rate. Finally, neuromuscular control of lower body stiffness can influence both RE and impacts transients. A high level of stiffness appears to be beneficial for RE, but can result in higher loading rate that may increase the risk of bony injuries. To date, to the best of our knowledge, no studies have previously investigated any of these factors with respect to a MFW transition period. This transition period should be carefully considered with regard to the design and progression of MFW exposure. The proposal for a transition programme with respect to the current body of literature, in addition to the individual study aims and objectives for this research project are considered in the next section.

CHAPTER THREE

Research Proposal

3. The Transition Programme and Overview of Study Design

This section will discuss the proposed transition programme for the present work with respect to the current literature in this area. In addition, section 3.2 will outline the aims and objectives of the studies involved in this work based on the literature review in section 2.0.

3.1 A Transition Proposal

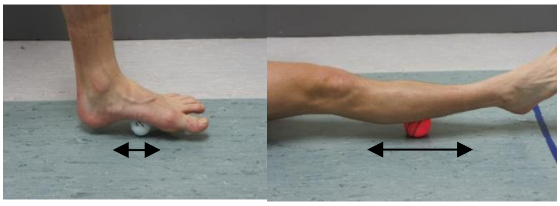
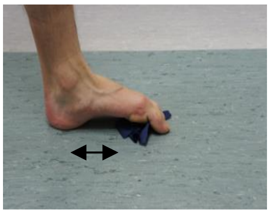
The period during which runners attempt to change their footwear is termed the "transition period". The transition process has not been examined to date in the scientific literature, but several authors have discussed important elements of this transition and these should be taken into account during the formation of this programme. Rothschild (2012b, pp 3) proposes "*an evidence-based preparation program should consist of activities and exercises that target the key biomechanical differences the barefoot runner will experience when compared with being shod* (Table 3.1a). *These key differences include: plantar sensitivity adaptation, foot strike pattern and related changes in stride rate and length, lower extremity proprioceptive ability, ankle joint flexibility, intrinsic foot strength, and eccentric strength of the lower limb to control impact forces. Learning the barefoot style, namely, a reduced heel strike is fundamental in the transition to barefoot running*" (Rothschild, 2012, pp 3). Whilst several of these factors could be considered gait changes, important adaptation elements such as intrinsic foot strength, eccentric exercises of the lower leg, and ankle joint flexibility would appear to be integral to a successful transition to avoid injury. It has also been suggested that MFW running can increase triceps surae tightness and soreness (Willson et al, 2014). Self-myofascial release techniques (foam rolling) have been suggested to be successful at reducing muscle tension and increasing range of movement about a joint (MacDonald et al, 2013), and therefore may be a feasible management exercise for this issue.

Table 3.1a. A barefoot transition proposal. Adapted from Rothschild (2012b).

Barefoot activity	Barefoot walking indoors
	Barefoot walking outdoors
	Barefoot running indoors
	Barefoot running outdoors – grass and asphalt
Running form drills	Forefoot striking
	Increased stride frequency
	Shorter step length
Proprioceptive exercises	Single-leg stance
	Single-leg stance on unstable surface
	Single-leg stance with resistive band
Flexibility exercises	Calf stretching against wall
	Calf stretching off the edge of a step
	PNF calf stretching
Strengthening exercises	Foot intrinsics
Plyometric activities	Single leg hops (forwards + hurdles)
	Jumps (squat jumps, depth jumps etc.)
	Horizontal and vertical bounds

This concept that the transition should include injury prevention resistance exercises may be important (Warburton, 2001). Nigg and Enders (2013) propose that barefoot activity will increase the strength of the ankle stabilisers in a similar fashion to wobble board training, and wobble board training has been found to reduce injury. Strong small stabilisers of the ankle due to barefoot training would be beneficial to athletes, and these movements must have a lateral component, as this increases muscle activity by 50% (Nigg and Enders, 2013; Nigg, 2010). This lateral component could be something as simple as single leg balance work. Therefore we identified the following important components for injury prevention and preparation for a familiarisation to MFW running – ankle mobility, foot longitudinal strength, lateral stability, eccentric triceps surae strength, and self-myofascial release techniques. The exercises for these components are outlined in Table 3.1b. Many of these exercises were recommended as a strength programme for injury prevention in high school runners (Tenforde et al, 2011).

Table 3.1b. *Injury prevention exercise programme for the present research. It was not specified if these exercises were completed on the same days as the MFW intervention or not.*

Exercise Programme (10 minutes)	
Plantar Fascia and Triceps Surae Rolling x 5 mins 	
Ankle Mobility (3 x 15) 	**Calf Raises (3 x 15)** 
Toe "Grabs" (3 x 15) 	**Single leg balance (60secs)** 

With regard to the process of increasing activity in MFW, training programmes should start with adequate barefoot activity in daily living before any running is begun (Hart and Smith, 2009; Warburton, 2001). Thirty minutes of daily barefoot movement is recommended including walking, jumping, playing games etc., to begin to allow development of the plantar surface and adaptations of the muscles and ligaments of the lower leg (Robbins et al, 1993; Hart and Smith, 2009). In addition, this transition should be gradually introduced over a period of no less than 4–8 weeks because of muscular adaptation to training taking this period of time (Sale, 1988). Likewise, 3-4 weeks is enough time to allow plantar surface adaptation when barefoot running (Robbins et al, 1993).

There is no apparent method of determining how “well” participants were familiarised to MFW. However, the research outlined in Table 2.6.3 as part of Irene Davis’ research group propose eight sessions is the minimum for adequate uptake of gait-retraining. The current programme has therefore been designed to incorporate at least eight MFW runs, and therefore at least eight “sessions” of MFW and gait-retraining. Whilst we do not suggest this is an “optimal” amount of time for either MFW or gait-retraining, it presents us with preliminary data from the initial four to eight weeks of a transition programme, and this is a good place to start.

In the absence of any other guidelines for transition, this approach would seem to be a logical place to start. The limited work above would suggest a transition to MFW should be examined from a minimum of four weeks and should include relevant injury prevention exercises (Table 3.1b) to reduce the risk of running related injury. The programme should also consider “barefoot” gait-retraining elements and discussed in the previous section. Popular gait-retraining elements include adopting a short stride length with higher stride frequency (Hobara et al, 2012; Goss and Gross, 2012b), the use of a mid or forefoot strike pattern (Lieberman et al, 2010; Goss and Gross, 2012b), a more forward hip alignment with the foot landing under the centre of mass (Lieberman et al, 2010; Goss and Gross, 2012b), and actively working on landing as light as possible to reduce landing velocity and the foot/ground collision (Crowell and Davis, 2011). These kinematic changes are discussed in the Review of Literature (Chapter two). The transition schedule proposed for the present work can be found in Table 3.1c that includes some simple barefoot activity at the beginning with a gradual progression of running on mixed surfaces. The higher exposure to running on grass than concrete may be noted as a limitation to this design, as more compliant surfaces may not instigate the same degree of impact attenuation as harder surfaces (Herzog, 1979; Willwacher, Fischer and Bruggemann, 2013). However the adoption of multiple surfaces will vary the stimuli, and represents a more realistic and safe scenario in today’s environment.

It was important for the design of this research project that the gait-retraining guidelines were not enforced regularly during the transition period. Whilst this could be considered a limitation in the study design, we recognised that the vast majority of runners would not have access to regular education or feedback and would instead rely upon a "once-off" session before attempting to incorporate the changes individually. Within the applied nature of the present work it was deemed important to understand how well these runners could adopt gait-retraining changes individually, and crucially this also allowed for observation of effects related to footwear. Any footwear effects would not be apparent if the runners were controlled for foot strike pattern, stride frequency etc., and this may occur with repeated gait-retraining sessions.

In addition, it is important that the runners experience the same amount of MFW exposure as part of this transition programme. This in itself presents a novel issue, because whilst the participants will complete the same amount of time in MFW during the transition, some of these runners will have a higher overall mileage in the week and therefore their exposure relative to their running in CRS will vary. For example, a runner who typically runs 70km/week will probably spend 30% of this time in MFW by the end of the intervention. In contrast, a participant who runs 25km per week may spend as much as 90-100% of their training in MFW by the final week of the programme. This may present an increased injury risk in these lower mileage runners, but maintenance of the total training volume in all participants is important to prevent de-training during this period.

The current transition programme is therefore focused on three important elements; 1) To ensure adequate exposure to the MFW condition, 2) to allow adequate time for participants to adopt the gait-retraining changes, and 3) to reduce the risk of injury as much as possible.

Table 3.1c. *An example of a preliminary 6 week familiarisation schedule for MFW running proposed for the present work.*

Week	MFW Training Programme
Week 1	Throughout: Wearing MFW and going barefoot as much as possible in normal daily routines 3 days: 5 -8 mins easy running on the spot or in corridors/garden at home 3 days: Prescribed exercises (Table 3.1b)
Week 2	3 days: 10 – 15 mins running on grass, 3 minutes on pavement 3 days: Prescribed exercises (Table 3.1b)
Week 3	2 days: 20 mins running on grass, 5 - 8 minutes on pavement 1 day: 25 mins running on grass 3 days: Prescribed exercises (Table 3.1b)
Week 4	2 days: 25 mins on grass, 10 mins on pavement 1day: 30 mins on grass 2 days: Prescribed exercises (Table 3.1b)
Week 5 + (	2-3 days: 30 mins on grass, 15 mins on pavement 1day: 40 mins on grass 2 days: Prescribed exercises (Table 3.1b)

3.2 Individual Study Aims and Objectives

We propose to complete the following studies as part of this investigation;

Chapter Four. Study One – "Does a familiarisation to MFW influence RE in trained male athletes when compared to running in CRS?"

Study Aim – To determine changes in RE as a result of a familiarisation period in MFW with no feedback on the running gait. This will be compared to the same participants wearing CRS.

Objectives –

- To evaluate if a four week familiarisation to MFW can influence RE in this footwear type
- To determine if there is a difference in RE between MFW and CRS.
- To record changes in simple kinematic measures such as foot strike patterns and stride frequency in order to determine the gait related changes associated with this transition period.

Chapter Five. Study Two – "Does a familiarisation to MFW and gait-retraining influence RE in trained male athletes when compared to running in CRS?"

Study Aim – To determine changes in RE as a result of a familiarisation period in MFW with a gait-retraining element included. This will be compared to the same participants wearing CRS, and also a control group with no MFW or gait-retraining exposure.

Objectives –

- To evaluate if an eight week familiarisation to MFW when combined with simple gait-retraining can influence RE.
- To determine if there is a difference in RE between MFW and CRS.
- To record changes in simple kinematic measures such as foot strike patterns and stride frequency in order to determine the gait related changes associated with this transition

Chapter Six. Study Three – "Does a familiarisation to MFW with gait-retraining influence plantar pressures and forces in trained female athletes when compared to running in CRS?"

Study Aim – To determine changes in plantar pressure distribution and mean plantar forces as a result of a familiarisation period in MFW with a gait-retraining element included. This will be compared to the same participants wearing CRS.

Objectives –

- To evaluate if a four week familiarisation to MFW can influence localised plantar pressures and mean forces acting on the plantar surface.
- To determine if there is a difference in regional plantar pressures and mean forces between MFW and CRS.
- To record changes in simple kinematic measures such as foot strike patterns and stride frequency in order to determine the gait related changes associated with this transition

Chapter Seven. Study Four– "Does a familiarisation to MFW with gait-retraining influence running kinetics and kinematics in trained male athletes when compared to running in CRS?"

Study Aim – To determine changes in kinetics (Fz1, loading rate) and neuromuscular factors (vertical and joint stiffness) as a result of a familiarisation period in MFW with gait-retraining. This will be compared to the same participants wearing CRS and a control group who undergo the gait-retraining only with no exposure to MFW running.

Objectives –

- To evaluate if a six week familiarisation to MFW can influence impact variables associated with injury risk (Fz1 and loading rate), and neuromuscular factors associated with injury risk (vertical and joint stiffness).
- To determine if there is a difference in these kinetic and kinematic measures between MFW and CRS.

CHAPTER FOUR

Study One

*“*Four weeks habituation to simulated barefoot running improves running economy when compared to shod running*”*

4. Study One – "Four weeks habituation to simulated barefoot running improves running economy when compared to shod running".

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STATEMENT OF CONTRIBUTION: GILES WARRINGTON WAS THE RESEARCH SUPERVISOR FOR THIS STUDY.

ABSTRACT

The purpose of this study was to evaluate the effects of 4-weeks familiarisation to simulated barefoot running (SBR) on running economy (RE) when compared to shod. Fifteen male trained runners (age: 24 ± 4yrs; stature: 177.2 ± 6.21cm; mass: 67.9 ± 7.4 kg and $\dot{V}O_{2max}$ 70.2 ± 5.2 $ml \cdot kg \cdot min^{-1}$·) were recruited. Participants completed two RE tests; 24 hours apart, in a random order, in both the SBR and shod condition (pre-test) at 11 and 13km/h. Oxygen uptake ($\dot{V}O_2$), heart-rate, stride frequency, and foot strike patterns were measured in both conditions. Participants then completed a 4-week familiarisation period of SBR, before repeating the 2 RE tests (post-test). At pre-test, there was no significant difference in RE between SBR and shod running (p=0.463), but following the 4 week familiarisation period RE was significantly better by 6.9% in the SBR condition compared to shod (46.4 ± 0.9 v 43.2 ± 1.2 $ml \cdot kg \cdot min^{-1}$; p=0.011). A significant improvement in RE was observed in the SBR condition (8.09%) between the pre-test and post-test (47.0 ± 1.2 v 43.2 ± 1.2 $ml \cdot kg \cdot min^{-1}$; p=0.002). RE improved in the SBR condition as a result of familiarisation, and became significantly lower in SBR compared with shod running.

4.1 Introduction

The evolution of mankind has reduced the pattern from running for everyday living and in order to survive, to an extra-curricular recreational and sporting activity that is considered important for health and wellbeing. Running has been largely influenced by footwear manufacturers in recent times, where large scale movement towards shoes offering comfort, cushioning, motion control and support have become the normal procedure for running enthusiasts. However, this large scale move into supportive footwear has been questioned in the literature over a number of years (Lieberman et al, 2010; Richards, Magin and Callister, 2009; Squadrone and Gallozzi, 2009; Robbins and Hanna, 1987), and has led to a recent growing interest and participation in barefoot (BR) or simulated barefoot running (SBR).

Aside from potential lower injury risk (Lieberman et al, 2010; Robbins and Hanna, 1987; Richards, Magin and Callister, 2009), it is suggested that the change in gait when transitioning into less cushioned shoes, SBR or when barefoot running can have a positive effect on running economy (RE) (Hanson et al, 2011; Squadrone and Gallozzi, 2009). There is a growing body of research suggesting that the change in gait mechanics due to a more natural fore-foot strike pattern (FFS) can lead to a more efficient movement pattern (Lieberman et al, 2010; Squadrone and Gallozzi, 2009; Divert et al, 2005b), which may be explained by a number of factors including the weight of shoes; changes in joint stiffness; a reduction in braking impulse; and increased storage and recovery of elastic energy when running barefoot or in a simulated condition (Asmussen and Bonde-Petersen, 1974; Divert et al, 2008; Hanson et al, 2011; Kyrolainen, Belli and Komi, 2001; Lieberman et al, 2010, Squadrone and Gallozzi, 2009). Despite this, a thorough search of the current scientific literature revealed there is no published research investigating differences in a habituated and non-habituated participants, as most studies have used initial responses or habitually barefoot runners for their investigations (Hanson et al, 2011; Lieberman et al, 2010, Squadrone and Gallozzi, 2009; Divert et al, 2008). Given that RE is considered an important determinant of endurance running performance (Lucia et al, 2006), it may be pertinent to investigate how changes related to familiarisation to simulated barefoot running can influence this variable.

With this rise in popularity, a new movement of “minimalist” shoes have become available. Brand specific research is limited, yet anecdotal evidence suggests that most “minimalistic” products available would seem to still offer some degree of cushioning or support that may not accurately reflect barefoot running (Wallden, 2010). One product however that exhibits minimal cushioning, support or structure is Vibram “FiveFingers” (VFF). This relatively new product provides a simple “second skin” for the foot in order to simply offer protection on modern day surfaces. Recent research by Squadrone and Gallozzi (2009) proposed that there are common characteristics between barefoot running and VFF’s that merits further investigation as a tool to simulate barefoot running (SBR).

The current study investigated the effects of SBR on RE when compared to traditional running shoes and therefore adds to the limited literature on SBR. The focus of the present research was to investigate the effects of a 4 week familiarisation period when transitioning into SBR when compared with the same group in a non-familiarised state and as such investigate the acute and chronic changes of this group, as this may be an important area for future prescription of barefoot running or SBR.

4.2 Methods

4.2.1 Participants: Fifteen trained male participants were recruited from a collegiate Athletics Academy on a volunteer basis via email (Age 24 ± 5 years; Stature 177.2 ± 6.2 cm; Mass 68 ± 7 kg; $\dot{V}0_{2max}$ 70.2 ± 5.2 $mL·min^{-1}·kg^{-1}$: 1500m PB 240.3 ± 8.0 seconds; 5000m PB 968.0 ± 50.1 seconds). All participants ran 6 - 7 days per week (a minimum of 50km per week) and competed in middle distance events (800 – 5000m). Testing took place out of the main competition season (February - March). Participants were excluded if they had reported any lower limb injuries in the last three months, had any previous barefoot running experience or currently used orthotics. All participants had previous experience with treadmill running. Prior to participation in the study testing procedures were explained in detail and participants completed a general health questionnaire and signed an informed consent form. Ethical approval for this study was granted by the Dublin City University Research Ethics Committee.

4.2.2 Experimental design: Participants were required to visit the human performance laboratories for 4 separate testing sessions. The study design consisted of two pre-tests performed in a random order, followed by a four week period of familiarisation and two post-tests, in the opposite order in a balanced Latin square design to minimize any possible order effect during testing. On the first visit, foot size was measured and participants were provided with one pair of SBR (VFF) footwear (~150g) and also a standard pair of high quality traditional running shoes of a neutral design (Shod)(~400g). The participants were allocated a footwear condition before conducting a running economy (RE) test, and repeated the test in the opposite condition 24 hours later. Thus all participants were tested in both the SBR and Shod condition at Pre and Post-tests, with the shod condition acting as the control.

4.2.3 Running economy tests: Participant height and body mass were initially recorded. Tests took place at the same time of day with the participants required to maintain a similar diet, sleep pattern and training routine between and before tests. Diet, sleep and training were recorded directly prior to the initial test and included all food and fluid consumed on that day, and was subsequently sent to each participant in order for exact replication on testing days. Resting blood lactate (Lactate Plus, Nova Biomedical, MA, USA) was sampled from the earlobe prior to the testing sessions. Respiratory data was measured using a Viasys Vmax Encore 299 on-line gas analysis system (Viasys Healthcare, Yorba Linda, CA, USA). The system was calibrated to the manufacturer guidelines, including atmospheric pressure and temperature. A treadmill (Woodway, Weil am Rhein, Germany) RE test was then conducted in the assigned footwear. Treadmill incline was set at 1% to account for air resistance (Jones and Doust, 1996) and participants ran for 6 minute intervals at 11 and 13km/h. At the end of each 6 minute stage, participants were asked to stand to the side of the treadmill and a blood lactate sample was collected within 30 seconds. The next stage was started after 1 minute of rest. At 5 minutes in each stage stride frequency (SF) was collected by counting the left foot contact with the treadmill belt for 60 seconds duration (this was repeated by the same investigator for validity in each participant and also filmed for a second assessment). Heart rate (Garmin, Dathe, KS, USA) and rated perceived exertion (RPE; BORG scale) were collected at 2 minute intervals. Rudimentary analysis foot strike pattern analysis was undertaken using a low cost video camera (Sony HDR-CX210, 60FPS; Sony, San Diego, CA, USA) in which participants were filmed in the sagittal plane at foot level over a 60 second period during the fourth minute of testing. The video footage was then used to assign 1, 2 or 3 (1= forefoot strike, 2= midfoot strike, 3=rearfoot strike) to the participants foot strike pattern using Dartfish video analysis software (Dartfish 5.5, Fribourg, Switzerland). A midfoot strike pattern was classified when there was no clear forefoot or heel initial contact.

The participants were then given a 24 hour recovery period where they were asked to control and record training, hours of sleep and diet, and then returned to the human performance laboratory to perform the pre-test in the opposite footwear with all other conditions remaining the same. Four weeks after the initial trial and following the familiarisation period, participants returned to the laboratory and were again assigned a footwear condition before conducting the same RE testing protocol previously outlined above. This was again repeated 24 hours later in the other footwear condition (post-tests). Due to the study design adopted, the post tests were conducted in the opposite order to the pre-tests.

4.2.4 Four week familiarisation phase: Before leaving the laboratory, each participant was provided with detailed guidelines including a structured progression of SBR over the four week familiarisation period. The programme incorporated SBR into the runners normally training routines, beginning with 2 runs of 15 minutes in the first week (~10% of total training volume), and gradually increasing to 3 - 4 x 30 minute runs by week four (~25% of training volume). This programme deliberately did not include any visual feedback or instruction on technique, but simply asked participants to run in the simulated barefoot condition at a comfortable velocity and to include some exercises that would reduce tightness specifically in the plantar fascia and calf muscles (calf raises on a step, and the use of a golf ball to massage the plantar surface of the foot). The rationale for adopting this approach was to evaluate “natural” rather than “enforced” changes as a result of SBR. Participants were required to maintain their normal training load in the shod condition at the same time, but may have substituted some shod running for SBR causing shod training volume to decrease slightly.

4.2.5 Testing procedure – $\dot{V}O_{2max}$: Before the four week familiarisation period, participants completed a $\dot{V}O_{2max}$ test. This involved a ramped protocol with the treadmill speed set at 12km/h for a 5 minute warm-up before increasing to 14km/h at 1% incline. The incline was then increased every minute until volitional exhaustion, participants achieved a respiratory quotient of 1.1 or above, or heart rate was within 10 beats of predicted maximum (220-age). Participants conducted this test in their own shoe choice. $\dot{V}0_{2max}$ was recorded as the highest mean value achieved over the course of 60 seconds.

4.2.6 Data analysis for RE tests: The RE data was averaged over the last two minutes of each stage when participants had reached steady state $\dot{V}O_2$. Mean heart rate values were recorded using the 4 and 6 minute recordings for each stage, as was RPE.

4.2.7 Statistics: Significant differences between condition, time, and velocity were established using repeated measures ANOVA tests (SPSS data analysis software V16.0) in order to establish within-subjects effects. Paired t-tests were completed to examine differences changes specific to each treadmill speed. Where the data violated Mauchly’s test of spherity, the Greenhouse-Geisser correction was established. For changes specific to time, pairwise comparisons were used under the Bonferroni adjustment. Statistical significance was accepted at $\alpha \leq 0.05$.

4.3 Results

The mean Pre and Post $\dot{V}0_2$, heart rate, stride frequency (strides per minute - SPM) and RPE are presented in table 4.3.The repeated measures ANOVA revealed a significant interaction between time (pre to post-tests) and condition (SBR vs. shod)($p=0.034$) for RE. This interaction revealed that; at pre-test, there was no significant difference for RE between SBR and shod conditions ($p=0.463$; 1.05%). During the familiarisation, SBR RE improved by 8.09% ($p=0.002$), whilst shod RE showed a non-significant improvement of 2.32% ($p=0.087$). Furthermore, the improvement in SBR RE was significantly larger than shod RE following the familiarisation, where SBR RE was superior to shod RE by 6.9% ($p=0.011$). The improvement was similar at both velocities using paired t-tests (Figure 4.3a). For example, analysis of the post-test statistics revealed a 7.01% reduction ($p=0.012$) in RE at 11km/h in the SBR condition compared to shod, and a 6.77% reduction ($p=0.016$) at 13km/h. These results were consistent across all variables and as a result, velocity was pooled for further analysis.

Table 4.3. *Summary of pre and post results (mean (±SD)) in the shod and SBR condition.*

	Pre-shod	Post-shod	Pre-SBR	Post-SBR
$VO_{2sub\text{-}max}$ (mL/min/kg)	47.5 (±0.9)	46.4 (±0.9)*	47.0 (±1.2)†	43.2 (±1.2)*
11 km/h $VO_{2sub\text{-}max}$	43.61 (±0.99)	42.53 (±0.82)*	42.99 (±1.15)†	39.55 (±1.04)*
13 km/h $VO_{2sub\text{-}max}$	51.44 (±1.23)	50.33 (±0.94)*	50.99 (±1.34)†	46.92 (±1.35)*
Heart rate (BPM)	143.83 (±3.56)	141.46 (±3.3)*	142.3 (±3.73)†	137.5 (±3.36)*
Stride frequency (SPM)	81.54 (±0.95)*	81.89 (±0.82)*	83.69 (±1.3)*	84.12 (±1.29)*
RPE (6–20)	9.25 (±0.56)	8.65 (±0.43)	9.21 (±0.47)†	8.34 (±0.35)

M ± SE; $n = 15$; $^{*}P < 0.05$; * = difference between condition; † = change over time.
BPM, beats per minute; SPM, strides per minute.

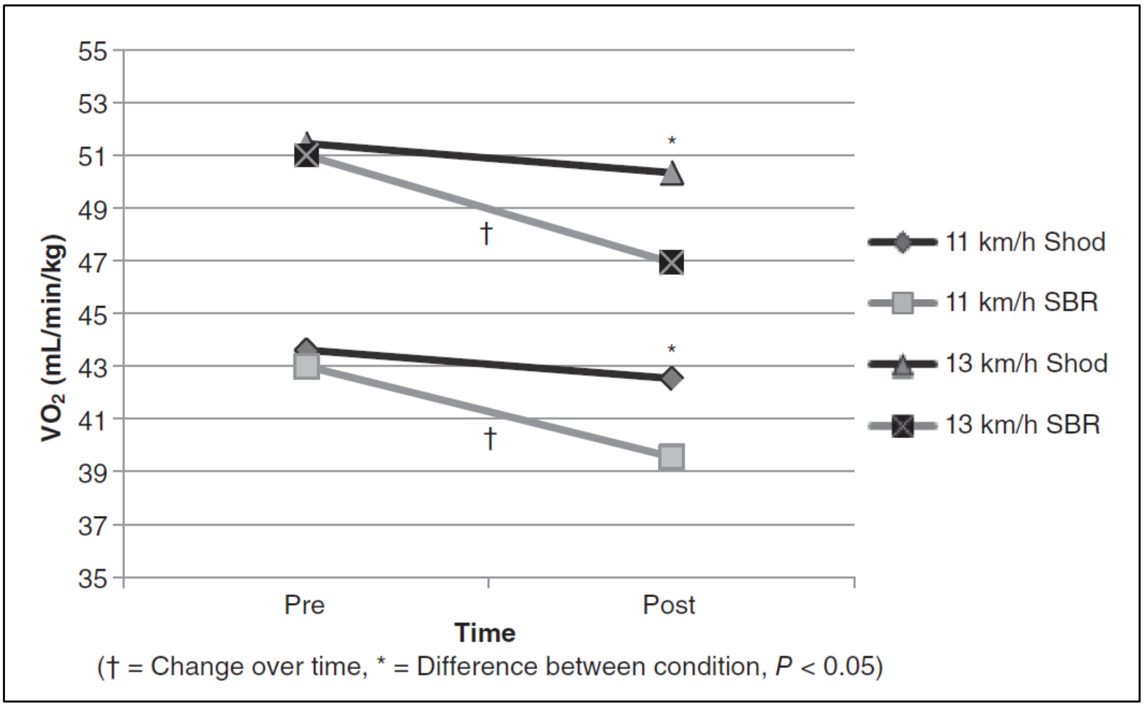

Figure 4.3a. *11 and 13km/h running economy data for pre and post-tests in the shod and SBR condition.*

Heart rate was not significantly different in the SBR condition at pre-test compared to shod (p=0.750). Heart rate did not significantly change during the familiarisation (SBR p=0.057; shod p=0.088), but was significantly lower in SBR by 2.8% at the post-test compared to shod (p=0.011). There was no difference observed at pre-tests between SBR and shod when examining RPE (p=0.897). During the familiarisation, SBR was found to decrease a significant 9.45% (p=0.024). There was no change in shod RPE during the familiarisation (p=0.233). At post-tests, no significant difference was observed between SBR and shod (p=0.060).

Further analysis using an ANOVA showed that there was a 2.64% higher stride frequency at pre-tests in the SBR condition when compared to shod, that was found to be significant (p=0.006). During the familiarisation, SBR and shod SF did not significantly improve (SBR p=0.392; shod p=0.500). Post-tests revealed that SBR was 2.72% higher than shod, that was found to be significant (p=0.001).

Analysis for foot strike pattern revealed that there was no significant difference between the SBR and shod condition at pre-tests (p=0.165) (Figure 4.3b). SBR significantly favoured a FFS during the familiarisation period (p=0.040), whilst shod was not found to significantly change (p=0.336). Furthermore, at post-tests the SBR group significantly favoured a FFS (p=0.003) when compared to shod.

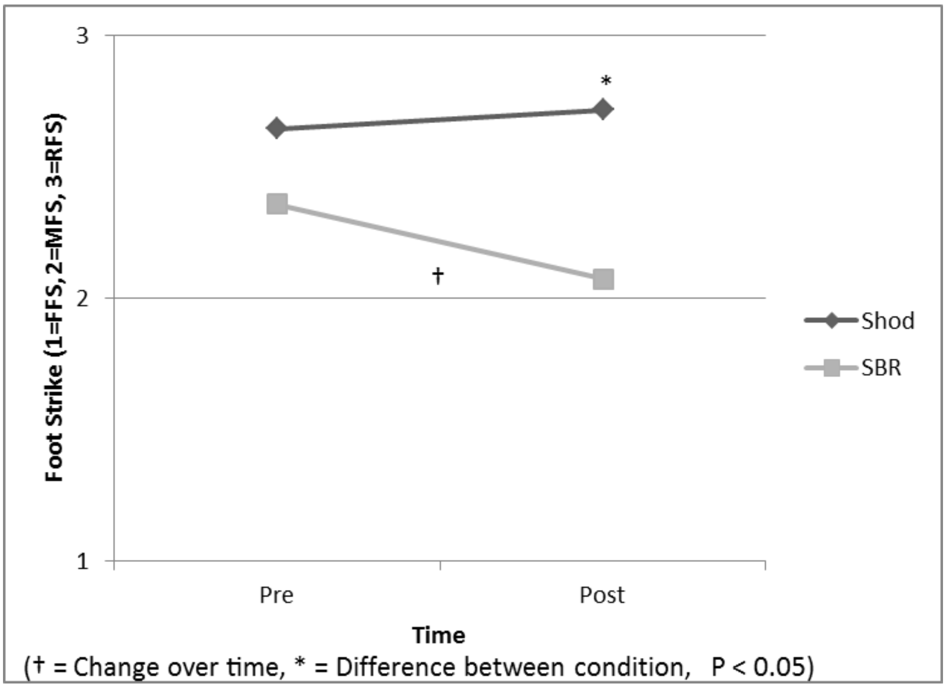

Figure 4.3b. *Individual comparison of foot strike patterns in the shod and SBR conditions from Pre to Post tests.*

4.4 Discussion

The main finding in the present study is that SBR RE significantly improved as a result of the familiarisation period (p=0.002) and became superior to shod RE (p=0.011). Given that the difference in RE between the two conditions improved from 1.05% at pre-tests to 6.9% at post-tests indicates that some degree of adaptation is taking place that cannot only be explained by changes in shoe weight or design (Divert et al, 2008). This study, to the best of the authors knowledge, is the first of its kind to investigate the effects of familiarisation in the SBF running condition with regard to RE. The results provide valuable information on the importance of an appropriate transition phase in order to adjust to a new running condition.

Divert et al (2008) and Franz, Wierzbinski and Kram (2012) have proposed that for every 100g added to the foot, RE is reduced by 1%. Given that the difference in shoe mass of the current study was ~250g, it was surprising that there was no difference in RE at pre-tests between the shod and SBR conditions. However, this may be a type II-error as the actual suspected difference is within the measuring error for the current method. When considering the change over time, it may be proposed that some degree of change must be related to physiological adaptations as opposed to biomechanical differences (Saunders et al, 2004b). One plausible explanation in this regard is related to the increased mechanical movement in the SBR group, associated with greater stride frequency and thus increased muscular contractions and ground contacts per minute (Divert et al, 2005a) that may improve the neuromuscular adaptations to exercise at a greater rate, similar to the improvements observed with plyometric training (Turner, Owings and Schwane, 2003). However any physiological changes would also have been observed in the shod condition and may not be accountable for the changes observed in the current study. To date, most studies have suggested changes in mechanics are the sole reason for any discrepancy in RE (Divert et al, 2005a; Squadrone and Gallozzi, 2009; Tseh, Caputo and Morgan, 2008). Given that the FSP was observed to change during the familiarisation, (and given that the SBR effect size from pre-post was n^2=0.062 for SF, which may be considered a reasonable change), it may be suggested that the observed difference in RE was as a result of changes in running technique.

