

The Effect of Minimal Footwear and Midsole Stiffness on Lower Limb Kinematics and Kinetics in Novice and Trained Runners

by

Nicholas Frank

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Kinesiology

Waterloo, Ontario, Canada, 2013

© Nicholas Frank 2013

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made available electronically to the public.

Nicholas S. Frank

ABSTRACT

Background: The most common injuries in new or novice runners include medial tibial stress syndrome and patellofemoral pain syndrome; both overuse injuries. It is known that novice runners use a rearfoot strike pattern 98% of the time while running in traditional running footwear. Furthermore, footwear that is constructed with less cushioning (minimal shoes) and is said to promote forefoot running has increased in popularity. It is still unknown if novice runners convert their strike pattern in minimal shoes or continue to use a rearfoot strike pattern. Consequences of continuing to use a rearfoot strike pattern with less cushioning underfoot include higher vertical loading rates which are directly related to the types of injuries experienced. Aside from the strike pattern in a given shoe, movement stability is an important feature in healthy locomotion. There is a trade-off between being overly stable and being too unstable while running. It is known that the level of experience in running is related to the amount of stride length variability. It is still unknown if altering midsole stiffness has an effect on local dynamic stability while running.

Purpose: The primary purpose of this thesis was to compare landing kinematics and kinetics between trained and novice runners in minimal and traditional shoes. The secondary purpose of this thesis was to examine the effect of running experience and midsole construction on local dynamic stability at the ankle, knee and hip.

Methods: Twelve trained runners and twelve novice runners were recruited for participation. Four prototypical shoe conditions were tested with midsole geometry and material stiffness being manipulated. This yielded traditional/soft, traditional/hard, minimal/soft and minimal/hard shoe conditions. Participants ran down a 30m indoor runway which was instrumented with force platforms to measure vertical loading rates and motion capture cameras to capture landing kinematics. Participants also ran on a treadmill in each shoe condition to allow for local dynamic stability to be estimated at the ankle, knee and hip in the sagittal plane.

Results: Novice runners landed with increased knee extension compared to trained runners. Increasing midsole thickness of the shoes caused an increase in dorsi-flexion of the ankle at heel strike. Manipulating material stiffness did not influence landing kinematics but did influence kinetics. Furthermore, decreasing material stiffness lowered vertical loading rates. Trained runners exhibited increased local dynamic stability (more stable) at the ankle, knee and hip compared to novice runners. Local dynamic stability was not affected by midsole stiffness.

Conclusions: Novice runners did not alter their strike pattern in minimally constructed shoes. For this reason, cushioning properties of the shoe dictated vertical loading rates upon the body. Shoe conditions did not alter landing kinematics above the ankle, which is where the between group differences existed as novice runners landed with a more extended knee. Running experience appears to play a role in knee orientation at landing and is unaffected by shoe condition. Local dynamic stability was affected by running experience and does not appear to be related to the shoe condition being worn. Even when kinematics changed across shoe conditions, the stability of the movement did not.

ACKNOWLEDGEMENTS

I would like to thank my supervisors, Dr. Steve Prentice and Dr. Jack Callaghan for their mentorship and the opportunity to pursue my passion in the area of footwear research. Five years ago, Dr. Prentice gave me, an undergraduate student with no experience, an opportunity to work in his lab for a co-op term. This co-op term formed the basis for my research interests and career path for which I am indebted to him. I would like to thank Dr. Callaghan for his mentorship over the past three years. Dr. Callaghan's mentorship is not bound between the hours of 9 a.m. and 5 p.m. His advice and guidance are available to his students any time it is required. I would also like to thank Dr. Stacey Acker for her expertise and guidance throughout the entire thesis process.

I would like to thank the Nike Sports Research Lab for supplying the footwear used in this thesis. Specifically, I would like to thank Dr. Matt Nurse and Jeff Pisciotta for their leadership during my time in the NSRL.

I owe an overwhelming thank you to the Biomechanics faculty members and Kinesiology staff as they allowed me to borrow equipment and intrude on their own lab space without hesitation.

My parents deserve the largest thank you, for providing me with love and support in everything and anything I have decided to do. I would like to thank my lab mates and office mates for listening to my thoughts and opinions regardless of the topic being discussed.

Lastly, I would like to thank Katelyn for always being there to listen and support me. It is the drive and dedication that I see in you that I hope to reflect in my own work.

Table of Contents

AUTHOR'S DECLARATION.....	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
LIST OF FIGURES.....	vii
LIST OF TABLES.....	viii
LIST OF ABBREVIATIONS.....	ix
CHAPTER 1.0 Introduction.....	1
CHAPTER 2.0 Purposes.....	4
CHAPTER 3.0 Hypotheses.....	5
CHAPTER 4.0 Literature Review	6
4.1 Minimal Footwear	6
4.1.1 Kinematics of Minimal Running Shoes	7
4.1.2 Kinetics of Minimal Running Shoes.....	8
4.1.3 Minimal Footwear and Physiological Measures.....	8
4.2 Barefoot Running.....	11
4.2.1 Loading Rates and Strike Patterns	11
4.2.2 Leg Stiffness.....	13
4.3 Midsole Cushioning.....	14
4.3.1 Perception of Cushioning.....	15
4.3.2 Midsole Hardness and Kinetics.....	16
4.3.3 Muscle Activity and Cushioning	16
2.4 Overuse Injuries	18
4.4.1 Running Injuries	19
4.4.2 Injuries in Novice Runners.....	19
4.4.3 Tissue Response to Repetitive Loading.....	21
4.5 Variability in Motor Control	23
4.5.1 Variability in Running	24
4.5.2 Lyapunov Exponents	26
CHAPTER 5.0 General Methods.....	29

CHAPTER 6.0.....	31
6.1 Introduction.....	31
6.2 Methods.....	35
6.3 Results.....	39
6.4 Discussion.....	47
CHAPTER 7.0.....	57
7.1 Introduction.....	57
7.2 Methods.....	60
7.3 Results.....	69
7.4 Discussion.....	74
CHAPTER 8.0 General Discussion.....	79
REFERENCES	82

LIST OF FIGURES

Figure 4.1: Bone adaptation outside of normal activity.....	22
Figure 4.2: Optimal movement variability figure.....	24
Figure 5.1: Shoe conditions used for all participants.....	30
Figure 6.1: Force platform arrangement.....	35
Figure 6.2: Rigid bodies placed on participant.....	36
Figure 6.3: Foot landing angle values for all shoe conditions.....	40
Figure 6.4: Kinematic time profiles for three participants.....	43
Figure 6.5: Vertical Instantaneous Loading Rate results.....	44
Figure 6.6: Impact peak interaction between midsole stiffness and thickness.....	45
Figure 6.7: Estimated loading rates based on stiffness and thickness ratio.....	50
Figure 7.1: Rigid bodies placed on the participant.....	59
Figure 7.2: Breakdown of the steps to calculate the LyE.....	63
Figure 7.3: An example of false nearest neighbours in state space.....	64
Figure 7.4: Average heart rate results between novice and trained runners.....	69
Figure 7.5: Lyapunov exponent results for the ankle, knee and hip.....	71
Figure 8.1: Conceptual framework from findings.....	79

LIST OF TABLES

Table 4.1: Kinematic comparisons between minimal and traditional footwear research.....	7
Table 4.2: Kinematic comparisons to trained barefoot runners.....	13
Table 6.1: Independent and dependent variables.....	39
Table 6.2: Participant demographics.....	40
Table 6.3: Strike pattern breakdown between novice and trained runners	41
Table 6.4: Average kinematic values at touch down.....	42
Table 6.5: Average kinetic values at touch down.....	46
Table 7.1: Results for the verified LyE signals.....	66
Table 7.2: Statistical table showing the independent and dependent variables for LyE.....	67
Table 7.3: Participant demographics.....	68
Table 7.4: Average reconstruction lag and embedding dimension values.....	69
Table 7.5: Lyapunov exponent results for the ankle, knee and hip.....	70

LIST OF ABBREVIATIONS

CRP: Continuous Relative Phase

EVA: Ethylene-Vinyl Acetate

FFS: Forefoot Strike

FNN: False Nearest Neighbours

ITBS: Ilio-Tibial Band Syndrome

LMM: Linear Mixed Model

LyE: Largest Lyapunov Exponent

MFS: Midfoot Strike

PFPS: Patello-Femoral Pain Syndrome

RFS: Rearfoot Strike

SI: Strike Index

TD: Touch Down

VALR: Vertical Average Loading Rate

VGRF: Vertical Ground Reaction Force

VILR: Vertical Instantaneous Loading Rate

CHAPTER 1.0 Introduction

Running for fitness can be very rewarding, but in order to reap the benefits, one must stay motivated and injury free. Currently, there is a wide array of footwear and running biomechanics research on trained runners. However, in order to become a trained runner, at some point in time, an individual must commit to running on a regular basis. Additionally, there is very little research on new or novice runners, with the vast majority of running research focused on experienced or trained runners. A novice runner has been defined as someone who has run less than a total of 10 km in the past year (Nielsen et al. 2013). The research that exists on novice runners has investigated injury rates and found that novice runners are at risk of overuse injuries such as patellofemoral pain syndrome (runner's knee) or medial tibial stress syndrome (shin splints) (Buist et al. 2008, Nielsen et al. 2013). More importantly, injury rates are highest among novice runners who do not have a history of playing sports with axial loading; a mode of loading that occurs frequently while running (Buist et al. 2010). Although there has been work to identify injury rates and risks in novice runners, there is limited research on their running kinematics and kinetics compared to experienced runners. It has been established that novice runners utilize a rearfoot strike pattern 98% of the time in traditional cushioned shoes (Bertelsen et al. 2012). Understanding the loading and impact placed upon novice runners, the way in which the lower limbs are oriented at impact, and how they may alter their running pattern while training are important factors in designing footwear that is appropriate for those who are starting to run.

To add complexity to this scenario, minimal footwear has increased in popularity across runners of all experience levels. Minimal footwear can be defined as a lightweight shoe sole and upper that is constructed to mimic some aspect of barefoot running (Hamill et al. 2011). Minimal footwear is constructed with less cushioning in comparison to traditional footwear. It has been proposed that the body naturally alters the runners' strike pattern to a midfoot or forefoot strike in minimal shoes in order to reduce the amount of impact at touch down (Lieberman et al. 2010). Trained runners who use a rearfoot strike pattern in minimal shoes, rather than a midfoot strike, have been shown to have much higher vertical loading rates, which have been linked to increased risk of stress fractures (Goss, Gross 2012, Zadpoor, Nikooyan 2011). Since novice runners have less experience running and use a rearfoot strike pattern a greater proportion of the time there is potential risk of injury due to higher loading rates while running in minimal shoes if their strike pattern does not change . There is currently no research that has investigated novice runners' kinematics and kinetics while running in minimal shoes compared to trained runners. The primary purpose of this thesis was to investigate overground running kinematics and kinetics in novice and trained runners while wearing minimal and traditional footwear.

With respect to running, local dynamic stability refers to the sensitivity of the motor control system to small perturbations such as stride to stride variations seen in running (Dingwell et al. 2001). Increased stability is a result of the movement

pattern (running) being insensitive to small perturbations and can be quantified by estimating the largest Lyapunov exponent (LyE), which gives an indication of the rate of divergence between nearest neighbors in state space. In hopping tasks, dynamic stability has been shown to improve while landing on firmer surfaces (Rose et al. 2011). Furthermore, centre of pressure sway is known to increase while standing on unstable surfaces such as foam (Schmit, Regis & Riley 2005). It is thought that softer underfoot material reduces the quality of afferent feedback coming from the ground, hence reducing one's stability. Interacting with a soft surface not only reduces the afferent information coming in to the body but also affects the quality of the motor output as pressing on a soft or hard surface will result in different reaction forces (Perry, Radtke & Goodwin 2007). Novice runners have shown increased stride to stride length variations compared to trained runners (Nakayama, Kudo & Ohtsuki 2010). This increased variability is presumably due to a lack of experience (skill development) in the novice running group (Ericsson 2004). Similarly, injured runners, once healthy again, have been shown to have reduced variability compared to healthy trained runners (Hamill et al. 1999). There is a spectrum of movement stability based upon a person's experience conducting an activity such as running. Furthermore, there is evidence that stability may be influenced by changing underfoot material causing a shift along the spectrum of movement stability. The secondary purpose of this thesis was to investigate how local dynamic stability is affected in trained and novice runners when material stiffness and thickness are manipulated.

CHAPTER 2.0 Purposes

The primary purpose of this thesis was to compare landing kinematics and kinetics between trained and novice runners in minimal and traditional shoes. Understanding how novice and trained runners altered their strike pattern in minimal shoes was important in identifying specific risk factors for overuse injuries based on one's level of experience. The secondary purpose of this thesis was to examine the effect of running experience and midsole construction on local dynamic stability at the ankle, knee and hip. Changing underfoot material has been shown to have implications on postural control (Rose et al. 2011). Movement stability that is either too stable or too unstable is less than ideal with respect to efficiency and injury prevention. Modifying midsole construction may have the ability to decrease local dynamic stability for a runner who is overly stable or increase stability for a runner who has less stability.