One possible causative factor explaining the improved RE observed in the current study, may be due to a more effective recovery of elastic energy in the working tendons and muscles (Asmussen and Bonde-Petersen, 1974; Bramble and Lieberman, 2004, Divert et al, 2005a, Saunders et al, 2004b; Kyrolainen, Belli and Komi, 2001) that may be increased as a result of a more plantarflexed foot placement and increase in stride frequency (that will reduce stride length). Saunders et al (2004b) reported that during the eccentric phase of contact, mechanical energy is stored in the connective tissues and this recovery of the elastic properties during the concentric phase reduces energy consumption. Additionally, the findings of a study by Divert et al (2005a) concluded that higher pre-stretch levels as well as reduction in contact time could enhance the stretch shortening cycle behaviour of the plantar flexor muscles and thus provide a better storage and recovery of elastic energy. Indeed barefoot running mechanics would appear to adopt a more plyometric-type movement, that promotes the stretch-shortening cycle (SSC) pattern that has previously been shown to improve RE (Turner, Owings and Schwane, 2003) by increasing lower leg musculotendinous stiffness (Spurrs et al, 2003), and increasing knee and ankle angles that will increase eccentric load (Divert et al, 2005a). Running in a simulated barefoot condition may be more attributable to the barefoot than the shod condition (Squadrone and Gallozzi, 2009) and thus may result in similar properties. The fact that the shod condition did not improve over the familiarisation period may support earlier studies suggesting that leg musculotendinous stiffness, stride frequency and ankle plantar flexion is increased as a result of increased proprioceptive feedback from the foot as a sensory effect to ground surface hardness (Divert et al, 2005a, 2005b, Robbins and Hanna, 1987), in order to actively protect the heel from localised pressure and attenuate impact (Saunders et al, 2004b; Robbins and Hanna, 1987; Divert et al, 2005b), that does not occur when wearing traditional shoes or immediately after removing shoes from the feet. Instead it may be reasonable to assume that these changes result as a learned effect. An increased co-ordination and pre-activation of the dominant running muscles in anticipation of ground contact due to increased proprioception in the foot may be responsible for this effect, (Bishop et al, 2006; Lieberman et al, 2010; Robbins and Hanna, 1987) that is improved as a training effect to barefoot simulated exercise.

The pre familiarisation difference in RE of 1.05% would appear to be smaller than that seen in previous studies when comparing conditions. Hanson et al (2011) reported a 3.8% improvement in RE in a barefoot group when compared to shod; Burkett, Kohrt and Buchbinder (1985) in an early review identified a 1.3% difference, Franz, Wierzbinski and Kram (2012) found no difference, and Squadrone and Gallozzi (2009) reported a 2.8% improved RE in the barefoot condition. The discrepancies in values between studies may be related to the traditional footwear model being used, treadmill incline, and error associated with RE testing (Saunders et al, 2004a), but are most likely as a result of shoe weight differences (Divert et al, 2008) or the fact that these participants had received different amounts of barefoot experience, in contrast to the current study in which participants had no previous experience. Based on these previous findings, it is reasonable to assume that improvements in RE appear to be in the region of 1-4% in the barefoot condition acutely. The current study findings of a significant change of 6.9% in RE between conditions in trained runners following a familiarisation period are much larger than those previously reported, however no study to the best of our knowledge has investigated a habituated participant group who have previously only ran in traditional shoes. This is a novel finding, in that the effects of a four week familiarisation can increase RE when running SBR by ~6%, which cannot be explained exclusively by changes in shoe weight or design (Divert et al, 2008). Thus biomechanical changes to running technique that occur over time such as a greater plantar flexion angle and minor changes in stride frequency would appear to be key contributory factors. Given that training, time of day and testing consistency was controlled, the change above 2.4% as noted by Saunders et al (2004a) can be considered a reasonable and worthwhile effect that is above typical RE error.

A novel finding of the current study was the improved RE observed in the shod group at post-test. Given that the participants were trained runners, it was unexpected that the shod condition improved by 2.32% between tests. There are several plausible explanations for these results; it is most likely that changes occurred as a training effect given that presumably all athletes may improve their general level of conditioning during base training leading up to the outdoor track season, and measurement error may also be attributable. It is also plausible that changes in RE in the shod group occurred as a result of adaptations and technical changes in the athletes as a result of the barefoot simulated training. While the current study cannot attempt to reject or accept this hypothesis, the concept is an exciting area of future research that warrants further investigation. It should be noted that the shod condition SF also increased by 0.43% from pre to post tests to the same degree as the SBR condition (0.51%) that suggests there was some interaction in technique taking place in the shod condition that is likely as a result of SBR.

Future studies are required to evaluate RE at higher velocities in the barefoot or SBR condition, because questions still remain as to the feasibility of racing in this condition at higher running velocities both from a biomechanical and physiological perspective. Data collection for the current study included measurement of 15km/h, however for 6 participants this velocity was above the individual lactate threshold (LT) due to the majority of participants training for 800/1500m and it was deemed an inaccurate representation of RE given that this value does not reach steady state within 6 minutes when above LT, and as such the velocity was excluded from examination (Jones and Poole, 2005). For future research, it may be appropriate to examine a similar participant group but with enforced changes to running technique including transitioning to a forefoot strike pattern and shortening stride length, as well as just investigating a naturally forefoot striking group compared to a naturally heel striking group of runners. It is also justifiable to provide a more in depth investigation into the biomechanics associated with these changes and their relationship to RE.

4.5 Perspective

Based on the findings of the current study, SBR using VFF's appears to be a valid method of improving running economy, and is particularly enhanced in this regard if time is taken to familiarise the runner to barefoot or SBR. The changes in RE are applicable to moderate velocities of 11 and 13km/h, yet still warrant further investigation at higher intensities. SBR significantly changes running mechanics with regard to FSP and SF that is improved over time. It is plausible to recommend that the minimalist footwear used in the current study is a valid means of simulating a barefoot running style while providing a 3mm sole for any abrasion of the foot on rough surfaces. The findings of the current study suggests that the improvements reported for the SBR condition may not be only related to shoe weight or design, but that the possible influence of biomechanical and physiological adaptations are introduced by the minimalist footwear condition that results in positive changes to RE related to chronic use of SBR.

4.6 Additional Methodological Discussion

Firstly, in all of our studies we employed an absolute intensity measure of 11km/h (with the exception of Study One that also examined other speeds). This method could be criticised, since a relative intensity (to either a % $\dot{V}0_{2max}$ value or lactate profile) would be more appropriate for determining that participants did not employ any slow component in their 0_2 kinetics, or any significant amount of anaerobic contribution to the exercise intensity (Brooks, Fahey and White, 1996). However, we have reason to believe that the running speed can have an effect on RE differences between footwear due to the "metabolic cost of cushioning" hypothesis (Franz, Wierzbinski and Kram, 2012). To elaborate, the potential benefits to RE of less mass (and cushioning) may be counteracted by the increased energy demands for impact attenuation at higher velocities, given that running faster results in greater forces being applied to the floor and hence to the lower extremity (Nilsson and Thorstensson, 1989). Our own data

(Study One – Figure 4.6) identified a greater difference in RE between footwear conditions at moderate velocities compared to higher velocities, in support of this theory. Our research aim was to determine the differences in RE cost between conditions for endurance running, and 11km/h has been suggested to be an appropriate endurance velocity for moderately trained runners (Hatala et al, 2013), as well as the most optimal running velocity for oxygen consumption (Mayhew, 1977). Also, the majority of the studies in this area also used a similar absolute intensity (e.g. Hanson et al, 2011; Squadrone and Gallozi, 2009; Franz, Wierzbinski and Kram, 2012). Whilst we acknowledge that running velocity and its influence on the footwear interaction is important, it was beyond the scope of this research to examine further.

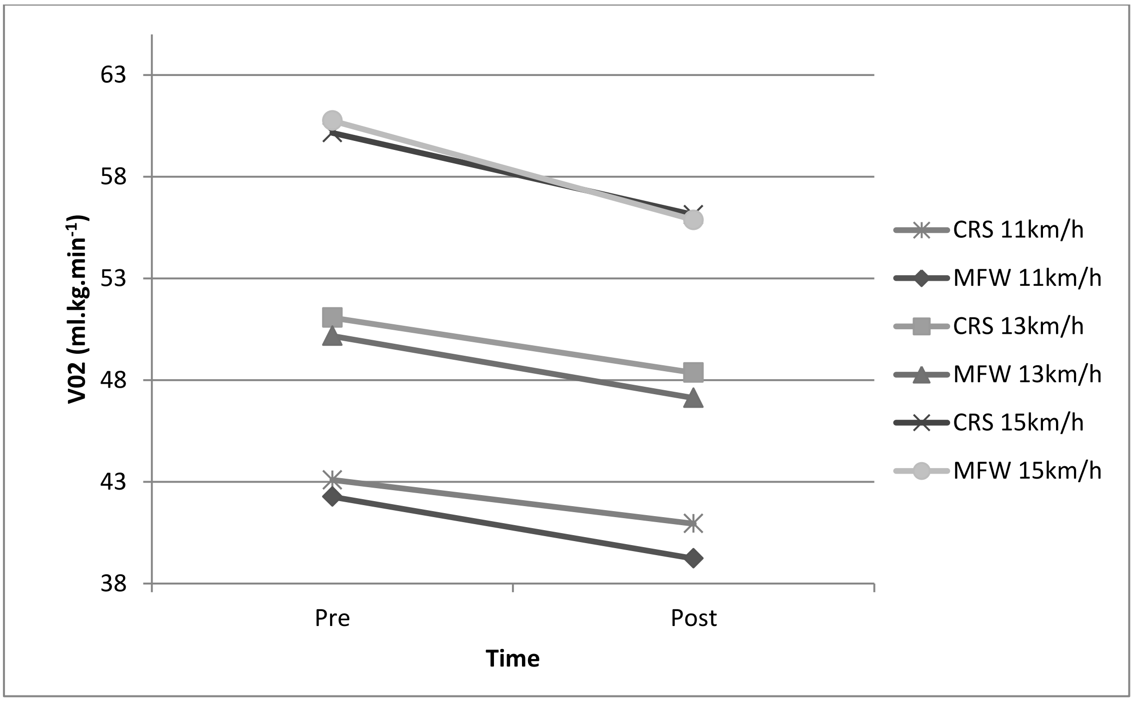

Figure 4.6. *The three speeds measured in Study One (11, 13 and 15km/h) comparing MFW and CRS with respect to changes from pre to post-tests. Note the absence of any difference between conditions at 15km/h.*

Secondly, it has been suggested that the expression of RE as the 0_2 cost of exercise does not take into account the substrates being utilised, and therefore may be a less sensitive measure than energy expenditure to changes in speed (Fletcher, Esau and MacIntosh, 2009; Shaw, Ingham and Folland, 2014). The respiratory quotient can be used as an indicator of the mix of carbohydrate and fat used and permits conversion of the $\dot{V}O_2$ for a given workload into units of energy (Fletcher, Esau and MacIntosh, 2009).

It is thus feasible to suggest energy expenditure expressed as calorific cost may also be more sensitive to changes in footwear condition than RE. Therefore we employed the Weir Equation (Weir, 1949) for our metabolic data, where;

$$Energy\ Expenditure\ (kcal \cdot min) = \mathrm{V}O_2\ (l\ \cdot min) \times \big((1.1 \times RQ) + 3.9\big)$$

However, the results did not identify any different interpretation of our findings. The statistical report and comparison to RE data can be observed in Appendix A.

Thirdly, we did not subtract resting metabolic rate from the exercising metabolic rate. This is because the assumption that resting metabolic rate does not change during exercise has not been confirmed, and therefore may detract from the accuracy of our comparisons. This “baseline subtraction issue” has been discussed in Stainsby and Barclay (1970).

4.7 Link to Chapter Five

Study One examined changes in RE over a four week period with a MFW transition and no feedback or inclusion of the gait-retraining elements as discussed earlier. This study identified very large improvements in the metabolic cost of running and suggests that familiarisation to MFW may improve performance over just a four week period. It remains to be determined if and how these changes will continue to evolve over a longer transition period and this will be examined in the next study. The findings of the current study suggests that the improvements reported for the MFW condition may not be only related to shoe weight or design, but that the possible influence of biomechanical and physiological adaptations are introduced by the minimalist footwear condition that results in positive changes to RE related to chronic use of MFW. Study Two represents a continuation of this research investigating how RE may be influenced by MFW. However this study will also include the deliberate gait-retraining as part of the transition. This element remains to be examined with respect to RE when combined with MFW use as the deliberate manipulation of the running gait may have consequences to metabolic cost. In addition, Study One abbreviated MFW as SBR throughout, however recent work by Bonacci et al (2013) has identified that MFW running is very different from barefoot running and this is not an appropriate abbreviation that has been removed.

CHAPTER FIVE

Study Two

"Eight weeks gait-retraining in minimalist footwear has no effect on running economy"

5. Study Two – "Eight weeks gait-retraining in minimalist footwear has no effect on running economy".

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Human Movement Science (IN REVIEW)

STATEMENT OF CONTRIBUTION: GILES WARRINGTON AND KIERAN MORAN WERE JOINTLY INVOLVED IN THE SUPERVISION OF THIS STUDY.

ABSTRACT

The purpose of this study was to evaluate the effects of an 8 week combined minimalist footwear (MFW) and gait-retraining intervention on running economy (RE) and kinematics in conventional footwear runners. Twenty-three trained male runners (Age: 43±10 years, stature: 177.2±9.2 cm, body mass: 72.8±10.2 kg, $\dot{V}0_{2max}$: 56.5±7.0 mL·min^{-1}·kg^{-1}) were recruited. Participants were assigned to either an intervention group (n=13) who gradually increased exposure to MFW and also implemented gait-retraining over an 8 week period. RE and kinematics were measured in both MFW and conventional running shoes (CRS) at pre-tests and 8 weeks, in a random order. In contrast the control group (n=10) had no MFW exposure or gait-retraining and were only tested in CRS. The intervention had no effect on RE when using either MFW or CRS ($p \leq 0.00$). However, RE was significantly better in MFW (mean difference 2.72%; p=0.002) at both pre and post-tests compared to CRS. Stride frequency increased as a result of the intervention (+3.26%; $p \leq 0.00$), and was also significantly higher in MFW vs. CRS (3.79%; $p \leq 0.00$). Whilst a better RE in MFW was observed when compared to CRS, familiarisation to MFW with gait-retraining was not found to influence RE.

5.1 Introduction

Recent scientific interest in barefoot and minimalist running has resulted in an increasing body of research in this area in relation to running performance (e.g. Divert et al, 2008; Hanson et al, 2011; Perl, Daoud and Lieberman, 2012; Squadrone and Gallozzi, 2009; Warne and Warrington, 2014). In a homogenous group of runners, running economy (RE) has been considered a strong predictor of endurance performance (Lucia et al, 2006). With regard to footwear, several studies have reported significant differences in RE between barefoot or minimalist footwear when compared to conventional footwear (Divert et al, 2008; Perl, Daoud and Lieberman, 2012; Squadrone and Gallozzi, 2009; Lussiana et al, 2013; Warne and Warrington, 2014) and so it appears that changing footwear may be a means to influence performance.

Despite these reported improvements in RE, only limited research has investigated the process and effects of the footwear transition in athletes when moving from habitual conventional running shoe wear into minimalist or barefoot running, as this is now a popular trend among runners (Rothschild, 2012b). Rather, the findings of the majority of studies are based on results from acute interventions or using previously habituated barefoot or minimalist runners (Divert et al, 2008; Hanson et al, 2011; Perl, Daoud and Lieberman, 2012; Squadrone and Gallozzi, 2009; Lussiana et al, 2013). Recently published data by our research group observed significant improvements in running economy (8.09%) following a four week familiarisation to minimalist footwear (MFW) with no gait-retraining, when compared with conventional running shoes (CRS) (Warne and Warrington, 2014). This study did not include any suggestions for changes in the running gait, but recently some authors have recommended the use of a barefoot running style (gait-retraining) in light of purported benefits to RE and a reduction in injury risk (Jenkins and Cauthon, 2011; Goss and Gross, 2013), largely in combination with the use of MFW, but also just in CRS (Goss and Gross, 2013). Gait-retraining has now become a popular intervention for runners (Goss and Gross, 2013; Dallam et al, 2005; Fletcher, Esau and MacIntosh, 2008) and manufacturers (www.merell.com), although long term prospective studies are still required. This gait-retraining proposes increasing stride frequency and adopting a mid or forefoot strike pattern (Goss and Gross, 2013; Fletcher, Esau and MacIntosh, 2008), but these factors examined individually or in combination have been found to have no effect on RE (Ardigo et al, 1995; Gruber et al, 2013a; Fletcher, Esau and MacIntosh, 2008). To date, there are no reported studies that have examined if the use of both a gait-retraining intervention and MFW transition can influence RE.

The aims of the present study were therefore twofold; 1) to determine the effects of a combined 8 week MFW and gait-retraining intervention on RE and simple kinematic changes (stride frequency and foot strike patterns) when compared to a control group in CRS with no intervention; 2) to examine if differences exist in RE and kinematics between MFW and CRS, both before and after exposure to the MFW and gait-retraining intervention.

5.2 Methods

5.2.1 Participants: Twenty three moderately trained male runners (Age: 43± 10 years, stature: 177.2 ± 9.2 cm, body mass: 72.8 ± 10.2 kg, $\dot{V}O_{2max}$: 56.54 ± 6.97 $mL \cdot min^{-1} \cdot kg^{-1}$) were recruited from local athletic clubs. Participants typically ran 4-6 days per week with a mean weekly running distance of 52 (±10) km at the time of the study. Participants were excluded if they had reported any running related injuries in the last three months, or had previous barefoot or minimalist running experience. Only male athletes were used to eliminate gender differences in running mechanics (Ferber, Davis and Williams, 2003). All participants had previous experience with treadmill running. The participants gave informed consent at the beginning of testing. Ethical approval for this study was granted by the Dublin City University Research Ethics Committee.

5.2.2 Experimental design: Twenty three participants were recruited for the study and were randomly assigned into 2 groups (Table 5.2.2). Group 1: the intervention group comprised of 13 participants. This group was tested in both MFW and CRS at pre-test and 8 weeks (post), and were required to gradually increase exposure to MFW as well as incorporate gait-retraining into their running over this period (The MFW and gait-retraining will be summarised as MFW). Group 2: the control group consisted of 10 participants, and were only tested in the CRS condition. This was in order to control for any potential learning effects related to the tests, or changes related to training season. In this regard participants were tested during the summer, and this would be considered a competitive period during the year. The control group were required to train as normal in CRS, and had no exposure to MFW or gait-retraining at any point. In order to avoid any potential diurnal effect, tests took place at the same time of day. Dietary intake, sleeping patterns, and training were recorded directly prior to the initial test and included all food and fluid consumed on that day for replication at post-tests. To balance order effects, a Latin square design was used to determine which footwear condition (MFW or CRS) was tested first in the intervention group between the pre and post-tests. On the first visit, foot size was measured and participants in the intervention group were provided with one pair of MFW (Vibram® Five Finger "KSO"; ~150 g), and all participants were provided with a neutral CRS (Asics® "GEL-Cumulus" 2012; ~400g).

Table 5.2.2. Anthropometric and descriptive data (M ± SD) for the intervention and control groups.

	Age (years)	**Stature (cm)**	**Body mass (kg)**	**$\dot{V}O_{2max}$ (mL·min-1·kg-1)**	**Km per week (km)**
Intervention group (n=12)	41 (±9)	177.2 (±10.4)	72.6 (±10.2)	52.1 (±7.5)	52 (±11)
Control group (n=8)	46 (±10)	177.1 (±7.5)	73.1 (±11.0)	56.3 (±6.7)	52 (±10)

5.2.3 Testing procedure: Resting blood lactate (Lactate Plus, Nova Biomedical, Waltham, Massachusetts, USA) was sampled from the earlobe prior to the testing sessions. Respiratory data were measured using a Viasys Vmax Encore 299 online gas analysis system (Viasys Healthcare, Yorba Linda, California, USA). The system was calibrated according to the manufacturer guidelines, including atmospheric pressure and temperature, before each new test. For this system, accuracy has been reported at 0.02% for 0_2 measures, following a 15 minute warm-up period and calibrated within 5% of absolute operating range. A treadmill (Cosmed T170, Sport Med, Weil am Rhein, Germany) RE test was then conducted in the assigned footwear. Treadmill incline was set at 1% to account for air resistance (Jones and Poole, 2005). Participants ran two trials lasting 6 minutes at 11 km/h. Eleven km/h has previously been considered an appropriate steady state "endurance running" velocity (Hatala et al, 2013). At the end of each 6-min stage, participants were asked to stand to the side of the treadmill and a blood lactate sample was collected within 30 s. The next stage was started after 3 minutes of rest to allow the shoe type to be swapped over. At 5-minutes in each stage, stride frequency was collected by counting the left foot contact with the treadmill belt for 60 seconds duration. This procedure was repeated by the same investigator for validity in each participant and also filmed for a second assessment (Sony HDR-CX210, 60FPS; Sony, San Diego, CA, USA). Rudimentary foot strike pattern (FSP) analysis was undertaken using a low-cost video camera, in which participants were filmed in the sagittal plane at foot level over a fifteen second period during the fourth minute of testing. The video footage was then used to assign 1, 2, or 3 (1 = forefoot strike, 2 = midfoot strike, 3 = rearfoot strike) to the participants' foot strike pattern using Dartfish video analysis software (Dartfish 5.5, Fribourg, Switzerland). A midfoot strike pattern was classified when there was no clear forefoot or heel initial contact. The validity of this method has been previously discussed by Altman and Davis (2012b).

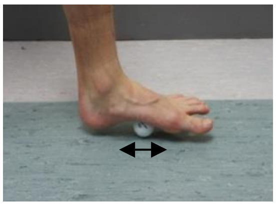
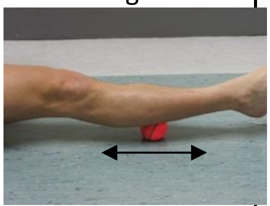
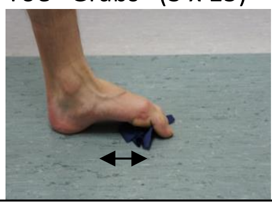
5.2.4 Intervention: Immediately after pre-tests, each participant in the intervention group was provided with a structured progression of MFW use over the eight week familiarisation period, a training diary to record their training, and relevant injury prevention exercises (Tenforde et al, 2011) (Table 5.2.4). The gait-retraining programme was provided based on current findings in the literature (Crowell and Davis, 2011; Daoud et al, 2012; Divert et al, 2005b; Lieberman et al, 2010; Robbins and Hanna, 1987; Squadrone and Gallozzi, 2009); these changes have also become the main kinematic changes promoted in established running gait-retraining programmes (e.g. Chumanov et al, 2012; Lenhart et al, 2014; Fletcher, Esau and MacIntosh, 2008; Dallam et al, 2005; Goss and Gross, 2013). Both the gait-retraining and exercises were fully demonstrated during a 30 minute session until changes to stride frequency (+10% steps per minute - spm), a mid/forefoot strike pattern, more upright posture and a softer landing were adopted by the participants. This was implemented using feedback from an experienced tester in line with the simple instructions provided in table 5.2.4. The programme incorporated MFW into the participant's normal training routines, where it was required that the MFW took place at the beginning of any training session, and then participants were allowed to continue their normal training load in their own preferred conventional running footwear, thus not reducing their overall training workload. The participants were asked to work on the gait-retraining changes both in MFW and CRS, gradually incorporating them into longer runs. The control group received no intervention or feedback, and were asked to not research or include any changes to running technique into their regular training for the duration of the testing.

5.2.5 Testing procedure –$\dot{V}O_{2MAX}$: A $\dot{V}0_{2max}$ test was completed at the end of the final testing day. This involved a ramped treadmill protocol at 12 km/h for a 5-min warm-up before increasing to 14 km/h at 1% incline. The incline was then increased every minute until volitional exhaustion, and correlated with participants achieving a respiratory quotient of 1.1 or above. Participants conducted this test in their own shoe choice. $\dot{V}O_{2max}$ was recorded as the highest breath-by-breath value averaged over 60 s.

5.2.6 Data processing: The RE values were determined from the mean data over the last 2 min of each stage when participants had reached a true steady-state $\dot{V}O_2$. This was verified by less than a 1mmol increase in blood lactate (post trial minus resting lactate) as this is considered well below maximal lactate steady state (Svedahl and MacIntosh, 2003), and an respiratory quotient of less than 1.0 (Brooks, Fahey and White, 1996). Foot strike patterns were reported as frequencies.

Table 5.2.4. *Eight week familiarization to MFW including running technique guidelines and simple exercises for injury prevention.*

Week	**MFW Training Programme**
Week 1	Throughout: Wearing MFW and going barefoot as much as possible in normal daily routines 3 days: 5 -8 mins easy running on the spot or in corridors/garden at home 3 days: Prescribed exercises*
Week 2	3 days: 10 – 15 mins running on grass, 3 minutes on pavement 3 days: Prescribed exercises*
Week 3	2 days: 20 mins running on grass, 5 - 8 minutes on pavement 1 day: 25 mins running on grass 3 days: Prescribed exercises*
Week 4	2 days: 20 mins on grass, 10 mins on pavement 1day: 30 mins on grass 2 days: Prescribed exercises*
Week 5 + 6	2 days: 20 mins on grass, 15 mins on pavement 1day: 35 mins on grass 2 days: Prescribed exercises*
Week 7 + 8	2 days: 30 mins on grass, 15 mins on pavement 1day: 40 mins on grass 2 days: Prescribed exercises*

Running technique guidelines	Exercise Programme (10 minutes)	
Keep stride short and increase cadence. (Divert et al, 2005b; Lieberman et al, 2010; Chumanov et al, 2012; Lenhart et al, 2014)	Plantar Fascia and Triceps Surae Rolling x 5 mins 	
Run as light and quiet as possible. (Crowell and Davis, 2011)		
Land on the forefoot, allowing heel to contact Immediately afterwards. (Lieberman et al, 2010; Robbins and Hanna, 1987; Daoud et al, 2012)	Ankle Mobility (3 x 15) 	Calf Raises (3 x 15) 
Keep hips forward and head up, running as tall and proud as possible. (Lieberman et al, 2010)	Toe "Grabs" (3 x 15) 	Single leg balance (60sec) 

* No specification was made as to whether the exercises were completed on the same days as the running intervention or not.

5.2.7 Data analysis: In order to examine aim 1 and 2, the effect of condition (MFW vs. CRS) and time (pre - post-tests) with regard to RE, stride frequency, heart rate, and RPE were examined using two-way repeated measures analyses of variance (ANOVA) for within-subjects effects. Differences between the intervention and control group were established with a two-way mixed ANOVA for between-subject effects, and changes over time in the control group were examined using paired t-tests. (Statistical Package for the Social Sciences data analysis software V16.0, SPSS Inc, Chicago, Illinois, USA). Statistical significance was accepted at $\alpha \leq 0.05$. Effect sizes are reported as eta squared (η^2) for ANOVA tests and Cohen's d for t tests. To make inferences about true (population) values for the effect of an MFW and gait-retraining intervention on RE, the uncertainty of the effect was expressed as 95% confidence limits and the likelihood that the true value of the effect represents substantial change (harm or benefit) (Batterham and Hopkins, 2006). The smallest worthwhile change in RE was calculated as 2.4% of the shod RE at pre-tests (Saunders et al, 2004). For the remaining variables, the smallest standardised change that is considered meaningful was assumed to be an effect size of 0.20 for Cohen's d and 0.01 for η^2 (Cohen, 1988).

5.3 Results

No participants were excluded based on any "slow component" for submaximal $\dot{V}0_2$ consumption, an increase in blood lactate of >1mmol (mean change from resting = 0.44 mmol), and a respiratory quotient greater than 1.0. During testing, one participant from the intervention group became injured (metatarsal stress fracture), and two participants from the control group became ill and were removed from the final data analysis (remaining n=20). Seven out of 13 participants in the intervention group also reported mild triceps surae soreness in the first two weeks, but this did not result in any reduction in training or intervention compliance. Participant compliance with the intervention schedule was good (mean compliance 78%, as recorded by feedback of missed runs or exercise sessions during intervention); all participants were able to complete the longer runs in the latter weeks and were well exposed to MFW running by week 8. The distribution of foot strike patterns are displayed in Figure 5.3 for the intervention group. 75% of participants adopted a rearfoot strike pattern in both CRS and MFW at pre-tests. At post-tests only 50% of participants in CRS used a rearfoot strike pattern, and 33% of participants in MFW used a rearfoot strike pattern.

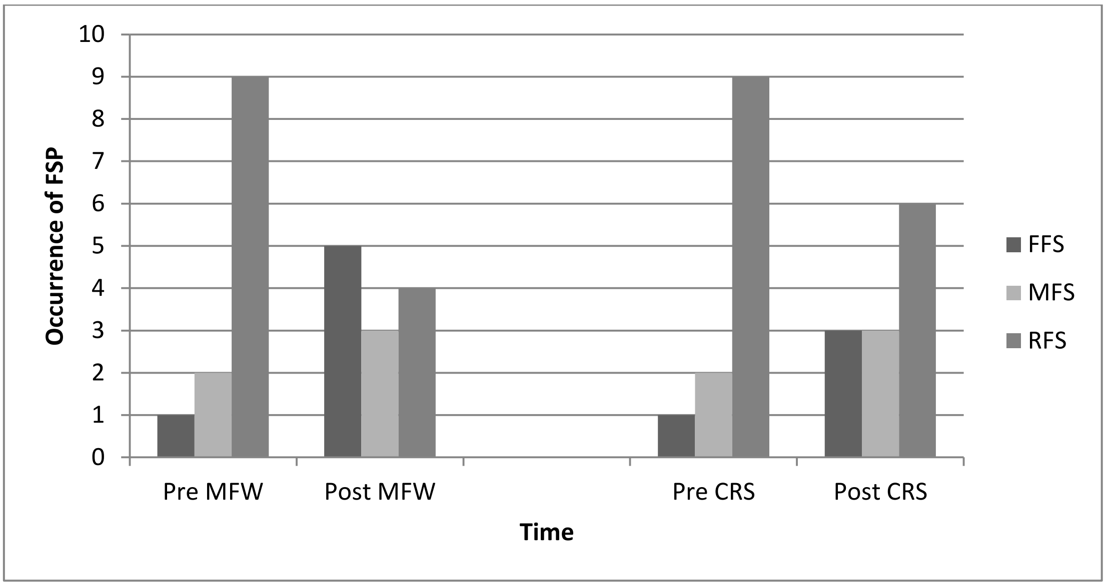


Figure 5.3. *Foot strike patterns of both the MFW and CRS condition during the 8 week intervention.*

Results are reported as the change in mean value [95% CI]). No difference for the change in RE over time was observed between the intervention and control group (p=0.78). Over the course of the 8 week trial, there was no significant change in the intervention group for RE (p=0.99; -0.0 $mL \cdot min^{-1} \cdot kg^{-1}$ [-2.3 to 2.3]; 18.9% - unlikely beneficial; $\eta^2 = 0.00$). There was, however, a significant increase in stride frequency (3.26%) as a result of the intervention ($p \leq 0.00$; 5.7 spm [3.8 to 7.6], $\eta^2 = 0.077$). No change in RE was observed in the control group from pre to post-tests (p=0.95; 0.1 $mL \cdot min^{-1} \cdot kg^{-1}$ [-2.7 to 2.9]; Cohen's d = 0.00). Stride frequency in the control group was found to decrease slightly (p=0.078; -1.7 spm [-3.7 to 0.3]; Cohen's d = 0.43).

Irrespective of the intervention, RE was significantly better in MFW (2.72%) when compared to CRS (p=0.002; -1.4 $mL \cdot min^{-1} \cdot kg^{-1}$ [-2.2 to -0.7]; 86.5% - likely beneficial; $\eta^2 = 0.035$). There was also a significantly higher stride frequency (3.79%) observed in MFW when compared to CRS ($p \leq 0.00$; 7.5 spm [6.0 to 9.0], $\eta^2 = 0.129$).

5.4 Discussion

The main finding of the present study revealed that an 8 week MFW and gait-retraining intervention did not result in any significant change in RE, when assessed in both MFW and CRS conditions. Whilst it is possible that a familiarisation to MFW does enhance RE (Warne and Warrington, 2014), this was not the case in the present study with a similar intervention that included gait-retraining. This finding is in accordance with previous research which reported that gait-retraining had no effect on RE (Ardigo et al, 1995; Gruber et al, 2013a; Fletcher, Esau and MacIntosh, 2008; Messier and Cirillo, 1989), or may even make RE worse (Dallam et al, 2005; Cavanagh and Williams, 1982; Tseh, Caputo and Morgan, 2008). To support these studies, Nigg and Enders (2013) and Saunders et al (2004b) have suggested that self-selected running kinematics rather than deliberate changes are more appropriate for optimising RE. Therefore this study compliments the already available body of literature suggesting RE cannot be improved with deliberate changes to running kinematics. This is however the first study to investigate both MFW and gait-retraining combined, and suggests that the inclusion of MFW to the gait-retraining intervention did not have any effect on RE either.

There are several other reasons why the results may have been different from Warne and Warrington (2014). Arampatzis et al (2006) have suggested that any improvements in RE are likely as a result of neuromuscular adaptation and not related to changes in observable kinematics such as stride frequency and foot strike patterns. In this regard, the participants in the present work were older (mean difference 19 years) and less well trained (mean difference 13.5 $mL.kg.min^{-1}$) than those in Warne and Warrington (2014). In this regard, older generations of participants have been found to display decreased neuromuscular control and elastic bounce (Legramandi, Schepens and Cavagna, 2013; Hoffren, Ishikawa and Komi, 2007). In addition, older subjects have experienced more long term exposure to CRS, and so may be less pre-disposed to changes after only 8 weeks of a new footwear condition or running technique. With regards to training status, lesser trained athlete populations have been observed to have less consistent running mechanics than their elite counterparts (Chapman et al, 2008a) as well as being less economical (Morgan et al, 1995). It is very possible that inconsistencies in both running mechanics and physiological adaptations in the less well trained participants would decrease the potential for there to be repetitive and consistent adaptations taking place specific to the footwear. However, these differences between groups require a more robust examination with future research.

The kinematic changes observed as a result of the intervention provide important information on the incorporation of the gait-retraining. Stride frequency was found to significantly increase during the eight weeks. Likewise there were changes to both the MFW and CRS with regard to foot strike patterns, although to a lesser extent in the CRS. This observed difference in foot strike pattern between MFW and CRS was observed in previous studies (Warne and Warrington, 2014; Warne et al, 2013), suggesting that CRS hinders selection of a midfoot or forefoot strike pattern. This may be due to the elevated profile of the shoe or a reduction of sensory feedback from the foot (Divert et al, 2005b; De Wit, De Clerq and Aerts, 2000). In the present work, stride frequency and foot strike pattern changes can provide an indication of kinematic change associated with the intervention, however there is no strong evidence that either stride frequency or the foot striking pattern can influence RE (e.g. Cavanagh and Williams, 1982; Gruber et al, 2013a). Given that we observed no change in RE, but a change in stride frequency and foot strike pattern, our results support these previous studies.

With regard to the second study aim, a significant and worthwhile improvement in RE was observed in the MFW condition when compared to CRS irrespective of the intervention (86.5% likely beneficial). Differences in RE between MFW and CRS have been reported previously (Perl, Daoud and Lieberman, 2012; Squadrone and Gallozzi, 2009; Warne and Warrington, 2014). Several authors have described a better RE in the barefoot condition to be solely related to the mass of traditional shoes (Divert et al, 2008; Flaherty, 1994), where a 1% increase in the oxygen cost of running has been observed for every 100g of added mass (Divert et al, 2008; Saunders et al, 2004b). Given that the difference in shoe mass in the present study was ~250g which was not controlled for, this may explain the majority (2.5%) of the observed difference in RE (2.7%) between the MFW and CRS conditions. Also, the MFW used in our study was found to result in a better RE than barefoot in Squadrone and Gallozzi (2009), and this may be due to the small protective layer of rubber that reduces the metabolic cost of cushioning the body (Franz, Wierzbinski and Kram, 2012). Saunders et al (2004a) have suggested that anything above a 2.4% change in RE is a worthwhile improvement in performance. Likewise Di Prampero et al (1993) concluded that a 5% improvement in RE elicited a 3.8% increase in run performance, suggesting that even changes due to shoe mass are worthwhile. Our study suggests that there is a meaningful and likely benefit to wearing MFW, irrespective of whether the participants are familiarised to this footwear or not.

We acknowledge that this intervention combines both MFW and gait-retraining without concern for the individual effects of either factor. Ideally this study should include two further groups with only a MFW or gait-retraining exposure, but this would require a very large body of participants. A limitation of the present study was the lack of any kinematic measurements throughout the intervention period to ensure that the gait-retraining changes were being effectively executed. Whilst we measured stride frequency and foot strike patterns and observed a change, a more comprehensive analysis to monitor the incorporation of the gait-retraining elements is recommended. Indeed previous work has found that participants cannot correctly report their running pattern (Goss and Gross, 2012a), and so may not be incorporating the "correct" changes, despite being under the impression that they were.

5.5 Conclusion

This study suggests that gait-retraining coupled with MFW use is not an effective means to improve RE. However, the use of MFW in itself can result in a significantly better RE (2.72%) when compared to CRS irrespective of whether participants are familiarised or not, and this may improve running performance. There was a significant increase in stride frequency, and a higher tendency to forefoot strike observed as a result of the intervention.

5.6 Additional Data

In controlled studies investigating CRS, it has been noted that changing stride frequency can negatively influence RE (Cavanagh and Williams, 1982; Heinert, Serfass and Stull, 1988), but has also been found to have no effect (Bailey and Messier, 1991; Messier and Cirillo, 1989). An increased stride frequency has been well documented whilst running in MFW or barefoot when compared to CRS (e.g. Divert et al, 2005b; Lieberman et al, 2010; Squadrone and Gallozzi, 2009), and it is possible that this difference in stride frequency related to footwear could influence RE. However, the changes to stride frequency in relation to footwear type are typically very small (~2%), and well below the magnitude of changes imposed in controlled studies (e.g. -/+8%, Heinert, Serfass and Stull, 1988). The small changes in stride frequency associated with different footwear remains to be examined with respect to RE. Therefore, we used the opportunity during data collection for Study Two to examine if small "footwear related" changes to stride frequency could have any effect on RE.

5.6.1 Additional Data Methodology

Following the two 6-minute RE tests in both MFW and CRS as outlined above, intervention participants then completed two more 6-minute efforts. This included forced changes in stride frequency controlled by a metronome (Android software "Mobile Metronome") set at the corresponding tempo to the opposite condition being tested (if participants ran in MFW, then their previous stride frequency in CRS was adopted, and vice versa; this was denoted using the subscript $_{revSF}$ [reversed stride frequency]. Thus, participants typically ran at a slower stride frequency in MFW than they would have self-selected, and vice versa for CRS (the mean increase in stride frequency for MFS vs. CRs was 6.6 ± 0.6 steps per minute). This was conducted at both pre and post-tests, in order to determine if there was any habituation effect for changes in stride frequency.

5.6.1 Additional Data Analysis

Direct comparisons between RE and RE_{revSF} (MFW vs. MFW_{revSF}, and CRS vs. CRS_{revSF}) were completed at pre and post tests using paired t-tests. To determine if stride frequency had any relationship to the difference observed in RE between footwear conditions, a Pearson Product-Moment Correlation Coefficient was implemented, calculated as ΔRE (MFW – CRS) correlated to Δstride frequency (MFW – CRS) at pre and post-tests. (Statistical Package for the Social Sciences data analysis software V16.0, SPSS Inc, Chicago, Illinois, USA). Statistical significance was accepted at $\alpha \leq 0.05$.

5.6.1 Additional Data Results and Discussion

RE was not affected by stride frequency, since no significant differences between RE and RE_{revSF} were identified at any time-point using paired t-tests for MFW (pre: $p=0.70$, post: $p=0.53$), or CRS (pre: $p=0.34$, post: $p=0.54$). Likewise, following a Pearson Product-Moment Correlation, no relationship was observed between the difference in RE and the difference in stride frequency between MFW and CRS ($r=0.002$, $p=0.99$).

Therefore, changes in stride frequency as a result of footwear condition (~2%) are not large enough to have any significant impact on RE. This supports previous work in this area suggesting that stride frequency is not an influencing factor for RE (Arampatzis et al, 2006; Kyrolainen, Belli and Komi, 2001; Williams and Cavanagh, 1987). For example, Franz, Wierzbinski and Kram (2012) estimate that the ~3% greater stride length observed during traditionally shod running when compared to barefoot would account for less than a 0.4% metabolic saving. Self-selected stride frequency has been found to be close to that which minimises running economy, with small deviations resulting in little or no change (Cavanagh and Williams, 1982). It appears as though realistic changes to stride frequency has no major role in increasing running performance with regard to RE.

5.7 Link to Chapter Six

Both Study One and Two investigated changes in RE with respect to a MFW transition both with and without a gait-retraining element included. The results were very different and highlighted the need for future research investigating how a MFW transition both with and without gait-retraining can influence RE. Study Two did not result in any significant improvements in RE with the MFW and gait-retraining intervention but we did observe a worthwhile improvement in RE in MFW as a result of a lower mass in this footwear type. This may also be important for prescribing footwear based on performance in the future. Now, we turn our attention to how changes in loading may influence this transition with respect to injury. Study Three examines changes in plantar pressure and forces during a four week transition to MFW with gait-retraining. Plantar pressures have been suggested to be involved in the increase in metatarsal stress fractures reported in the literature as a result of running in MFW (Ridge et al, 2013), but no research has examined how these loads may change during a transition to MFW.

CHAPTER SIX

Study Three

“A four week instructed minimalist running transition and gait-retraining changes plantar pressure and force”

6. Study Three – “A four week instructed minimalist running transition and gait-retraining changes plantar pressure and force”.

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ABSTRACT

The purpose of this study is to compare changes in plantar pressure and force using conventional running shoes (CRS) and minimalist footwear (MFW) pre and post a four week MFW familiarisation period. Ten female runners (age: 21±2 yrs, stature: 165.8±4.5 cm, mass: 55.9±3.2 kg) completed two 11 km/h treadmill runs, 24 hours apart, in both CRS and MFW (pre-test). Plantar data were measured using sensory insoles for foot strike patterns, stride frequency, mean maximum force ($\overline{\mathbf{MF}}$), mean maximum pressure ($\overline{\mathbf{MP}}$), and eight mean maximum regional pressures. Participants then completed a four-week familiarisation period consisting of running in MFW and simple gait-retraining, before repeating the tests (post-test). During the pre-tests, 30% of participants adopted a forefoot strike pattern in MFW, following familiarisation this increased to 80%**;** no change occurred in CRS. A significant decrease in $\overline{\mathbf{MF}}$ in both MFW and CRS (p=0.024) was observed from pre-post, and a significant decrease in heel pressures in MFW. $\overline{\mathbf{MP}}$ was higher in MFW throughout testing (p<0.001).A four week familiarisation to MFW resulted in a significant reduction in $\overline{\mathbf{MF}}$ in both the CRS and MFW conditions, as well as a reduction in heel pressures. Higher $\overline{\mathbf{MP}}$ was observed throughout testing in the MFW condition.

6.1 Introduction

Running has been a fundamental part of human existence for thousands of years and historically humans ran barefoot or in minimalist moccasin style footwear, in evidence as early as 300,000 - 30,000 years ago (Trinkaus, 2005). Footwear has since developed over time resulting in the proliferation of different types of running shoes, each advertising different proposed benefits such as pronation control, elevation, and cushioning properties. Recently, studies have reported a relatively high injury rate in running, with between 19% and 79% of runners suffering a musculoskeletal injury on at least one occasion per year (Van Gent et al, 2007). To date, no research has yet to investigate the potential impact that changes in running surfaces and increased intensity of running (as evident by increases in mass participation events) may have on these high injury rates. It has been noted that this high injury rate remains largely unchanged despite many advances in running shoe design over the last forty years, and as such footwear has recently been highlighted as a possible factor related to injury (Lieberman et al, 2010). Whether footwear is partly responsible for the incidence of running related injuries remains to be determined. However, there now appears to be a growing trend back to running barefoot, and shoes that attempt to simulate barefoot running have now been designed, known as minimalist footwear (MFW) and are gaining popularity. The modern barefoot and minimalist running movement is driven mainly by a growing body of research suggesting improved performance (Hanson et al, 2011; Jenkins and Cauthon, 2011; Squadrone and Gallozzi, 2009; Warne and Warrington, 2014) and reduced injury risk (Divert et al, 2005a; Lieberman et al, 2010; Jenkins and Cauthon, 2011; Lohman et al, 2011). This has led to many runners opting to “transition” into MFW or go barefoot, using training programmes and simple running drills. However, the adaptive elements of transitioning to minimalist or barefoot running remains to be investigated from an injury perspective.

Most injuries in runners occur in the lower limb and can be related to previous injury, mileage, running experience, type of training and external characteristics such as footwear and training surface (Yeung and Yeung, 2001). The theory that repeated excessive forces may cause injury (Hreljac, 2004) has led to the assumption that running shoes with enhanced cushioning properties would reduce these forces, thus reducing the likelihood of injury (Lafortune and Hennig, 1992). However the ability of a cushioned heel to reduce this loading has been questioned (Lieberman et al, 2010; Nigg and Wakeling, 2001), with recent studies now suggesting that conventional running shoes (CRS) may actually increase impact transients when compared to barefoot (Lieberman et al, 2010) as a result of detrimentally influencing running technique. Several other studies also suggest that CRS can increase the likelihood of injury due to their cushioned and supportive properties (Divert et al, 2005a; Robbins, Gouw and Hanna, 1989; Robbins et al, 1993). Whilst most studies investigate ground reaction forces (e.g. Lieberman et al, 2010), it has been suggested that changes in plantar pressures and peak plantar forces also provide accurate data as to how the foot is loaded with respect to the supporting surface, as unnatural or localised loading may predict or indicate injury risk (Orlin and McPoil, 2000), in particular tibial and metatarsal stress fractures (Davis, Milner and Hamill, 2004; Giuliani et al, 2011). Despite this, to the best of the author's knowledge, no research to date has documented changes in plantar pressure and plantar force when investigating the transition to MFW and this information may be important for injury prevention in the future (Hong et al, 2012). Plantar pressure offers specific information on the distribution of force, and can be related to potential damaging effects to local tissues, where force is largely related to the overall loading effect of the foot contact (Rosenbaum and Becker, 1997), and this knowledge may be essential in determining "*in vivo*" foot loading (Shorten and Mientjes, 2011). Any reduction in plantar pressure or force during running may represent a potential for injury reduction, as impact and pressure have been extensively linked to running related injury (Davis, Milner and Hamill, 2004; Hong et al, 2012; Rosenbaum and Becker, 1997), and this requires further research with respect to new minimalist footwear models.

It has been noted that humans, unlike other mammals, use several footfall patterns that are classified by the region of the foot that initially contacts the floor (Hamill and Gruber, 2012). Divert et al (2005a) and Squadrone and Gallozzi (2009) suggest that participants who run barefoot reduced the high mechanical stress at the heel by switching from a rear-foot strike pattern (RFS) to a forefoot strike pattern (FFS). Given that Lieberman et al (2010) suggest that a FFS can reduce or eliminate the passive impact peak when compared to a RFS, a logical study design should attempt to manipulate foot strike patterns (FSP) and observe any effects in a developed western population of runners, given that this is now the population “buying in” to this minimalist trend. The same principle can be applied to manipulation of stride frequency which has been observed to reduce lower extremity loading when it is increased by 15% (Hobara et al, 2012), although a 15% increase does not adequately represent the smaller 2-3% change observed whilst in MFW (Squadrone and Gallozzi, 2009; Warne and Warrington, 2014). Interestingly, several researchers have observed an acute reduction in impact force, a move towards a FFS, and an increase in stride frequency when comparing experienced barefoot and minimalist running to CRS athletes (De Wit, De Clerq and Aerts, 2000, Lieberman et al, 2010, Squadrone and Gallozzi, 2009). Despite this, no research to date has documented the transitional period of a group of inexperienced barefoot or minimalist runners and its effects on these variables and plantar pressures. How well habituated shod runners can adapt to new changes in MFW remains to be examined. Early research has identified significant changes related to MFW in four weeks (Warne and Warrington, 2014), and simple gait re-training feedback was found to be successful after just two weeks (Crowell and Davis, 2011). Thus for preliminary reports in this regard, four weeks appears to be enough to exhibit some degree of adaptation or motor learning, and has been selected for the present study.

The purpose of this study therefore was to investigate if any changes occur with regard to plantar force and regional pressure in both a MFW and CRS condition as a result of instructed familiarisation to MFW over a four week period. The study aimed to document the resultant changes in relation to foot strike patterns and stride frequency in order to further understand the transitional period for minimalist running and its relationship to plantar pressures and forces. The authors hypothesise that 1) plantar forces will be reduced as a result of the intervention, and to a greater degree in the MFW, and 2) a reduction in heel pressure in the MFW will be observed. This will result in elevated metatarsal pressures due to the change in foot strike pattern; however this will not occur in the CRS.

6.2 Methods

6.2.1 Participants: Ten trained female runners (Age: 21 ± 2 yrs, stature: 165.8 ± 4.5 cm, body mass: 55.9 ± 3.2 kg) were recruited from local athletic clubs and collegiate teams via email. Participants typically ran 3-5 days per week, running on average 45.0 (± 23.0) km in that time. Participants were excluded if they had reported any lower limb injuries in the last three months, had previous barefoot or minimalist running experience or currently used orthotics. Only female athletes were used to eliminate gender differences in running mechanics (Ferber, Davis and Williams, 2003). All participants had previous experience with treadmill running. The participants gave informed consent at the beginning of testing. Ethical approval for this study was granted by the Dublin City University Research Ethics Committee.

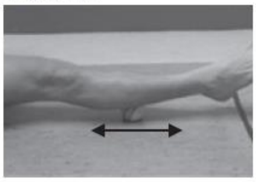
6.2.2 Experimental protocol: A randomised crossover design for footwear type (MFW vs. CRS) was used, with crossover from day 1 to day 2, and pre-tests to post-tests (separated by the four week familiarisation period). The testing design eliminated the chance that footwear would result in any order effect. Each testing session required the participants to visit the human performance laboratory in which participants ran on a treadmill (Cosmed T170, SportMed, Germany) at a fixed velocity (11km/h) for two bouts of eight minutes, one bout in CRS (Asics Cumulus 2012) and one bout in the MFW (Vivo Barefoot “Evo”), the order of which was randomly assigned. Familiarisation took place in Vibram “Five Finger” KSO (VFF) (Vibram®, Milan, Italy) footwear, because of its popularity and availability in the laboratory, however the sensory insoles would not fit in the individual toe design for data collection and so the “Evo” was sourced as the closest alternative, also being 3mm thick with zero “drop” and advertising no cushioning or foot control. Between each eight-minute bout the participants were given a fifteen-minute recovery while they changed to the opposite footwear and re-inserted the insoles. Sensory insoles (Novel Pedar X, Munich, Germany) were placed inside either the MFW (“Evo”), or CRS before each test and calibrated to technical specification including ascertaining a zero unloaded value before insertion**.** Each insole contained 99 10mm force sensors, with data collected at 100Hz, and has previously shown a high degree of repeatability (Ramanathan et al, 2010)**.** The Pedar X unit was attached to the participant’s waistline at the rear using a Velcro belt, and wires leading to the insoles were attached to participant's legs using a pliant Velcro strap that did not impede with normal running movement. Data was collected for 60 seconds at the 7th minute of running, allowing enough time above the four minutes that has been suggested to be required to optimise leg stiffness and running technique depending on surface and shoe hardness (Divert et al, 2005a). Given that endurance running involves repetitive impacts, a long sample period of 60 seconds was selected to more adequately represent average loading over a longer period of time. Stride frequency was calculated by the number of steps that occurred on the right foot during the 60 second duration using the recorded foot contact data. The testing protocol was repeated 24 hours later in the opposite shoe order and at the same time of day, with no training allowed for participants within that period (pre-tests). Participants also repeated the entire protocol again in a randomised order following the four week familiarisation (post-tests). During the post tests, participants were reminded before testing commenced to concentrate on running technique irrespective of footwear as described in the next section, but were given no feedback whilst running in order to maintain technical consistency.

6.2.3 Four week familiarisation phase: Immediately after pre-tests, each participant was provided with a structured progression of running in MFW over the four week familiarisation period and relevant injury prevention exercises. Running technique guidelines were also provided based on current findings in the literature (Table 6.2.3). Both the technique changes and exercises were fully demonstrated. The programme incorporated MFW running into the participant's normal training routines (increasing from ~10% to ~25%), where it was required that the MFW running took place at the beginning of any training session, and then participants were allowed to continue their normal training load in their own preferred conventional running footwear. Thus participants would gradually increase exposure to MFW during this period, whilst also maintaining the remainder of their training schedule in CRS. This programme included running both on grass and concrete, and was not limited to one surface. Participants were asked to concentrate on the running technique guidelines in both CRS and MFW; it was not specific to MFW alone. This allowed a measure of changes both in CRS and MFW in the same participants, thus representing a realistic representation of how one may transition to MFW and the resulting effects this may have on CRS running.

Table 6.2.3. *Four week familiarization to MFW, including running technique guidelines and simple exercises for injury prevention.*

Week	MFW training program
Week 1	Throughout: Wearing MFW and going barefoot as much as possible in normal daily routines 3 days: 5–8 min easy running on the spot or in corridors/garden at home 3 days: Prescribed exercises*
Week 2	3 days: 10–15 min running on grass, 3 min on pavement 3 days: Prescribed exercises*
Week 3	2 days: 20 min running on grass, 5–8 min on pavement 1 day: 25 min running on grass 3 days: Prescribed exercises*
Week 4	2 days: 25 min on grass, 10 min on pavement 1 day: 30 min on grass 2 days: Prescribed exercises*

*No specification was made as to whether the exercises were completed on the same days as the running intervention or not.

Running technique guidelines	Exercise program (10 min)	
Keep stride short and increase cadence (Divert et al., 2005a; Lieberman et al., 2010; Hobara et al., 2012). Run as light and quiet as possible (Crowell & Davis, 2011).	Plantar fascia and triceps surae rolling × 5 min 	
Land on the forefoot, allowing heel to contact immediately afterwards (Robbins et al., 1989; Squadrone & Gallozzi, 2009; Daoud et al., 2012).	Ankle mobility (3 × 15) 	Calf raises (3 × 15) 
Keep hips forward and head up, running as tall and proud as possible (Lieberman et al., 2010).	Toe "grabs" (3 × 15) 	Single leg balance (60 s) 

6.2.4 Data processing: Pedar (Pedar X expert 20.1.35) analysis software was used for data processing, using right foot data (Hong et al, 2012) averaged over 60 seconds. Foot strike patterns were identified using the foot strike index (Altman and Davis, 2012b), where the plantar surface was divided into thirds (heel, midfoot, forefoot), and the foot strike pattern was identified by the location of the centre of pressure at its initial contact point when averaged over all steps. This was then allocated 1=forefoot strike; 2=midfoot strike; and 3=rearfoot strike, for the purpose of correlation analysis. The plantar surface was divided into 8 sections as previously described in Hong et al (2012) (Figure 6.2.4) and pressure values were established within each. Regional pressure, mean maximum force ($\overline{\textbf{MF}}$; total plantar surface), and mean maximum pressure ($\overline{\mathbf{MP}}$; total plantar surface) were calculated from within-step maxima averaged over the 60 seconds data collection period.

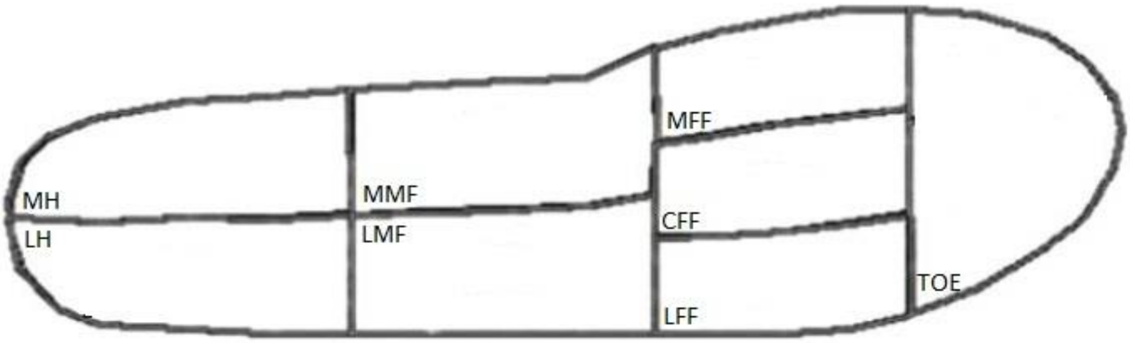


Figure 6.2.4. *Regional areas of the 8 insole masks. MH (Medial Heel), LH (lateral Heel), MMF (Medial Mid-Foot), LMF (Lateral Mid-Foot), MFF (Medial Forefoot), CFF (Central Forefoot), LFF (Lateral Forefoot), TOE (Toes). Adapted from Hong et al (2012) with permission.*

6.2.5 Data analysis: Three tests were conducted for stride frequency, $\overline{\mathbf{MF}}$ and $\overline{\mathbf{MP}}$. These were three-way repeated measures ANOVA for within-subject effects and interactions (condition [MFW vs. CRS], time [Pre vs. Post], and day [day 1, day 2]). A four-way repeated measures ANOVA was also conducted for regional pressure analysis (condition [MFW vs. CRS], time [Pre vs. Post], day [day 1, day 2], and region [1-8]). Where main effects were determined, pairwise comparisons were reported utilising a Bonferroni correction to account for the extra comparisons, and accepted as $p \leq 0.05$. Where the data violated Mauchly's test of sphericity, the Huynh-Feldt correction was utilised. Statistical significance was accepted at $\alpha \leq 0.05$. A Pearson Product-Moment Correlation Coefficient was also used to determine if significant relationships occurred between foot strike patterns, stride frequency, $\overline{\mathbf{MF}}$, and $\overline{\mathbf{MP}}$. This required 24 individual tests, and thus has been adjusted using the Bonferroni correction to account for multiple comparisons, and accepted as $p \leq 0.0021$ (SPSS data analysis software V16.0).

6.3 Results

No participants reported any injury or discomfort during the four week familiarisation, or any change in current performances during training. All participants reported good compliance (mean completion rate of 92%) with the intervention schedule (no participant missed more than 2 prescribed running days, or 3 exercise sessions in total), in that by the end of the four week period they had received significant exposure to running in MFW.

The distribution of foot strike patterns is displayed in Figure 6.3a. During the pre-tests in the MFW condition, 30% of participants adopted a FFS, 30% a RFS, and 40% a MFS. At post-tests, a total of 80% of participants had opted for a FFS, with only 20% retaining a RFS. In contrast, no such change was observed in the CRS condition, in which 50% of participants RFS, 40% MFS, and 10% of participants FFS during pre-tests, with only one participant changing from a MFS to a FFS at post-tests.

For stride frequency, no interaction effects were observed (day*time*condition, p=0.575). A significant increase for time was observed (2.45% increase; p=0.011), and there was also a significant difference for condition (MFW > CRS 2.34%; p=0.002). There was no effect of day (p=0.075) (Figure 6.3a).

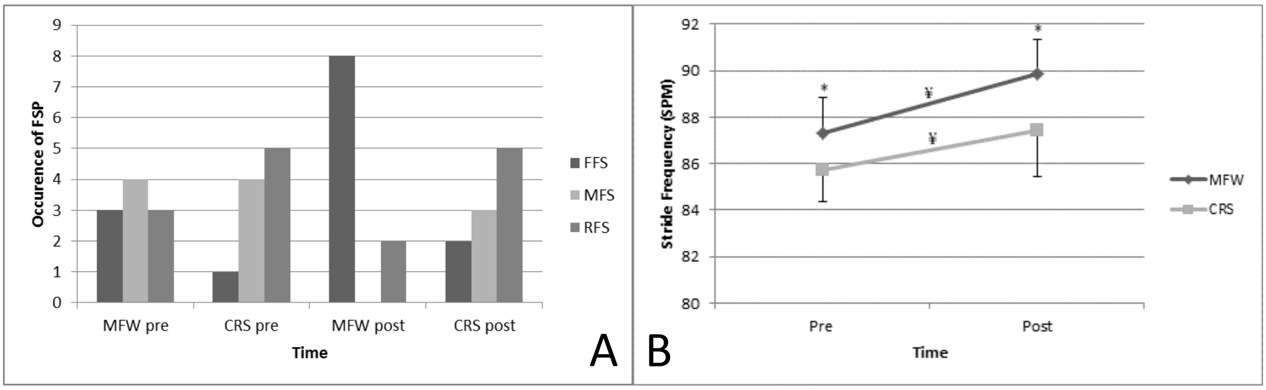


Figure 6.3a. *Graphical representation of both the MFW and CRS condition from pre to post with regard to A) Foot Strike Patterns B) Stride Frequency.*

*(¥= Change from pre to post-tests, * = Difference between condition, p < 0.05, error bars represent SE)*

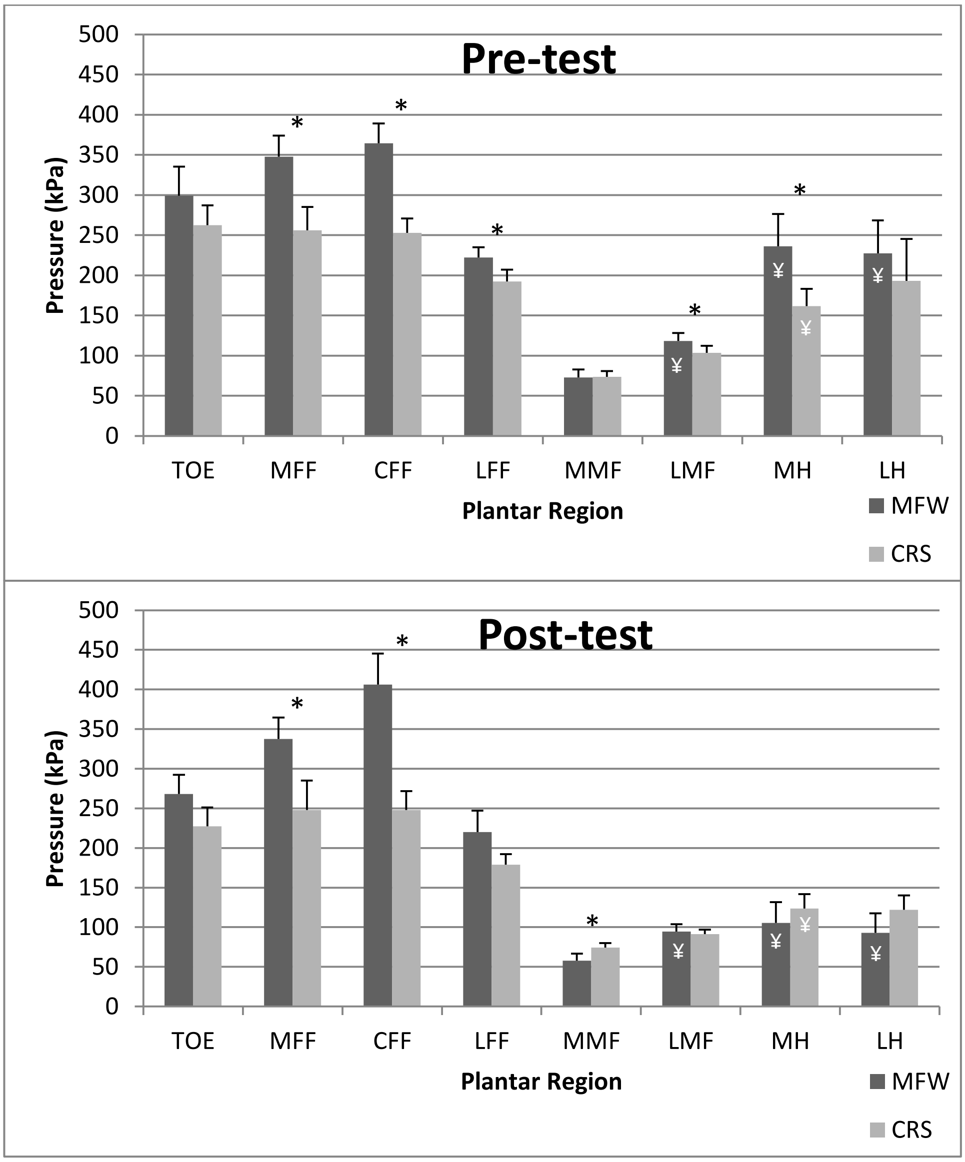
A significant effect for $\overline{\textbf{MF}}$ was observed for change over time (17.63% decrease; p=0.024), and also a significant difference in condition (MFW > CRS 7.43%; p=0.043). No effect of day was established (p=0.319), and there was also no interaction effect (day*time*condition, p=0.788) (Table 6.3a). There was a significant interaction effect observed for $\overline{\textbf{MP}}$ between time * condition (p=0.049). Whilst the MFW condition has a significantly higher $\overline{\textbf{MP}}$ when compared to CRS throughout testing (47.49% higher; p<0.001), the MFW condition was found to increase from pre to post-tests, where the CRS condition decreased from pre to post-tests. No effect for day was observed when analysing $\overline{\textbf{MP}}$ (p=0.515), and there was no interaction for day*time*condition (p=0.449) (Table 6.3a).

Table 6.3a. *$\overline{\textbf{MF}}$, $\overline{\textbf{MP}}$ and regional pressure results for the MFW and CRS condition.*

Condition	**MFW (n=10)**		**CRS (n=10)**	
Time	***Pre***	***Post***	***Pre***	***Post***
$\overline{MF}$ (N)	1325.28±70.94*¥	1089.8±55.75	1229.52±56.56¥	1018.54±41.82
	MFW vs. CRS p=0.006	MFW vs. CRS p=0.270		
	pre vs. post: p=0.032		pre vs. post: p=0.030	
$\overline{MP}$ (kPa)	446.95±27.18*	477.02±48.41*	343.09±37.21	283.39±19.99
	MFW vs. CRS p=0.014	MFW vs. CRS p < 0.001		
	pre vs. post: p=0.473		pre vs. post: p=0.182	

Data presented as mean ± SE, *difference between condition, ¥ change from pre to post-tests, *p < 0.05*.

With regard to regional pressures, there was a significant interaction effect for time*condition*region (p=0.010), but not for time*condition*region*day (p=0.213). The differences at the pre and post-tests with regard to regional pressure are summarised in Figure 6.3b. It was observed that the intervention resulted in regional pressures under the heel being reduced in both footwear types (medial heel [p=0.003] and lateral heel [p=0.011] in MFW, and medial heel [p=0.008] in CRS), as well as in the lateral mid-foot in MFW (p=0.042). Heel pressures were observed to be lower in MFW when compared to CRS at post-tests, despite being significantly higher at pre-tests (medial heel p=0.005). This reduction in heel pressure in both conditions did not result in any increase in pressures in the forefoot, but did appear to slightly localise regional pressure under the central forefoot in the MFW condition, which was found to approach significance (p=0.085). In the forefoot, MFW was found to have significantly higher pressures than CRS (medial forefoot [p<0.001], central forefoot [p=0.001], lateral forefoot [p=0.007] at pre-tests, and medial forefoot [p<0.001], central forefoot [p=0.001], at post-tests. Lateral forefoot at post-tests approached significance [p=0.052]).