CHAPTER 3.0 Hypotheses

1) Primary Purpose – Overground Running Kinematics and Kinetics

- a) It was hypothesized that novice runners would use a rearfoot strike pattern to a greater degree in all shoe conditions compared to trained runners (Bertelsen et al. 2012). Consequently, it was hypothesized that vertical loading rates would be higher in novice runners compared to trained runners for all shoe conditions due to their preference in using a rearfoot strike pattern. Novice runners would have an increased foot landing angle with respect to the horizontal plane and increased knee extension upon landing which is associated with a rearfoot strike pattern as predominantly used by this population (Bertelsen et al. 2012).
- b) It was also hypothesized that vertical loading rates would be higher in minimal shoes and shoes with stiffer midsoles compared to traditional shoes and shoes constructed with softer midsoles.

2) Secondary Purpose – Local Dynamic Stability

- a) It was hypothesized that local dynamic stability would be decreased in novice runners in comparison to trained runners due to less experience (Nakayama, Kudo & Ohtsuki 2010). It was also hypothesized that softer underfoot material would increase local dynamic stability due to the decreased perception of impact across shoe conditions and the ability to change ones landing patterns over a running trial (De Clercq, Aerts & Kunnen 1994).

CHAPTER 4.0 Literature Review

4.1 Minimal Footwear

Eleven years ago the term minimal footwear was non-existent. A literature search using “Web of Science”, with the term “Minimal Footwear” resulted in 14 citations in 2002 and 72 citations in 2012. Minimal footwear has been previously defined as a flexible shoe with lightweight material including a thin midsole which promotes running kinematics to be similar to barefoot running (Hamill et al. 2011). The increased popularity began with Vibram Fivefingers™ and Nike Free™ products as it was hypothesized that benefits such as increased foot flexibility and strength result from running in minimally constructed shoes (Goldmann, Potthast & Brüggemann 2013).

Barefoot running kinematics and kinetics are an important foundation for this thesis as the goal of minimal footwear is to replicate kinematics and kinetics of barefoot running without actually being barefoot (Nigg 2009). The following sections address the direct comparison between minimal footwear and traditional footwear. Features of minimal footwear that have been investigated include flexibility, midsole thickness and hardness (Squadrone, Gallozzi 2009, Potthast et al. 2005, Tenbroek 2011).

4.1.1 Kinematics of Minimal Running Shoes

The major kinematic changes associated with minimal footwear consist of a flatter foot landing angle, increased plantar-flexion and increased knee flexion at heel strike (Squadrone, Gallozzi 2009, Tenbroek 2011). Differences from Squadrone & Gallozzi (2009) are greater in magnitude than the differences reported by Tenbroek (2011) due to alterations in the style of minimal footwear used in the two studies (Table 4.1). Ankle angles upon heel strike differ between traditional and minimal footwear by up to 6° (Squadrone, Gallozzi 2009). More importantly, Squadrone & Gallozzi (2009) found that upon heel strike, the ankle changes from being dorsi-flexed to plantar-flexed in minimal footwear. It has been noted in the literature that kinematic changes while wearing minimal footwear are driven by a need to increase damping in the lower limbs as there is less cushioning in the midsole, which would normally damp a majority of the ground impact forces (Hardin, Van Den Bogert & Hamill 2004). Kinematic values at heel strike can be found for the foot, ankle and knee in Table 4.1, comparing results from studies referenced above.

Table 4.1. Comparison of kinematic data upon heel strike in minimal and traditional footwear. The large differences in values are due to different minimal footwear conditions.

Author	Foot (+ Above Horizontal)		Ankle (+ Dorsi-flexion)		Knee (+ Flexion)	
	Minimal	Traditional	Minimal	Traditional	Minimal	Traditional
Squadrone et al. (2009)	4.0 (4.0)	12.0 (4.0)*	-3.0 (4.0)	3.0 (5.0)*	24.0 (3.0)	21.0 (4.0)
Sinclair et al. (2013)			4.5 (7.4)	7.6 (6.1)*	17.74 (9.43)	18.47 (9.43)
Tenbroek (2011)	20 (3.3)	23.4 (3.5)*	7.93 (2.8)	10.9 (2.9)*	6.06 (4.1)	5.60 (4.1)

* Denotes sig. difference

4.1.2 Kinetics of Minimal Running Shoes

Literature regarding kinetic analysis of minimal footwear is sparse. Squadrone & Gallozzi (2009) used an instrumented treadmill to capture ground reaction forces while running barefoot, in minimal footwear and in traditional shoes. During running, the vertical ground reaction force has a noticeable impact peak or impact transient (Cavanagh, Lafortune 1980). The magnitude and timing of this impact peak are directly related to vertical loading rates which have been associated with increased risk of injury (Davis, Milner & Hamill 2004). Squadrone & Gallozzi (2009) found that the magnitude of the impact peak was decreased in minimal footwear, although loading rates were not directly calculated or reported. Strike index (SI) is a measure used in the scientific running literature and is defined as the position of the centre of pressure about the long axis of the foot upon heel strike with 0% being most posterior and 100% most anterior (Cavanagh, Lafortune 1980). Researchers define rearfoot (0 – 33%), midfoot (33% - 66%) and forefoot (66% - 100%) striking based upon the strike index. It has been shown that the foot landing angle, ground reaction force and strike index are all correlated ($R^2 = 0.85$) (Altman, Davis 2012, Lieberman et al. 2010). As increased plantar-flexion at heel strike has been shown, strike index increases and the magnitude of the impact transient decreases (Squadrone, Gallozzi 2009).

4.1.3 Minimal Footwear and Physiological Measures

One key attribute of minimal footwear is the flexibility of the shoe compared to traditional running footwear. Specifically for the Nike Free (Nike Inc. Beaverton,

OR) sipes or grooves are often cut into the midsole to promote flexibility while maintaining the cushioning properties that were intended for the product. A study by Potthast et al. (2005) investigated the long term effects of minimal footwear usage by examining changes in muscle volume and toe flexor strength pre and post 6 months in a control and minimal group using Nike Free (Nike Inc. Beaverton, OR). The experimental group showed a 5% increase in volume of the Flexor Hallicus Longus and increased toe flexor strength of 20% (47 N), while the control group did not show any differences between pre and post testing (Potthast et al. 2005). The experimental group also showed decreased range of motion while walking by 3° at the MPJ leading the authors to believe that the joint became stiffer (Potthast et al. 2005). Other literature that examined shoe flexibility was concerned with sprinting performance and it was found that increased stiffness of the shoe is a performance enhancer (Stefanyshyn, Fusco 2004). The study by Potthast et al. (2005) is only one example that examined the changes in strength and morphology of the intrinsic foot musculature with minimal footwear. A relationship was found between flexibility and strength yet the direct implication on performance is still not proven and requires prospective research designs.

Running economy in minimal and barefoot shoes versus traditional shoes has become a debated topic recently. In the early 80's it was found that reducing shoe mass had an impact on oxygen consumption (Frederick 1984). For every 100 g reduction on each foot, there was a reduction of oxygen consumption by 1% (Frederick 1984). Recent work has compared barefoot to shod running while on a treadmill and overground (Hanson et al. 2010). Results showed that there was no

statistical difference in running economy between barefoot and shod conditions while running on a treadmill. In contrast, overground running trials, showed that barefoot running had reduced oxygen consumption of 5% compared to running with shoes (Hanson et al. 2010). The accuracy of these results have been questioned as it has been stated in a letter to the editor in the *International Journal of Sports Medicine* that these results show the largest difference in oxygen consumption from any study that has compared barefoot to shod running economy and the equipment used has not been previously validated for research use (Kram, Franz 2012).

Variables highlighted above, such as reduced mass and cushioning, have both demonstrated a positive effect on running economy (Frederick 1984). Reduced mass and increased cushioning appear to be factors that have competing interests when it comes to making an ideal shoe. A lot of cushioning may be desirable for running economy, but adds weight to the shoe. While a lightweight shoe is desirable but is paired with less cushioning. Therefore, it becomes apparent that there is a trade-off between mass of the shoe and cushioning when discussing running economy. Kram et al. (2012) had experienced runners run barefoot on a cushioned treadmill, creating a scenario where there was no mass on the foot while in the presence of cushioning. Running economy improved by 1.83% when running barefoot on the cushioned treadmill, however, values did not meet the same level as a shod condition in a study by Franz et al. (2012). It was concluded that there is a trade off between the effect of mass and the effect of cushioning although there are technological limits that prevent a highly cushioned shoe with very low mass which would be most advantageous for economy (Kram et al. 2012).

4.2 Barefoot Running

The popularity of barefoot running is partially due to the author of “Born to Run”, Christopher McDougall who proclaimed personal success after transitioning away from running shod (McDougall 2009). It should be made clear that barefoot running results are not the same as minimal footwear results. The goal of minimal footwear is to mimic some aspect of barefoot running. For this reason, barefoot running kinematics and kinetics will be presented.

4.2.1 Loading Rates and Strike Patterns

Loading rates of the vertical ground reaction force have been identified as an important variable in barefoot running (Hamill et al. 2011). Early literature examining barefoot running found that vertical loading rates were higher when running barefoot due to an absence of cushioned material under the foot (De Wit, De Clercq & Aerts 2000, De Clercq, Aerts & Kunnen 1994). Since these studies were published, it has been recognized that ground reaction force characteristics are not dependent upon being barefoot or shod; rather they rely upon the foot strike pattern (Lieberman et al. 2010). Early investigations that found higher vertical loading rates when barefoot were due to forcing participants to heel strike whereas current work has found that the preferred strike pattern changes to a midfoot or forefoot pattern that which reduces vertical loading rates when barefoot (Lieberman et al. 2010, Hamill et al. 2011). Loading rates are reduced up 42% when barefoot, however, results are reliant upon the shoe conditions that are being compared to the barefoot condition (Hamill et al. 2011).

Participants in barefoot running studies are often trained barefoot runners (Divert et al. 2005b, De Wit, De Clercq & Aerts 2000, Lieberman et al. 2010, Squadrone, Gallozzi 2009). Knowing the kinematic differences in barefoot runners compared to shod runners is helpful as it defines the degree of adaptation that may be required of an untrained barefoot runner. Lieberman et al. (2010) included trained shod and trained barefoot runners and had all participants perform barefoot and shod running trials (Lieberman et al. 2010). Habitually shod adults included in the study (N=8) tended to rearfoot strike when shod (100%) and most maintained a rearfoot strike when asked to run barefoot (83%). When barefoot runners included in the study (N = 8) ran barefoot, 75% ran with a forefoot strike pattern, which decreased to 37% when the group ran shod (Lieberman et al. 2010). These results (Table 4.2) show that running barefoot does take practice and accommodation as shod runners did not immediately alter their footfall patterns to match their trained barefoot counterparts. Some researchers have been interested in the time it takes runners to alter their footfall pattern. When participants are instructed and cognisant of the changes that need to be made, they are able to match forefoot running kinematics quite closely (Williams, McClay & Manal 2000). From the literature it is apparent that one key aspect of learning to run barefoot or with a forefoot strike pattern is being mindful of the changes that need to take place.

Table 4.2. Comparison of trained barefoot runners to trained runners while shod and barefoot at touch down

	Foot (+ Plantar)		Ankle (+ Plantar)		Knee (+ Flexion)	
	Barefoot	Shod	Barefoot	Shod	Barefoot	Shod
Habitually Shod Adults, USA	-16.4 (4.4)	-28.3 (6.2)	0.2 (3.0)	-9.3 (6.5)	12.1 (7.9)	9.1 (6.4)
Habitually Barefoot Adults, USA	8.4 (4.4)	-2.2 (14.0)	17.6 (5.8)	8.1 (15.9)	17.3 (2.5)	16.6 (2.4)

Table adapted from Lieberman (2010)

4.2.2 Leg Stiffness

The typical sagittal plane kinematics during barefoot and minimal running were highlighted earlier. The changes include a flatter foot landing, increased plantar-flexion at the ankle and increased knee flexion at touch down. It has been mentioned that the lower limb adaptations cause the thigh to be in a more vertical position so that the position of the foot at heel strike is closer to the centre of mass (COM) (Rothschild et al. 2012). Vertical stiffness of the body is calculated by dividing the maximum vertical GRF by the maximum vertical displacement of the COM (Cavagna et al. 1988). It is accepted that vertical stiffness of the center of mass of the body remains constant across different running speeds (Farley, Glasheen & McMahon 1993) while leg stiffness is dependent upon surface stiffness (Ferris, Liang & Farley 1999) and to keep constant total body center of mass stiffness constant. When comparing barefoot to shod running, vertical stiffness and leg stiffness are both higher during barefoot running by $2.6 \text{ kN}\cdot\text{m}^{-1}$ and $0.87 \text{ kN}\cdot\text{m}^{-1}$ respectively (Divert et al. 2005a). Increased stiffness is partially attributed to increased muscle activation prior to touch down (TD) while barefoot in the gastrocnemii and soleus (Divert et al. 2005b). Running economy improves with

increased leg stiffness, which is attributed to an increase in elastic energy storage within the Achilles tendon (Divert et al. 2005a, Dalleau et al. 1998). It would be expected that there is increased strain upon both the Achilles tendon and Longitudinal Arch during barefoot running as the foot dorsi-flexes shortly after TD, stretching the Achilles tendon and flattening the Arch. Perl et al. (2012) measured Achilles tendon and Arch strain while running barefoot with a rearfoot and forefoot strike pattern. This was accomplished by creating an arch between three markers which were located on the medial aspect of the calcaneus, the navicular and first metatarsal head while running on a force instrumented treadmill (Perl, Daoud & Lieberman 2012). There was 44% more vertical strain on the arch while using a forefoot strike pattern (Perl, Daoud & Lieberman 2012). The points discussed within this paragraph show how barefoot running has advantages which are reliant upon the ability of tissues to adapt to new loads placed upon them. The claimed advantages include improved running economy, increased loading on the feet, and increased foot strength.

4.3 Midsole Cushioning

In modern running shoes, cushioning is one of the most important aspects when it comes to marketing and selling a running shoe. This section of the literature review will first discuss how runners (consumers) perceive cushioning followed by analysis of how muscle activity and motor patterns can be changed by midsole properties.

4.3.1 Perception of Cushioning

Biomechanists are often concerned with cushioning properties as it is traditionally thought that risk of injury can be decreased due to the cushioning elements within a shoe (Mundermann, Stefanyshyn & Nigg 2001, Milani, Hennig & Lafortune 1997).

While performance of a product and its ability to decrease risk of injury are important, footwear companies are also interested in perception of cushioning.

Numerous studies have found that runners correlate decreased plantar pressure with increased comfort (Hennig, Valiant & Liu 1996, Hennig 2011, Mundermann, Stefanyshyn & Nigg 2001). Correlation values have been reported as high as $r = +0.95$ when comparing overall liking of a shoe to shock attenuation (Hennig 2011).

For this reason, traditional shoe cushioning has become softer since the early 2000's where there was a trend towards making firmer midsoles (Hennig 2011). Along the same lines as comfort, it has been shown that oxygen consumption is reduced by 0.7% on average (max 1.9%) while running in shoes that are subjectively classified as being more comfortable (Luo et al. 2009). Damping ratios have been calculated for runners while running in their preferred strike pattern and non-preferred strike pattern. Damping ratio of the musculoskeletal system can be defined as the logarithmic decay of an acceleration signal collected from skin mounted accelerometers on the gastrocnemius (Enders, von Tscharner & Nigg 2012). Higher damping ratios mean that there is an increased ability of the lower limbs to attenuate shock. It was found that there are lower damping ratios when running with one's preferred strike pattern, regardless of strike type. It was concluded by the authors that reduced damping ratios might be linked to improved running

economy while using preferred strike patterns which relates back to improved economy while running in comfortable shoes (Enders, von Tscharner & Nigg 2012). It appears that there are benefits from running in what is perceived as a comfortable shoe which is related to improved running economy. There are also benefits from utilizing one's preferred strike pattern which is related to a movement pattern that someone is used to using (Enders, von Tscharner & Nigg 2012, Luo et al. 2009).

4.3.2 Midsole Hardness and Kinetics

Multiple studies have systematically altered midsole hardness while keeping all other features of the shoe consistent (Hennig, Valiant & Liu 1996, Hamill et al. 2011, Nigg et al. 1987, Milani, Hennig & Lafortune 1997, Hardin, Van Den Bogert & Hamill 2004). There is a consensus between published studies that lower limb kinematics are unaffected between shoes with different midsole hardness (Nigg et al. 1987, Hardin, Van Den Bogert & Hamill 2004, Sinclair et al. 2013). Although kinematics may be unaffected, loading rates and plantar pressures vary greatly with different midsole conditions. As midsoles become firmer, the magnitude of the impact peak decreases which is a trend that is also seen in barefoot running, which is attributed to running on a harder surface (Sinclair et al. 2013, Nigg et al. 1987, Hamill et al. 2011, Hennig, Valiant & Liu 1996).

4.3.3 Muscle Activity and Cushioning

Research has investigated the relationship between midsole cushioning and muscle activity because altering this relationship could be related to impact

attenuation and metabolic benefits (Wakeling, Pascual & Nigg 2002, Nigg, Gérin-Lajoie 2011). Material stiffness is often assessed on a scale from 0 – 100, with higher values representing stiffer material. Midsole foam is typically rated on the Shore durometer scale, which indicates the shape of the indenter, and is used to assess the material stiffness. Early work had runners use two shoe conditions which were a hard (Shore 61 C) and a soft condition (Shore 41 C) to see if there were differences in EMG intensity just prior to heel strike (Wakeling, Pascual & Nigg 2002). Wavelet analysis was employed to measure EMG differences between shoe conditions. The advantages of wavelet analyses allow for relative EMG intensities within frequency bands and over time to be quantified (von Tscharnner 2000). Results showed that EMG intensity responses across different frequency bands were subject specific to midsole conditions (Wakeling, Pascual & Nigg 2002). Frequency content of impact to the body while running is in the range of 10 – 20 Hz, while the natural frequencies of soft tissues in the lower limbs is between 10 – 60 Hz (Wakeling, Nigg 2001). It has been hypothesized by Nigg et al. (2001) that the muscles in the lower limbs have increased activation, which increases stiffness, prior to heel impact which acts to shift the frequency range of the soft tissues away and avoid resonance (Nigg, Wakeling 2001). Further work has examined the effect of age gender and midsole hardness on muscle activity while running (Nigg, Gérin-Lajoie 2011). While gender and age had significant effects on muscle activity, midsole hardness did not influence muscle activity for the Gastrocnemius Medialis, Biceps Femoris and Vastus Medialis (Nigg, Gérin-Lajoie 2011).

Cushioning is an important aspect of footwear that is directly related to lower limb kinetic variables and runner's perceptions of footwear comfort (Hamill et al. 2011, Hennig, Valiant & Liu 1996). It has been shown that cushioning is not significantly related to muscle activity and kinematic patterns in the lower limbs (Nigg, Gérin-Lajoie 2011, Nigg et al. 1987, Hardin, Van Den Bogert & Hamill 2004). Cushioning plays a critical role during the impact phase of running which has been associated with the passive component of the vertical ground reaction force (Shorten, Mientjes 2011). The lack of cushioning in minimal footwear may be important for different running abilities in ensuring that kinematic accommodations are paired with appropriate impact attenuation to reduce risk of injury.

2.4 Overuse Injuries

The greatest risk while participating in running is the high incidence of overuse or repetitive strain injuries. Rates of overuse injuries in the literature vary between 30% and 70% of all runners annually (Ferber, Hreljac & Kendall 2009). An overuse injury has been defined as any injury that causes one to reduce mileage or stop running (Taunton et al. 2002). One of the main reasons why minimal footwear has become popular is due to the claimed benefits associated with running barefoot. For this reason, this section will discuss types of overuse running injuries, injuries in novice runners, general tissue responses to repetitive loading and a brief introduction to reduced variability and injuries. This section will serve to set up the following section on variability in motor control, which the second hypothesis is based upon.

4.4.1 Running Injuries

The most common site in the body to become injured from running is the knee (Taunton et al. 2002). A retrospective study conducted by Taunton et al. (2002) included 2002 runners and 42% of injuries occurred at the knee while other studies have found rates to be 50% at the knee (Ferber, Hreljac & Kendall 2009). The single most common injury in runners is Patellofemoral Pain Syndrome (PFPS) or commonly known as runner's knee. Rates have been reported to be around 16.5% while Ilio-Tibial Band Syndrome (ITBS) is the second most common injury occurring 8.4% of the time (Taunton et al. 2002). A study by Daoud et al. (2012) followed college runners over a couple of years and tracked injury rates. Runners were placed into two groups defined by their footstrike pattern. Both rearfoot (RFS) and forefoot (FFS) strikers showed similar injury rates yet different types of injuries (Daoud et al. 2012). Examples of injuries in the RFS group included hip pain, stress fractures above the ankle and shin splints. The FFS group injuries included Achilles Tendinopathy, foot pain and metatarsal stress fractures (Daoud et al. 2012). It was argued that injury rates were similar between the two groups as the participants followed over time were college runners who were conducting heavy training and frequent racing (Daoud et al. 2012).

4.4.2 Injuries in Novice Runners

Research on novice runners is limited yet literature that has examined novice runners consistently shows that they are at a higher risk for overuse injuries (Buist et al. 2010). This factor paired with new found motivation to run in minimal

footwear has the potential to make running in minimal footwear a high risk activity for this group. Incidence rates of running injuries in novice runners range between 12 – 33 per 1000 hours of participation (Buist et al. 2010, Bovens et al. 1989). Incidence rates for trained runners vary greatly between 7 and 59 injuries per 1000 hours of participation (Buist et al. 2008). The term novice runner has been defined as those who have not run on a regular basis for exercise (Buist et al. 2010). Variables that predict running injuries in novice runners include high BMI, participation in sports without axial loading (i.e. swimming, biking) and previous lower limb injury (Buist et al. 2010). These risk factors were collected without regard for type of strike pattern or footwear used. There is no research on minimal footwear in novice runners which makes it difficult to conclude if injury rates would be similar if learning to run while using minimal footwear for the first time.

Earlier research by Buist et al. (2008) looked into the effect of the 10% rule while learning to run. The 10% rule is a common training rule which controls the increase in mileage from week to week (Johnston et al. 2003). Buist et al. (2008) used a 13 week training program for novice runners. Two groups were created, one that followed the 10% progression rule while the other followed a training program which increased mileage by more than 10% per week. Incidence rates did not differ between the two groups over the training program highlighting the fact that the risk of injury is the same if you are conservative or not (Buist et al. 2008). One limitation of this study was that mileage was self-reported with training logs (Buist et al. 2008). Rather than rely upon training logs, GPS has been used in other studies and

the same trend has been found whereby the risk of injury is the same if a runner follows the 10% rule or not (Nielsen et al.). Similar to trained running groups, novice running injuries are most prevalent in the knee region (Buist et al. 2008). The specific injuries to the knee were not collected, but based on previous literature it can be assumed that PFPS and ITBS are the most common (Taunton et al. 2002).

4.4.3 Tissue Response to Repetitive Loading

Runners experience repetitive impacts for long periods of time. Wolff's law suggests that bone will adapt to the loads placed upon it (Wolff 1986). This law is a good example of the plasticity or adaptability of the musculoskeletal system. However, tolerances of bone must be considered to reduce risk of injury. Increased loading upon biological tissue is beneficial, but if acute injury tolerances are exceeded, risk of injury is dramatically increased (McGill, Cholewicki & Peach 1997). Barak et al. (2011) conducted a study where the direction of applied load was altered in order to show how formation of trabecular bone orientation responds. Two groups of sheep were included, one which trotted on a level treadmill, the other which trotted on an inclined treadmill (7°). Trabecular orientation was altered in the inclined trotting group, thus supporting Wolff's Law (Barak, Lieberman & Hublin 2011). It is clear that bone adapts to loads placed upon it (Barak, Lieberman & Hublin 2011, Turner 1998). It is known that there is a range of normal loading where bone adaptation is minimal. When loading is outside the normal range, bone remodelling will increase or decrease (Frost 1990, Frost 1987). Figure 4.1 was adapted from Turner (1998) and shows the normal range for bone remodelling.

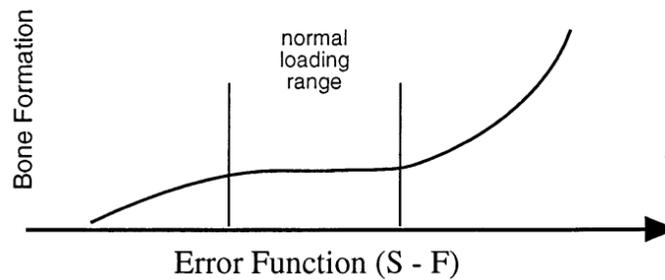


Figure 4.1. Normal loading range is shown. Error function on the x - axis is the difference between daily stimulus (S) and normal loading (F).

When a novice starts to run, bone formation may take place as the daily stimulus is greater than the normal loading. Tissue tolerance must be considered in the equation as bone formation requires adequate rest. Tissue tolerance may be very different in novice runners compared to trained runners whose normal loading range is much higher in comparison. Decreased tolerance and a sudden increase in stimulus may be a situation where risk of injury is extremely high.

Tissue that is exposed to repetitive loading will fail if enough cycles are repeated without time for adequate recovery. Research where the porcine spine is repetitively flexed and extended under compressive load shows that disc herniation can be induced systematically (Callaghan, McGill 2001). Although not directly related to the bone remodelling discussion above, movement that is repetitive in nature has the ability to decrease tissue tolerance, which is related to the aforementioned scenario (McGill 1997). It is clear that a relationship exists between bone remodelling, stimulus (activity) and tissue tolerances. These factors relate to the purpose of this thesis as novice runners may adapt to minimal footwear in different ways compared to trained runners.