(= Difference between condition, ¥ = change from pre to post-tests, $p < 0.05$, error bars represent SE)*

Figure 6.3b. *Regional pressure values both the MFW and CRS condition at both pre and post-tests (regional pressure descriptives can be found in Table 6.2.4).*

Following a Pearson Product-Moment Correlation, no significant correlation was observed between any of the variables at any point in testing (Table 6.3b).

Table 6.3b. *Pearson Product-Moment Correlation results for foot strike patterns (FSP), stride frequency (SF), mean maximum force ($\overline{MF}$), and mean maximum pressure ($\overline{MP}$).*

	SF MFW “Pre”	SF MFW ”Post”	SF CRS ”Pre”	SF CRS “Post”
FSP MFW “Pre”	r: -0.462			
FSP MFW ”Post”		r: -0.740		
FSP CRS ”Pre”			r: -0.526	
FSP CRS “Post”				r: -0.476
	$\overline{MF}$ MFW “Pre”	**$\overline{MF}$ MFW ”Post”**	**$\overline{MF}$ CRS ”Pre”**	**$\overline{MF}$ CRS “Post”**
FSP MFW “Pre”	r: 0.212			
FSP MFW ”Post”		r: 0.178		
FSP CRS ”Pre”			r: 0.058	
FSP CRS “Post”				r: 0.093
	$\overline{MP}$ MFW “Pre”	**$\overline{MP}$ MFW ”Post”**	**$\overline{MP}$ CRS ”Pre”**	**$\overline{MP}$ CRS “Post”**
FSP MFW “Pre”	r: -0.134			
FSP MFW ”Post”		r: -0.308		
FSP CRS ”Pre”			r: -0.088	
FSP CRS “Post”				r: -0.462
	$\overline{MF}$ MFW “Pre”	**$\overline{MF}$ MFW ”Post”**	**$\overline{MF}$ CRS ”Pre”**	**$\overline{MF}$ CRS “Post”**
SF MFW “Pre”	r: -0.180			
SF MFW ”Post”		r: -0.377		
SF CRS ”Pre”			r: -0.226	
SF CRS “Post”				r: 0.017
	$\overline{MP}$ MFW “Pre”	**$\overline{MP}$ MFW ”Post”**	**$\overline{MP}$ CRS ”Pre”**	**$\overline{MP}$ CRS “Post”**
SF MFW “Pre”	r: -0.248			
SF MFW ”Post”		r: -0.044		
SF CRS ”Pre”			r: 0.045	
SF CRS “Post”				r: -0.136
	$\overline{MP}$ MFW “Pre”	**$\overline{MP}$ MFW ”Post”**	**$\overline{MP}$ CRS ”Pre”**	**$\overline{MP}$ CRS “Post”**
$\overline{MF}$ MFW “Pre”	r: 0.434			
$\overline{MF}$ MFW ”Post”		r: 0.602		
$\overline{MF}$ CRS ”Pre”			r: 0.413	
$\overline{MF}$ CRS “Post”				r: 0.246

n=10, no significant correlations noted.

6.4 Discussion

The main findings of the present study suggest that a four week instructed familiarisation in MFW significantly changed foot strike patterns and stride frequency in MFW and that this does not occur to the same degree in the CRS condition. A total of 8 participants (80%) FFS in the post-tests where only 3 (30%) were found to do so at pre-testing in MFW. In contrast, CRS showed no change from pre to post, with only one participant opting to FFS instead of MFS at post-tests when compared to pre-tests. A similar trend was observed in stride frequency, for whilst both conditions increased over time a 2.34% increase was observed in MFW when compared to CRS ($p=0.002$). It appears that the learned and/or adaptive responses to changes in foot strike patterns were significantly reduced when wearing CRS even when instruction to change these techniques in both footwear was provided. Given that a FFS and increased stride frequency have been related to a decrease in impact and improved loading strategy (Hobara et al. 2012) (and thus the potential to decrease musculoskeletal injury), the question arises; why do runners adapt to a large extent in MFW following four weeks familiarisation, but do not adopt these techniques whilst in CRS following the same intervention? The question becomes particularly meaningful in the present study where guidelines for changes in foot strike pattern and stride frequency were provided independent to the footwear condition was being tested, although participants may have spent more time focusing on the changes whilst in MFW due to it being a novel condition. One other possible explanation relates to a reduction in sensory feedback of the plantar surface, which may primarily be due to the shoe elevation and cushioning in CRS. In this regard, it has been speculated that reducing sensory feedback results in participants not actively making changes to impact attenuation since they simply cannot effectively feel what is happening underfoot (Lieberman et al, 2010; Robbins, Gouw and Hanna, 1989). Significant kinematic differences between CRS and barefoot are common in the literature, where active changes in technique are apparent whilst barefoot but not in CRS (Burkett, Kohrt and Buchbinder, 1985; De Wit, De Clerq and Aerts, 2000; Divert et al, 2005a; Lohman et al, 2011; Squadrone and Gallozzi, 2009) that support this concept. In addition, it has previously been suggested that a FFS becomes more difficult as a result of the elevated heel design in CRS, because an increased degree of plantar flexion and a more vertical shank angle at touchdown is required in order to FFS or MFS in this condition (De Wit, De Clerq and Aerts, 2000), that may also explain the lack of change of this group with regard to foot strike patterns. To better understand the mechanisms underlying the above, the authors discussed the difference with the participants after test completion. The overwhelming feedback from participants was that it was easier to adopt the “old” running form in CRS, but that MFW acted as a constant reminder (being so different and thin) for a “new” running style.

Perhaps the most important finding of the current study was a significant reduction in $\overline{\mathbf{MF}}$ in both MFW (17.8%) and CRS (17.2%) as a result of the intervention, which suggests that a four week familiarisation to MFW may reduce maximal forces applied to the plantar surface. This accepts our hypothesis that a lower force would be observed in the MFW as a result of the transition; however we did not expect to see the same result in CRS. As discussed above, it has previously been argued that foot strike patterns and stride frequency are largely responsible for changes in loading of the lower extremities (Divert et al, 2005a; Hobara et al, 2012; Lieberman et al, 2010; Lohman et al, 2011). However this was not observed in the present study, as CRS was not found to change with regard to foot strike patterns, but yet a reduction in $\overline{\mathbf{MF}}$ of a similar magnitude as MFW was observed. Similarly, no significant relationship was found between foot strike patterns / stride frequency and $\overline{\mathbf{MF}}$ during correlational analysis for either condition. These findings support the recent view of Hamill and Gruber (2012) which argued that no clear relationship had been established in the existing body of scientific research literature between foot strike patterns, kinetics and injury. This is not the first time that a reduction in force, a move towards a FFS and an increase in stride frequency has been observed in a minimalist (Squadrone and Gallozi, 2009; Giandolini et al, 2013a) or barefoot condition (De Wit, De Clerq and Aerts, 2000; Divert et al, 2005a; Lieberman et al, 2010) but with the exception of one recently published study (Warne and Warrington, 2014), no other research to the authors best knowledge has previously reported any positive changes to running in CRS as a result of a minimalist intervention. Based on these findings, it seems that the most significant effects reported could be related to neuromuscular adaptions thereby warranting further investigation. Neuromuscular changes have previously been related to muscle firing patterns and changes of joint stiffness that may be optimised in the minimalist or barefoot condition (De Wit, De Clerq and Aerts, 2000, Divert et al, 2005b), and thus may transfer to the CRS condition. This includes increased coordination and pre-activation of the dominant running muscles in anticipation of ground contact when no protection is present in order to manage foot contact with the floor (Bishop et al, 2006; Lieberman et al, 2010; Robbins, Gouw and Hanna, 1989), and/or a decrease in knee joint stiffness that will reduce impact peak magnitude and rate of force development (Nigg, 2009). It may also be plausible that the reduction in $\overline{\mathbf{MF}}$ was simply due to the technical guidelines ("run as light and quiet as possible" etc.) (table 6.2.3), despite this not resulting in changes in foot strike patterns and stride frequency that manifested as an observable effect.

The differentiation between acute and chronic changes to running technique is still largely unexplored. In the present study, the higher $\overline{\mathbf{MF}}$ observed in MFW at pre and post-tests in comparison to CRS could be related to the reduced shoe cushioning characteristics in MFW, in contrast to conventional footwear (Hennig and Milani, 1995). Lieberman et al (2010) observed a continued trend towards RFS in a habitually shod group even whilst barefoot running using an acute measure, that suggest impact attenuation tactics do not occur immediately and may predispose the novice minimalist/barefoot runner to higher loading for a period of time, however whilst both conditions did indeed show reduced loading as a chronic measure, the cushioning differences (7.43% higher $\overline{\mathbf{MF}}$ in MFW) was still apparent. Whilst it is possible to suggest that participants actively changed their running technique to compensate for this increased load over a four week period in MFW, this manifested in impact attenuation changes in both conditions, and not specific to the MFW, despite changes in foot strike patterns and stride frequency being more pronounced in this condition. However it is not possible to definitively conclude, from the findings of the present study, as to whether these changes would continue to occur or are optimised in this four week familiarisation period, and whether specific impact attenuation in MFW would result in any compensation for the reduced cushioning that was not apparent in the present study. In other words, the question arises as to whether running in MFW eventually results in similar or lower loading to the plantar surface when compared to CRS, as this has previously been observed in the barefoot condition (Divert et al, 2005a; Lieberman et al, 2010; Lohman et al, 2011)? If indeed there is a need to allow adequate sensory feedback but also incorporate some degree of cushioning for today's running surfaces, then where does the trade-off between natural impact attenuation and shoe cushioning become optimised? In the same line of thought, the authors direct the reader to a recent review by Lieberman (2012), in which the author states "*Put in simple terms: how one runs probably is more important than what is on one's feet, but what is on one's feet may affect how one runs*" (Lieberman, 2012, pp 64).

With regard to regional pressure, a significant reduction in pressure was observed in the heel and midfoot regions in both MFW and CRS from pre to post-tests. Importantly, pressure was found to be lower at the heel and medial mid-foot in MFW compared to CRS, despite displaying significantly higher values during the pre-tests. These results were expected given that the increase in participant's forefoot striking in MFW was appreciably higher at post-tests indicating an increase in foot plantar flexion at initial contact. These findings can again be related to impact attenuation tactics, where participants in previous studies have been noted to actively move away from heel contact whilst barefoot or in MFW in order to reduce localised pressure under the bony heel of the foot (DeWit et al, 2000; Divert et al, 2005a; Lieberman et al, 2010; Robbins, Gouw and Hanna, 1989; Squadrone and Gallozzi, 2009). Perhaps surprisingly, the reduction in regional pressure under the heel in both conditions did not manifest into significantly increased pressure under the forefoot or toe region at post-tests, with the possible exception of the central forefoot in MFW (Pre - 364.41±24.56 kPa; Post - 406.02±39.15 kPa), that appeared to have a localised increase. This increased metatarsal pressure has been previously observed (Squadrone and Gallozzi, 2009), and also identified as a risk factor for metatarsal stress fractures (Giuliani et al, 2011). Aside from the reduced heel pressure in MFW at post-tests, this condition displayed significantly higher regional and $\overline{\mathbf{MP}}$ pressures throughout testing (47.49% higher). MFW was also observed to increase in $\overline{\mathbf{MP}}$, compared to a decrease observed in CRS as a result of testing. This could be argued to potentially increase stress fracture risk in the MFW condition, particularly during the transitional period. This has been observed elsewhere, in which a minimal shoe displayed increased peak pressure and a smaller contact area of the foot when compared to CRS, due to a reduction in cushioning properties (Wiegerinck et al, 2009). This is of particular importance since the MFW condition was found to take more strides per minute, further increasing the frequency of loading taking place on the foot. Again, whether this is the case when athletes adopt minimalist footwear for a prolonged (> 4 weeks) period of time remains to be determined. In this regard, a major limitation of the present study was the inability to use the shoes implemented for the familiarisation during data collection. The sensory insoles are a fixed design and would not fit into the individual toe pockets of the Vibram Five-fingers. The effect of having separate toe compartments is very likely to influence plantar pressure, and the analysis using a “similar” shoe is not ideal. The authors would thus suggest that the application of this study be reduced to the global effect of minimalist, zero drop, 3mm sole footwear, and not specific to any individual shoe type.

The training intervention used in the present study involved a simple progression of running in MFW in order to raise exposure to this condition on multiple surfaces (grass and concrete), as well as injury prevention exercises and simple guidelines based on current literature findings (Table 6.2.3). The authors do not attempt to suggest that this necessarily represents the gold standard familiarisation strategy, but instead based the programme on what might be considered educated coaching guidelines to successful minimalist transition in order to observe the effects. It might be considered more applicable to apply the same protocol without any technical intervention in order to observe natural instinctive changes, yet given that most athletes today have access to some kind of educational material (e.g. via the internet) this seems less applicable to today’s athletic population. The higher exposure to running on grass than concrete may be noted as a limitation to this study, as more compliant surfaces may not instigate the same degree of impact attenuation as harder surfaces (Herzog, 1979). However the adoption of multiple surfaces, with a safe increment, represents a realistic and safer scenario in today’s environment. In this study, the effects of the MFW, technique instruction, and simple exercises cannot be teased apart and represent the intervention as a whole. The reduction in $\overline{\mathbf{MF}}$ and increase in stride frequency observed here represent positive changes to running technique that demand further research for application to the wider community, with different interventions and technical feedback undergoing individual scrutiny. It would also be beneficial to include a control group who underwent no intervention in order to be sure that no potential learning effect took place, however our model utilised two days testing at both pre and post-tests in order to account for this effect, and found no significant effect of day. Our research presents novel and important information regarding the familiarisation process to minimalist running, and suggest that minimalist running using instructed queue's and simple exercises can be used either as a training tool to improve impact attenuation tactics in both CRS and MFW running conditions, or as a feasible means to transition successfully into MFW only. These findings coupled with our previous reports of potential performance gains in MFW (Warne and Warrington, 2014), present exciting possibilities for the future of footwear prescription. No injuries or discomfort were reported during the four week familiarisation, however longer periods of familiarisation are required in future studies to determine the degree to which these changes could potentially continue to evolve over time, and to also evaluate prospective injury rates. Regardless, our laboratory has now identified an 8% improvement in running economy (Warne and Warrington, 2014) and a 17% reduction in plantar force following a short term four week MFW familiarisation with no injuries experienced by the participants.

A further consideration for these results is that we only examined treadmill running during the plantar pressure analysis sessions. Treadmill running has been associated with lower plantar pressures and forces than over ground running (Hong et al, 2012), and therefore we may be "underestimating" the effects when applied to over ground running.

6.5 Conclusion

To the best of the authors' knowledge, the current research is the first to begin to document changes in plantar running kinetics and kinematics in habitually shod runners as a result of running in MFW. Following a four week minimalist familiarisation that included technique guidelines and simple exercises, more participants adopted a forefoot strike pattern in MFW and also had a greater increase in stride frequency when compared to CRS. A significant reduction in plantar forces in both the CRS and MFW conditions suggests that impact attenuation tactics are improved as a result of running in MFW that does not directly relate to foot strike patterns and stride frequency when examining correlations. The mechanisms for this apparent reduction in plantar forces require further investigation. In line with previous research, our regional pressure results suggest that participants actively attempt to limit local pressures under the heel while in MFW, but higher plantar pressure values are still apparent in MFW compared to CRS. A four week familiarisation programme in MFW was found to result in significant positive changes to running technique and loading in both conditions. Finally, no injury or discomfort was observed at any time in the intervention, but a longer period of time is required to determine prospective injury rates in runners attempting to transition to MFW.

6.6 Perspective

Research investigating the transitional effects of different footwear and gait-retraining is as yet limited, with most studies to this date using acute measures only. The current study adds to the limited body of research suggesting that a gradual progression into minimalist footwear that includes some simple gait-retraining can have positive effects on plantar forces and simple kinematics of running. The present authors observed significant changes in plantar pressures as a result of the intervention that suggests adaptation or a change in technique may take time to manifest. The higher pressure observed in the minimalist footwear may predispose the novice transitional athlete to injury, but the present work has identified a feasible means to begin this transitional process. The study suggests that a successful transition to minimal running is possible, and that positive changes to impact and kinematics warrant such a transition.

6.7 Link to Chapter Seven

Study Three examined changes in plantar pressures and forces during a four week transition to MFW with gait-retraining. The higher pressure observed in the minimalist footwear may predispose the novice transitional athlete to injury, however significant reductions in plantar forces may also be seen as a positive result of this transition and so the result is not so straightforward. It may be pertinent to investigate external forces in addition to these plantar pressures in order to develop a more comprehensive picture of the changes associated with transitioning to MFW with gait-retraining. Our final study, Study Four, was intended to examine external loads that have been associated with running related injury. These include the Fz1 and loading rate of the vGRF. In addition, neuromuscular control has been associated with both performance and injury in the literature and this can be examined indirectly using joint stiffness measures (Butler, Crowell and Davis, 2003). Therefore, we also used this opportunity to measure joint stiffness and attempted to correlate changes in stiffness to RE, Fz1 and loading rate in order to further our understanding of how neuromuscular components may play a role in the use of MFW.

CHAPTER SEVEN

Study Four

"Kinetic and kinematic changes during a six week minimal footwear and gait-retraining intervention in runners"

7. Study Four - "Kinetic and kinematic changes during a six week minimal footwear and gait-retraining intervention in runners".

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STATEMENT OF CONTRIBUTION: GILES WARRINGTON AND KIERAN MORAN WERE JOINTLY INVOLVED IN THE SUPERVISION OF THIS STUDY. BARRY SMYTH, JOHN FAGAN AND MICHELLE HONE WERE INVOLVED IN DATA COLLECTION AND STUDY MANAGEMENT. ALAN NEVILL WAS INVOLVED IN STATISTICAL DESIGN AND ANALYSIS. CHRIS RICHTER DESIGNED THE CUSTOM MATLAB SOFTWARE FOR THE INVERSE DYNAMICS EQUATIONS.

ABSTRACT

The purpose of this study was to evaluate the effects of a 6 week combined minimalist footwear (MFW) and gait-retraining intervention on impact measures (impact peak [Fz1] and loading rate), leg stiffness, and kinematic changes in both MFW and conventional running shoes (CRS). Twenty-four trained male runners (Age: 35 ± 8 years, stature: 179.5 ± 4.9 cm, body mass: 79.2 ± 9.6 kg, $\dot{V}0_{2max}$: 60.25 ± 7.4 $ml \cdot kg \cdot min^{-1}$) were randomly assigned to either; A group that gradually increased exposure to MFW and also implemented gait-retraining over a 6 week period (COMBINED; n=12) who were examined in both MFW and CRS, and a group that completed the gait-retraining only with no MFW exposure (GRT; n=12). The COMBINED group significantly reduced loading rate from pre to post-tests in MFW (33% reduction), but not to the same extent in CRS (14% reduction). A similar result in CRS was observed in the GRT group (18% reduction). Fz1 was also reduced 9% in the COMBINED group. No stiffness measure was changed as a result of the intervention. Loading rate was much higher in MFW than CRS both pre and post the intervention. Vertical stiffness was higher in MFW than CRS both pre and post the intervention. A COMBINED intervention can significantly reduce loading rate and Fz1. However, much higher loading rate in MFW vs. CRS both during pre and post-tests was observed and therefore a GRT intervention may be a safer alternative to reduce loading rate without MFW use.

7.1 Introduction

Running is a popular and healthy exercise modality of which participation has increased over the last number of years; for example running has increased 10% since 2010 in the USA and now has a total of 35.5million participants (Rothschild, 2012b). However, the amount of lower extremity injuries experienced by runners today remains exceptionally high (19.4 to 79.3%; Van Gent et al, 2007). As a result, many strategies have been adopted by runners to reduce injury risk.

One strategy is the use of minimalist footwear (MFW). MFW are shoes with a smaller mass, greater sole flexibility, a lower profile, and lower heel-to-toe drop than conventional running shoes (CRS) (Lussiana et al, 2014). Runners in this footwear type have been found to be more likely to adopt a non-rearfoot strike pattern (Larson, 2014; Giandolini et al, 2013a; Altman and Davis, 2011), and a non-rearfoot strike pattern has been found to reduce impact forces (Cheung, 2013, Altman and Davis, 2011; Lieberman et al, 2010; Giandolini et al, 2013b). Impact characteristics of the vertical ground reaction force such as the loading rate and the impact peak (Fz1) have been associated with increased injury risk in runners for injuries such as stress fractures (Milner, Hamill and Davis, 2006; Crowell and Davis, 2011), plantar fasciitis (Pohl, Hamill and Davis, 2009), and patellofemoral pain (Cheung and Davis, 2011). However, an important consideration with regard to MFW use is that some runners do not adapt their running style despite the reduction in cushioning properties of the shoe (Lieberman et al, 2010; Willson et al, 2014). This can result in significantly higher loading rates particularly with a rearfoot strike pattern (Kulmala et al, 2013; Divert et al, 2005b; De Wit, De Clerq and Aerts, 2000), since these MFW do not have any heel cushioning to attenuate this impact (Lieberman et al, 2010; De Wit, De Clerq and Aerts, 2000). This may be a reason that higher impact related injuries such as stress fractures have been observed during a MFW transition (Ryan et al, 2013; Daumer et al, 2014; Salzler et al, 2012; Giuliani et al, 2011). Therefore, it may be beneficial to include "barefoot inspired" gait-retraining when transitioning to MFW. Indeed gait-retraining for runners is increasing in popularity for this reason (e.g. Goss and Gross, 2012b).

Gait-retraining has been prescribed as a means to promote a more "natural" running gait that is theorised from barefoot movement, both in the literature (e.g. Goss and

Gross, 2013; Giandolini et al, 2013a) and from footwear manufacturers (e.g. http://www.merrell.com/US/en/MConnect_Learn). In addition to promoting a non-rearfoot strike pattern, this popular gait-retraining also advocates increases in stride frequency, lighter steps, and a more upright posture during running (e.g. “Chi” or “Pose” running; Goss and Gross, 2012b; Dallam et al, 2005; Fletcher, Esau and MacIntosh, 2008). Elements of this gait-retraining have been found to reduce loading rate (Crowell and Davis, 2011; Goss and Gross, 2012b; Arendse et al, 2004) and Fz1 (Crowell and Davis, 2011; Arendse et al, 2004).

It therefore appears that both MFW use and gait-retraining can have a positive effect on reducing impact forces. However, no study has attempted to combine both of these elements. This may be beneficial for both the MFW and gait-retraining intervention, because if some runners do not adopt a non-rearfoot strike pattern in MFW then gait-retraining could be of benefit to increase the likelihood of this change. Likewise, runners undergoing gait-retraining may benefit from MFW use, since some authors have suggested that CRS may reduce the runner’s ability to adopt a non-rearfoot strike pattern and increase stride frequency due to shoe design and sensory “insulation” (Lieberman et al, 2010; De Wit, De Clerq and Aerts, 2000; Robbins and Hanna, 1987). Indeed, MFW use has been found to increase stride frequency, and promote a mid or fore-foot strike pattern in runners without any gait-retraining or feedback being provided (Warne and Warrington, 2014), and so a combined MFW and gait-retraining intervention may prove to be more effective than just gait-retraining in CRS. This has yet to be examined.

While it has been suggested that experienced MFW runners may be less likely to suffer a running related injury than their shod counterparts (Goss and Gross, 2012a; Daumer et al, 2014), the transition period to MFW has been suggested to be a time of high risk of injury because of reduced cushioning and bending stiffness in MFW compared to CRS (Ryan et al, 2013; Daumer et al, 2014; Salzler et al, 2012). In the literature, the effect of reduced cushioning of MFW with regard to loading rate (Sinclair et al, 2013; Lieberman et al, 2010; Willson et al, 2014) and Fz1 (Braunstein et al, 2010; Squadrone and Gallozzi, 2009; Lussiana et al, 2014) when compared to CRS has been equivocal. Therefore, we also sought to determine differences in impact characteristics between MFW and CRS.

Finally, stiffness has been suggested to be a key factor in the neuromuscular control of running and may influence performance and injury (Butler, Crowell and Davis, 2003). Any increase in stiffness will result in increased loading rate and Fz1 due to a less compliant structure in the first period of stance (Williams et al, 2004; Butler, Crowell and Davis, 2003). Indeed, higher leg stiffness has been related to increased bony injuries (McMahon, Comfort and Pearson, 2012). No research has examined how joint or vertical stiffness can change during a transition to MFW incorporating gait-retraining and this may be important for understanding injury risk with regard to bony injuries. During this study we also measured popular running kinematics (vertical oscillation, ground contact time, and joint angles) to describe the running gait with respect to differences between MFW and CRS, and changes associated with the intervention.

The aims of the present study are therefore: 1) to investigate the effects of a 6 week combined MFW and gait-retraining (COMBINED), or only gait-retraining (GRT) intervention on the Fz1, loading rate, vertical and joint stiffness, and selected kinematic data during running, 2) To determine the effect of footwear (MFW vs. CRS) on these variables.

7.2 Methods

7.2.1 Participants: Twenty-eight trained male runners (Age: 35 ± 8 years, stature: 179.5 ± 4.9 cm, body mass: 79.2 ± 9.6 kg, $\dot{V}O_{2max}$: 60.2 ± 7.4 $ml \cdot kg \cdot min^{-1}$) were recruited from local athletic clubs via internet advertising. Participants typically ran 5 to 7 days per week, with a mean weekly distance of 62 (±15) kilometres at the time of this study. Participants were excluded if they had reported any lower limb injuries in the last three months, or had previous barefoot or minimalist running experience. Only male athletes were used to eliminate gender differences in running mechanics (Ferber, Davis and Williams, 2003). The participants gave informed consent at the beginning of testing. Ethical approval for this study was granted by the Dublin City University Research Ethics Committee.

7.2.2 Experimental Design: Two groups of 14 participants were randomly established before testing commenced. Group characteristics can be seen in Table 7.2.3. The first group was tested in both MFW and CRS at pre and post-tests, and were required to gradually increase exposure to MFW as well as incorporate gait re-training into their running over this six week period (COMBINED). The second group were only tested in CRS at pre and post tests, but also included the gait-retraining (GRT). The GRT group was required to train as normal, and had absolutely no exposure to MFW at any point. To balance order effects in the COMBINED group, a Latin square design was used to determine which footwear condition (MFW or CRS) was tested first between the pre and post tests. On the first visit, foot size was measured and participants in the COMBINED group were provided with one pair of MFW (Vibram® Five Finger "KSO"; ~150 g), and all participants were provided with a neutral CRS (Asics® "GEL-Cumulus" 2012; ~400g).

Table 7.2.3. *Anthropometric and descriptive data for the COMBINED and GRT groups.*

Group	**Age (years)**	**Stature (cm)**	**Body mass (kg)**	**$\dot{V}0_{2max}$ (ml·kg·min^{-1})**	**kilometres per week (km)**
COMBINED (n=12)	36 (±7)	179 (±4.6)	78.8 (±10.2)	60.94 (±7.36)	64 (±20)
GRT (n=12)	34 (±9)	180.2 (±5.4)	79.7 (±9.2)	60.56 (±8.08)	60 (±14)

(Mean ± SD)

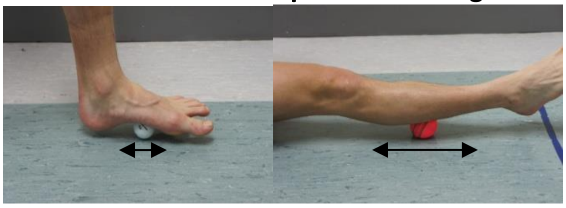
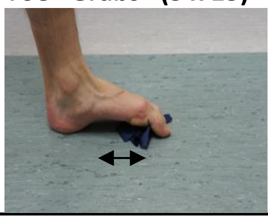
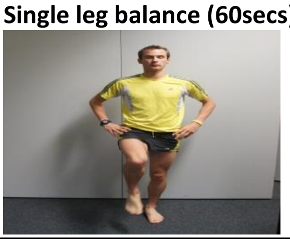
7.2.3 Testing Procedure: A motion analysis system (Vicon 512 M, Oxford Metrics Ltd, England) was used to record the position of six reflective markers (250Hz). Reflective markers were attached unilaterally (right side), using double sided tape on the following anatomical landmarks; distal head of the fifth metatarsal bone, heel, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and the glenohumeral joint. One force plate (BP-600900, AMTI, MA, USA) recorded the ground reaction forces (1000Hz). Before motion analysis tests began in each footwear condition for the COMBINED group, participants were required to run on a treadmill for 4 minutes at 11km/h, as four minutes has been suggested to optimise leg stiffness and running technique depending on surface and shoe hardness (Divert et al, 2005a). This strategy was employed to prevent any "carry-over" of neuromuscular strategies from one type of footwear to another given that both footwear types were tested on the same day. Over ground runs were performed over a distance of 25 metres. Speed was controlled at 11km/h (3.05m/s) using speed gates (Browser Timing Systems, CM L5 MEM, Salt Lake City, Utah, USA) and kept within 5% variance. Participants had no awareness of the force plate embedded into the floor, in order to avoid regional targeting. A test was considered successful when participants made contact using the right foot with the force plate. This procedure was repeated to ensure that each participant made 5 successful contacts with the force plate (Morgan et al, 1991). Participants were not informed at any point what was being measured or examined (Morin, Samozino and Peyrot, 2009). The GRT group underwent the same procedure but only tested in CRS. Stride frequency and foot strike pattern distribution were ascertained from treadmill running prior to the four minute warm up period using Pedar X sensory insoles (Novel Pedar X, Munich, Germany) as part of a wider study with these participants. The methods for this approach from a previous study can be found in Warne et al (2013).

7.2.4 The Intervention: Immediately after pre-tests, each participant in the COMBINED group was provided with a structured progression of MFW use over the six week familiarisation period and relevant injury prevention exercises (Rothschild, 2012b; Tenforde et al, 2011) that might be expected from any coach or professional administering this kind of programme (see Table 7.2.4). The gait-retraining was provided to all participants and is based on current findings in the literature (Crowell and Davis, 2011; Daoud et al, 2012; Divert et al, 2005b; Lieberman et al, 2010; Robbins and Hanna, 1987; Squadrone and Gallozzi, 2009); these changes have also become the main kinematic changes promoted in the running gait-retraining marketplace (Chumanov et al, 2012; Lenhart et al, 2014; Fletcher, Esau and MacIntosh, 2008; Dallam et al, 2005; Goss and Gross, 2013). Both the gait-retraining and exercises were fully demonstrated during a 30 minute session until changes to stride frequency

(+10%), a forefoot strike pattern, more upright posture and a softer landing were adopted by the participants. This was implemented using feedback from an experienced tester in line with the simple instructions provided in Table 7.2.4. The programme incorporated MFW into the participants normal training routines, where it was required that the MFW took place at the beginning of any training session, and then participants were allowed to continue their normal training load in their own preferred conventional running footwear, thus not reducing their overall training workload. The participants were asked to work on the gait re-training changes both in MFW and CRS, gradually incorporating it into longer runs. The GRT group received no MFW intervention, and were asked to remain in their regular CRS for the duration of the testing, whilst including the same gait-retraining elements and the injury prevention exercises.

Table 7.2.4. *Six week familiarization to MFW including running technique guidelines and simple exercises for injury prevention.*

Week	MFW Training Programme
Week 1	Throughout: Wearing MFW and going barefoot as much as possible in normal daily routines 3 days: 5 -8 mins easy running on the spot or in corridors/garden at home 3 days: Prescribed exercises*
Week 2	3 days: 10 – 15 mins running on grass, 3 minutes on pavement 3 days: Prescribed exercises*
Week 3	2 days: 20 mins running on grass, 5 - 8 minutes on pavement 1 day: 25 mins running on grass 3 days: Prescribed exercises*
Week 4	2 days: 25 mins on grass, 10 mins on pavement 1day: 30 mins on grass 2 days: Prescribed exercises*
Week 5 + 6	2-3 days: 30 mins on grass, 15 mins on pavement 1day: 40 mins on grass 2 days: Prescribed exercises*

Running technique guidelines	**Exercise Programme (10 minutes)**	
Keep stride short and increased cadence (Divert et al, 2005b; Lieberman et al, 2010; Hobara et al, 2011; Chumanov et al, 2012) **Run as light and quiet as possible (Crowell and Davis, 2011)**	**Plantar Fascia and Triceps Surae Rolling x 5 mins** 	
Land on the forefoot, allowing heel to contact Immediately afterwards. (Lieberman et al, 2010; Squadrone and Gallozzi, 2009; Robbins and Hanna, 1987; Daoud et al, 2012)	**Ankle Mobility (3 x 15)** 	**Calf Raises (3 x 15)** 
Keep hips forward and head up, running as tall and proud as possible (Lieberman et al, 2010)	**Toe "Grabs" (3 x 15)** 	**Single leg balance (60secs)** 

* No specification was made as to whether the exercises were completed on the same days as the running intervention or not.

7.2.5 Participant Characterisation: A $\dot{V}0_{2max}$ test was completed for participant characterisation at the end of the final testing day. This involved a ramped treadmill protocol at 12 km/h for a 5-min warm-up before increasing to 14 km/h. The incline was then increased every minute until volitional exhaustion, and correlated with participants achieving a respiratory quotient of 1.1 or above. Participants conducted this test in their own shoe choice. $\dot{V}O_{2max}$ was recorded as the highest breath-by-breath value averaged over 60 s.