4.5 Variability in Motor Control

Variability in biomechanics research has received increased attention within the past ten years (Stergiou, Decker 2011, Hamill, Haddad & McDermott 2000, Hamill et al. 1999, Meardon, Hamill & Derrick 2011). Variability has traditionally been treated as noise in the musculoskeletal system as there should be an optimum movement to achieve a defined goal (Bartlett, Wheat & Robins 2007, van Wegen 2000). Recently, variability has been given more credit as it allows for flexibility and adaptation in movement (van Wegen 2000). This section will touch upon healthy variability and how it is quantified. It is important to note that discussing variability in motor control is context specific. Increased body sway measures in older adults have typically been linked to that population being unstable (Woollacott, Shumway-Cook & Nashner 1986). However, in Parkinson's patients, there is markedly reduced sway yet this population is known to have issues with postural stability (Rocchi, Chiari & Horak 2002). More sway may not necessarily mean one's balance is unstable, it has been postulated that increased sway may be an exploratory behaviour in the healthy motor control system (Riccio 1993). Reduced variability in running has been linked to improved motor control to an extent (Nakayama, Kudo & Ohtsuki 2010), while severe reduction is linked to PFPS (Hamill et al. 1999). Stergiou et al. (2006) have presented the optimal movement variability model, which suggests that complexity and predictability of movement interacts to create an inverted U- shape relationship. Figure 4.2 was adapted from Stergiou & Decker (2011) and shows how optimal variability can exist by plotting three examples; white noise (Random), the Lorenz attractor (Chaotic) and a sine wave (Periodic).

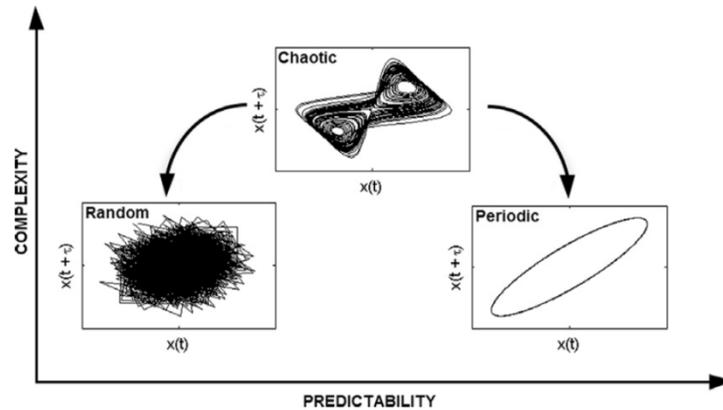


Figure 4.2. The optimal movement variability model presented by Stergiou & Decker (2011).

Predictability of a system can be quantified using the maximal Lyapunov Exponent (LyE). Jordan *et al.* (2009) stated that “the LyE quantifies the average rate of divergence of initially nearby trajectories in state space over a specified time interval”. Using the example from figure 4.2, the maximum LyE for random noise is 0.469, while the LyE for the sine wave is -0.001 (Stergiou, Decker 2011). As predictability in a signal increases, the rate of divergence between neighbouring trajectories becomes insignificant resulting in lower LyE. LyE values are specific to the data set analyzed and it has been noted that the importance should be placed upon how the LyE is influenced by independent variables as opposed to the magnitude of the values (Rosenstein, Collins & De Luca 1993).

4.5.1 Variability in Running

Variability in physiological functions has been shown to be a healthy attribute allowing for flexibility and adaptation (van Wegen 2000). Specific to

running, variability may be beneficial as there is a broader distribution of stress among different tissues (Hamill et al. 1999). Distributing stress avoids the same internal structures from being repetitively overloaded. There is some evidence that variability increases as underfoot material becomes harder (Altman, Davis 2012, Tenbroek 2011). Altman & Davis (2011) compared trained barefoot runners to shod runners and measured trial to trial variability using standard deviation. Barefoot runners showed increased variability in kinetic measures such as Strike Index (SI), vertical instantaneous loading rate (VILR / maximum loading for a given stride) and vertical average loading rate (VALR / average loading for a given stride). Both magnitude and variability in these dependent variables were significantly different between groups. Ankle and knee angles were also measured at heel strike between the groups of interest. Knee angle values in the barefoot and shod groups were -21.3° (4.0°) and -12.7° (3.0°) while ankle angles were -1.2° (3.6°) and 8.0° (7.9°). The magnitude of joint angles was different between the groups, yet trial to trial variability was not significantly different for these kinematic measures (Altman, Davis 2011).

Measures that fall under dynamic systems theory include continuous relative phase (CRP) which allows for the relationship between two segments to be understood (Hamill, Haddad & McDermott 2000). CRP has been employed by Tenbroek (2011) to investigate the relationship between footwear with different midsole thicknesses. Results from this work compliment Altman & Davis's (2011) findings as the relationship between Shank_{Fl/Ext} and Foot_{Fl/Ext} is insensitive to different midsole thickness, which is related to peak underfoot pressure (Tenbroek

2011). CRP relationships that were affected by midsole thickness include Thigh_{Fl/Ext} – Shank_{Rot}, Thigh_{Ab/Ad} – Shank_{Rot}, Shank_{Rot} – Foot_{Ev/In}. Variability was always greatest in the barefoot condition compared to all shod conditions.

4.5.2 Lyapunov Exponents

Calculating the maximum LyE gives insight into the predictability of a system (Rosenstein, Collins & De Luca 1993). Determining the LyE requires reconstruction of the signal in state space for the original time series and its time delayed copies (Jordan et al. 2009). Prior to computing LyE, one must determine the reconstruction lag and embedding dimension to use. The reconstruction lag determines the number of successive data points that are used in analysis (Stergiou 2004). If the reconstruction lag is too small, successive data points in state space may be too close to be independent (Stergiou, 2004). On the other hand, if the reconstruction lag is too large, the data points may be too far apart and make the signal more random than it truly is (Stergiou 2004). The reconstruction delay is often determined by using an autocorrelation, or the average mutual information algorithm of the signal to obtain an idea of the frequency of oscillation (Rosenstein, Collins & De Luca 1993, Abarbanel 1996).

Determining the correct embedding dimension to use has been completed by using a false nearest neighbour's algorithm (Abarbanel, Kennel 1993). Similar to determining the reconstruction lag, if the number of embedding dimensions is too small, the number of false nearest neighbours will be too large, giving a misrepresentation of the LyE (Stergiou 2004). If the embedding dimension is too

large, the closest neighbours become too far apart and make the signal appear more random than it truly is.

Once the reconstruction lag and embedding dimension are determined, the average rate of separation for all pairs of neighbours is calculated and is equal to the LyE (Jordan et al. 2009). The embedding dimension for kinematic data is normally 5, while the reconstruction lag is subject specific as it is related to stride frequency.

The equations used to calculate the LyE can be found in Appendix 1.

Applications for using LyE include understanding motor control development, effect of fatigue on kinematics, and walk to run transitions (Cignetti, Schena & Rouard 2009, Dusing, Harbourne 2010, Jordan et al. 2009). Findings pertinent to the topic of this thesis include a study that compared lower limb variability during treadmill and overground walking (Dingwell et al. 2001). LyEs were computed for ankle, knee and hip sagittal kinematics and acceleration signals from overground walking trials and treadmill walking trials (Dingwell et al. 2001). Treadmill walking had a lower maximum LyE, which means that there is increased local dynamic stability. It was explained that local dynamic stability may be increased on a treadmill due to the constant belt speed or the differences in surface stiffness between the ground and the treadmill (Dingwell et al. 2001).

Calculation of LyE in biomechanics requires successive strides of information (Stergiou 2004). Due to the constraint of collecting continuous data over time, fatigue may become a confounding factor in measuring local dynamic stability. When elite cross country skiers were pushed to fatigue, it was found that there was more instability in lower limb kinematics (Cignetti, Schena & Rouard 2009). This is

an important finding with respect to this thesis as novice runners will be running continuously in order to quantify LyE. Ankle, knee and hip sagittal plane kinematics will be utilized in estimating the largest LyE. Control over this aspect of the thesis is discussed in the methods section.

CHAPTER 5.0 General Methods

Methods that are common between the overground running chapter (6.0) and the local dynamic stability chapter (7.0) have been placed here, in a general methods section to reduce the amount of redundancy. Methods that are specific to each study can be found within their respective chapters.

Participants

Twenty four male participants were recruited to participate in this study. A novice runner and trained runner group were created with each group consisting twelve participants. Selection criteria for the groups were as follows: novice runners ran less than a total of 10 km within the past year (Bertelsen et al. 2012), while trained runners ran a minimum of 30 km per week on average. All participants had to be free from injury within the past three months and have had no experience using any type of product that had been marketed as a barefoot / minimal running shoe. This study received ethics clearance from the University of Waterloo's Office of Research Ethics review board prior to participant recruitment.

Footwear

Four shoe conditions were included in this study. Both the material stiffness and thickness were manipulated to differentiate minimal shoes from traditional shoes. The two levels of material stiffness that were used included 40 Asker C (Soft) and 70 Asker C (Hard). Two variables that are manipulated with running shoe

construction include stack height and heel to toe drop. Stack height is defined as the thickness of the midsole whereas heel to toe off set is the difference between the heel region's height and the forefoot regions height. Stack height and heel toe drop were different between the minimal and traditional shoes. For the minimal shoes, stack height was 13 mm and the heel to toe drop was 4 mm. For the traditional shoes, stack height was 20 mm and the heel to toe drop was 12 mm. For improved control, the same upper was used for all shoe conditions and would fall into a traditional construction category.



Figure 5.1. Four different shoe conditions were used based on altering midsole thickness and material stiffness

CHAPTER 6.0

Kinematic and Kinetic Comparison of Novice Runners to Trained Runners in Traditional and Minimal Footwear

6.1 Introduction

Running for fitness can be rewarding, but requires the individual to stay motivated and injury free. Novice runners typically utilize a rearfoot strike (RFS) pattern in traditional shoes and can be defined as those who run less than a total of 10 km per year (Bertelsen et al. 2012, Nielsen et al. 2013). In comparison, trained runners have been shown to use a RFS about 70% of the time with the remaining 30% using either a midfoot or forefoot strike pattern (Hasegawa, Yamauchi & Kraemer 2007). Novice runner injury reports indicate that medial tibial stress syndrome and patella-femoral pain syndrome are two common pathologies in this population (Nielsen et al. 2013). It is known that higher loading rates occur when a RFS is used compared to a midfoot (MFS) or forefoot (FFS) pattern (Goss et al. 2012, Lieberman et al. 2010). Additionally, higher loading rates have been associated with increased prevalence of stress fractures in runners (Zadpoor, Nikooyan 2011). In recent years, minimal shoes have increased in popularity and are specifically designed with less cushioning in order to mimic running while barefoot. It is presumed that all types of runners are using minimal footwear and there is a potential risk of injury in novice runners who may use a RFS while in a shoe with less cushioning. Risk of injury may be influenced by using a RFS in minimal shoes paired with less running experience. There is currently no previous work

investigating how novice runners respond to running in minimal footwear in comparison to trained runners.

Regardless of one's running experience, high vertical loading rates are associated with increased risk of stress fractures (Zadpoor, Nikooyan 2011). Increased cushioning in footwear has been shown to lower these loading rates via foam deformation thus extending the time to impact peak (Hamill et al. 2011, Sterzing et al. 2013). A recent study recruited experienced runners who ran in minimal shoes. When asked about their strike pattern, all who ran in minimal shoes claimed to use a midfoot strike pattern as recommended. However, after having their strike pattern measured in the lab, it was found that 34% of self-reported midfoot strikers, actually use a rearfoot strike without knowing (Goss, Gross 2012). Those who used a rearfoot strike pattern in minimal shoes had vertical loading rates that were 157% greater than runners who use a rearfoot strike pattern in traditional cushioned shoes (Goss, Gross 2012). These findings suggest that even if someone is making a conscious effort to use a midfoot strike, they may not be executing the movement properly.

Bone is known to respond to applied mechanical stimuli. Bone remodeling occurs if stimuli are greater than or less than typical loading patterns (Turner 1998). When comparing a group of trained runners to people who do not run, it may be assumed that the typical accumulation of axial loading experienced by trained runners is greater throughout a typical day. For this reason it seems even more important to investigate loading in novice runners, as they may be experiencing greater relative loading than they typically would regardless of the shoe they are

wearing. Recent work using bone marrow edema scores as a marker of bone stress has shown that over a ten week transition program, 53% (10/19) of runners in a minimal shoe group presented stress fracture syndromes compared to only 6% (1/16) in a traditional shoe group (Ridge et al. 2013). This work highlights that even when a conservative transition to minimal shoes is taken in trained runners, there is still risk of injury to the bones of the feet. Footwear can be made with different material stiffness and in different thicknesses which have the ability to influence running kinematics and kinetics.

Minimal shoes vary in midsole and upper design across manufacturers. Factors such as stack height, heel to toe drop and material stiffness dictate the degree to which a minimal shoe is similar or dissimilar to a barefoot condition. Midsole thickness and stiffness have been investigated previously in trained runners (Sinclair et al. 2013, Gruber et al. 2013, TenBroek et al. 2013, Sterzing et al. 2013). It has been hypothesized that thicker midsoles promote a rear foot strike pattern (Horvais, Samozino 2013). Increasing stack height and heel to toe drop has been shown to increase dorsi-flexion upon landing by up to 3° (TenBroek et al. 2013). Along with increased dorsi-flexion at the ankle, the knee also becomes more extended in traditional shoes compared to thin shoes (TenBroek et al. 2013). In other work, using a more conservative minimal shoe, it has been shown that there is only a 1° change at the knee compared to traditional shoes, which is probably not a functional difference (Sinclair et al. 2013). This example highlights the spectrum of minimal footwear available to consumers, as well as the wide array of kinematic adaptations that have been observed in the literature.

When surface stiffness is manipulated, it has been found that most trained runners use a rearfoot strike pattern on a soft foam surface comparable to the same amount of cushioning in running shoes (55 Asker C) (Gruber et al. 2013). When the same runners were required to run on a hard surface, only 43% of rearfoot strikers converted to a midfoot or forefoot strike (Gruber et al. 2013). Similarly, when shoes were constructed with a hard midsole in the heel region, vertical loading rates increased compared to shoes constructed with soft midsoles in the heel region for the same given strike pattern (Sterzing et al. 2013). This indicates that if the strike pattern remains constant while surface stiffness is increased, loading rates are expected to increase as well. Both midsole thickness and material stiffness have the potential to influence footstrike patterns in a portion of the running population. It is those runners who do not convert their strike pattern in thin and stiff shoes who may be at risk of injury. It remains unknown how novice runners differ from trained runners in traditional and minimal shoes.

The purpose of this work was to compare landing kinematics and kinetics between trained and novice runners in minimal and traditional shoes. It was hypothesized that novice runners will use a rearfoot strike pattern to a greater degree in all shoe conditions compared to trained runners. Consequently, it is hypothesized that vertical average loading rates and instantaneous vertical loading rates will be higher in novice runners compared to trained runners. It is also suggested that loading rates will be higher in minimal shoes constructed with less cushioning. Novice runners will have an increased foot landing angle with respect to the horizontal plane and increased knee extension upon landing which is associated

with a rearfoot strike pattern as predominantly used by this population (Bertelsen et al. 2012).

6.2 Methods

Experimental Setup

Ground reaction forces were collected with four AMTI force plates (OR6, AMTI, Watertown, MA) sampling at 1000 Hz. The force plates were arranged in a two by two configuration as seen in figure 6.1.

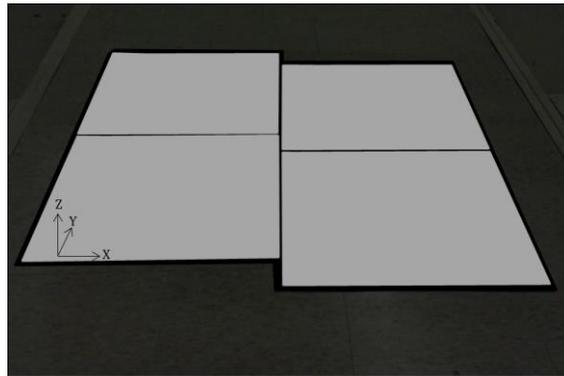


Figure 6.1. Force plate configuration in the lab

Timing gates were set up around the force plates and were set to a distance of 3.84 meters apart spanning the force platforms. Running speed was set to 3.84 m/s for all participants and all shoes. Kinematic data were collected using an Optotrak motion capture system (NDI, Waterloo, ON), sampled at 100 Hz. Rigid bodies were placed on the pelvis, right thigh, shank and foot to track the segmental motion (Figure 6.2). The pelvis and foot rigid bodies each consisted of five markers, while the thigh and shank clusters each consisted of six markers. A digitizing probe was used to define each segment. Digitized points on the pelvis included; right and left posterior superior iliac spine, iliac crests, anterior superior iliac spines and

greater trochanters. The thigh was defined from the right greater trochanter to the lateral and medial epicondyle. The shank was defined from the lateral and medial epicondyles to the lateral and medial malleoli. Digitized points on the foot included the medial and lateral epicondyles, the most posterior point of the sole of the shoe, the head of the 5th and 1st metatarsals and the most anterior part of the shoe sole. Each of the four shoes had its own rigid body and the foot segment was re-digitized between each condition. Marks on the malleoli were used to improve between shoe reliability.



Figure 6.2. Participant with rigid bodies placed on the foot, shank, thigh and pelvis

Protocol

Shoe order was randomized within each group and matched between the novice and trained groups. For each shoe, participants ran along a 36 m runway within the lab. Ten acceptable trials were collected in each shoe. Criteria for an acceptable trial included landing of the right foot upon any of the force platforms and running at the proper speed \pm 5%. Participants had no knowledge that ground reaction forces were being collected, which helped prevent targeting of the force

plates. A standing calibration trial was collected prior to each shoe condition in order to normalize joint angles.

Data Analysis

Data were processed using Visual 3D V 4.85.0 (C-Motion Inc., Germantown, MD). Kinematic and kinetic data were filtered using a 2nd order dual pass Butterworth filters with cutoffs of 15 Hz and 100 Hz, respectively. Missing data points were interpolated using a 3rd order cubic spline up to a maximum of 15 frames.

A rigid link model was constructed consisting of the pelvis, right thigh, shank and foot. The hip and knee joint centers were determined from functional joints (Schwartz, Rozumalski 2005). Functional joints are determined by using an iterative process whereby the point of rotation about two adjacent segments is determined using a search radius (Schwartz, Rozumalski 2005). Two functional trials were collected and each had a length of 30 seconds. For the functional hip trial, participants were instructed to flex and extend the hip, abduct and adduct followed by circumduction. For the functional knee trial, flexion/extension was conducted for the full 30 seconds. The ankle joint center was defined as the midway point between malleoli markers.

Contact upon the force plate was determined when the vertical force exceed 15 N. This event was then used to determine landing kinematics for the ankle, knee, hip and shoe sole angle relative to the global coordinate system. Kinematic profiles for the ankle knee and hip were normalized to 100% stride. 0% was corresponded

with right toe off one full stride preceding the force plate while 100% was right toe off from the force plate. Kinematic dependent variables included ankle, knee, hip and foot angles upon heel contact.

Ground reaction forces were normalized to participant's body weight. The vertical ground reaction force was used to calculate vertical average loading rate (VALR), instantaneous vertical loading rate (VILR) and impact peak magnitude (IP). VILR was defined as the single highest value of the slope from contact to impact peak. If no impact peak was present the VILR was the highest slope value up to peak vGRF. Impact peak magnitude was defined as the local maxima in body weights. If no impact peak was present, the value at 13% stance was used for IP. VALR was defined as the average slope of the vertical GRF from 20% to 80% of the impact peak (Lieberman et al. 2010, Altman, Davis 2011). If no impact peak was present the 13% rule was used to define what 20% and 80% would be along the curve.

Strike index was calculated as the position of the center of pressure relative to the length of the foot at heel contact (Cavanagh, LaFortune 1980). A separate local coordinate system was created to allow for representation of the center of pressure with respect to the total length of the foot. This local coordinate system was defined as the distance between the heel and tip of the shoe. This approach is advantageous as it takes into account any rotation of the foot with respect to the anterior-posterior global coordinate system.

Statistics

A three way mixed general linear model was used for analysis. Between subject factors included running group, which contained two levels of novice and

trained runners. Within subject factors included midsole thickness and material stiffness. Midsole thickness consisted of two levels; which were minimal and traditional. Material stiffness had two levels, which were hard and soft. Individual paired t-tests were conducted for all significant interactions. Alpha was set to 0.05 prior to conducting the experiment. Cohen’s *d* effect sizes were calculated for values that were between an alpha value of 0.1 and 0.05.

Table 6.1. Each of the factors that were used in the GLM. Their corresponding levels can be found in adjacent cells.

Independent Variables		Dependent Variables	Statistical Model
Factor	Level		
Running Group (Between Subjects Factor)	Novice vs. Trained	<u><i>Kinematics</i></u> Sagittal Foot θ @ Heel Strike Sagittal Ankle θ @ Heel Strike Sagittal Knee θ @ Heel Strike Sagittal Hip θ @ Heel Strike <u><i>Kinetics</i></u> VILR VALR Impact Peak Magnitude Strike Index	3 Way Mixed Linear Model ANOVA
Midsole Thickness (Within Subjects Factor)	Traditional vs. Minimal		
Material Stiffness (Within Subjects Factor)	Soft vs. Hard		

6.3 Results

Overall, it was found that novice runners land with increased knee extension compared to all trained runners regardless of shoe condition. The ankle and hip landing angles were similar between the two running groups. Additionally, traditional midsole thickness caused all runners to land with increased ankle dorsiflexion compared to the minimal thickness. Vertical loading rates were influenced by midsole thickness and material stiffness. Lower vertical loading rates were observed while running in traditional shoes and in shoes with soft midsoles. Only one out of twelve novice runners converted their strike pattern while running in the

minimal shoe conditions while the remainder used a rearfoot strike pattern across all shoe conditions.

Participants in the trained running group ran 61.7 km/week on average. The novice running group confirmed that they ran less than a total of 10 km in the past year. Demographic results can be found on table 6.2. Groups only differed in body mass as the novice runners were heavier on average compared to trained runners ($P < 0.02$). All kinetic variables concerned with mass were normalized to the participant's body weight.

Table 6.2. Participant demographics.

	Novice	Trained
Age (Y)	21.5 (2.71)	23.3(5.82)
Height (m)	1.77 (0.06)	1.75(0.05)
Weight (Kg)	75.8 (9.8)	68.3(5.1)
Weekly Mileage (km/week)		61.7(28.2)
Easy Training Pace (min/km)		4:37(0:23)
<u>Hard Training Pace (min/km)</u>		<u>3:36(0:20)</u>

Kinematics

Landing kinematics differed between shoes and groups in several ways. The foot angle upon ground contact was influenced by thickness of the midsole ($F_{1,22} = 15.42, p < 0.001$). The average foot landing angle in thin shoes across all subjects was 17.8° (8.5°) and 21.7° (8.1°) for the shoes with traditional midsoles (Figure 6.3).

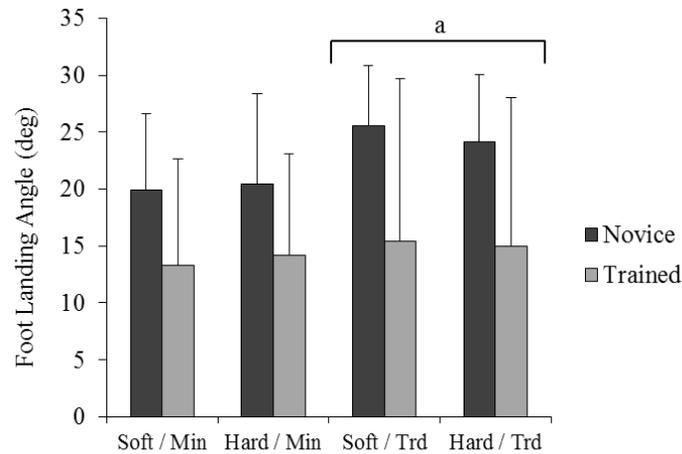


Figure 6.3. Foot landing angle for running groups and shoe conditions. A main effect of thickness is shown ($p < 0.05$).

Foot landing angle between novice and trained runners was not statistically significant ($F_{1,22} = 3.35$, $p = 0.08$, $d = 0.70$), with the novice group landing at an average of 22.5° (6.8°) across all shoes while the trained group's foot landing angle was 16.9° (9.2°) across all shoe conditions.

Ankle angle at ground contact was influenced by a main effect of midsole thickness ($F_{1,22} = 19.43$, $p < 0.001$). The ankle was more dorsi-flexed by 3.3° in shoes constructed with traditional midsoles compared to shoes with thin midsoles. There were no differences between the novice and trained running group for the ankle angle ($p = 0.35$). For the knee angle upon landing, novice runners landed with increased knee extension compared to the trained running group ($F_{1,22} = 8.27$, $p = 0.009$). Material stiffness and midsole thickness did not influence the knee kinematics at heel contact. No differences were found for the hip landing angle across all independent variables.

Table 6.3. A breakdown of the proportion of runners who utilized different strike patterns across all shoe conditions. Note how often novice runners use a rearfoot strike pattern.

	Trained				Novice			
	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional
% FFS	8.3%	8.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% MFS	16.7%	16.7%	16.7%	25.0%	8.3%	8.3%	0.0%	0.0%
% RFS	75.0%	75.0%	83.3%	75.0%	91.7%	91.7%	100.0%	100.0%

Strike index results showed a trend towards a three-way interaction ($F_{1,22} = 4.058, p = 0.056$). The trained running group's strike index increased in minimal hard shoes while the novice group's strike index decreased in minimal hard shoes compared to the minimal soft shoes. It should be noted that the decrease in strike index in the novice group was from 8.5% to 8.1% and the increase in the trained group was from 18.0% to 20.1% (Table 6.4).