7.2.6 Data Processing: The marker data was filtered using a recursive second order low pass Butterworth digital filter (Winter, 2009). The marker set and force plate data were filtered using a 9Hz and 50Hz cut of frequency, respectfully. The information of the captured markers was reduced to the sagittal plane and used to create a four-segment model with frictionless hinge joints. Segments of the model were the foot, shank, and thigh, which were connected by markers that represent the ankle, knee and hip joint (Winter, 2009). An inverse dynamics approach was adopted using anthropometric data from Winter (2009) with a custom Matlab software package (R2012a, MathWorks Inc., USA). K_{Knee} was calculated as K=Δjoint moment/Δjoint angle from initial contact to midstance (Kuitunen, Komi and Kyrolainen, 2002; Hamill et al, 2012). Hamill, Gruber and Derrick (2012b) have previously reported ankle stiffness calculated in the same manner. However, since the ankle is very likely to both plantarflex and then dorsiflex with a rearfoot strike pattern during the first half of stance, this method of comparing foot strike patterns may overestimate K_{ankle} during a rearfoot strike, since the Δjoint angle calculation does not take into account the change in direction. In contrast, a forefoot strike pattern will only experience dorsiflexion in the first half of stance and thus this Δjoint angle will be higher. Therefore, we calculated Δjoint angle from the point in which the ankle began to dorsiflex until midstance, irrespective of the foot strike adopted. This can be considered "plantar flexor stiffness" of the ankle and a method we consider to be more applicable when comparing foot strike patterns. K_{vert} was calculated as K=F/ΔL, where F is equal to the peak vertical (z) GRF, and ΔL is the change in displacement of the greater trochanter marker that is used as a proxy for the CoM (Centre of Mass) (Kuitunen, Komi and Kyrolainen, 2002; Butler, Crowell and Davis, 2003). Vertical oscillation was determined by subtracting the lowest point of the greater trochanter marker from the height of this marker at initial contact (IC). Ground contact time was measured from initial contact to toe-off. The direction for joint angles at IC and mid-stance (MS; 50% of stance; Linley et al, 2010) can be found in Figure 7.2.6. Fz1 was determined using the GRFz data normalised to body weight and manually identifying the first impact peak. In the case that this peak was absent, a representative value of 13% of stance was used (Willy, Pohl and Davis, 2008). Loading rate was calculated as the slope of the line from 20-80% of the Fz1 (normalised to body weight). Again in the case where no Fz1 was apparent, a substituted value of the slope of the line from 2-10% of stance was adopted (adapted from Willy, Pohl and Davis, 2008).

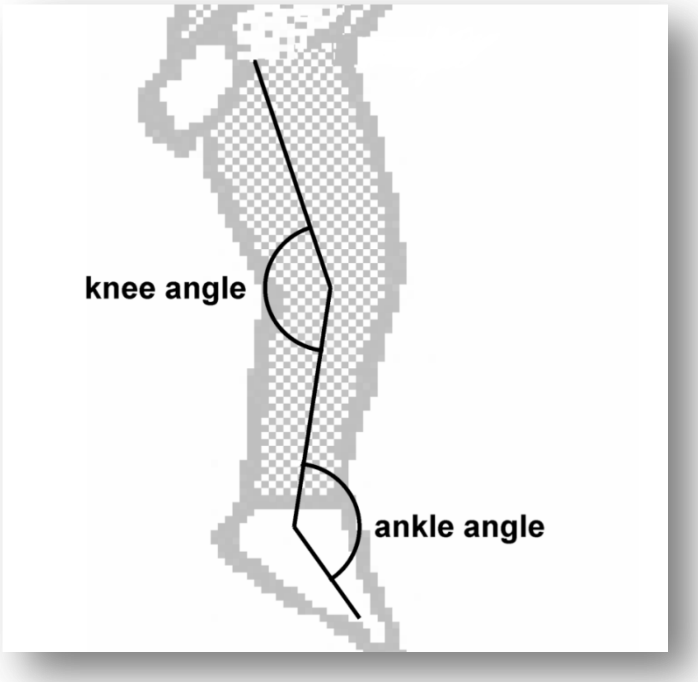


Figure 7.2.6. *Direction of joint angles for the ankle and knee.*

7.2.7 Data Analysis: In order to examine aim 1 and 2 in the COMBINED group, the effect of time (pre to post intervention) and condition (MFW vs. CRS) were examined using two-way repeated measures ANOVA for within-subjects effects. Post hoc analysis was undertaken for any interaction effects under the SPSS Bonferroni correction for multiple comparisons (SPSS Bonferroni adjusted p). Differences between the COMBINED and GRT group in CRS were established with a two-way mixed ANOVA for between-subject effects. Changes over time in the GRT group were examined using paired t-tests. (Statistical Package for the Social Sciences data analysis software V16.0, SPSS Inc., Chicago, Illinois, USA). Statistical significance was accepted at $\alpha \leq 0.05$. Effect sizes are reported as eta squared (η^2) for ANOVA tests and Cohen's d for t tests. To make inferences about true (population) values, the uncertainty of the effect was expressed as 95% confidence limits (mean change [lower to upper confidence interval]) (Batterham and Hopkins, 2006). The smallest standardised change that is considered meaningful was assumed to be an effect size of 0.20 for Cohen's d and 0.01 for η^2 (Cohen, 1988).

7.3 Results

During testing, two COMBINED participants became injured (hamstring and gastrocnemius issues), and two GRT group participants did not return for subsequent testing (remaining n=24; intervention n=12; control n=12). Seven COMBINED and one GRT group participants reported triceps surae soreness, with three of these cases being severe resulting in a temporary reduction in running mileage for several days. One GRT participant reported a minor pain in the second metatarsal, and one further GRT participant reported tightness in the medial longitudinal arch but these did not result in any missed training. Participant compliance with the intervention schedule was established using the training diaries and expressed as a percentage of total completion for both the exercises and the MFW transition. The COMBINED group completed 87±27% of the injury prevention exercises, and 96±6% of the MFW intervention; the GRT group completed 92±15% of the injury prevention programme. All COMBINED participants were able to complete the longer MFW runs in the latter weeks and were well exposed to MFW running by week 6.

When considering the differences between COMBINED and GRT groups when in CRS, no significant group differences, or time by group interactions, were observed for any variable.

The mean difference, 95% confidence intervals, and effect sizes for all variables with respect to change over time and difference between conditions (COMBINED) are presented in Table 7.3. There was an interaction effect for loading rate between time and condition in the COMBINED group; loading rate was observed to be 72.8% higher in the MFW condition compared to CRS at pre-tests (p≤0.00, -40.457 BW·s^{-1} [-54.46 to -26.45], Cohen's d = 0.81), but this difference was reduced to 35.4% at post-tests (p=0.046, -16.81 BW·s^{-1} [-33.3 to -0.32], Cohen's d = 0.34). This was due to a significant 33.0% reduction in loading rate in the MFW condition from pre to post-tests (p=0.001; -31.67 BW·s^{-1} [-47.56 to -15.78], Cohen's d = 0.66) that did not occur to the same magnitude (14.4% reduction) in CRS (p=0.08, -8.02 BW·s^{-1} [-17.15 to 1.1], Cohen's d = 0.28). In addition, we tested the difference between the pre CRS and the post MFW values for loading rate in the COMBINED group; no significant difference was noted (p=0.40, -8.79 BW·s^{-1} [-31.23 to 13.64], Cohen's d = 0.07).

In addition, as observed in Table 7.3, there was no change in the Fz1 from pre to post-tests or any differences between footwear conditions. However, the change over time (pre to post-tests) for Fz1 was found to exhibit a high effect size ($\eta 2$ = 0.044; p=0.08) and this represents a worthwhile reduction in the Fz1. We also noted a meaningful reduction in loading rate in the GRT group from pre to post-tests when examining the effect size (Cohen's d=0.27) that was found to approach significance (p=0.07).

Table 7.3. *Mean change/difference data, 95% confidence intervals and effect sizes for main effects over time (pre to post-tests) and between conditions (MFW vs. CRS).*

COMBINED group (n=12)	Analysis	Mean effect	95% confidence levels		P value	Effect size
	F tests		Lower	Upper		η^2
Loading rate (BW·s^{-1})	Time	-19.85	-31.08	-8.61	0.003*	0.182
	Condition	28.635	14.77	42.5	0.001*	0.302
	Time*Condition	see	text		0.002*	0.081
Fz1 (BW)	Time	-0.14	-0.29	0.02	0.08	0.044
	Condition	0.06	-0.21	0.09	0.43	0.008
K_{Vert} (n·m^{-1})	Time	760.851	-1779.69	3301.39	0.52	0.010
	Condition	3231.34	1543.68	4919.01	0.002*	0.171
K_{Knee} (n·m·deg^{-1})	Time	0.16	-1.14	1.46	0.79	0.003
	Condition	-0.44	-0.97	0.09	0.09	0.028
K_{ankle} (n·m·deg^{-1})	Time	-0.12	-0.70	0.465	0.66	0.001
	Condition	0.48	-0.41	1.37	0.26	0.015
Stride frequency (spm)	Time	1.46	-0.44	3.35	0.12	0.019
	Condition	1.54	0.78	2.3	0.001*	0.023
GCT(s)	Time	0.011	0.004	0.019	0.008*	0.043
	Condition	-0.007	-0.013	-0.001	0.03*	0.042
VOSC (cm)	Time	-0.21	-0.64	0.22	0.31	0.017
	Condition	-0.48	-0.74	-0.23	0.002*	0.092
ϑIC_{Knee} (deg)	Time	1.29	-3.47	6.04	0.56	0.008
	Condition	-0.62	-2.8	1.56	0.54	0.002
ϑMS_{Knee} (deg)	Time	4.27	0.63	7.92	0.03*	0.160
	Condition	2.78	1.22	4.33	0.003*	0.095
ϑIC_{Ankle} (deg)	Time	3.32	1.73	4.92	0.001*	0.079
	Condition	2.98	-0.32	6.27	0.07	0.057
ϑMS_{Ankle} (deg)	Time	1.15	-1.7	3.99	0.39	0.025
	Condition	0.47	-0.92	1.87	0.47	0.006

GRT group (n=12)	*t tests*					Cohen's d
Loading rate (BW·s^{-1})	Time	-11.32	-23.67	1.04	0.07	0.27
Fz1 (BW)	Time	-0.1	-0.31	0.09	0.28	0.11
K_{Vert} (n·m^{-1})	Time	2476.06	-944.38	5896.51	0.14	0.19
K_{Knee} (n·m·deg^{-1})	Time	-0.27	-1.76	1.22	0.7	0.01
K_{ankle} (n·m·deg^{-1})	Time	-1.23	-2.34	-0.14	0.03*	0.36
Stride frequency (spm)	Time	4.17	0.86	7.47	0.02*	0.41
GCT(s)	Time	-0.004	-0.009	0.002	0.19	0.15
VOSC (cm)	Time	-0.41	-0.95	0.13	0.12	0.21
ϑIC_{Knee} (deg)	Time	1.0	-2.69	4.71	0.56	0.03
ϑMS_{Knee} (deg)	Time	4.26	0.99	7.52	0.02*	0.43
ϑIC_{Ankle} (deg)	Time	4.49	0.45	8.53	0.03*	0.35
ϑMS_{Ankle} (deg)	Time	1.03	-1.41	3.47	0.37	0.07

Effect for Time, minus represents a reduction at post-tests. $^{*}p \leq 0.05$
Effect for condition, minus represents a lower value in MFW.

The distribution of foot strike patterns is displayed in Figure 7.3 and represented as frequencies.

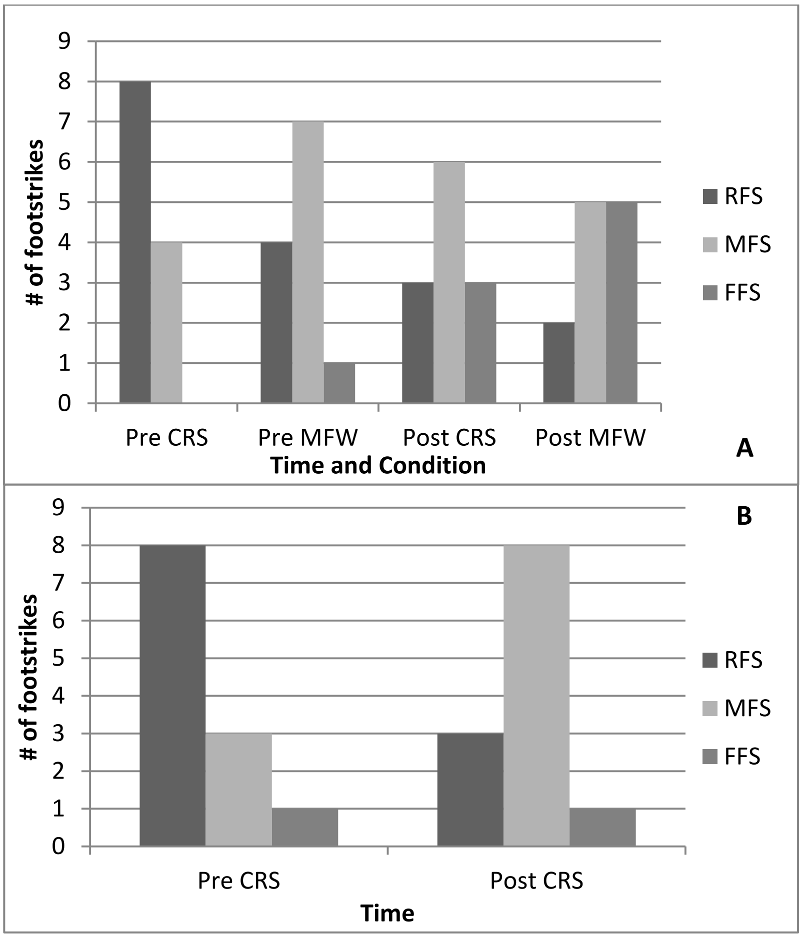


Figure 7.3. *Foot strike pattern changes represented by the number of participants adopting each foot strike pattern pre and post the 6 week intervention, in A) the COMBINED group (CRS and MFW), and B) the GRT group (CRS only).*

7.4 Discussion

7.4.1 Impact Related Variables

The main finding of the present study was a significant reduction in loading rate in MFW as a result of a six week MFW and gait-retraining intervention (COMBINED). This has not been measured during a familiarisation period with gait-retraining previously in the literature. We observed a 33% reduction in loading rate in MFW, and a 14% reduction in CRS in the COMBINED group. This reduction in both CRS and MFW was both likely and meaningful when considering the CI and effect sizes. One possible explanation for the greater reduction in loading rate in the MFW condition associated with the COMBINED intervention may be a result of necessary impact attenuation tactics to counteract the higher loading rate when in MFW compared to the cushioned surface in CRS. This could be considered a positive improvement in the running gait, as increased loading rate has been linked to injury in numerous studies (Milner, Hamill and Davis, 2006; Crowell and Davis, 2011; Pohl, Hamill and Davis, 2009; Cheung and Davis, 2011). However, loading rate was still significantly higher in MFW than CRS throughout testing and therefore it would not be recommended to utilise MFW for reducing loading rate, irrespective of whether a COMBINED familiarisation period and gait-retraining is employed or not. A higher loading rate has been observed previously in different MFW when directly compared to CRS (Sinclair et al, 2013; Willy and Davis, 2014; Paquette, Zhang and Baumgartner, 2013) that may be due to a reduction in the cushioning properties of MFW footwear that reduce the time over which the impact occurs (Lieberman et al, 2010). This may predispose novice MFW runners to injuries associated with higher loading rate such as stress fractures (Ridge et al, 2013; Salzler et al, 2012). A further consideration however is that the Post MFW values were not significantly different than the Pre CRS values for loading rate, suggesting that if one was keen to introduce MFW into a training schedule, there is no greater risk of injury in either CRS or MFW when considering familiarised MFW runners. If one was to introduce the use of MFW into a training schedule for other reasons than reduced loading rate, a COMBINED intervention may therefore be necessary to maintain a "normal" loading rate of the vertical ground reaction force to manage the risk of bony injuries.

The observation that the GRT group in the present study did meaningfully reduce loading rate (based on a CI and effect size approach) suggests that the gait-retraining alone may be a feasible method to reduce this variable. Using gait-retraining has been observed elsewhere to reduce loading rate and has been associated with the adoption of a non-rearfoot strike pattern (Giandolini et al, 2013a; Altman and Davis, 2011; Crowell and Davis, 2011; Goss and Gross, 2012a). Therefore the use of gait-retraining in CRS may be a safe and effective way to reduce loading rate, without the danger of exposure to higher rates of loading when incorporating MFW into the programme.

With respect to the Fz1, we observed a likely and meaningful reduction in this variable in the COMBINED group from pre to post-tests (~9% reduction), but no reduction in

Fz1 in the GRT group; this contrasts the findings for loading rate. The Fz1 has also been linked to injury in previous studies (Hreljac, Marshall and Hume, 2000), in particular tibial stress fractures (Zifchock, Davis and Hamill, 2006). Therefore, if the focus of a training intervention was to reduce Fz1, a COMBINED intervention may be more effective than a GRT intervention. When considering the difference between CRS and MFW in the COMBINED group with respect to the Fz1, previous research has been equivocal, with some studies observing either a higher (Willy and Davis, 2014), lower (Squadrone and Gallozzi, 2009), or equal Fz1 (Sinclair et al, 2013; Paquette, Zhang and Baumgartner, 2013) in MFW compared to CRS. Therefore the current research supports the findings of Sinclair et al (2013) and Paquette, Zhang and Baumgartner (2013) in that there is no significant difference in Fz1 between MFW and CRS. Therefore it appears that a COMBINED intervention is effective at reducing the Fz1 in both CRS and MFW.

In summary, it appears that if the desired outcome of a training intervention is to reduce loading rate, one should adopt the use of simple gait-retraining in CRS. However, familiarising one-self to MFW using a COMBINED intervention will result in a similar loading rate to original values in CRS if adopting MFW is necessary. Likewise, in order to reduce the Fz1, one may consider adopting a combined MFW and gait-retraining programme. However, this initial use of MFW may place runners at increased risk of bony injury due to a higher loading rate and therefore should be considered with caution.

7.4.2 Vertical and Joint Stiffness

We observed no change in K_{vert} in either the COMBINED or GRT group from pre to post-tests. However, when examining the difference between CRS and MFW, there was a significantly higher K_{vert} in MFW in the COMBINED group. This has been observed previously when running on a +8% gradient (Lussiana et al, 2014), but not on flat ground (Shih, Lin and Shiang, 2013). In addition, previous research comparing barefoot vs. CRS has observed a higher K_{vert} when barefoot (Divert et al, 2005a). The observation that a significantly lower vertical oscillation was observed in MFW compared to CRS is the most likely cause for this difference, suggesting that running in MFW results in less vertical excursion of the CoM. In addition, CRS compliance will also slightly reduce K_{vert} when compared to the stiffer outsole of MFW (Divert et al, 2005a). It may also be due to an increased plantar-flexion angle and pre-activation of the triceps surae complex that has been found to increase stiffness when barefoot (De Wit, De Clerq and Aerts, 2000), and the observed change in ankle angle as a result of MFW use would suggest higher triceps surae activity. K_{vert} was also found to be higher with a +10% increase in stride frequency (Giandolini et al, 2013a), and indeed MFW was found to increase stride frequency in the present work. Higher stiffness has been associated with increased risk of bony injuries due to a reduction in system compliance (Butler, Crowell and Davis, 2003); indeed the higher loading rate in MFW compared to CRS, in conjunction with this higher K_{vert}, supports previous research suggesting increased risk of stress fractures during a MFW transition (Ridge et al, 2013). However, no such injuries were observed in the present study. There was no change in K_{Ankle} or K_{Knee} in the COMBINED group from pre to post-tests. Contrastingly K_{Ankle} was reduced in the GRT group, but why this was observed is not clear, since a similar change in foot strike pattern was observed in both groups.

When examining the difference between MFW and CRS with regard to K_{Ankle} and K_{Knee} in the COMBINED group, there was no difference in K_{Ankle} between conditions, but a lower K_{Knee} in MFW (when considering the CI and effect size). Recent work investigating barefoot vs. 0mm,2mm,4mm,8mm, and 16mm midsole footwear found no significant difference between the 0mm shoe (MFW) and any of the other midsole thickness models (CRS) for K_{Ankle}, but a significantly lower K_{Ankle} between the barefoot and all shod (0,2,4,8,16mm) conditions (Chambon et al, 2014). This suggests that the present MFW may not provide enough sensory feedback to elicit any difference in joint stiffness for impact attenuation (Robbins and Hanna, 1987), but the barefoot condition may (Chambon et al, 2014). However this method of calculating K_{Ankle} may not be appropriate (see methods). That being said, K_{Knee} was found to be lower somewhat in MFW vs. CRS (-6.7%) which suggests reduced knee moments or increased knee excursion in the MFW condition compared to CRS. This is supported by Coyles et al (2001) who observed a reduction in knee stiffness when barefoot compared to CRS, but no other research has investigated joint stiffness differences between MFW and CRS to the best of our knowledge.

7.4.3 Kinematic Variables

We observed an increase in the plantar flexion angle at initial contact, and a greater knee extension at mid-stance as a result of the intervention in both MFW and CRS in the COMBINED group and CRS in the GRT group. With respect to the CI and effect sizes, again these changes were greater in the MFW condition compared to the CRS condition in the COMBINED group. Previous research in MFW (Willy and Davis, 2014; Squadrone and Gallozzi, 2009; Lussiana et al, 2013), and gait-retraining (Arendse et al, 2004) support these findings. The increase in plantar flexion angle has been noted acutely between barefoot and CRS, and suggested to be due to impact attenuation tactics to reduce effective mass (Lieberman et al, 2010) and/or localised pressures under the heel (De Wit, De Clerq and Aerts, 2000). This is most likely due to higher plantar surface subcutaneous feedback (Robbins, Gouw and Hanna, 1989), and this could also be the case here in MFW. Interestingly there was a large increase in ground contact time in the COMBINED group in both CRS and MFW. It is possible that the reduction in loading rate occurred via a longer absorption phase of stance that resulted in this increase in ground contact time. However, the change in foot strike pattern to a preference of a non-rearfoot strike pattern in the majority of participants does not help to explain this finding, since a forefoot strike pattern has been correlated to reduced ground contact time elsewhere (Ardigo et al, 1995; Nunns et al, 2013; Hasegawa, Yamauchi and Kraemer, 2007). In the GRT group, stride frequency was found to increase and this contrasts with the findings in the COMBINED group. Both groups increased ϑIC_{Ankle} and $\vartheta MS_{Knee,}$ which would suggest similar kinematic changes that may be due to the gait-retraining, but this does not explain why the GRT group experienced significant changes in stride frequency and the COMBINED group did not. One explanation may be that the greater stride frequency in MFW compared to CRS in the COMBINED group may reduce the need for further increases in stride frequency over time. This may have counteracted the "need" for this group to increase this variable, whereas the GRT group were only influenced by conscious increases to stride frequency and so made efforts to increase this value during the intervention period.

When directly comparing MFW to CRS in the COMBINED group, MFW resulted in higher stride frequency, higher $\vartheta MS_{Knee,}$ lower ground contact time and lower vertical oscillation. It is well established that running barefoot and in MFW will result in increased stride frequency and $\vartheta MS_{Knee,}$ and a decreased vertical oscillation and ground contact time (De Wit, De Clerq and Aerts, 2000; Squadrone and Gallozzi, 2009; Chambon et al, 2014; Sinclair et al, 2013; Divert et al, 2005b; Lussiana et al, 2014), and given that the present MFW has some similar characteristics to barefoot (Squadrone and Gallozzi, 2009), one may expect some similarities to the barefoot research. Stride frequency, $\vartheta MS_{Knee,}$ vertical oscillation and ground contact time are closely related, since an increase in stride frequency will reduce ground contact time (Sinclair et al, 2013; De Wit, De Clerq and Aerts, 2000; Dugan and Bhat, 2005), and also reduce vertical oscillation since the CoM moves through a lower horizontal displacement with increased stride frequency (and a shorter step length) (Sinclair et al, 2013; Goss and Gross 2012b). These kinematic differences in MFW vs. CRS support the "plantar sensation hypothesis" in which a greater degree of impact attenuation tactics are observed with higher feedback from the plantar surface of the foot in MFW (Robbins, Gouw and Hanna, 1989). However these changes in impact attenuation were not sufficient to reduce the high loading rate observed in MFW that is most likely due to the absence of shoe cushioning and not because of kinematic differences associated with footwear.

There are several considerations for this 3D movement analysis. Firstly, we used shoe mounted markers for our foot movement data. The use of 3D markers on the outside of the shoe presents a limitation as it does not give accurate measures regarding bone movement within the foot structure (Arnold and Bishop, 2013). Ideally, all of the footwear should have been restructured to include "windows" for which markers could be placed directly on the body. However, as is apparent, we also used these shoes for other testing sessions including RE where shoe mass was important. Therefore it was not feasible or affordable to provide a different set of footwear just for this analysis. Secondly, we examined the 3D motion analysis of gait during over ground running indoors and our lab was restricted to 25 metres in length making the "run through" quite short. Examining kinematics over a limited number of steps may be inadequate, because of inter-subject variation in step parameters during running (Divert et al, 2005b), and also because it may take runners several minutes to optimise leg stiffness and the running gait depending on the surface/shoe hardness (Divert et al, 2005a). In an attempt to counteract this problem, immediately prior to testing participants ran for four minutes in the footwear about to be tested on a treadmill in the same room. Four minutes has been suggested to be sufficient to optimise leg stiffness and running technique depending on surface and shoe hardness (Divert et al, 2005a). However, the surface of the treadmill and over ground track were different, and therefore we cannot be fully confident that the results can apply to true over ground running over an extended amount of steps.

Limitations to this study include the absence of an additional group who only underwent a MFW intervention without any gait-retraining. If there is any "extra" change associated with running in MFW then it should be established without gait-retraining as a confounding factor. Further research in this area should focus on longer term changes related to MFW use, as this study examined a short six-week intervention that may not identify the changes that occur with long term MFW and gait-retraining. There is also a need for more studies comparing habitually barefoot or MFW runners to matched CRS counterparts with regard to factors associated with injury. We used a common MFW that has gained popularity over the last number of years as a shoe that can "mimic" barefoot movement. However, no shoe can simulate being barefoot, and also that each different MFW with their various degrees of "minimalism" should be considered as very separate conditions and not lumped together as one "MFW" category (Bonacci et al, 2013; Chambon et al, 2014).

7.5 Conclusion

The adoption of a MFW and gait-retraining COMBINED intervention may be beneficial for the reduction of Fz1 over a six week period. However, this can result in significantly higher loading rate in the MFW condition compared to CRS initially that may increase the risk of injury in the MFW condition. Therefore if the aim of a training intervention was to reduce loading rate, it may be more feasible to do so in CRS only whilst adopting gait-retraining changes. It appears that neither a COMBINED nor a GRT intervention influences K_{vert} or K_{Knee}, but a GRT intervention can reduce K_{Ankle}. When comparing MFW to CRS, we observed a higher K_{vert}, and a lower K_{Knee} in the MFW condition in addition to increased stride frequency, a lower vertical oscillation, and a shorter ground contact time. Irrespective of these kinematic differences, the Fz1 was not different between CRS and MFW and the loading rate was significantly higher in MFW that suggests these kinematic differences have little influence on impact variables.

7.6 Additional Data

In addition to the data presented above, a number of other variables were assessed. These include running economy, regional plantar pressure, mean maximum force ($\overline{\mathbf{MF}}$), and mean maximum pressure ($\overline{\mathbf{MP}}$). We also conducted a Pearson product moment correlation to determine relationships between RE, loading rate and Fz1 with respect to the stiffness and kinematic variables. The results and methodology have been provided below. Please see the section 8.0 for the relevant discussion.

7.6.1 Additional Data Methodology

The order of testing and data collection can be observed in Figure 7.6.1 and included; 1) plantar pressure tests, 2) RE tests, 3) over ground running 3D motion analysis (as described above). The COMBINED and GRT group ran for 6-min for both the plantar pressure and RE tests at 11 km/h which has been considered an appropriate “endurance running” velocity (Hatala et al, 2013), in both MFW and CRS, pre and post the intervention. The GRT group were only tested in CRS but underwent the same testing protocol. Before testing commenced all participants underwent a familiarisation session that included running on a treadmill at the relevant speed whilst wearing a nose clip and mouthpiece to simulate the collection of metabolic data for 15 minutes. Participants’ height and body mass were recorded. In order to avoid any potential diurnal effect, tests took place at the same time of day with the participants required to maintain a similar diet and training routine between and before tests. Dietary intake and training were recorded directly prior to the initial test and included all food and fluid consumed on that day. This data was subsequently sent to each participant in order for exact replication at post-tests.

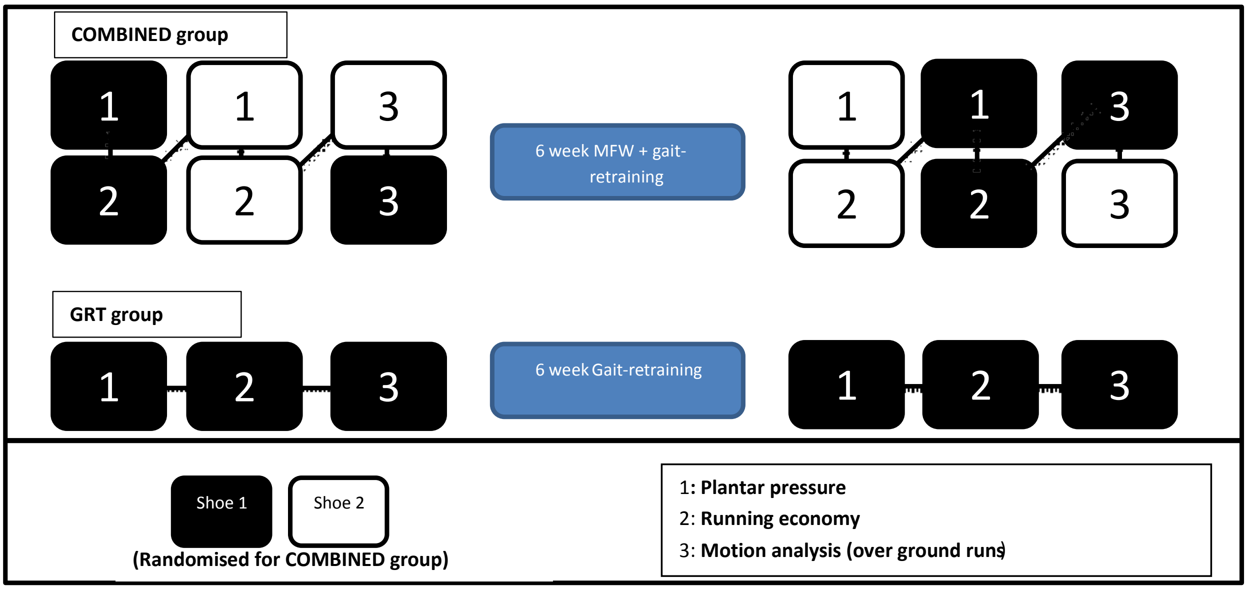


Figure 7.6.1. *Schematic represenation of the testing procedure, including the COMBINED and GRT group.*

For the plantar pressure tests in the COMBINED group, sensory insoles (Novel Pedar X, Munich, Germany) were placed inside either the MFW (Vivo Barefoot "Evo"®), or CRS before each test and calibrated to technical specification including ascertaining a zero unloaded value before insertion. Each insole contained 99 10mm force sensors, with data collected at 100Hz, and has previously shown a high degree of repeatability (Ramanathan et al, 2010). Familiarisation took place in Vibram "Five Finger" KSO® (Vibram®, Milan, Italy) footwear, because of its popularity and availability in the laboratory, however the sensory insoles would not fit in the individual toe design for data collection and so the Vivo Barefoot "Evo"® was sourced as the closest alternative, also being 3mm thick with zero "drop" and advertising no cushioning or foot control. This has been discussed in Study Three. The Pedar X unit was attached to the participant's waistline at the rear using a Velcro belt, and wires leading to the insoles were attached to participant's legs using a pliant Velcro strap that did not impede with normal running movement. Data was collected for 60 seconds at the 6th minute of running, allowing enough time above the four minutes that has been suggested to be required to optimise leg stiffness and running technique depending on surface and shoe hardness (Divert et al, 2005a). Given that endurance running involves repetitive impacts, a long sample period of 60 seconds was selected to more adequately represent average loading over a longer period of time. Stride frequency was calculated by the number of strides that occurred on the right foot during the 60 second duration using the recorded foot contact data. The insoles were removed for subsequent data collection.

Metabolic data was then sampled breath-by-breath using a Viasys Vmax Encore 299 online gas analysis system (Viasys Healthcare, Yorba Linda, California, USA). The system was calibrated according to the manufacturer guidelines, including atmospheric pressure and temperature, before each new test. For this system, accuracy has been reported at 0.02% for 02 measures, following a 15 minute warm-up period and calibrated within 5% of absolute operating range. Treadmill incline was set at 1% to account for air resistance (Jones and Poole, 2005).