Table 6.4. Mean (SD) kinematic dependent variables at heel strike for all shoe conditions

	Trained				Novice				Sig.
	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	
Foot (°)	15.3	15.3	18.5	18.4	19.9	20.5	25.5	24.2	a
S.D	(9.1)	(9.6)	(9.4)	(9.2)	(6.7)	(7.9)	(5.4)	(5.8)	
Ankle (°)	2.5	3.1	5.4	5.5	4.8	5.4	9.4	8.9	a
S.D	(9.8)	(10.2)	(9.6)	(10.0)	(6.2)	(6.0)	(4.1)	(4.6)	
Knee (°)	-14.3	-15.1	-14.0	-14.3	-9.5	-10.4	-9.8	-9.7	c
S.D	(4.7)	(4.2)	(3.1)	(4.5)	(4.6)	(4.4)	(4.0)	(5.4)	
Hip (°)	30.8	30.5	30.2	31.6	32.8	32.7	32.7	34.0	
S.D	(5.2)	(5.4)	(7.1)	(5.4)	(4.5)	(5.1)	(3.8)	(4.6)	
S.I (%)	18.0	20.1	17.5	18.9	8.5	8.1	5.9	7.3	
S.D	(23.3)	(23.5)	(21.2)	(21.0)	(12.2)	(15.2)	(1.9)	(7.3)	

a denotes a main effect of thickness ($p < 0.05$)

b denotes a main effect of stiffness ($p < 0.05$)

c denotes a main effect of group ($p < 0.05$)

Ensemble kinematic profiles for the ankle, knee and hip were generated for each participant in each shoe condition (Figure 6.4). Examination of the profiles revealed that the knee and hip profiles were unaffected by shoe condition while the ankle angle was. The bottom row of figure 6.4 shows a novice runner who was the only participant to convert their strike pattern between minimal and traditional shoes. The ankle profile for the participant shows increased dorsiflexion in late swing and early stance while running in traditional soft and traditional hard shoe conditions, indicating that a rearfoot strike pattern was used.

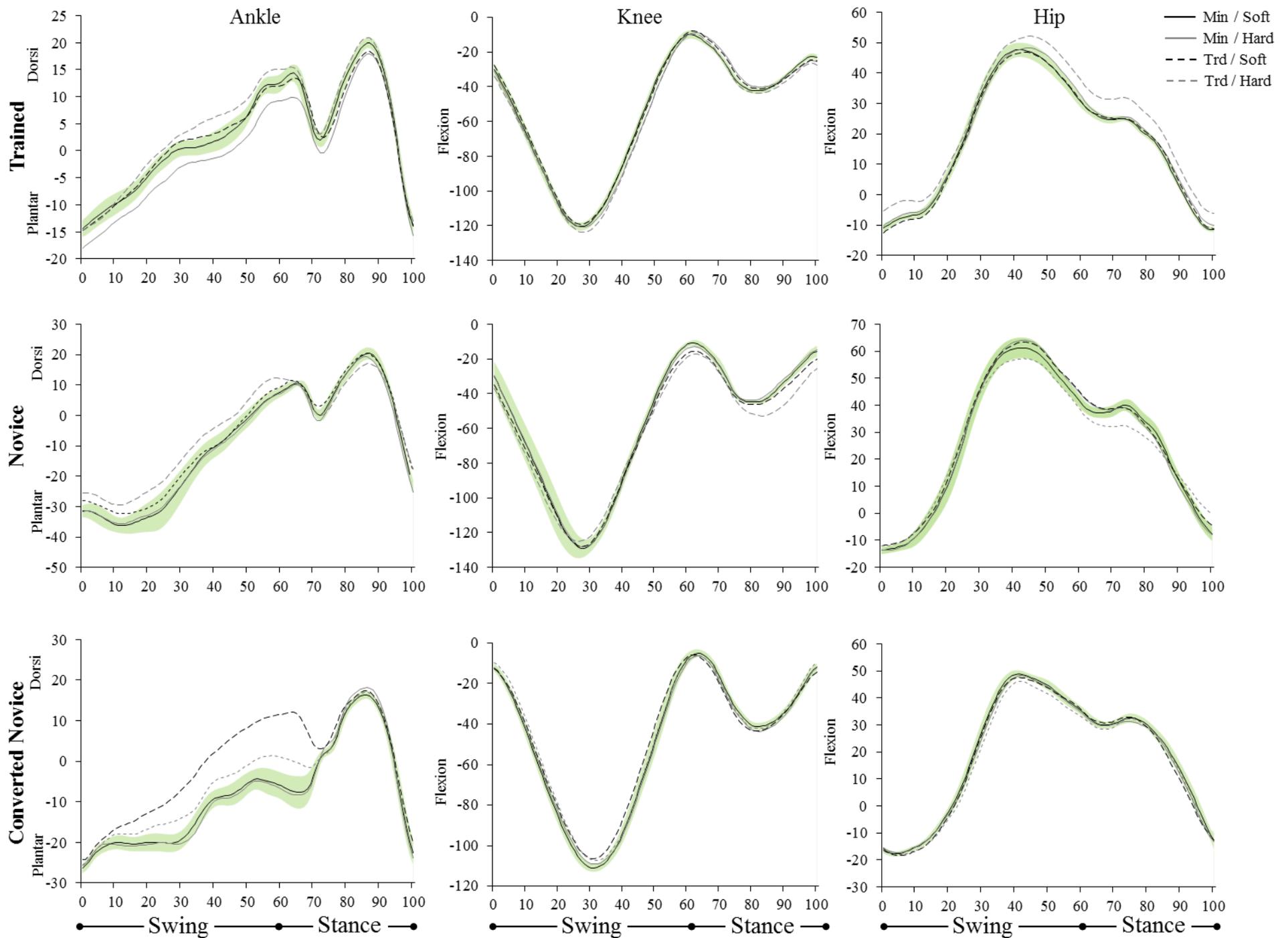


Figure 6.4. Kinematic profiles of the ankle knee and hip for three different participants. The green band represents ± 1 S.D for the minimal soft shoe and gives an indication of the amount of variability within a shoe condition. The top row displays an exemplary trained runner who has different ankle profiles between the traditional hard and minimal hard shoes. The middle row is an exemplary novice runner who landed with increased dorsi flexion in traditional footwear. The bottom row displays the only novice runner who converted their strike pattern between minimal and traditional footwear. Note the large change between conditions in the ankle profile but lack of change in the knee and ankle profiles.

Kinetics

Lower instantaneous and vertical average loading rates were found in shoes constructed with thicker, traditional midsoles and soft midsoles as seen on Figure 6.5 ($p < 0.05$). A main effect of thickness lowered the VILR from 147.6 BW/s in minimal shoes to 124.6 BW/s in traditional shoes ($F_{1,22} = 23.40, p < .001$). Similarly, a main effect of stiffness lowered instantaneous vertical loading rates from 139.7 BW/s in shoes with hard midsoles, to 132.4 BW/s in shoes with soft midsoles ($F_{1,22} = 5.24, p = 0.03$). No between group differences were found for VILR ($F_{1,22} = 0.97, p = 0.34, d = 0.34$).

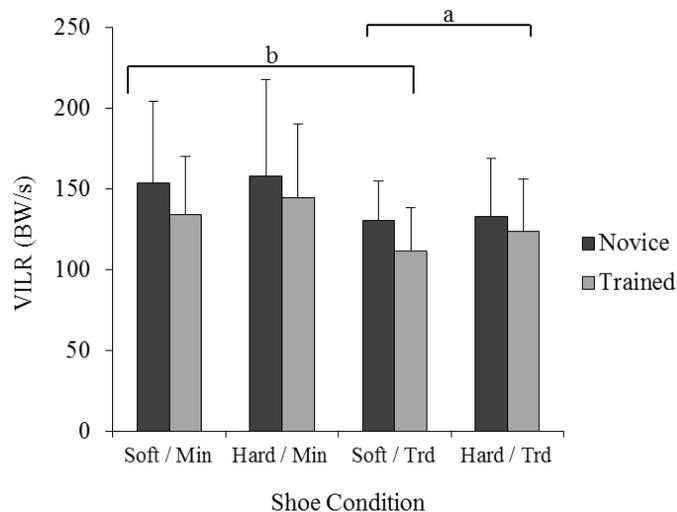


Figure 6.5. Vertical instantaneous loading rate was not significantly different between novice and trained runners. The letter "a" denotes a sig. main effect of thickness ($p < 0.05$). The letter "b" denotes a sig. main effect of stiffness ($p < 0.05$).

VALR was lower in traditional shoes and shoes with softer midsoles. VALR was lower by 8 BW/s in traditional shoes compared to minimal shoes ($F_{1,22} = 13.06, p = 0.002$). Shoes with soft midsoles had VALR that were 5.7 BW/s lower than shoes with hard midsoles and can be found on table 6.5 ($F_{1,22} = 22.93, p < 0.001$). No main effect of group was calculated for VALR ($F_{1,22} = 2.24, p = 0.15, d = 0.55$).

A significant interaction between midsole thickness and material stiffness existed for impact peak magnitude as seen on figure 6.6 ($F_{1,22} = 7.88, p = 0.01$). *Post-hoc* analysis revealed that minimal shoes had similar impact peak magnitudes between both soft (1.87 BW) and hard (1.86 BW) midsoles ($p = 0.70$) while traditional shoes had larger differences between soft (1.99 BW) and hard (1.87 BW) ($p = 0.002$). The main effect of group was not significant ($F_{1,22} = 2.96, p = 0.087, d = 0.69$).

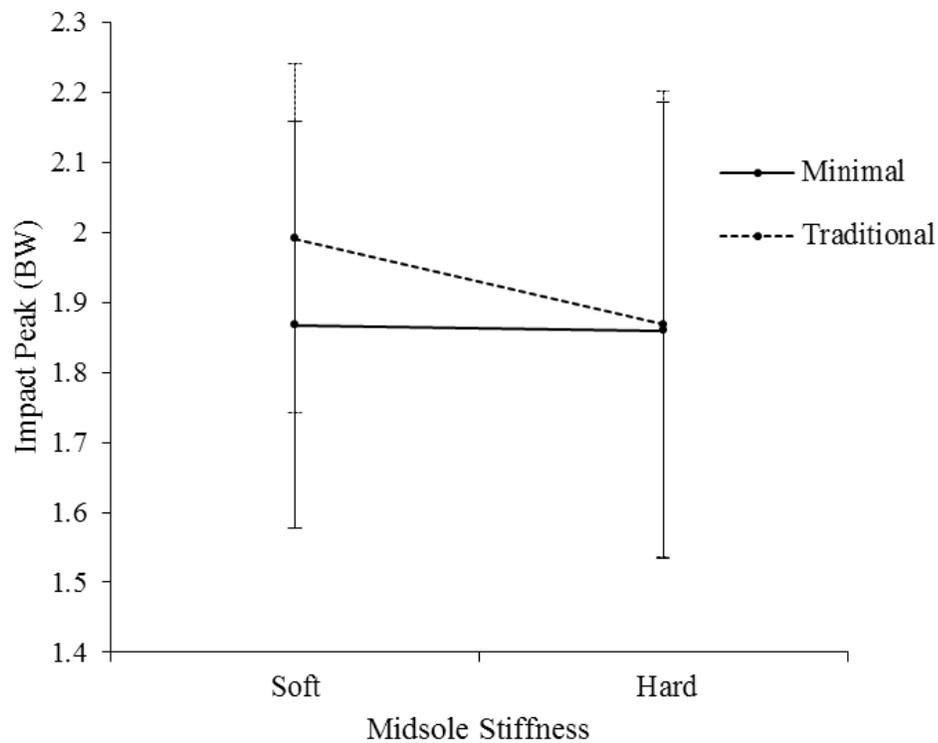


Figure 6.6. Significant interaction for the impact peak between midsole thickness and material stiffness. The soft traditional shoes had a larger impact peak in comparison to the traditional hard shoes.

Table 6.5. Mean (SD) kinetic variables calculated from the vertical ground reaction force.

	Trained				Novice				Sig.
	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	
IVLR (BW/s)	134.3	144.3	111.7	123.7	153.4	158.3	130.3	132.7	a, b
S.D	(35.7)	(45.8)	(26.6)	(32.3)	(51.3)	(59.4)	(24.5)	(36.4)	
AVLR (BW/s)	70.5	76.3	62.0	69.3	80.1	84.1	72.2	77.7	a, b
S.D	(12.6)	(15.6)	(13.6)	(12.9)	(20.4)	(23.4)	(13.2)	(14.0)	
I.P (BW)	1.8	1.8	1.9	1.7	2.0	1.9	2.1	2.0	d
S.D	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)	(0.3)	(0.2)	(0.3)	

a denotes a main effect of thickness ($p < 0.05$)
b denotes a main effect of stiffness ($p < 0.05$)
c denotes a main effect of group ($p < 0.05$)
d denotes a stiffness x thickness interaction ($p < 0.05$)

6.4 Discussion

Novice versus Trained Runners

Similar to other findings, this experiment found that 100% of novice runners used a rearfoot strike pattern in traditional shoes (Bertelsen et al. 2012). While running in minimal shoes, eleven out of twelve novice runners continued to used a rear foot strike pattern with only one novice participant demonstrating a change of their strike pattern to a midfoot pattern. Additionally, trained runners used a rearfoot strike pattern 79% of the time in traditional shoes and 75% of the time in minimal shoes. These values are consistent with previously published results showing that trained runners use a RFS pattern 75% of the time (Hasegawa, Yamauchi & Kraemer 2007).

Foot landing angle was not different between novice and trained runners ($P = 0.056$), however, the effect size ($d = 0.7$) indicates that there was a trend towards a

difference in foot landing angle in more experienced runners. The trained running group consisted of a larger proportion of midfoot and forefoot strikers. For this reason, the trained running group as a whole had lower foot landing angle. Moreover, the trained running group included midfoot and forefoot strikers, which resulted in greater variability across the group of trained runners compared to the novice group.