7.6.2 Additional Data Processing

The RE values were determined from the mean $\dot{V}O_2$ ($ml \cdot kg \cdot min^{-1}$) data over the last 2 minutes of each stage when participants had reached steady-state. This was also confirmed with a blood lactate increase of less than 1mmol (Svedahl and MacIntosh, 2003), or a respiratory quotient of less than 1.0 (Brooks, Fahey and White, 1996). Pedar (Pedar X expert 20.1.35) analysis software was used for data processing, using right foot data (Hong et al, 2012) averaged over 60 seconds. Foot strike patterns were identified using the foot strike index (Altman and Davis, 2012b), where the plantar surface was divided into thirds (heel, midfoot, forefoot), and the foot strike pattern was identified by the location of the centre of pressure at its initial contact point when averaged over all steps. This was then allocated 1=forefoot strike; 2=midfoot strike; and 3=rearfoot strike. Stride frequency was determined using the foot contact data over 60 seconds from the plantar pressure software. The plantar surface was divided into 8 sections (Figure7.6.2) and pressure values were established within each. Regional pressure, mean maximum force ($\overline{\mathbf{MF}}$; total plantar surface), and mean maximum pressure ($\overline{\mathbf{MP}}$; total plantar surface) were calculated from within-step maxima averaged over the 60 seconds data collection period.

Figure 7.6.2. *Regional areas of the 8 insole masks. Heel, MMF (Medial Mid-Foot, LMF (Lateral Mid-Foot), M1 (Medial Forefoot), M2 (Central Forefoot), M3 (Lateral Forefoot, TOE (Toes), and Hallux. Adapted from Hong et al (2012).*

7.6.3 Additional Data Statistical Analysis

RE, $\overline{\textbf{MF}}$ and $\overline{\textbf{MP}}$ were analysed for the COMBINED group using two-way repeated measures ANOVA for within-subject effects and interactions (condition [MFW vs. CRS], and time [Pre vs. Post]. A three-way mixed repeated measures ANOVA was also conducted for regional pressure analysis (condition [MFW vs. CRS], time [Pre vs. Post], and region [1-8]). For the GRT group, the "condition" comparison was not included. Where main effects were determined, pairwise comparisons were reported utilising a Bonferroni correction to account for the extra comparisons, and accepted as $p \leq 0.05$ (SPSS adjusted p). Correlation analysis was established for ΔRE, ΔFz1 and Δ loading rate (Δ = change from pre to post-tests) and were correlated to the same change in the remaining variables in each specific shoe. This was determined using a Pearson Product-Moment Correlation for the intervention group [CRS and MFW], and the control group [CNT]. Where the data violated Mauchly's test of sphericity, the Huynh-Feldt correction was utilised. Statistical significance was accepted at $\alpha \leq 0.05$.

7.6.4 Additional Data Results and Discussion

The mean change and 95% confidence intervals are provided for the RE, $\overline{\textbf{\textit{MF}}}$ *, and* $\overline{\textbf{\textit{MP}}}$ variables in Table 7.6.4a for both the COMBINED and GRT group. In addition, it is worth noting that the interaction between Time and Condition for $\overline{\mathbf{MF}}$ in the COMBINED group approached significance (p=0.073) (Figure 7.6.4a). The mean change in lactate from baseline was 0.73mmol (±0.32) for all participants pooled.

Table 7.6.4a. *Mean change, 95% confidence intervals and effect sizes for running economy,* $\overline{\mathbf{MF}}$ *, and* $\overline{\mathbf{MP}}$ *in the COMBINED and GRT groups.*

COMBINED group (n=12)	**Analysis**	**Mean effect**	**95% confidence levels**		**P value**	**Effect size**
			Lower	**Upper**		**η^2**
RE ($ml \cdot kg \cdot min^{-1}$)	Time	0.597	-1.63	2.83	0.57	0.004
	Condition	-0.77	-1.47	-0.08	0.032*	0.007
$\overline{\mathbf{MF}}$ (N)	Time	-107.31	-206.24	-8.38	0.036*	0.076
	Condition	120.95	60.3	181.59	0.001*	0.103
$\overline{\mathbf{MP}}$ (kPa)	Time	-11.43	-62.77	39.91	0.63	0.006
	Condition	122.82	90.22	155.41	0.000*	0.442
GRT group (n=12)						**Cohen's d**
RE ($ml \cdot kg \cdot min^{-1}$)	Time	0.75	-1.7	3.21	0.51	0.04
$\overline{\mathbf{MF}}$ (N)	Time	21.03	-44.78	86.85	0.49	0.04
$\overline{\mathbf{MP}}$ (kPa)	Time	2.28	-29.39	33.95	0.88	0.002

Effect for Time, minus represents a reduction at post-tests. *$^{*}p \leq 0.05$*
Effect for condition, minus represents a lower value in MFW.

For the regional pressure analysis in the COMBINED group, the Time*Condition*Region interaction was found to approach significance (p = 0.082). A significant Condition*Region interaction was also observed (p ≤ 0.00). When examining these main effects, there was no effect of time (p = 0.79), but a significant effect for condition (p ≤ 0.00) and region (p ≤ 0.00) was observed. There was no significant change over time as a result of the intervention in the GRT group (p = 0.48).

Pairwise comparisons of the interaction in the COMBINED group between condition and region revealed significantly higher pressures in MFW in the metatarsals and heel at pre-tests, and in the metatarsals, hallux and lateral midfoot at post-tests. With respect to time, pressures at the heel were reduced in MFW and slightly increased in the hallux from pre-post tests. In addition, first metatarsal pressure was found to significantly drop in CRS from pre to post-tests (Figure 7.6.4b).

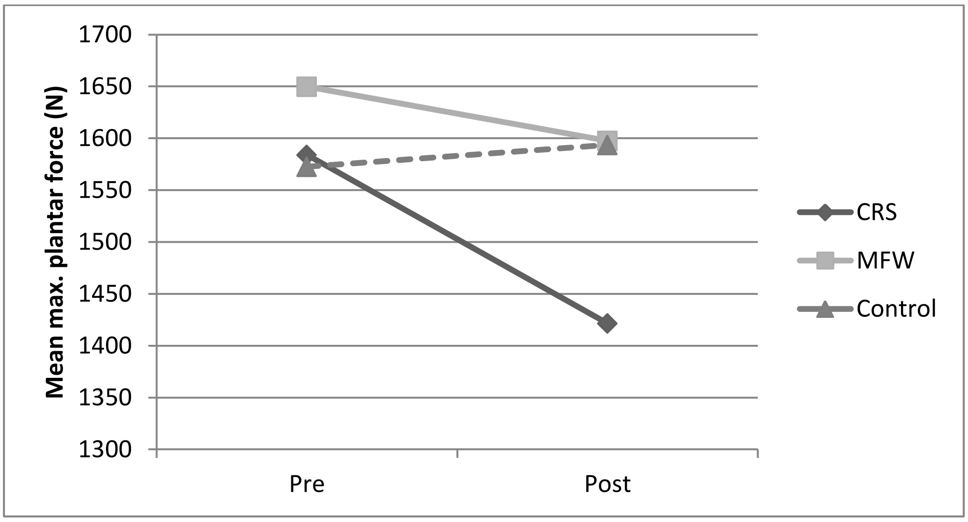


Figure 7.6.4a. $\overline{\textbf{\textit{MP}}}$ *changes from pre to post-tests in both the CRS and MFW condition in the COMBINED group, and in CRS in the GRT group. Note the greater reduction in force in CRS over time.*

The RE results are identical to the observed effects of Study Two where we noted no change in RE from pre to post-tests. However again we did note a significantly better RE in MFW compared to CRS irrespective of whether the participants were familiarised to MFW. With respect to $\overline{\textbf{MF}}$, again the results were identical to Study Three in which a significant reduction over time in both MFW and CRS, and a higher $\overline{\textbf{MF}}$ in MFW was observed. The GRT group did not reduce $\overline{\textbf{MF}}$ and this suggests that the gait-retraining was most likely not the cause of this reduced $\overline{\textbf{MF}}$ observed in the COMBINED group. This again relates back to impact attenuation tactics in MFW that appear to result in significantly reduced forces as a result of familiarisation (De Wit, De Clerq and Aerts, 2000). Finally, the $\overline{\textbf{MP}}$ and regional pressure values were again significantly higher in MFW and this may predispose these COMBINED athletes to metatarsal stress fractures, particularly during this transition period (Ridge et al, 2013).

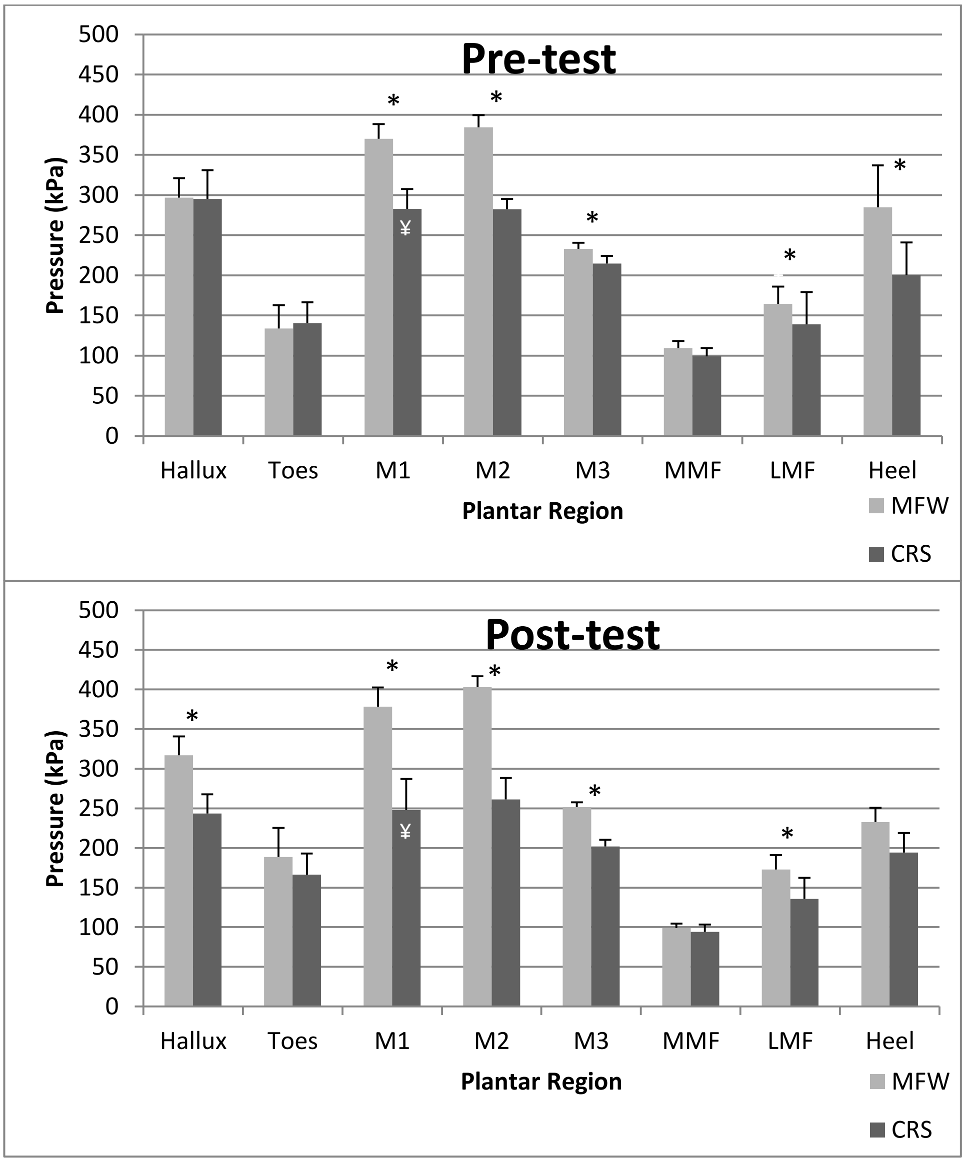


Figure 7.6.4b. *Pre and Post-test regional pressure differences for the COMBINED group between MFW and CRS (* = p ≤ 0.05), and changes specific to each condition as a result of the intervention (¥ = p ≤ 0.05). The abbreviations are explained in Figure 7.6.2 above.*

With regard to correlations between RE, Fz1 and loading rate with respect to any other kinematic or stiffness variables, there were no consistent correlations for any specific variable (Table 7.6.4b). There was a significant negative correlation between RE and Fz1 (r=-0.651, p=0.030), and loading rate and K_{vert} (r=-0.651, p=0.012) for the COMBINED group when in CRS. Likewise we observed a significant correlation between loading rate and θIC_{Knee} (r=0.629, p=0.038), and loading rate and θMS_{Ankle} (r=0.616, p=0.044) for the COMBINED group when in MFW. In the GRT group, there was a significant correlation between loading rate and K_{Knee} (r=-0.615, p=0.033), and loading rate and Fz1 (r=0.745, p=0.005).

Table 7.6.4b. *Pearson Product-Moment Correlation results with respect to change (from pre to post-tests) for the COMBINED group (CRS and MFW) and the GRT group (GRT).*

	RE	Fz1	loading rate
RE		CRS r: -0.651* MFW r: 0.481 GRT r: -0.094	CRS r: 0.435 MFW r: 0.401 GRT r: -0.222
Fz1	CRS r: -0.651* MFW r: 0.481 GRT r: -0.094		CRS r: 0.157 MFW r: 0.010 GRT r: 0.745*
loading rate	CRS r: 0.435 MFW r: 0.401 GRT r: -0.222	CRS r: 0.157 MFW r: 0.010 GRT r: 0.745*	
Contact time (s)	CRS r: -0.408 MFW r: 0.370 GRT r: 0.092	CRS r: -0.140 MFW r: 0.217 GRT r: -0.503	CRS r: -0.529 MFW r: 0.596 GRT r: -0.433
Vertical oscillation (cm)	CRS r: -0.027 MFW r: 0.229 GRT r: 0.407	CRS r: -0.363 MFW r: 0.060 GRT r: -0.096	CRS r: -0.433 MFW r: 0.075 GRT r: -0.346
Stride frequency (spm)	CRS r: -0.455 MFW r: -0.438 GRT r: 0.043	CRS r: 0.586 MFW r: -0.431 GRT r: -0.441	CRS r: 0.098 MFW r: -0.248 GRT r: -0.447
K_{Vert} (n·m)	CRS r: 0.399 MFW r: -0.037 GRT r: -0.366	CRS r: 0.218 MFW r: 0.196 GRT r: 0.204	CRS r: 0.753* MFW r: -0.151 GRT r: 0.333
K_{ankle} (n·m·deg^{-1})	CRS r: -0.469 MFW r: 0.125 GRT r: 0.298	CRS r: 0.376 MFW r: -0.069 GRT r: -0.154	CRS r: -0.279 MFW r: 0.175 GRT r: -0.075
K_{Knee} (n·m·deg^{-1})	CRS r: 0.456 MFW r: -0.073 GRT r: -0.202	CRS r: -0.325 MFW r: -0.028 GRT r: -0.488	CRS r: 0.035 MFW r: -0.592 GRT r: -0.615*
θIC_{Ankle} (deg)	CRS r: 0.592 MFW r: 0.324 GRT r: -0.160	CRS r: -0.271 MFW r: 0.331 GRT r: 0.127	CRS r: 0.314 MFW r: 0.202 GRT r: 0.127
θIC_{Knee} (deg)	CRS r: -0.335 MFW r: 0.176 GRT r: 0.385	CRS r: 0.038 MFW r: -0.210 GRT r: 0.226	CRS r: -0.142 MFW r: 0.629* GRT r: 0.372
θMS_{Ankle} (deg)	CRS r: 0.552 MFW r: 0.521 GRT r: -0.130	CRS r: -0.233 MFW r: -0.229 GRT r: 0.126	CRS r: 0.473 MFW r: 0.616* GRT r: 0.257
θMS_{Knee} (deg)	CRS r: -0.199 MFW r: -0.015 GRT r: 0.312	CRS r: 0.064 MFW r: -0.156 GRT r: -0.008	CRS r: -0.039 MFW r: 0.549 GRT r: 0.232

n=12, $^{*}p \leq .05$ significant correlation observed.

CHAPTER EIGHT

Global Discussion

8. Global Discussion

The relevant discussion for each study has been provided in each study section, and therefore this section will not revisit these considerations. The following discussion attempt to discuss the overall research findings by examining the themes common to each paper. In addition, a discussion on the familiarisation programme is included here. These "overall" findings will then be used to form major conclusions from our work.

8.1 Running Economy

The RE results are discussed below with regard to change over time (pre to post-tests), and difference between conditions (MFW vs. CRS).

8.1.1. Effect of the Intervention

Three studies were conducted to investigate changes in RE as the result of a MFW intervention, and two of these studies also included deliberate gait-retraining. The findings of the two different types of studies (natural vs. gait-retraining) are contrasting (Figure 8.1.1a). Study One (without gait-retraining) identified an 8% improvement in RE for the MFW condition over the four week intervention, which did not occur in the CRS condition. Study Two and Four however identified no significant change in RE as a result of the intervention which included deliberate gait-retraining elements, in either CRS or MFW.

There is a school of thought in the literature that adopting a "barefoot running style" may be a more economical running pattern due to changes in the foot strike pattern, leg geometry, leg stiffness and increased storage and recovery of elastic energy (Perl, Daoud and Lieberman, 2012; Asmussen and Bonde-Petersen, 1974; Divert et al, 2008; Hanson et al, 2011; Kyrolainen, Belli and Komi, 2001; Lieberman et al, 2010, Squadrone and Gallozzi, 2009). However, there is limited evidence to support this theory. For example, there is currently no strong evidence that adopting a forefoot strike pattern is more economical during running that a rearfoot strike pattern (Ardigo et al, 1995;

Perl, Daoud and Lieberman, 2012; Cunningham et al, 2010; Gruber et al, 2013a). We observed a significant improvement in RE following participant familiarisation to MFW over four weeks in Study One. No previous studies to the best of our knowledge have examined how RE changes during a familiarisation to a novel footwear type such as MFW, it therefore becomes difficult to compare or contrast results to studies using acute measures. There is however some evidence that running in MFW can result in better RE than CRS in habitual MFW or barefoot runners as a result of potentially better storage and recovery of elastic energy in the lower leg (Perl, Daoud and Lieberman, 2012), and this would support our novel results in Study One. This improvement in RE in Study One was found to be very likely and worthwhile as can be observed in Figure 8.1.1a below. This 8% change is far above any other positive RE change that has been recorded in the literature and so could be considered dubious. However, our *a posteriori* power analysis revealed high statistical power for this effect (effect for time - 97%; effect for condition - 68%), as well as a large effect size (effect for time - $\eta^2 = 0.12$; effect for condition - $\eta^2 = 0.07$), and so we are confident of the result. That being said, clearly further studies employing this specific intervention are merited.

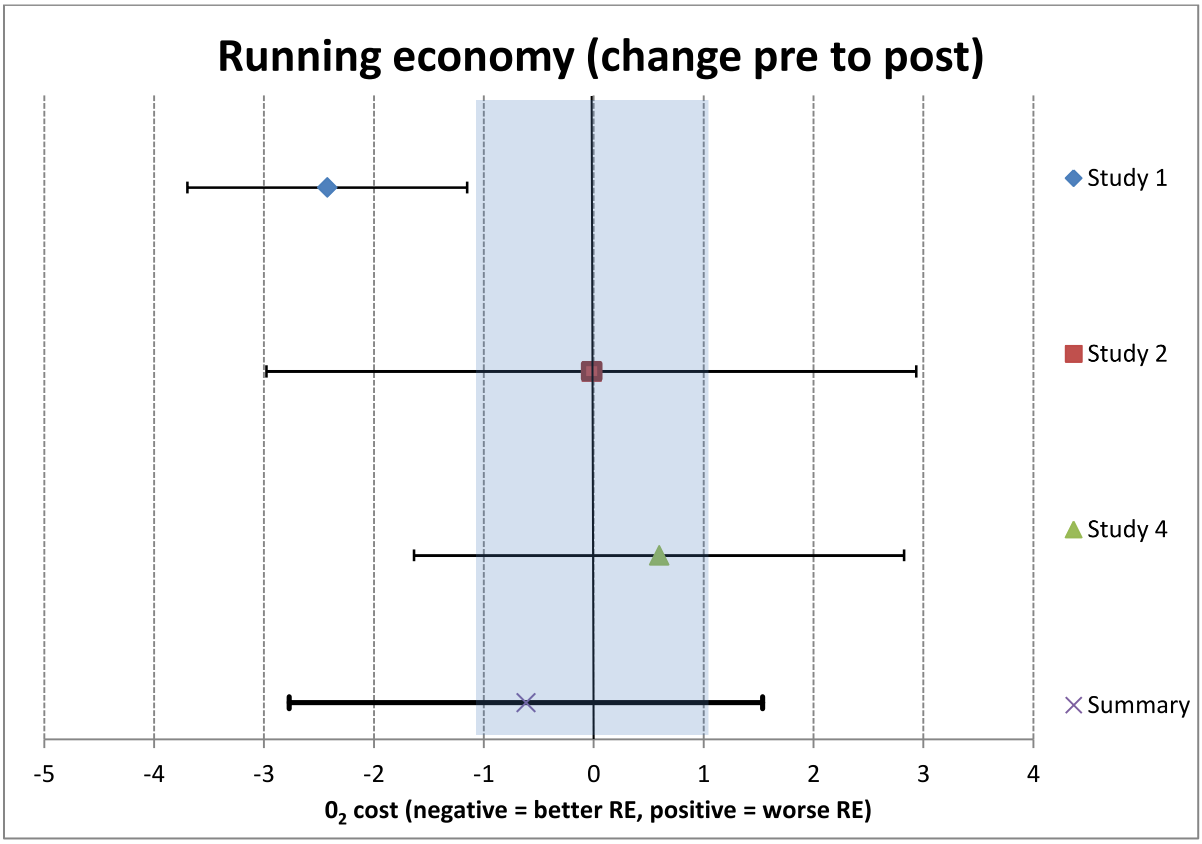


Figure 8.1.1a. *Mean effects and 95% confidence intervals for the change in RE over time with respect to the zero line and the smallest worthwhile change threshold (2.4% - Saunders et al, 2004), identified by the grey area. Also included is a summary plot, representing the average of the three studies.*

The second and fourth study also examined RE, but included deliberate gait-retraining elements (see section 3.1). Previous work examining the effect of gait-retraining on RE has either observed no change (Ardigo et al, 1995; Gruber et al, 2013a; Fletcher, Esau and MacIntosh, 2008; Messier and Cirillo, 1989; Hamill, Derrick and Holt, 1995), or a negative effect (Dallam et al, 2005; Cavanagh and Williams, 1982; Tseh, Caputo and Morgan, 2008). It has also been suggested that self-selected kinematics is the more economical choice for runners, and is optimised over time (Moore, Jones and Dixon, 2013). *"Encouraging runners to naturally self-optimise when running in minimalist footwear could actually be more beneficial for their performance than encouraging them to adopt a 'barefoot running form'"* (Moore, Jones and Dixon, 2013, pp 182). Therefore, it is perhaps not surprising that we observed no main effect for time with regard to RE in both of these studies. It is also possible that the familiarisation to MFW did enhance RE (Study One), but this effect was counteracted by a reduction in RE from the gait-retraining element. Indeed, runners who made deliberate changes to their running kinematics have been found to significantly reduce their RE (Tseh, Caputo and Morgan, 2008), and so we cannot rule out the possibility that these two factors (MFW and gait-retraining) did not interact. We have evidence that a MFW intervention improves RE (Study One), and also that a gait-retraining intervention does not improve RE (Study Four – control group), and so the possibility that one "ruled out" the other is not unjustified.

It is also possible that differences in RE changes between the studies are related to the participant groups. In Study One, we examined a very highly trained, younger group than in the subsequent studies. Both Study Two and Study Four examined lesser trained, club level athletes who were also much older that the first group in Study One (mean age 24 ± 4, 43 ± 10, 35 ± 8, in studies One, Two and Four respectively). In this respect, it appears that the younger and more highly trained participants, in Study One, responded in a more positive fashion than the other groups. Our understanding of neuromuscular control with respect to training is still in its infancy (Bonacci et al, 2009), but it is plausible to suggest that the Study One participants may have been more susceptible to adaptations in this system. In addition, one may also suggest that the lower in-step variability in motor patterns displayed in better trained athletes could result in a more positive adaptation since this group will experience the same motor pattern more regularly than the more variable novice groups (Chapman et al, 2008a; Chapman et al, 2008b). However this does require further experimental research in order to gain a better understanding of this phenomenon.

A large inter-individual variation was observed among participants in the response to changes in RE, particularly in study 2 and 4. This can be in Figure 8.1.1b. With this in mind, it appears that there was a large individual response with some participants having a very positive response to the transition, whilst others were very negative. The understanding of how and why this is the case is unclear. Nigg and Enders (2013) noted that there was large variability when participants ran barefoot for the first time, as opposed to their habitual footwear, and so the individual responses to the increased sensory feedback when in MFW could be significantly influential. Whilst the changes could be associated with specific kinematic differences in the participants, the relationship between biomechanics and RE is equivocal, with no strong evidence that any factor can result in improved RE (e.g. Cavanagh and Williams, 1982; Gruber et al, 2013a). Therefore, we cannot associate any changes in RE to any particular kinematic factor.

Therefore, it appears that a MFW transition with no feedback or retraining of the gait pattern can have a meaningful and likely positive effect on RE. However, when gait-retraining which includes adopting a non-rearfoot strike pattern and increased stride frequency is included, there is no benefit with regard to RE.

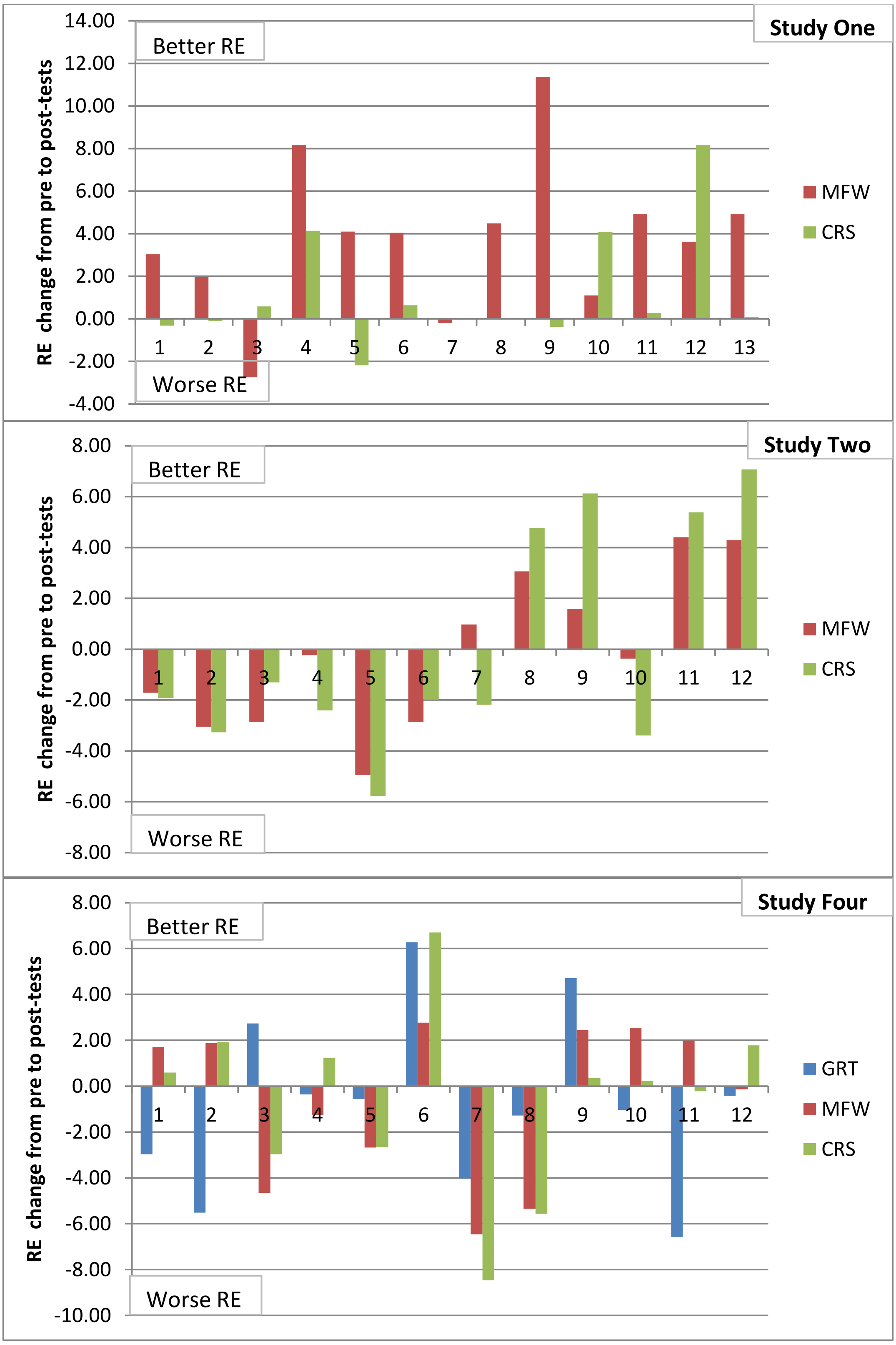


Figure 8.1.1b. *Individual variation with respect to the change in RE as a result of the intervention in Study One, Two and Four.*

8.1.2 Effect of Footwear Condition

Three of the current studies investigated the difference in RE between MFW and CRS (Study One, Two and Four), the results and mean summary can be observed in Figure 8.1.2. From this summary, we can conclude that it is somewhat likely that we will observe a worthwhile improvement in RE when running in MFW.

As discussed previously, there has been a documented "mass effect" in footwear, in which a 1% reduction in RE has been observed for every 100g of added shoe mass (e.g. Divert et al, 2008; Franz, Wierzbinski and Kram, 2012; Saunders et al, 2004). In all of our studies, the difference in mass between the MFW and CRS was approximately 250g. Therefore, when looking at Figure 8.1.2, the predicted threshold for a mass effect has been emphasised with a dashed line (2.5%). In this case, it appears as though we can attribute the consistent trend of better RE in the MFW condition mostly to shoe mass differences. In Study Four, we used correlation analysis to examine relationships between kinematic variables and the RE differences between MFW and CRS. Most notably, a lower vertical oscillation and contact time were observed in MFW vs. CRS. These factors have been previously associated with improved RE (e.g. Moore, Jones and Dixon, 2013; Kyrolainen, Belli and Komi, 2001), and indeed we noted a better RE in the MFW condition compared to CRS. However this difference is most likely to be due to the mass difference of these shoes, because during additional data exploration, we observed no consistent correlations between RE and vertical oscillation or contact time (see section 7.6.4). These results suggest that, at least in Study Four, kinematic differences between MFW and CRS are not determining factors for RE, and this supports our observation that the effect is mostly due to shoe mass.

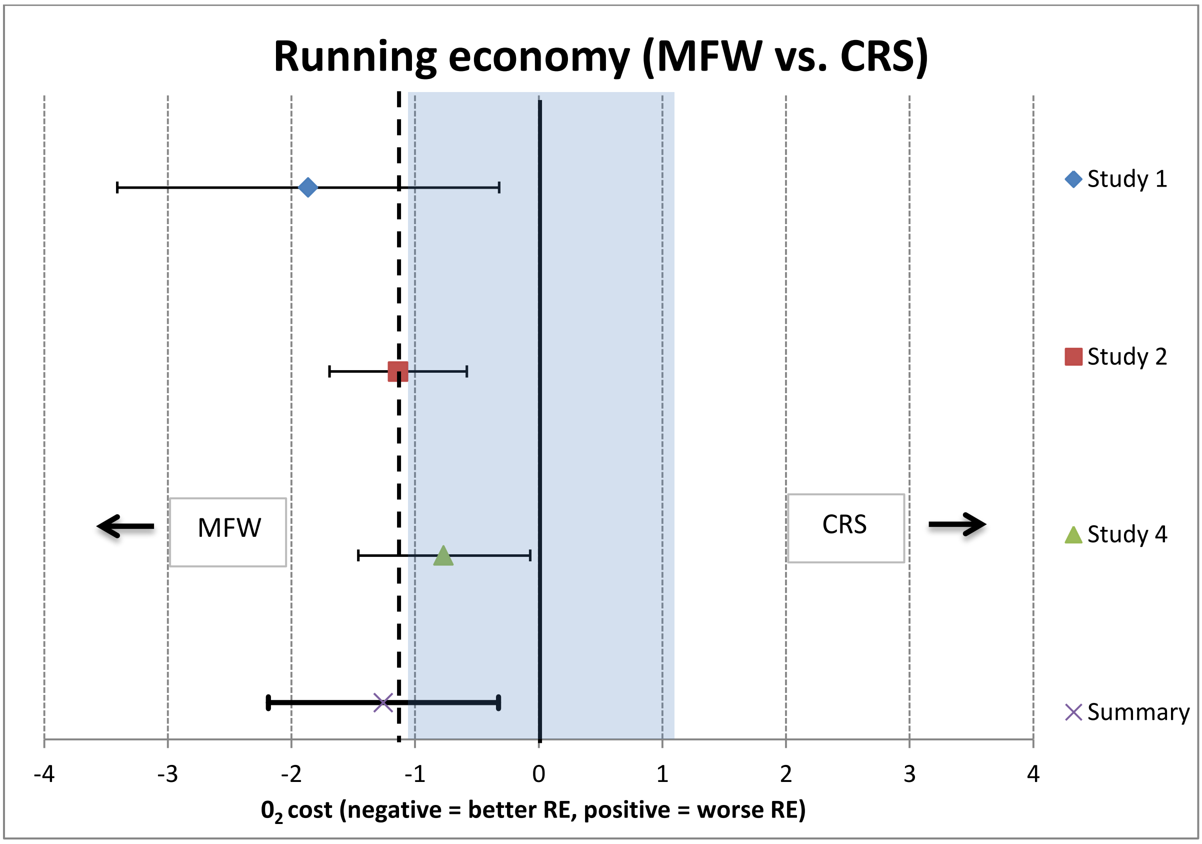


Figure 8.1.2. *Mean effects and 95% confidence intervals for the difference in RE between MFW (left) and CRS (right) with respect to the zero line and the smallest worthwhile change threshold (2.4% - Saunders et al, 2004a), identified by the grey area. The dashed line represents the predicted threshold (2.5%) for any mass effect associated with CRS. Also included is a summary plot, representing the average of the three studies.*

In Study One however; we observed a much higher difference in RE between MFW and CRS at post-tests (6.9% better in MFW). This result suggests that these participants did not only benefit from a mass effect but also other factors that could improve RE in this condition following familiarisation. Perl, Daoud and Lieberman (2012) noted a better RE in MFW when compared to CRS even when mass was controlled for in habituated barefoot and MFW runners. The authors proposed that improved energy storage and recoil in the longitudinal arch of the foot during MFW running may be very similar to barefoot, since shoe longitudinal bending stiffness is much higher in CRS than in MFW (the same MFW as the present work was used). The authors also indirectly noted a higher knee stiffness in the MFW condition when compared to CRS (a lower knee excursion in the MFW condition) (Perl, Daoud and Lieberman, 2012), and a greater overall stiffness is related to improved RE as discussed above (Butler, Crowell and Davis, 2003). Therefore, there may be other factors such as elastic energy potential (Perl, Daoud and Lieberman, 2012) and changes in neuromuscular control of running (Bonacci et al, 2009) in MFW that could benefit habituated MFW runners. Due to the limited current research available, this requires further investigation.

To put this change in RE into perspective, Saunders et al (2004a) have suggested that anything above a 2.4% change in RE is a worthwhile improvement in performance. Likewise Di Prampero et al (1993) concluded that a 5% improvement in RE elicited a 3.8% increase in run performance, suggesting that even changes due to shoe mass are worthwhile. Our studies suggest that there is a meaningful and somewhat likely change in RE when wearing MFW, irrespective of whether the participants are familiarised to this footwear or not. We also identified a large potential improvement in RE in MFW when participants were allowed to self-select their own running kinematics throughout the intervention (Study One). This positive change may improve run performance, although run performance was not directly measured in the present work.

8.2 Plantar Pressures and Plantar Forces

In Studies Three and Four plantar pressures and plantar forces were examined. Plantar pressure measurements have become an increasing popular source of data analysis for foot biomechanics and pathologies (Giacomozzi, 2011). This measure can provide detailed regional loading properties of the foot, and also will influence movement of the entire lower extremity (Rosenbaum and Becker, 1997; Orlin and McPoil, 2000). High localised plantar pressures have been associated with stress fractures (Hennig and Milani, 1995; Davis, Milner and Hamill, 2004), and this injury has been reported during a transition to MFW (Giuliani et al, 2011; Nunns, Stiles and Dixon, 2012). Therefore, we examined changes in plantar pressures in both CRS and MFW before and after a MFW and gait-retraining intervention in order to examine if this increase in reported injuries is justified. It is important to note that the regional pressure analysis was slightly different for Study Three and Four. Our plantar pressure software only allows for 8 plantar regions during a single analysis, and following completion of Study Three we made the decision to represent the heel as one region (as opposed to lateral and medial heel – see Figure 6.2.4), and to divide the [TOE] region into [Hallux and Toe] for Study Four (Figure 7.6.2).

In both of these studies, we observed significantly higher mean maximal pressure ($\overline{\mathbf{MP}}$) in MFW compared to CRS (Study Three, 47.5% higher; Study Four, 36.9% higher). This increased pressure in MFW has been previously observed (Squadrone and Gallozzi, 2009; Wiegerinck et al, 2009), and also identified as a risk factor for metatarsal stress fractures (Giuliani et al, 2011; Ridge et al, 2013). These peak pressures remained higher in MFW irrespective of the intervention, and therefore may present increased risk of foot injury in runners who have not adapted to this added plantar stress.

With regard to regional plantar pressure changes as a result of the MFW and gait-retraining intervention, we did not observe any significant changes to pressure distribution in Study Four. In contrast significant changes over time were observed in Study Three, where a significant reduction in pressure was observed in the heel and midfoot regions in both MFW and CRS from pre to post-tests. Both of these studies employed gait-retraining guidelines and familiarisation to MFW in a similar fashion and so it is unclear why the results differed between studies. Of further interest, when examining the foot strike patterns of the participant groups in Study Four, we observed as many midfoot strike patterns as forefoot strike patterns post the intervention, in contrast to paper three in which there was a strong tendency to forefoot strike with no midfoot strike patterns present. This higher prevalence of midfoot strike patterns (with the foot landing both with the heel and forefoot simultaneously) in paper four would have reduced the likelihood of reducing heel pressures in this study and indeed this seems to be the case. A forefoot strike pattern will increase foot plantar flexion at initial contact, with less direct contact at the heel as a result. These findings can again be related to impact attenuation tactics, where participants in previous studies have been noted to actively move away from heel contact whilst barefoot or in MFW in order to reduce localised pressure under the bony heel of the foot (DeWit et al, 2000; Divert et al, 2005a; Lieberman et al, 2010; Robbins, Gouw and Hanna, 1989; Squadrone and Gallozzi, 2009).

In addition, it is worth noting that we did not observe significantly higher forefoot pressures post the intervention in either study, despite the increased tendency to non-rearfoot strike pattern in both papers. This is an interesting finding, because even though the MFW in itself can increase plantar pressures (see next paragraph), the intervention and subsequent adoption of a non-rearfoot strike pattern does not appear to increase the risk of bony injury to the anterior foot portion. Controlling the foot striking pattern would have been an interesting means of examining this effect further, but this was not in line with the present research aims. Finally, the control group in Study Four that underwent a gait-retraining programme with no MFW exposure was not found to change regional pressures as a result of the intervention. Given that an interaction between Time*Condition*Region approached significance in the intervention group in this study, the lack of change in the control group somewhat supports the theory that any change in regional pressure is to reduce localised pressures at the heel in MFW or barefoot and not because of gait related changes (De Wit, De Clerq and Aerts, 2000). In other words, this was a footwear effect. Again it would be expected that instruction to adopt a non-rearfoot strike pattern would significantly change plantar pressure distribution, but again the participants were found to predominantly use a midfoot strike pattern at post-tests and this may not redistribute plantar pressures enough to observe a significant effect when compared to a high prevalence of forefoot striking, such as in the intervention participants in Study Three.

With respect to the difference in regional plantar pressures between MFW and CRS, higher plantar pressures were observed throughout testing in the metatarsal region in both studies. In addition, for both Study Three and Four, heel and lateral midfoot pressures were significantly higher in MFW vs. CRS at pre-tests, but not at post-tests. This has been observed elsewhere, in which a minimal shoe displayed increased peak pressure and a smaller contact area of the foot when compared with CRS because of a reduction in cushioning properties (Wiegerinck et al, 2009), and may increase the likelihood of stress fractures when running in MFW or barefoot (Guiliani et al, 2011; Ridge et al, 2013).

Finally, with regard to the mean maximal force ($\overline{\mathbf{MF}}$), Study Three and four were consistent in that $\overline{\mathbf{MF}}$ was found to be significantly reduced as a result of the intervention, and also significantly lower in CRS vs. MFW (Figure 8.2). When compared to the control group who only underwent a gait-retraining programme (with no MFW exposure) in Study Four, it again becomes apparent that the reduction in $\overline{\mathbf{MF}}$ may largely be due to the MFW intervention. This is because the control group was not found to reduce $\overline{\mathbf{MF}}$, in combination with the lack of regional change for pressure outlined above, when compared to the groups who experienced the MFW transition. Despite $\overline{\mathbf{MF}}$ being higher in MFW, the reduction as a result of the intervention reduced the post MFW values to a lower (Study Three) or similar (Study Four) value as the pre CRS value, and therefore may be a feasible method for reducing forces acting on the foot overall. That being said, the relationship between plantar forces and injury has not been specifically examined to the best of our knowledge, in contrast to the relationship between plantar pressures and injury (e.g. Hennig and Milani, 1995).

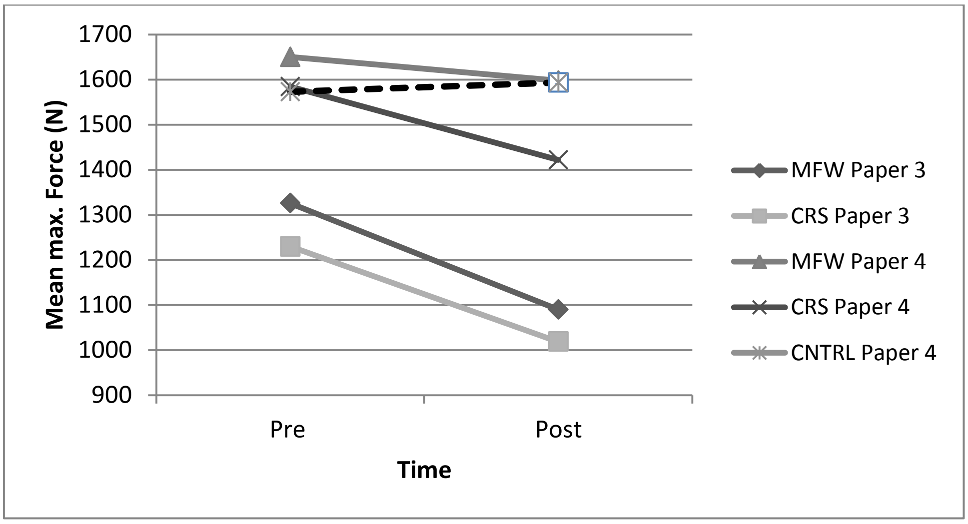


Figure 8.2. *Mean maximal Force ($\overline{\mathbf{MF}}$) comparison for Study Three and Four, from pre to post-tests, in both CRS and MFW. Also included is the control group from Study Four who only underwent a gait-retraining programme with no MFW exposure (dashed line).*

Overall, we observed significantly higher regional pressures and $\overline{\mathbf{MP}}$ in MFW compared to CRS. These pressures were not found to reduce in MFW if participants were familiarised to some degree to this novel condition. In fact, $\overline{\mathbf{MP}}$ was found to increase in MFW over time in Study Three. This observation, combined with higher regional pressures in the MFW condition particularly in the forefoot, may predispose these runners to injury risk. $\overline{\mathbf{MF}}$ was also found to be higher in MFW, but was found to significantly decrease as a result of a MFW and gait-retraining intervention in contrast to the control group with just a gait-retraining intervention that did not reduce $\overline{\mathbf{MF}}$. Therefore the use of MFW may be a primary reason for this observed reduction in $\overline{\mathbf{MF}}$.

8.3 Kinematics

All four of the current studies examined stride frequency and the distribution of foot strike patterns. In addition, Study Four measured kinematic data in both the intervention and control group using 3D movement analysis.

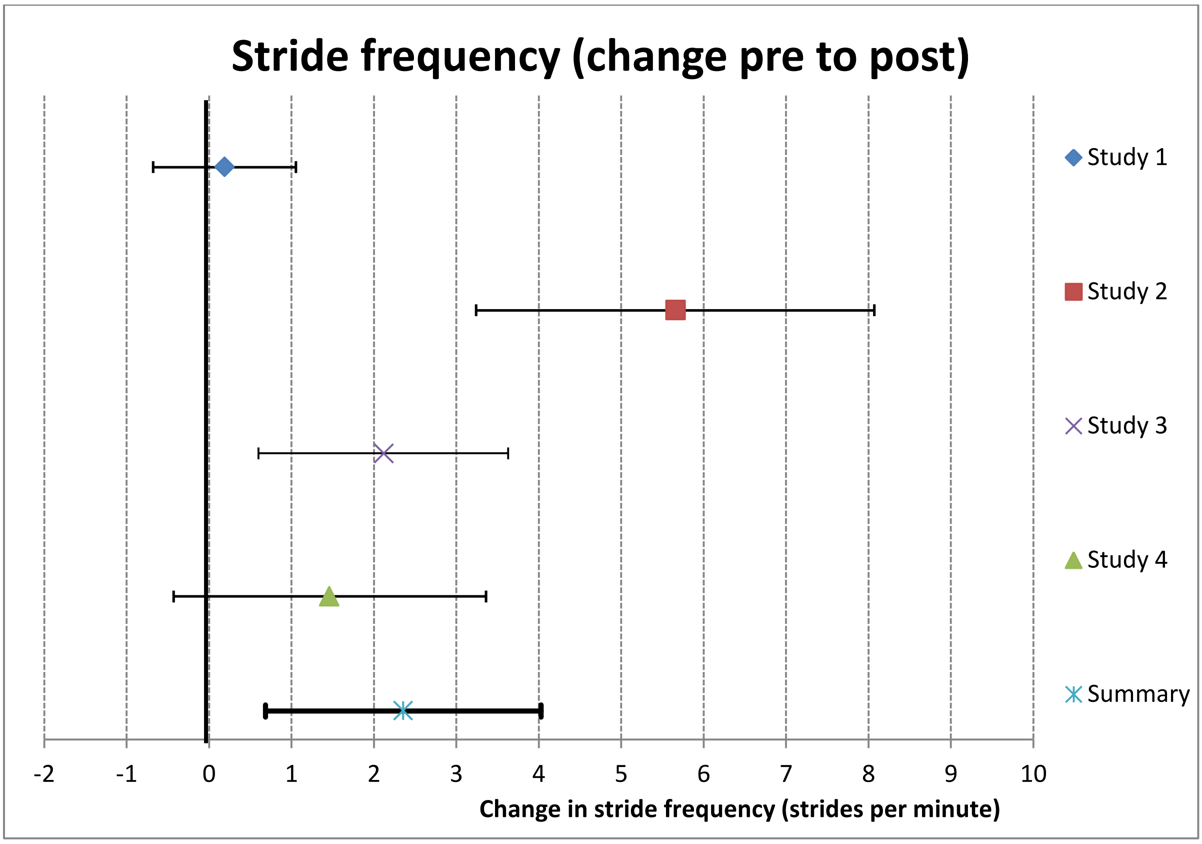


Figure 8.3a. *Mean effects and 95% confidence intervals for the change in stride frequency over time with respect to the zero line. Also included is a summary plot, representing the average of the four studies.*

A forest plot has been adopted for the comparison of stride frequency between each of the four studies, with respect to 1) change associated with the intervention (Figure 8.3a), and 2) difference between MFW and CRS (Figure 8.3b). With respect to the effect of the intervention on stride frequency changes, it is apparent that the addition of gait-retraining (and participants being told to increase stride frequency) has resulted in a more pronounced increase in this kinematic factor (Study Two, Three, and Four). This is in comparison to Study One, which only examined self-selected changes to stride frequency with a MFW transition period and found no change in stride frequency from pre to post-tests. Therefore, we suggest that the inclusion of gait-retraining to a MFW intervention can increase stride frequency between 1 and 4 strides per minute, and this is a very likely effect. In addition, we found a consistent increase in stride frequency when participants ran in MFW vs. CRS in all of our studies (Figure 8.3b; mean change 2-4 strides per minute), and this was also very likely to occur. A combination of gait-retraining and using MFW instead of CRS can therefore be a feasible option for increasing stride frequency. However, our own pilot data have suggested that this kinematic factor is not associated with improved economy (see section 5.6.1). In addition, stride frequency changes of less than +10% have not been found to have any benefit to reducing loading variables (Hamill, Derrick and Holt, 1995). It has been suggested that increasing stride frequency will increase the number of loading cycles per unit time (Hall et al, 2013), however this theory was tested in Edwards et al (2009) where it was observed the increase in stride frequency of 10% (and subsequent reduction in loading variables) was more injury protective than the risk of taking more steps per minute. Nevertheless, our data suggests that both a MFW and gait-retraining intervention, as well as simply adopting the use of MFW instead of CRS, can only increase stride frequency in the region of 1-4%. It is therefore doubtful as to whether this small change in stride frequency, however likely, will have any benefit to the aspiring distance runner.

Our research focused on stride / step frequency throughout this thesis, but it may be important in future studies to examine the relationship between stride length and stride frequency. Whilst this is difficult when using absolute velocities, the effect of stride length on running performance without velocity controlled (as a result of potential changes in footwear) presents an unexplored area for future researchers.

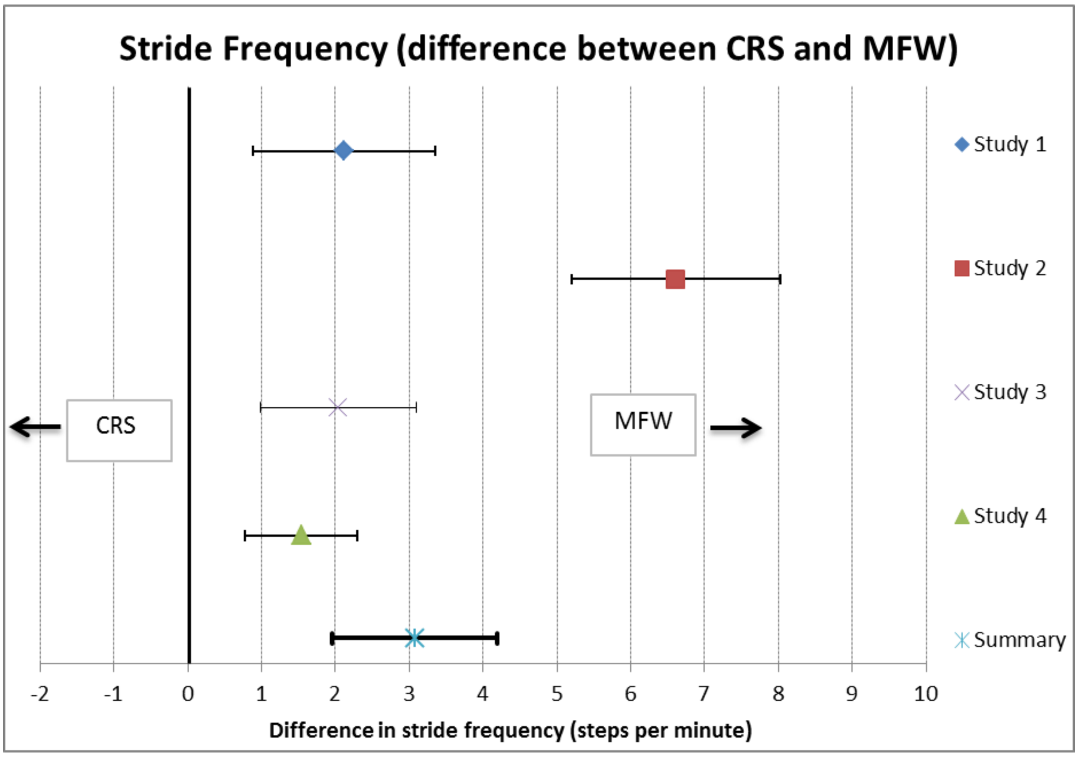


Figure 8.3b. *Mean effects and 95% confidence intervals for the difference in stride frequency between MFW (right) and CRS (left) with respect to the zero line. A positive value indicates a higher stride frequency in MFW and vice versa. Also included is a summary plot, representing the average of the four studies.*

Finally, we have reported the frequencies of the three common foot strike patterns (forefoot, midfoot, and rearfoot) in MFW and CRS, and the change as a result of the intervention (Figure 8.3c). It was apparent that participants were more likely to adopt a non-rearfoot strike pattern when in MFW vs. CRS irrespective of the intervention. However, some participants continued to rearfoot strike pattern in MFW. The intervention period in MFW (with gait-retraining in all but Study One) did further reduce the amount of rearfoot strikes in both MFW and CRS, but some participants in MFW, and the majority of participants in CRS retained their initial rearfoot strike pattern. This was the case even in the participants who were given specific instruction to adopt a non rearfoot strike pattern. Whilst there is no strong evidence that any foot strike type is more economical (see section 2.2.2), the participants who continued to rearfoot strike in MFW may be at increased risk of injury due to higher loading rate in this footwear type with no cushioning properties (e.g. Lieberman et al, 2010; De Wit, De Clerq and Aerts, 2000). However, higher joint forces and eccentric loads during a forefoot strike pattern may also predispose a running to triceps surae injuries (Kirby and McDermott, 1983; Almonroeder, Willson and Kernozek, 2013; Kulmala et al, 2013).

If sensory feedback via the plantar surface of the foot is indicative of impact attenuation tactics and changes in leg geometry, then it appears that for some participants the 3mm hard outsole is "thin" enough to allow this feedback, but for other participants, it is not. Understanding how and why some participants adopt significant changes in a MFW compared to others requires future research. It could simply be however that this pattern is a learned effect engrained in the neuromuscular system over years of running activity (Sinnatamby, 2011).

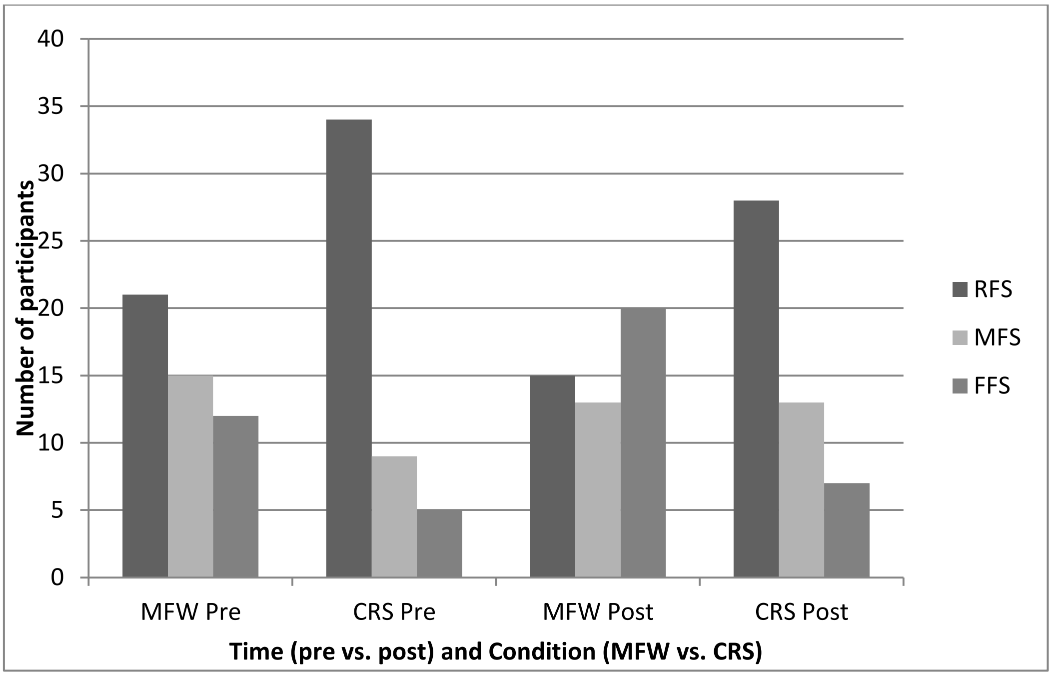


Figure 8.3c. *The number of participants adopting a foot strike pattern with respect to rearfoot (RFS), midfoot (MFS), and forefoot (FFS) at both pre and post tests, in the MFW and CRS condition using the pooled data from all four studies*.

This concept of how and why runners respond to reduced cushioning has been noted in the literature previously; "*an as yet unexplored area of barefoot [and MFW] running theory is the process by which biomechanical adaptations occur and whether these are universally learnt. This is crucial both clinically and practically, because some individuals may be incapable of achieving the potentially favourable biomechanical changes. These individuals may be exposed to increased risk of injury according to the previously described factors, particularly early on, and fully understanding the process* *by which the barefoot condition [or MFW] changes biomechanics is crucial to the clinical and performance management of an athlete*." (Tam et al, 2013, pp 4). Whilst we have noted the importance of inducing a non-rearfoot strike pattern for reduced loading rate, it is also important to note that changing one's running kinematics will also redistribute the load on the internal joint structures (Nigg, 2010). For example, a forefoot strike pattern has been found to reduce knee loads, but increase the work at the ankle (Kirby and McDermott, 1983; Almonroeder, Willson and Kernozek, 2013; Kulmala et al, 2013), and may increase the risk of triceps surae injuries particularly in novice forefoot strike pattern runners (Williams et al, 2012). This was not examined in the present work, but should be taken into account when considering the foot strike pattern and injury risk in runners.

8.4. The Familiarisation Programme and Injury

As part of this research project, we designed a simple familiarisation programme and injury prevention exercises based on recommendations in the literature (section 3.1). The design of the transition programme had three considerations; 1) To ensure adequate exposure to the MFW condition, 2) to allow adequate time for participants to adopt the gait-retraining changes, and 3) to reduce the risk of injury as much as possible. One method of gauging the success of our familiarisation programme is to discuss the injuries experienced during this period;

Injuries during the transition to MFW have been suggested to be extremely high (Daumer et al, 2014 – 33.27 injuries per 10,000km during a transition compared to 12.77 in habitual CRS runners and 5.63 in habitual MFW or barefoot runners), although many runners have been found to transition over just two weeks (Rothschild 2012a) and this will dramatically increase the risk of injury. Ryan et al (2013) observed 7 injuries in 35 MFW runners during a 12 week transition, and about 50% of these occurred in the first 6 weeks (within the time frame of our study). Likewise, during a ten week transition to VFF's, Ridge et al (2013) observed metatarsal stress fractures in 2 out of 19 participants (10.5%) following the transition, with 11 of these participants displaying dangerous bone edema. Thus, we expected to see a reasonable amount of issues arise in the present work when running in this ultra-minimal MFW, particularly when using only habitual CRS runners. The injuries experienced in the present work have been summarised in Table 8.4. Throughout all four studies, using a total of 52 intervention participants, only 5.8% of our participants were injured. This is below the incidence injuries reported elsewhere during the 12 week full-minimalist transition (20%; Ryan et al, 2013), and the VFF transition (10.5%; Ridge et al, 2013). Therefore, it might be reasonable to suggest that a gradual transition programme such as that outlined in the present work, with included injury prevention exercises, presents a feasible and reasonably safe schedule for any runners who wish to begin training in MFW. That being said, our research does not provide any data regarding how long term use of a specific footwear type can influence running related injuries.

One limitation to our investigation of injuries during this transition was that data regarding the participant's weekly training volume was only collected at post-tests. Therefore we cannot determine if this factor was related to the risk of injury. As mentioned in section 3.1, participants with a lower weekly training volume will spend more of their training time in MFW and this may increase the risk of injury. Future research should examine if relative exposure to MFW presents an increased risk of injury during this transition.

Table 8.4. *Injuries experienced in studies involved in this research project in the intervention (INT), and control (CNT) groups where applicable. Soreness is classified as a pain not resulting in injury or dropout in the study. * Three cases of triceps surae soreness were severe enough to result in several missed days of training (1-3 days).*

Study	Injuries INT	Injuries CNT	Soreness
Study One	0/15	N/A	4/15 (INT)
Study Two	1/13 (Metatarsal stress fracture)	0/8	7/13 (INT)
Study Three	0/10	N/A	0/10 (INT)
Study Four	2/14 (Hamstring tear, gastrocnemius tear)	0/14	7/14* INT; 3/12 CNT

Aside from injuries resulting in dropout or several missed training days, several authors have reported significant delayed onset muscle soreness in the triceps surae during the initial period in MFW or when adopting a non-rearfoot strike pattern (100% of participants asked to adopt a non-rearfoot strike pattern -Williams et al, 2000; 40% - Crowell and Davis, 2011; "*significantly more in MFW group*" - Ryan et al, 2013; *"the majority" of 17 participants*" - Willson et al, 2014). This was also observed during the present work, where 35% of participants reported soreness and tightness. In addition, for three of these participants in Study Four the discomfort was high enough to cause several missed days of training. These participants did not drop out of the study, and were able to continue the intervention following 2-3 reduced or no-training days. All participants reported that after several weeks the discomfort was absent or significantly diminished. We therefore suggest that whilst there may be some triceps surae discomfort associated with this MFW transition programme, it appears that the structure adopted here including the injury prevention exercises, gait-retraining and progression of MFW exposure has resulted in fewer injuries than experienced in other, less structures transitions. However, we do not provide any data on injuries experienced in different footwear types outside of this transition period.

8.5 Inter-Participant Variability

There are several small but important additional considerations that have been highlighted during this research project. Firstly, it is not uncommon to observe large inter-individual variation with biomechanical variables and footwear (De Wit and De Clerq, 2000; Divert et al, 2005b; Tam et al, 2013), particularly when asking shod athletes to run barefoot or in MFW, due to differences in proprioceptive feedback and neuromuscular control (Lieberman, 2012; Kurz and Stergiou, 2003). This large inter-individual variation has also been observed with regard to RE, and has been suggested to be due to physiological, biomechanical, environmental, anthropometrical or psychological factors, and is thus poorly understood (Nummela, Keranen and Mikkelsson, 2007; Kyrolainen, Belli and Komi, 2001). This was very much apparent in the present work, where large inter-individual responses to MFW was observed with regard to RE, factors associated with injury (loading rate, Fz1, stiffness), and kinematics. How and why some runners appear to "respond" to changes in footwear in either an acute or chronic sense remains to be fully understood. Why some runners show immediate "instinctive" adaptations to changes in surface or footwear conditions and others did not, is an interesting area of future research. An interesting concept is that of “multiple intelligences”, in which some people display higher levels of body-kinaesthetic intelligence, whilst others are stronger in other areas, which may explain the “non-responders” to significant changes in footwear condition (Gardner, 1999). There is also conflicting reports on what priority runners place on economy versus impact attenuation. Some authors suggest that runners “self-optimise” for optimal running economy (Nigg and Enders, 2013; Moore, Jones and Dixon, 2013), others have suggested that kinematic changes are primarily for the reduction of impacts or loads on the lower extremities (Hamill, Derrick and Holt, 1995; De Wit, De Clerq and Aerts, 2000). There are possibly numerous combinations of factors that determine individual responses to changes in footwear or surface hardness, and future research should examine this in more detail in order to improve our current prescription of footwear for runners.

CHAPTER NINE

Conclusions and Future Recommendations

9. Conclusions and Future Recommendations

9.1 Conclusions

The aim of this research project was to investigate any change in RE or factors related to injury before and after a MFW transition with gait-retraining, and also to determine differences in these factors between both CRS and MFW.

We identified a significant 8.1% improvement in RE in the MFW condition during a four week transition period when participants were allowed to naturally self-select running kinematics. However, when participants were asked to include conscious gait-retraining changes to the transition over both 6 and 8 weeks, no change in RE was observed. Therefore is appears that any potential improvement in RE with a MFW transition is counteracted by deliberate gait-retraining than has been found to be detrimental to movement economy, and should not be included if improved RE is the goal for runners.

In addition, we found that when comparing the difference in RE between MFW and CRS irrespective of whether participants were familiarised or not, there was a significant and very likely improvement in RE in the MFW condition. This is most likely due to mass differences in this footwear type. Again, following a transition to MFW with no deliberate gait retraining, MFW RE was found to be 6.9% better than CRS RE. This however cannot be solely attributed to a mass effect, suggesting that other potential factors such as the storage and recovery of elastic energy, associated with an increased preponderance of a forefoot striking pattern when in the MFW condition, may be improved. We therefore suggest that running in the lighter MFW compared to CRS can be beneficial for performance when no forced gait changes are included.

The research project also examined factors associated with injury. These included plantar pressures, impact related variables, and lower body stiffness measures. We observed significantly higher plantar pressures in MFW compared to CRS throughout testing, and whilst there were reduced heel pressures in MFW as a result of the intervention, higher localised pressures in the forefoot in MFW may increase the risk of bone injury in this region. However, plantar forces and the Fz1 were found to be reduced as a result of the MFW and gait-retraining intervention, and this may be positive for the reduction of long term impact related injuries. The vertical loading rate has perhaps the strongest link to running related injury in the literature, and loading rate was also reduced as a result of the intervention. However loading rate was observed to be significantly higher in MFW compared to CRS throughout testing, thereby possibly increasing the risk of injury during this transition period. Nevertheless, it is important to note that the post-test loading rate values in MFW were found to be no different than the pre-test CRS loading rate, suggesting that this intervention is effective at reducing loading rate to "normal" levels if running in MFW is required for other reasons.

One method that was found to be successful at reducing loading rate was gait-retraining in CRS, since this applies the "barefoot inspired" movement patterns in particular a non-rearfoot strike pattern, but with the cushioning of modern conventional shoes that will reduce localised forces and high rates of loading on the foot. However, this use of gait-retraining in CRS did not have any effect on reducing Fz1 or peak plantar forces, or improving RE, and so how best to minimise the risk of injury when also improving performance remains to be determined.

We measured several kinematic changes associated with a MFW transition or when comparing differences between MFW and CRS. Whilst there were significant increases in stride frequency and vertical stiffness (K_{vert}), and lower vertical oscillation and contact time associated with MFW use, none of these variables have been associated with either RE or impact related factors in our work during correlation analysis. There is also limited evidence for this relationship when examining the relevant literature. We observed a high tendency to non-rearfoot strike pattern in MFW, but this did not occur in all participants and may therefore increase the risk of injury in these rearfoot striking minimal footwear runners.