Interestingly, novice runners had increased knee extension at heel contact compared to trained runners. Increased knee extension in the novice group has implications for the types of injuries that are experienced by novice runners. Recent work has shown that injury rates do not differ between motion control and neutral running shoes (Nielsen et al. 2013). More importantly, it was found that two of the most common injuries in novice runners are medial tibial stress syndrome (shin splints) and patellofemoral pain syndrome (Nielsen et al. 2013), which are similar to common injuries in trained runners (Taunton et al. 2002). Development of patellofemoral pain syndrome has been linked to increased knee extension during drop landings in naval recruits (Boling et al. 2009). Recent work has revealed that patellofemoral stress is lower while barefoot running (Bonacci et al. 2013). Participants ran in barefoot and shod conditions and patellofemoral stress was calculated for each condition (Bonacci et al. 2013). Patellofemoral stress was lower in barefoot running which was attributed to lower peak knee extensor moments at midstance (Bonacci et al. 2013). Novice runners who land with increased knee extension may potentially have higher risk of PFP development compared to those who land with a less extended knee. Furthermore, knee angles were similar across all shoe conditions, which means that this difference may come with increased running experience and was not related to the shoe condition being worn.

Minimal versus Traditional Shoes

It was found that midsole thickness influences landing kinematics at the foot and ankle. Shoes constructed with thinner midsoles and lower heel to toe offsets lowered the foot landing angle to 16.9° from 20.0° in traditional shoes. Material stiffness did not affect foot or ankle angles at heel contact. Previous work has found that running on hard and soft surfaces alters the landing patterns in 43% of runners (Gruber et al. 2013). Runners converted from a RFS on a cushioned runway to a MFS while running barefoot on a concrete runway (Gruber et al. 2013). These findings show an increased conversion rate of strike pattern compared to the current findings which may be explained for several reasons. When running barefoot on a concrete surface, the surface stiffness is much greater than any shoe condition with a midsole. For this reason, some runners actively change their landing pattern to reduce the amount of impact (Lieberman et al. 2010). As soon as there was the presence of a soft material under the foot, most runners choose to use a rearfoot strike pattern. Even in this study, where the hard midsole condition was much stiffer than most commercially available running shoes, the stiffness was not great enough to alter the landing kinematics between the soft and hard conditions. Both rear foot striking and harder midsoles increase loading rate. A lack of kinematic adaptation to harder midsoles will therefore compound the risk of loading-rate-related injury.

Previous work has manipulated both shoe material stiffness and running surface stiffness (Hardin, Van Den Bogert & Hamill 2004). It was found that landing kinematics were influenced by changing the surface stiffness and not the shoe material stiffness. These findings are similar to the current study and to the study by Gruber *et al.* (2013) whereby

surface stiffness modulated landing kinematics yet material stiffness did not. In order to cause a conversion in strike pattern it seems that the change in underfoot stiffness needs to be very high, higher than the hard material stiffness used in this study. As noted previously, it is important to highlight the fact that landing the same way with shoes of greater material stiffness will result in higher vertical loading rates.

Kinetics

Material stiffness did not influence landing kinematics. It has been shown that runners correlate lower plantar pressure from soft shoes with increased comfort (Hennig, Valiant & Liu 1996). This shows that people do have the ability to differentiate the cushioning properties under their feet. However, landing kinematics between soft and hard midsole conditions were the same indicating that the feel of a shoe may not be related to how someone runs in it. Due to the same landing pattern, vertical loading rates were different caused by the change in stiffness across shoe conditions. Vertical loading rates were lower in traditional shoes and in soft shoes. Overall midsole stiffness can be determined from three variables, which include material thickness, contact area and elastic modulus of the material (material stiffness) (Eq. 1).

$$k = \frac{AE}{L} \quad \text{Eq. 1}$$

Where k is stiffness, A is contact area, E is elastic modulus and L is the thickness of the material. By increasing the thickness (L) the midsole stiffness decreases proportionally,

which was related to the observed lower loading rates. Other work has found similar trends with increasing midsole thickness but the findings weren't statistically significant (Hamill et al. 2011). Similarly, by increasing the elastic modulus (E), the midsole stiffness will increase proportionally, yielding higher vertical loading rates for the same given impact. These findings are consistent with previous work that has found that loading rates are lower when softer material was underfoot (Shorten, Mientjes 2003).

When the midsole stiffness was estimated from the ratio of durometer and thickness used, it becomes clear how it relates to loading rates. Shoes were constructed with hard (70 Asker C), soft (40 Asker C), thick (32 mm) and thin (13 mm) midsoles (Figure 6.7).

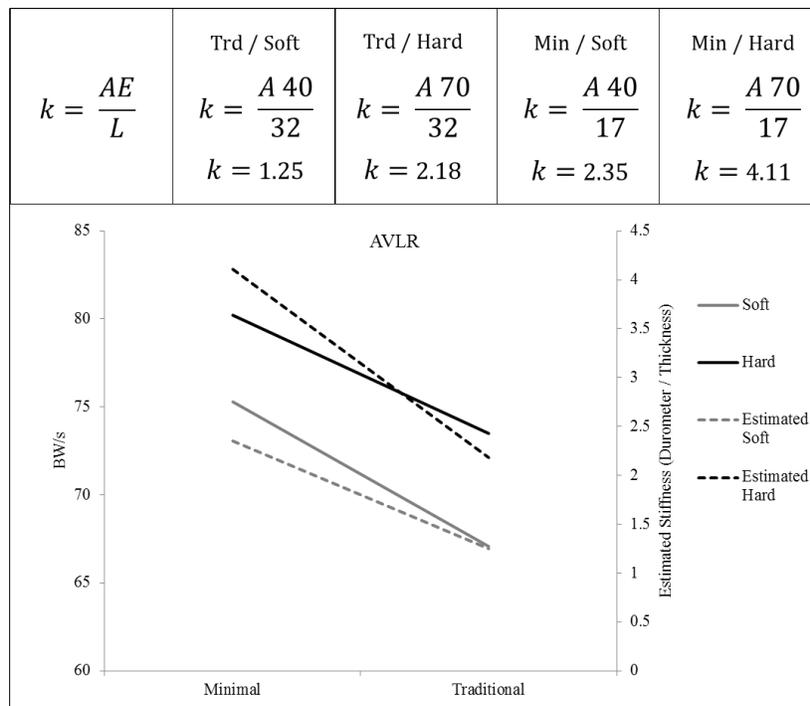


Figure 6.7. An estimate of material stiffness can be calculated between shoe conditions using midsole durometer and thickness. When plotted with the vertical average loading rate, similar trends can be seen. Loading rates are related to the material stiffness. Kinematic changes were seen between minimal and traditional shoes, but not soft and hard midsole conditions.

Measured loading rates and estimated stiffness are plotted on the same figure to show how the two are related. Interestingly, the midsole stiffness between the minimal soft shoe and the traditional hard shoe are the most similar across all shoes tested. Although the two conditions have similar midsole stiffness, kinematics were different at the ankle, suggesting that midsole geometry (heel height / heel to toe offset) play an important role in landing kinematics. It should be noted that average vertical loading rates cannot be estimated from this simplistic ratio; rather, the relative differences can be estimated when either material stiffness or thickness are manipulated.

While running in traditional shoes, the foot landing angle was increased and the ankle had increased dorsi-flexion; thus a greater rearfoot strike pattern (decreased Strike Index). It is known that landing with an increased RFS pattern is associated with higher vertical loading rates (Lieberman et al. 2010). This was not the case as lower vertical loading rates were observed in traditional shoes. This potentially means that the increase in midsole thickness was great enough to outweigh the increased vertical loading that would be attributed to an increased RFS pattern. It must be stated that this scenario was only concerned with passive forces, as active forces from muscle activity were not investigated.

The instantaneous and vertical average loading rates depict the same relationship across shoe conditions. The VILR results are relatively high when compared to values observed in the literature. The lowest VILR observed in this study occurred while running in the traditional soft shoe, which was 121.0 BW/s. The highest VILR observed in this study occurred in the minimal hard shoe, which had a value of 151.3 BW/s. These two values, the lowest and highest for this experiment, both fall within the range of loading rates that are

associated with increased prevalence of stress fractures (Zadpoor, Nikooyan 2011). The VALR values from this study compared to values from the literature are very similar. The highest and lowest VALR were observed in the minimal hard shoes (80.2 BW/s) and the traditional soft shoes (67.1 BW/s). In a systematic review by Zadpoor *et al.* (2011), the group of runners without risk of stress fractures depicted VALR values between 66.3 BW/s and 77.5 BW/s. Although not directly tested, tissue strength between the running groups should be considered when referring to the observed loading rates. Relative loading, with respect to one's typical loading patterns on a daily basis, may be different between the trained and novice running groups.

Impact peak magnitude showed an interaction between midsole thickness and material stiffness. The interaction between these two variables was due to similar impact peak values between the traditional hard and the minimal hard shoes, whereas there was a large difference between the minimal soft and traditional soft shoe conditions. Impact peak magnitude was highest in the traditional soft shoe.

The impact peak has been shown as a summation of the high frequency content from impact under the heel and the low frequency content that was transmitted through the heel and forefoot (Shorten, Mientjes 2011). Force platforms are limited in detailing spatial information of force as only the center of pressure and the resultant force can be measured. For this reason, it was difficult to assess the amount of heel impact on the impact peak magnitude without being able to parse out the low frequency content (Shorten, Mientjes 2011). One potential explanation for the very large impact peak magnitude in traditional soft shoes (1.99 BW) could be due to the decreased loading rate, which causes the impact peak to occur later into the stance phase. As the impact peak

occurrence is delayed, it is summed with a higher proportion of low frequency content, thus increasing the observed impact peak magnitude from the force platform (Shorten, Mientjes 2003).

Limitations

This experiment included several limitations. The runway used was 36m in length, which does not directly replicate running outside for a prolonged period of time. Running speed was set to 3.84 m/s for all participants in all shoe conditions. The running speed was similar to other overground studies and was selected to avoid differences that arise from running at different speeds (Nigg et al. 1987). Two time points allowed for rest during the protocol. The first was between running trials whereby participants walked back along the runway to their starting point. The second was between shoe conditions; when participants were given time to rest if they felt any fatigue. The selected pace may be challenging for novice runners to sustain over a prolonged period of time, but they did not appear to have significant challenge running down the runway at the set speed for the ten required trials.

The minimal shoes included in this study were constructed with a traditional upper. Most minimal shoes are constructed with a lightweight and flexible upper, which contributes to the overall minimal shoe definition. The authors chose to keep the upper construction the same across all shoe conditions to in order to avoid confounding factors on material stiffness and midsole thickness.

Conclusions

In summary, this study presents several important findings. The first is that kinematics between trained runners and novice runners are different at the knee joint upon ground contact and that footwear conditions only influenced the foot and ankle

angles. Novice runners have increased knee extension at ground contact, which may be related to the RFS pattern that was prevalent in this population. Further investigation on loading at the knee joint between trained and novice runners may be important in identifying risk factors that are specific to novice runners and the development of patellofemoral pain syndrome. Vertical loading rates were higher in novice runners but this was not statistically different between the groups. Consideration should be given to the relative loading with respect to typical loading patterns in each population. Although not directly tested, it was assumed that trained runners on average experience greater axial loading to the musculoskeletal system on a typical training day whereas novice runners do not. With proper tissue adaptation it may be that the trained runners have higher absolute tissue tolerances compared to novice runners. This was important, as it was found that absolute loading values were similar between running groups but the relative loading experienced within the protocol may have been much higher in the novice running group.

Shoe comparisons resulted in several interesting findings. Across all participants, midsole thickness influenced the foot and ankle landing angles, which are tightly coupled. This change is probably due to the change in lever arm length between the minimal and traditional midsole. Footwear conditions did not influence kinematics at the knee or hip, which was where between group differences were found and running injuries are prevalent (Taunton et al. 2002). When running in shoes that are constructed with lower stack heights and lower heel to toe offsets, foot landing angle and ankle dorsi-flexion were decreased. In the conditions tested, the changes observed in minimal shoes were not great enough to alter the strike pattern. Participants who used a RFS in traditional shoes, maintained a RFS pattern in minimal shoes, but to a lesser degree.

Vertical loading rates were lower in shoes constructed with thicker and softer midsoles. Midsole stiffness is dependent upon both the hardness and thickness, which may explain the differences observed across all shoe conditions. It was originally thought that strike pattern would change in minimal shoes. Since this did not occur, the loading rates observed are related to the midsole properties of each shoe. Previous work has found altered strike patterns when surface stiffness was changed (Gruber et al. 2013). Strike patterns did not change when material stiffness was altered in this study or other studies (Hardin, Van Den Bogert & Hamill 2004). Changing surface stiffness may have a greater effect on kinematics in comparison to changing the underfoot material which appears to have a greater influence on the kinetics, as seen in this study. The results from this study support the notion that midsole geometry was an important determinant in how runners land, while the material stiffness was an important determinant in the loading rates placed upon runner's bodies.

Trained and novice runners show similarities in how they run. A higher proportion of novice runners use a rearfoot strike pattern compared to trained runners. Novice runners also have increased knee extension upon landing, which was probably related to the strike pattern employed. Future work should include how novice runners change their strike pattern over time as experience was gained. Another interesting study may be to create many shoe conditions with the same overall midsole stiffness (k) with differing ratios of elastic modulus and midsole thickness to see if landing kinematics change with the same vertical loading rates.