Finally, the transition schedule that was developed as part of this research has been found to result in fewer injuries than other similar studies in this area. Whilst these other studies were examined over a longer period of time, we suggest that our familiarisation programme, at least for the first 4-8 weeks, offers a feasible and reasonably safe schedule for familiarisation to MFW. Whilst adopting the use of MFW can be potentially beneficial for RE, it remains to be determined whether this transition to MFW is worthwhile with regard to long term injury risk in runners.

9.2 Future Recommendations

Based on the findings and observations during this research project, a number of important future research opportunities have been identified which warrant further examination. These include;

- Research to determine if a MFW transition can influence RE with respect to the inclusion and absence of gait-retraining. A randomised control design implementing both a gait-retraining and no gait-retraining programme is advised.
- Future studies should attempt to determine how factors associated with injury are influenced by a MFW transition with no gait-retraining. It would be beneficial to compare this group to both a habitual CRS and habitual MFW running group using a prospective study design.
- Where improvements in RE are noted following a familiarisation to MFW, research it required to examine how and why this occurs. Particular attention should be given to utilisation of the SSC and changes in neuromuscular control of running.
- Future research should examine the retention of changes associated with MFW and gait-retraining, particularly if participants continue to run in CRS following this type of intervention. This will further our understanding of whether MFW and gait-retraining can have a long term influence on CRS and/or MFW running.
- There is a strong need for long term, prospective, randomised trials in habitual MFW and CRS runners to determine the injury rates among these different populations.
- We suggest that researchers attempt to determine if running economy, or impact, or both of these factors are the driving factors for running kinematics in various footwear. This will further our ability to prescribe footwear in an effective manner.
- Why some runners immediately adapt their running kinematics when in MFW and others do not, is an important question that should be examined in future research.

CHAPTER TEN

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10. Bibliography

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CHAPTER ELEVEN

Appendices

11. Appendices

A. Additional Data

A.1 Comparison of energy expenditure (kcal/min) and running economy ($\dot{V}O_{2submax}$)

Table A1. *A comparison between results for energy expenditure (EE; kcal/min) and running economy (RE; $\dot{V}O_{2submax}$) regarding the two tested main effects; 1) Time (change from pre to post-tests), and 2) Condition (difference between MFW and CRS).*

Study	Statistical design		RE result	EE result	Correlations
Study One	2 x 2 x 2 RM ANOVA (Time, Condition, Speed)	Effect for time	P = 0.001	P = 0.010	
		Effect for condition	P = 0.022	P = 0.034	
Study Two	2 x 2 RM ANOVA (Time, Condition)	Effect for time	P = 0.99	P = 0.564	
		Effect for condition	P = 0.002	P = 0.001	
Study Three	2 x 2 RM ANOVA (Time, Condition)	Effect for time	P = 0.568	P = 0.245	
		Effect for condition	P = 0.032	P = 0.033	

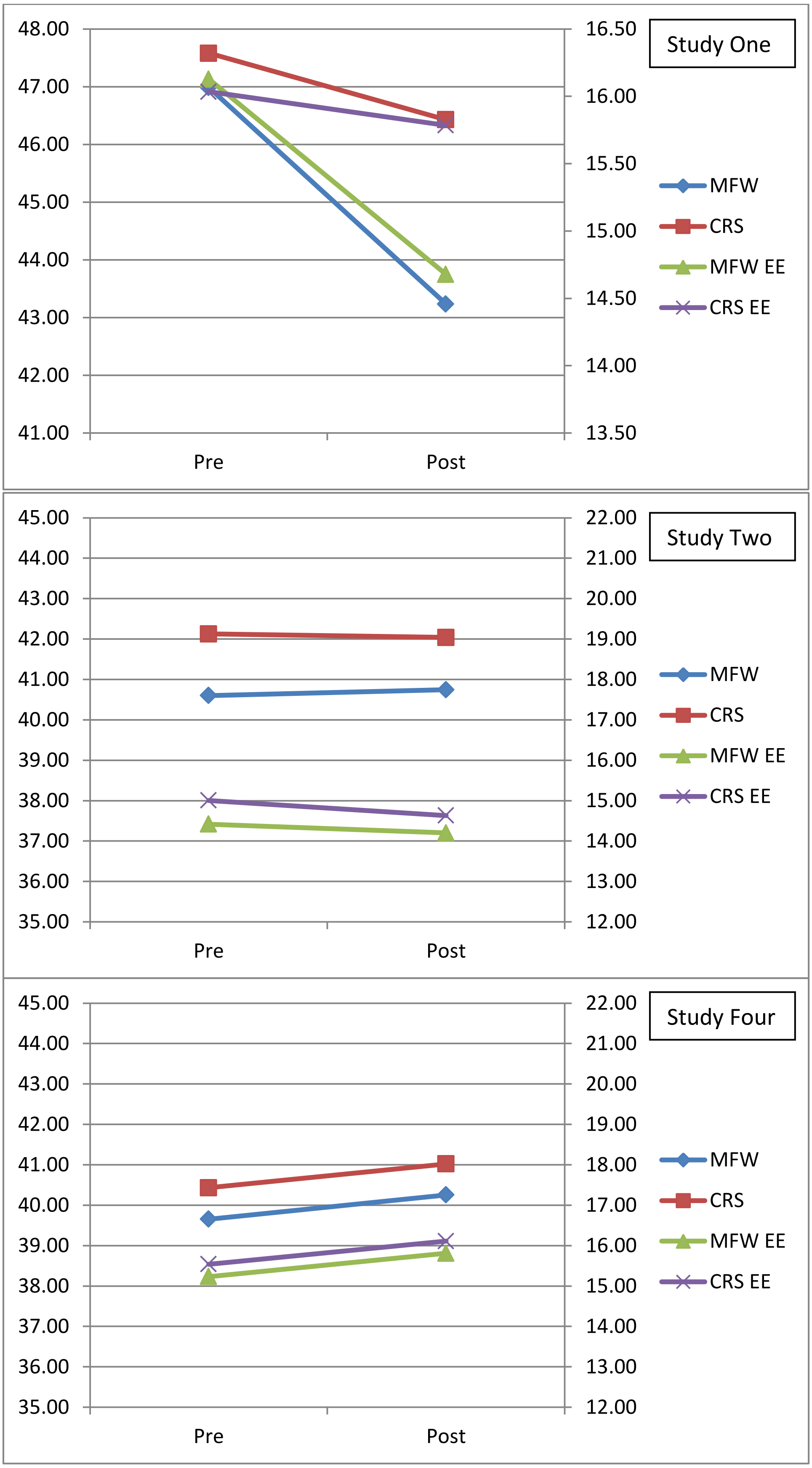

Figure A.1. *A comparison between results for energy expenditure (EE; kcal/min; right axes) and running economy (RE; $\dot{V}O_{2submax}$; left axes) for each study.*

B. Published Research Papers

C. Ethics Application

Dublin City University
RESEARCH ETHICS COMMITTEE

APPLICATION FOR APPROVAL OF A PROJECT INVOLVING **HUMAN PARTICIPANTS**

Application No. *(office use only)* DCUREC/2010/ ☐☐☐

Period of Approval *(office use only)* ....../....../...... to ....../....../....

This application form is to be used by researchers seeking ethics approval for individual projects and studies. The **signed original and an electronic copy** of your completed application must be submitted to the DCU Research Ethics Committee.

NB - The hard copy must be signed by the PI. The electronic copy should consist of <u>one file only</u>, which incorporates all supplementary documentation. The completed application must be proofread and spellchecked before submission to the REC. All sections of the application form should be completed. Applications which do not adhere to these requirements will not be accepted for review and will be returned directly to the applicant.

Applications must be completed on the form; answers in the form of attachments will not be accepted, except where indicated. No handwritten applications will be accepted. **Research must <u>not</u> commence until written approval has been received from the Research Ethics Committee.**

PROJECT TITLE	**The effect of barefoot simulated running on physiological variables related to endurance performance and injury prevention.**
PRINCIPAL INVESTIGATOR(S)	**Dr. Giles Warrington**

Please confirm that **<u>all</u>** supplementary information is included in your application (in both signed original and electronic copy). If questionnaire or interview questions are submitted in draft form, a copy of the final documentation must be submitted for final approval when available.

	INCLUDED		**NOT APPLICABLE**
Bibliography	☒		☐
Recruitment advertisement	☐		☒
Plain language statement/Information Statement	☒		☐
Informed Consent form	☒		☐
Evidence of external approvals related to the research	☐		☒
Questionnaire	☐ draft	☐ final	☒
Interview Schedule	☐ draft	☐ final	☒
Debriefing material	☐		☒
Other	☐		☒

Please note:

1. Any amendments to the original approved proposal must receive prior REC approval.
2. As a condition of approval investigators are required to document and report immediately to the Secretary of the Research Ethics Committee any adverse events, any issues which might negatively impact on the conduct of the research and/or any complaint from a participant relating to their participation in the study

Please submit the **signed original, plus the electronic copy** of your completed application to:
Ms. Fiona Brennan, Research Officer, Office of the Vice-President for Research
(fiona.brennan@dcu.ie, Ph. 01-7007816)

1. ADMINISTRATIVE DETAILS

THIS PROJECT IS:
(tick as many as apply)

☐ Research Project
☐ Practical Class
☒ Student Research Project
(please give details)
  ☒ Research Masters   ☐ Taught Masters
  ☐ PhD   ☐ Undergraduate

☐ Funded Consultancy
☐ Clinical Trial
☐ Other - *Please Describe:*

Project Start Date: 1/12/2010 **Project End date: 1/12/2012**

1.1 INVESTIGATOR CONTACT DETAILS *(see Guidelines)*

PRINCIPAL INVESTIGATOR(S):

TITLE	*SURNAME*	*FIRST NAME*	*PHONE*	*FAX*	*EMAIL*
Dr	Warrington	Giles	(01)7008803		Giles.warrington@dcu.ie

OTHER INVESTIGATORS:

TITLE	*SURNAME*	*FIRST NAME*	*PHONE*	*FAX*	*EMAIL*
Mr	Warne	Joe	0861039917		Warnej2@mail.dcu.ie

FACULTY/DEPARTMENT/SCHOOL/ CENTRE: School of Health and Human Performance

1.2 WILL THE RESEARCH BE UNDERTAKEN ON-SITE AT DUBLIN CITY UNIVERSITY?

☒ YES ☐ NO *(If NO, give details of off-campus location.)*

1.3 IS THIS PROTOCOL BEING SUBMITTED TO ANOTHER ETHICS COMMITTEE, OR HAS IT BEEN PREVIOUSLY SUBMITTED TO AN ETHICS COMMITTEE?*)*

☐ YES ☒ NO *(If YES, please provide details and copies of approval(s) received etc.)*

DECLARATION BY INVESTIGATORS

The information contained herein is, to the best of my knowledge and belief, accurate. I have read the University's current research ethics guidelines, and accept responsibility for the conduct of the procedures set out in the attached application in accordance with the guidelines, the University's policy on Conflict of Interest and any other condition laid down by the Dublin City University Research Ethics Committee or its Sub-Committees. I have attempted to identify all risks related to the research that may arise in conducting this research and acknowledge my obligations and the rights of the participants.

If there any affiliation or financial interest for researcher(s) in this research or its outcomes or any other circumstances which might represent a perceived, potential or actual conflict of interest this should be declared in accordance with Dublin City University policy on Conflicts of Interest.

I and my co-investigators or supporting staff have the appropriate qualifications, experience and facilities to conduct the research set out in the attached application and to deal with any emergencies and contingencies related to the research that may arise.

Signature(s):

Principal investigator(s): ____________________________

Print name(s) in block letters: Dr *Giles Warrington*

2. PROJECT OUTLINE

2.1 LAY DESCRIPTION *(see Guidelines)*

The study will investigate any changes that occur when exercising in light-weight footwear designed to simulate running in bare feet (Vibram FiveFingers) and compare this to running in conventional running shoe. This research project will look at differences in the energy required when running on a treadmill at different speed using the 2 different shoe types. The study will also evaluate changes in running technique, as well as establish whether there is are any differences in the impact forces placed on the lower leg during the two different exercise trials.

The participants will be required to first become familiar to running in Vibram FiveFingers (VFF) for a minimum of three weeks, which will require running twice per week for 30 minutes in the shoe. Before, during and after this period each participant will be filmed using a video camera to document any changes in running technique. They will also be required to run on a treadmill at different speeds, during which the amount of oxygen they are consuming and their heart rate will be measured.

During testing on the treadmill after having worn VFF for a minimum of three weeks, subjects will be asked to run at different speeds in both VFF and conventional running shoes in a random order. During each test oxygen consumption, heart rate, blood lactate (by taking a small blood sample from the ear lobe), stride frequency, video analysis, and impact forces placed on the lower leg will all be assessed. The subjects will then be required to return to the laboratory in 3-7 days and repeat the procedure wearing the opposite shoe.

On a separate occasion, the subjects will be taken to an indoor athletics arena where field based testing will take place. Again this will involve running at different speeds in both conventional running shoes and VFF. A portable system will be used to measure oxygen consumption during these tests. Running speed will be controlled using an electronic pacing system and GPS.

2.2 AIMS OF AND JUSTIFICATION FOR THE RESEARCH *(see Guidelines)*

The large scale move towards the use of supportive footwear, which occurred in the early 1970's, has been questioned in the literature over recent years. Studies have suggested that injuries of the lower extremities are substantially higher in the shod population (Robbins & Hanna, 1987) when compared to barefoot runners. More recently, there has been an increasing number of studies published suggesting that running shoes offering structure and cushioning are a large cause of injuries due to weakened structures of the foot and higher impact forces (Richards, Magin and Callister, 2010; Lieberman et al, 2010; Wallden, 2009; Squadrone & Gallozzi, 2009; Warburton, 2001).

As a consequence of these findings the growing body of research in this area has brought into question the use of traditional running footwear. This has resulted in a growing trend towards the use of barefoot or barefoot-simulated running. Indeed the limited research available to date supports a more naturalist approach to running footwear. Products such as Nike "Free's", Newton's, and Vibram "FiveFingers" are becoming increasingly popular and claim to offer minimalist or altered designs that promote a more natural running gait (Wallden, 2010). Furthermore, within the literature, there is increasing research to suggest that running without excessive cushioning and support leads to less impact and stronger feet and lower limbs respectively, thus potentially reducing chronic injuries through long term use (Lieberman et al, 2010; Nigg et al, 2003; Knapik et al, 2010).

Aside from the suggested reduced injury risks, it has also been proposed that the change in gait when running in less cushioned shoes or when barefoot running (due to a shortened stride length as well as a fore-foot strike, as opposed to the more common heel-strike seen when in traditional footwear) can have a positive effect on running economy (Lieberman et al, 2010; Squadrone & Gallozzi, 2009). While this improvement had also been related to the weight of shoes (Divert et al, 2008), there is growing research suggesting that the change in gait mechanics due to a more natural fore-foot strike, as a result of reduced heel cushioning can lead to a more efficient movement pattern (Squadrone & Gallozzi, 2009; Wallden 2009; Liebermanet al, 2010). Despite this, there is a need for further research in this area as few studies have investigated differences in running economy during barefoot or barefoot-simulated condition with conventional running shoes.

Anecdotal evidence, based on a review in Wallden (2009), suggests that brand specific research is even more limited, yet most "minimalistic" products available would seem to still offer some degree of cushioning or support that may not accurately reflect barefoot running. One product however that exhibits no cushioning, support or structure is Vibram "FiveFingers". This relatively new product provides a simple "second skin" for the foot in order to simply offer protection on modern day surfaces. A recent study by Sqadrone and Gallozzi (2009) is currently the only published research investigating on this product, yet the author's findings suggest that there are very common characteristics between barefoot running and "FiveFingers". The study examined spatio-temporal variables, ground pressure distribution, and running economy in experienced barefoot runners, yet the design offered some limitations that the authors strongly suggested required further investigation. Specifically, assessment of running economy was conducted at only 12km/h and also used only 8 participants. The authors concluded that running at higher velocities may be necessary to establish a more realistic change in economy, as "the principle of minimising the loss of energy that was successful for power activities such as sprinting, running at higher speeds and jumping may not be valid". The author's findings were also significantly lower with regard to running economy compared to previous studies, supporting this view (Flaherty, 1994).

2.3 PROPOSED METHOD *(see Guidelines)*

Subjects will be required to undergo initial familiarisation running in Vibram FiveFingers (VFF) for a minimum of three weeks, which will require running twice per week for 30 minutes in the product. Before, during and after this habituation period the subjects will be filmed using a high definition camera to document any changes to running technique. They will then be required to undergo running economy testing in DCU Sports Science testing laboratories on two separate days.

During the running economy testing on a treadmill, subjects will be required to run a different fixed velocities in both VFF's and conventional shoes in a random order. During each trial time heart rate, blood lactate, stride frequency, video analysis, and impact data (using accelerometers on the hip, knee and ankle joints) will be recorded. Oxygen uptake (VO2) will also be measured using indirect calorimetry throughout each test. The subjects will then be required to return to the lab in 3-7 days and repeat the procedure on the opposite order.

On a separate occasion, the subjects will be taken to an indoor athletics arena (Nenagh, Ireland) where field based testing can take place. Subjects will be required to again run at fixed velocities in both conventional shoes and VFF's. A portable system will be used to analyse oxygen consumption and related variables. The velocity will be controlled using an electronic pacing system and GPS.

2.4 PARTICIPANT PROFILE *(see Guidelines)*

Fifteen male athletes between the age of 17 and 26 will be recruited for the purpose of the study. Participants will be selected from national level middle distance runners (800m – 5000m) who have been training injury free for a minimum of three months. Subjects will be excluded if they have completed a large volume of their training barefoot or in a barefoot simulated condition. Participants will also be excluded if they display very poor biomechanics when running (excessive exaggerated movements or unnatural running style), if they smoke, have diabetes, unstable or a history of cardiovascular disease, chronic previous injuries, and have no history of clinical conditions that may preclude them from exercise

2.5 MEANS BY WHICH PARTICIPANTS ARE TO BE RECRUITED *(see Guidelines)*

Subjects will be contacted and recruited through DCU Athletics Academy (or affiliated athletics organisations) through the Director of Athletics. Potential subjects will be asked to attend an information session in the School of Health and Human Performance where the study explained to them in detail. They will have an opportunity to ask questions and, before leaving, will be provided with a informed consent for them to review. If they agree to participate in the study they will be required to provide written informed consent, which will be witnessed on their next visit to the School of Health and Human Performance. Contact details will be provided to ensure all queries or concerns of the subject can be dealt with immediately.

2.6 PLEASE EXPLAIN WHEN, HOW, WHERE, AND TO WHOM RESULTS WILL BE DISSEMINATED, INCLUDING WHETHER PARTICIPANTS WILL BE PROVIDED WITH ANY INFORMATION AS TO THE FINDINGS OR OUTCOMES OF THE PROJECT?

Subjects will be provided with a report, which will summarise the relevant results from their participation in the research project. The results will form the basis for a postgraduate thesis and may be presented at scientific meetings and published in scientific journals. The identity of individual subjects will not be divulged and will only be presented as part of a group in numerical data.

2.7 OTHER APPROVALS REQUIRED *Has permission to gain access to another location, organisation etc. been obtained? Copies of letters of approval to be provided when available.*

☐ YES ☐ NO ☒ NOT APPLICABLE

(If YES, please specify from whom and attach a copy. If NO, please explain when this will be obtained.)

2.8 HAS A SIMILAR PROPOSAL BEEN PREVIOUSLY APPROVED BY THE REC?

☐ YES ☒ NO

(If YES, please state both the REC Application Number and Project Title)

3. RISK AND RISK MANAGEMENT

3.1 ARE THE RISKS TO SUBJECTS AND/OR RESEARCHERS ASSOCIATED WITH YOUR PROJECT GREATER THAN THOSE ENCOUNTERED IN EVERYDAY LIFE?

☐ YES ☒ NO

If YES, this proposal will be subject to full REC review

If NO, this proposal may be processed by expedited administrative review

3.2 DOES THE RESEARCH INVOLVE:

	YES	NO
• use of a questionnaire? (attach copy)?	☐	☒
• interviews (attach interview questions)?	☐	☒
• observation of participants without their knowledge?	☐	☒
• participant observation (provide details in section 2)?	☐	☒
• audio- or video-taping interviewees or events?	☒	☐
• access to personal and/or confidential data (including student, patient or client data) without the participant's specific consent?	☐	☒
• administration of any stimuli, tasks, investigations or procedures which may be experienced by participants as physically or mentally painful, stressful or unpleasant during or after the research process?	☒	☐
• performance of any acts which might diminish the self-esteem of participants or cause them to experience embarrassment, regret or depression?	☐	☒
• investigation of participants involved in illegal activities?	☐	☒
• procedures that involve deception of participants?	☐	☒
• administration of any substance or agent?	☐	☒
• use of non-treatment of placebo control conditions?	☒	☐
• collection of body tissues or fluid samples?	☒	☐
• collection and/or testing of DNA samples?	☐	☒
• participation in a clinical trial?	☐	☒
• administration of ionising radiation to participants?	☐	☒

3.3 POTENTIAL RISKS TO PARTICIPANTS AND RISK MANAGEMENT PROCEDURES *(see Guidelines)*

As with any sudden onset of exercise, subjects may experience muscle soreness on the day or days following any tests. Running barefoot may be attributable to starting new exercise, and subjects may find the familiarisation period slightly uncomfortable for the initial period. Previous research in this area, however, has indicated injury risk to be minimal.

Exercise testing carries with it a very small risk of abnormal heart rhythms, heart attack or death. The risk of sudden death during exercise for healthy men is 1:15000-18000. The laboratory is equipped with an emergency crash cart and a defibrillator. An individual trained in resuscitation will be present during each test. Subjects with diabetes, anaemia, liver dysfunction, history of heart disease or other major signs or symptoms suggestive of cardiovascular or pulmonary disease (angina, palpitations or tachycardia, known heart murmur, or unusual fatigue or shortness of breath with usual exercise) will be excluded from the study.

Research procedures require blood samples to be taken at several time points throughout the testing process. The total amount of blood taken from each subject throughout the study will be approximately 25ml. This is much less than the 568ml (one pint) of blood that is usually donated at blood banks. Trained users will make a tiny pin prick incision into the ear lobe, from which all samples will be taken. Subjects may feel light headed or experience syncope during any operation that reveals blood. In the event of an individual fainting or feeling light headed, they will be placed lying on their back with their feet elevated.

3.4 ARE THERE LIKELY TO BE ANY BENEFITS (DIRECT OR INDIRECT) TO PARTICIPANTS FROM THIS RESEARCH?

☒ YES ☐ NO *(If YES, provide details.)* In addition to potentially enhancing their performance through improved running economy running barefoot may significantly reduce overuse injuries in these athletes and provide them with a safer way to train on a regular basis.

3.5 ARE THERE ANY SPECIFIC RISKS TO RESEARCHERS? *(e.g. risk of infection or where research is undertaken at an off-campus location)*

☒ YES ☐ NO *(If YES, please describe.)* Dealing with blood always offers the potential risks of cross contamination if protocols are not strictly adhered to. Researches will be trained in taking blood samples in a safe and efficient manner. They will also have completed a course of Hepatitis B vaccinations prior to testing.

3.6 ADVERSE/UNEXPECTED OUTCOMES *(see Guidelines)*

The School of Health and Human Performance has the facilities to deal with all aspects of this study and an emergency plan is in place for adverse events. All minor injuries will be addressed by an individual trained in first aid (either a member of the research team or the staff). The laboratory is equipped with an emergency crash cart and defibrillator. An individual trained in first aid (or Advanced Cardiac Life Support) will be present during each test. In the unlikely event of a serious adverse outcome, an ambulance will be called and the subject will immediately be sent to Beaumont Hospital.

3.7 MONITORING *(see Guidelines)*

The research team will have weekly meetings to update on all aspects of the study. The School of Health and Human Performance has a detailed list of Standard Operating Procedures for each of the protocols in this study. All researchers, including postgraduate students, must be familiar with the procedures and the Safety Statement before beginning data collection.

3.8 SUPPORT FOR PARTICIPANTS *(see Guidelines)*

We do not anticipate the need for additional support for participants involved in this research project.

3.9 DO YOU PROPOSE TO OFFER PAYMENTS OR INCENTIVES TO PARTICIPANTS?

☐ YES ☒ NO *(If YES, please provide further details.)*

4. INVESTIGATORS' QUALIFICATIONS, EXPERIENCE AND SKILLS *(Approx. 200 words – see Guidelines)*

Dr. Giles Warrington is a lecturer at the School of Health and Human Performance. He has supervised numerous undergraduate and postgraduate projects in this field of study.

Joe Warne is a postgraduate student at the School of Health and Human Performance. He has a degree in sports science and health and has previous experience in carrying out testing of this nature.

5. CONFIDENTIALITY/ANONYMITY

5.1 WILL THE IDENTITY OF THE PARTICIPANTS BE PROTECTED?

☒ YES ☐ NO *(If NO, please explain)*

IF YOU ANSWERED YES TO 5.1, PLEASE ANSWER THE FOLLOWING QUESTIONS:

5.2 HOW WILL THE ANONYMITY OF THE PARTICIPANTS BE RESPECTED? *(see Guidelines)*
Confidentiality is an important issue during data collection. Participant's identity, or other personal information, will not be revealed or published. Subjects will be assigned an ID number under which all personal information will be stored in a secure file and saved in password protected file in a computer at DCU. The investigators alone will have access to the data.

5.3 LEGAL LIMITATIONS TO DATA CONFIDENTIALITY: *(Have you included appropriate information in the plain language statement and consent form? See Guidelines)*

☒ YES ☐ NO *(If NO, please advise how participants will be advised.)*

6 DATA/SAMPLE STORAGE, SECURITY AND DISPOSAL *(see Guidelines)*

6.1 HOW WILL THE DATA/SAMPLES BE STORED? *(The REC recommends that all data be stored on campus)*

Stored at DCU ☒
Stored at another site ☐ **(***Please explain where and for what purpose)*

6.2 WHO WILL HAVE ACCESS TO DATA/SAMPLES?

Access by named researchers only ☒

Access by people other than named researcher(s) ☐ **(***Please explain who and for what purpose)*
Other *:* ☐ **(***Please explain)*

6.3 IF DATA/SAMPLES ARE TO BE DISPOSED OF, PLEASE EXPLAIN HOW, WHEN AND BY WHOM THIS WILL BE DONE?
Data will be stored for 12-months following the completion of the project, in line with University regulations for examinations. The data will be destroyed by the principal investigator.

7. FUNDING

7.1 HOW IS THIS WORK BEING FUNDED?
This work is being funded by the researcher himself.

7.2 PROJECT GRANT NUMBER (If relevant and/or known)

7.3 DOES THE PROJECT REQUIRE APPROVAL BEFORE CONSIDERATION FOR FUNDING BY A GRANTING BODY?

☐ YES ☒ NO

7.4HOW WILL PARTICIPANTS BE INFORMED OF THE SOURCE OF THE FUNDING?

7.5 DO ANY OF THE RESEARCHERS, SUPERVISORS OR FUNDERS OF THIS PROJECT HAVE A PERSONAL, FINANCIAL OR COMMERCIAL INTEREST IN ITS OUTCOME THAT MIGHT COMPROMISE THE INDEPENDENCE AND INTEGRITY OF THE RESEARCH, OR BIAS THE CONDUCT OR RESULTS OF THE RESEARCH, OR UNDULY DELAY OR OTHERWISE AFFECT THEIR PUBLICATION?

YES ☐ NO *(If Yes, please specify how this conflict of interest will be addressed.)*

The Vibram FiveFingers will be donated for the research project, on an unconditional basis, by the Irish Distributor of this brand (Barefoot Ltd). However no direct financial support will be received. The research will therefore remain completely independent and IP will remain exclusively in the ownership of DCU.

8. PLAIN LANGUAGE STATEMENT *(Approx. 400 words – see Guidelines)*

Plain Language Statement

I. Introduction to the Research Study

Research Study Title: **The effect of barefoot simulated running on physiological variables related to performance and injury prevention**.
University Department: School of Health and Human Performance
Principal Investigator: Dr. Giles Warrington
Other Investigator: Joe Warne, BSc

II. Details of what involvement in the Research Study will require

The study will investigate any changes that occur when exercising in light-weight footwear designed to simulate running in bare feet (Vibram FiveFingers) and compare this to running in conventional running shoe. This research project will look at differences in the energy required when running on a treadmill at different speed using the 2 different shoe types. The study will also evaluate changes in running technique, as well as establish whether there is are any differences in the impact forces placed on the lower leg during the two different exercise trials.

You will be required to first become familiar to running in Vibram FiveFingers (VFF) for a minimum of three weeks, which will require running twice per week for 30 minutes in the shoe. Before, during and after this period you will be filmed using a video camera to document any changes to technique. You will also be required to run on a treadmill at different speeds, during which the amount of oxygen you are consuming and your heart rate will be measured.

During testing on the treadmill after having worn VFF for a minimum of three weeks, you will be asked to run at different speeds in both VFF and conventional running shoes in a random order. During each test oxygen consumption, heart rate, blood lactate (by taking a small blood sample from the ear lobe), stride frequency, video analysis, and impact forces placed on the lower leg will all be assessed. You will then be required to return to the laboratory in 3-7 days and repeat the procedure wearing the opposite shoe.

On a separate occasion, you will be taken to an indoor athletics arena where field based testing will take place. Again this will involve running at different speeds in both conventional running shoes and VFF. A portable system will be used to measure oxygen consumption during these tests. Running speed will be controlled using an electronic pacing system and GPS.

III. Potential risks to participants from involvement in the Research Study (if greater than that encountered in everyday life)

Exercise testing carries with it a very small risk of abnormal heart rhythms, heart attack or death. The likelihood of these risks in asymptomatic healthy males less than 30 years of age is very low This risk of sudden exercise related death is 1:15000-18000 for healthy men. As blood samples must be taken from the earlobe only there may be discomfort and the development of a small bruise at the site of puncture. As with any sudden onset of exercise, you may experience muscle soreness on the day or days following any tests or while becoming familiarised with running in the Vibram FiveFingers.

IV. Benefits (direct or indirect) to participants from involvement in the Research Study

You will be given a copy of your own results as well as a summary of the overall study findings. which if adopted, may potentially reduce injury risk as well as improve running economy.

V. Advice as to arrangements to be made to protect confidentiality of data, including that confidentiality of information provided is subject to legal limitations

Confidentiality is an important issue during data collection. Your identity, or other personal information, will not be revealed or published. You will be assigned an ID number under which all personal information will be stored in a secure file and saved in password protected file in a computer at DCU. The investigators alone will have access to the data.

Confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions.

VI. Advice as to whether or not data is to be destroyed after a minimum period

Data will be stored for 12 months following the completion of the project, in line with University regulations for examinations. The data will be destroyed by the principal investigator Dr. Giles Warrington.

VII. Statement that involvement in the Research Study is voluntary

Your participation in this study is voluntary and you may withdraw from the Research Study at any point. There will be no penalty for withdrawing before all stages of the Research Study have been completed.

If participants have concerns about this study and wish to contact an independent person, please contact:

The Secretary, Dublin City University Research Ethics Committee, c/o Office of the Vice-President for Research

9. INFORMED CONSENT FORM *(Approx. 300 words – see Guidelines)*

DUBLIN CITY UNIVERSITY
Informed Consent Form

I. Research Study Title: The effect of barefoot simulated running on physiological variables related to performance and injury prevention.
University Department: School of Health and Human Performance
Principal investigator: Dr. Giles Warrington
Other Investigator: Joe Warne BSc.

II. Clarification of the purpose of the research

This study will attempt to investigate any changes that occur when running in barefoot simulated products (Vibram FiveFingers) compared to running in conventional running footwear. The study will investigate any changes in the energy cost as measured by the oxygen consumed during each of the two trials, as well as the amount of times the foot hits the floor at identical speeds, changes in running technique, and whether there is any change between the two interventions on impact forces at the lower leg joints.

III. Confirmation of particular requirements as highlighted in the Plain Language Statement

I will be asked to visit Dublin City University on three separate days, and I will also be asked to attend a field based study in Nenagh indoor stadium at a later date. I will be provided with a pair of Vibram FiveFingers on the first day and given instruction for familiarisation. Several weeks later I will be asked to return to the labs and undergo a running economy test on a treadmill. This will involve running at a number of fixed velocities in both the Vibram FiveFingers and traditional running shoes. During this time I will be filmed, be asked to provide blood samples from the ear, and will wear mask during the test that will measure my oxygen uptake, as well as being asked to wear accelerometers on my lower limb joints. I will then repeat the same protocol 3-7 days later but in the opposite order. The field based study will involve the same procedure but will take place on an indoor track using a metronome and GPS as my pacing signal.

<u>Participant – please complete the following (Circle Yes or No for each question)</u>
Have you read or had read to you the Plain Language Statement
Yes/No
Do you understand the information provided?
Yes/No
Have you had an opportunity to ask questions and discuss this study?
Yes/No
Have you received satisfactory answers to all your questions?
Yes/No

IV. Confirmation that involvement in the Research Study is voluntary

I understand that I may withdraw from the testing procedures at any time. No penalty will be incurred for failure to complete all stages of the research study.

V. Advice as to arrangements to be made to protect confidentiality of data, including that confidentiality of information provided is subject to legal limitations

Confidentiality is an important issue during data collection. My identity, or other personal information, will not be revealed or published. I will be assigned an ID number under which all personal information will be stored in a secure file and saved in password protected file in a computer at DCU. The investigators alone will have access to the data.
Confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions.

VII. <u>Signature:</u>

I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project

Participants Signature: ______________________________

Name in Block Capitals: ______________________________

Witness: ______________________________

10. REFERENCES

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