CHAPTER 7.0

Local Dynamic Stability of Novice and Trained Runners in Traditional and Minimal Footwear

7.1 Introduction

Novice runners can be defined as those who run less than a total of 10 km per year (Bertelsen et al. 2012). It has been shown that the coefficient of variation in stride length in novice runners is greater than their trained runner counterparts (Nakayama, Kudo & Ohtsuki 2010). These findings lend themselves in explaining improved performance with experience and training (Ericsson 2004). From a running economy perspective, training over time is beneficial in reducing variability hence improving consistency in motor output. On the other hand, there is evidence that reduced variability in running is linked to risk of injury (Hamill et al. 1999). From an injury perspective, it has been suggested that when tissue fails, the rate of tissue remodelling is less than the rate of tissue damage (Williams 1993). In distance running, where repetitive stress is applied, overuse injuries at the knee are common (Taunton et al. 2002). Runners with a history of patellofemoral pain (PFP) have been shown to have lower variability in continuous relative phase (segment coupling) compared to runners with no history of knee injury (Hamill et al. 1999). From these examples it becomes apparent that too much variability may be related to conducting a new task, while reduced variability may be linked to increased risk of injury. This work seeks to quantify the local dynamic stability between trained and novice runners. Understanding the differences between groups, and investigating how groups respond to shoes with differing midsoles can aid in designing footwear that is tailored to someone's running experience.

There remains some uncertainty whether or not variability is a good or bad attribute. Some may suggest that too much variability is bad as it results in an inefficient movement pattern (Nakayama, Kudo & Ohtsuki 2010). Others may suggest that too little variability in running is bad as it may be related to risk for overuse injuries (Hamill et al. 1999). For efficient locomotion to occur, it is apparent that a balance is needed between too little and too much variability from stride to stride. Optimal movement variability is a concept that describes a spectrum of variability (Stergiou, Harbourne & Cavanaugh 2006). If a movement has zero variability from trial to trial, or in running, from stride to stride, the output is completely predictable. Fortunately, in running there are fluctuations, which allows for adaptability upon different surfaces and obstacles. Furthermore, a movement that is completely random, or has a lot of variability is not ideal as the movement is inefficient and lacks control.

Variability in running may be related to the quality of afferent feedback from the plantar surface of the foot. Additionally, altering running shoe midsole properties has the ability to change this afferent feedback (Rose et al. 2011). In postural control research, standing on foam, or an unstable surface is often related to an increased amount of sway (Schmit, Regis & Riley 2005). Similarly, dynamic stability improves while hopping onto one leg while barefoot in comparison to wearing running shoes (Rose et al. 2011). It is hypothesized that midsole material acts to degrade the quality of afferent information that would otherwise be gained directly from the ground. Analogous to filtered afferent feedback is the concept that postural adjustments may be less effective while standing on foam as the intended force output to the ground may be partially absorbed via foam deformation of the midsole (Perry, Radtke & Goodwin 2007).

Previous work has found a relationship between severity of impacts and perceived comfort in different cushioning conditions (Lake, Lafortune 1998, Hennig, Valiant & Liu 1996). Shoes with softer midsoles have been shown to attenuate vertical loading rates (Heidenfelder, Sterzing & Milani 2010). The amount of variability while running barefoot and shod has been assessed previously with findings indicating that variability is increased while running barefoot both in kinematics (Kurz, Stergiou 2003), and kinetics (Altman, Davis 2011). It is suggested that variability increases while barefoot to decrease the risk of injury by preventing overloading under the heel (De Clercq, Aerts & Kunnen 1994). It is still unknown how local dynamic stability is influenced between novice and trained runners and the potential for each group to sense different cushioning properties, which may influence local dynamic stability.

The purpose of this study was to examine the effect of running experience and midsole construction on local dynamic stability at the ankle, knee and hip. It was hypothesized that local dynamic stability would be decreased in novice runners in comparison to trained runners due to lack of experience and training. It is also hypothesized that firmer underfoot material will decrease local dynamic stability for all participants while softer underfoot material will increase local dynamic stability due to the perceived impact across shoe conditions and the ability to change ones landing patterns over the running trial.

7.2 Methods

Experimental Setup

Kinematics were collected using an Optotrak motion capture system (NDI, Waterloo, ON), sampled at 100 Hz. Rigid bodies were placed on the pelvis, right thigh, shank and foot. The pelvis and foot rigid bodies each consisted of five markers, while the thigh and shank clusters each consisted of six markers (Figure 7.1). A digitizing probe was used to define each segment. Digitized points on the pelvis included; right and left posterior superior iliac spine, iliac crests, anterior superior iliac spines and greater trochanters. The thigh was defined from the right greater trochanter to the lateral and medial epicondyle. The shank was defined from the lateral and medial epicondyles to the lateral and medial malleoli. Digitized points on the foot included the medial and lateral epicondyles, the most posterior point of the sole of the shoe, the head of the 5th and 1st metatarsals and the most anterior part of the shoe sole. Each of the four shoes had its own rigid body and the foot segment was re-digitized between each condition.



Figure 7.1. Participant with rigid bodies placed on the foot, shank, thigh and pelvis

Participants wore a heart rate monitor throughout the data collection to allow for a similar work rate between the trained and novice running groups (Garmin Forerunner 405).

Protocol

Rating of Perceived Exertion (RPE) was used as a guideline to control for the running intensity between novice and trained runners (Borg 1982). Prior to data collection, participants were given time to warm up on the treadmill. Participants were instructed to control the speed of the treadmill and were periodically asked for an RPE score. Once the RPE score was equal to '3' or a moderate effort, the treadmill speed was written down and participants were given approximately three minutes to run at this speed. Heart rate was collected for the full duration of this warm up trial. The aim for this procedure was to have similar heart rate values between groups based on bringing everyone to the same RPE

score. Since the level of running expertise was different between groups, preferred running speed will be different with the same amount of perceived exertion experienced by all, therefore normalizing the relative intensity between groups (Demello et al. 1987).

A standing calibration trial was collected prior to each shoe condition in order to normalize joint angles. Shoe order was randomized within each group and matched between the novice and trained groups. For each shoe, participants ran for three minutes on a treadmill at the predetermined speed. Adequate rest was given between running shoe trials.

Data Analysis

Data were processed using Visual 3D V 4.85.0 (C-Motion Inc., Germantown, MD). Data were filtered using a 2nd order dual pass Butterworth filter with a cutoff of 15 Hz. The cutoff frequency for the kinematic data was determined by using a residual analysis (Wells, Winter 1980). Missing data points were interpolated using a 3rd order cubic spline up to a maximum of 15 frames.

A rigid link model was constructed consisting of the pelvis, right thigh, shank and foot. The hip and knee joint centers were determined from functional joints (Schwartz, Rozumalski 2005). Two functional trials were collected and each had a length of 30 seconds. For the hip functional trial, participants were instructed to flex and extend the hip, abduct and adduct followed by circumduction. For the knee functional trial, flexion/extension was conducted for the full 30 seconds. The ankle joint center was defined as the midway point between malleoli markers.

LyE Estimation

Local dynamic stability from kinematic data can be estimated from the largest Lyapunov exponent (LyE). The LyE represents the maximum rate of divergence of nearby trajectories in state space. Extremely large divergence of nearby trajectories would indicate a random signal while no divergence of nearby trajectories would indicate a deterministic signal. When analyzing kinematic data, there are typically two types of algorithms used to estimate the LyE which are the Rosenstein and the Wolf algorithms (Rosenstein, Collins & De Luca 1993, Wolf et al. 1985). Briefly, the Rosenstein algorithm estimates divergence based on following nearest neighbours iteratively and yields a function of divergence over time. In order to calculate the rate of divergence the slope of the curve must be calculated which may be subjective as divergence over time is not linear (Cignetti, Decker & Stergiou 2012). The Wolf algorithm directly measures the rate of divergence by taking the number of time steps into account (Cignetti, Decker & Stergiou 2012). Recent work has compared both algorithms on small data sets and found that the Wolf algorithm is more robust when dealing with small gait data sets (Cignetti, Decker & Stergiou 2012).

Before estimation of the LyE, the original time series data were reconstructed in states space. The reconstructed state space vector was composed of multiple (M) time delayed copies (τ), where M is the appropriate number of dimensions and τ was the time delay to reconstruct the attractor dynamics (Equation 2).

$$y(t) = [x(t), x(t + \tau), \dots, (t + (M - 1)\tau)] \quad \text{Eq. 2}$$

The reconstruction lag (τ) was determined from the average mutual information algorithm (Abarbanel 1996). The average mutual information algorithm calculates the probability that the original time series data is different from the reconstructed time delayed copy, for each time lag (Wurdeman, Myers & Stergiou 2012). The proper reconstruction lag was selected from the first local minimum of the average mutual information algorithm (Figure 7.2c).

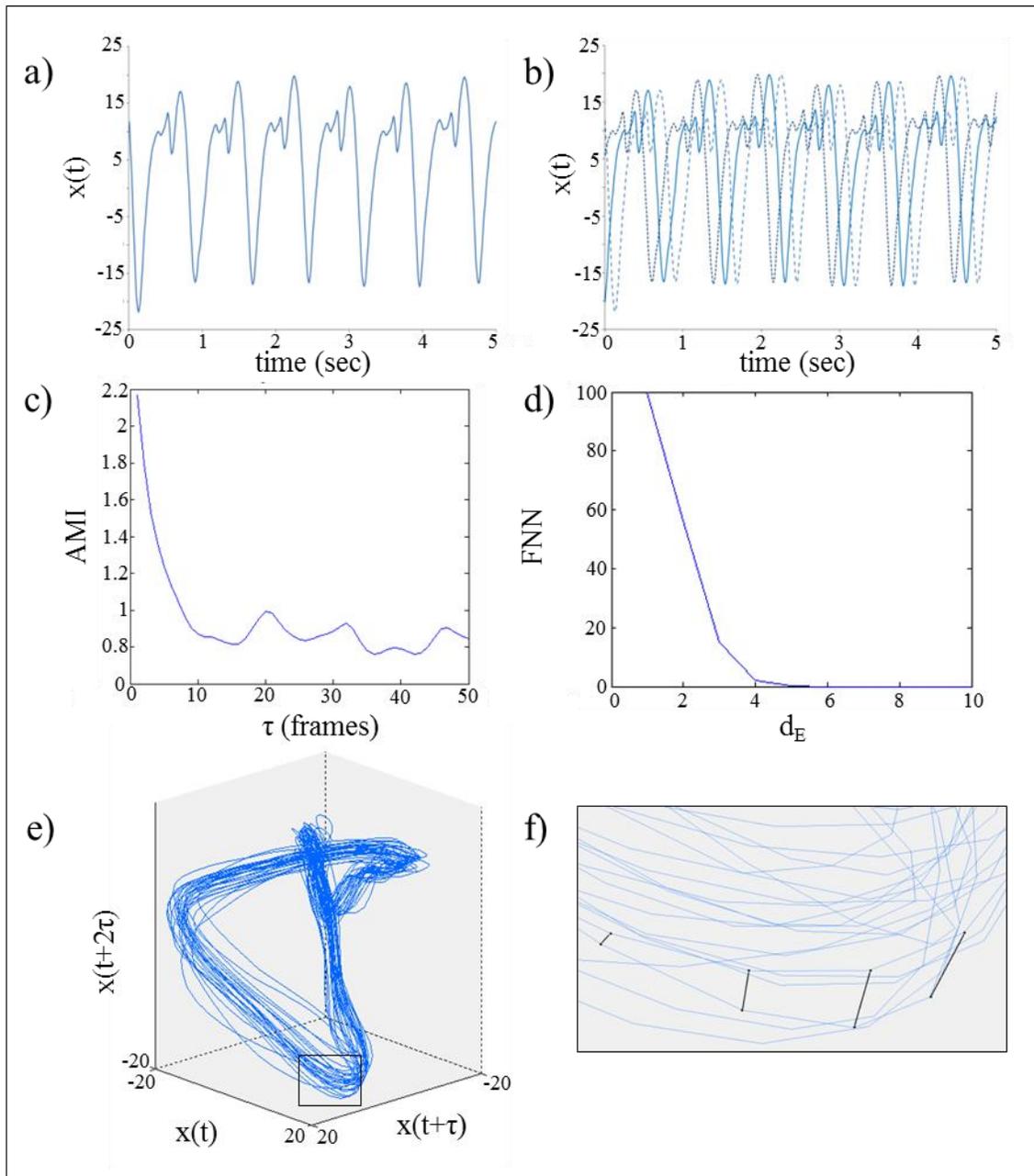


Figure 7.2. Ankle kinematics were used to generate the following plots. Estimation of the largest Lyapunov exponent requires several steps. a) Original time series joint angles are used. b) Time delays copies of the original time series are created. The size of the time delay is dependent upon the results from (c) the average mutual information algorithm and (d) the false nearest neighbors algorithm. e) When each time delayed copy is plotted against each other in state space (3 dimensions in this example), the rate of divergence between nearest neighbors can be calculated. f) An inset from the rectangle in (e) depicting nearby neighbors in state space.

Embedding dimension (M) was determined from the global false nearest neighbours algorithm (Abarbanel 1996). As described by Wurdeman *et al.* (2012 pg. 3), “the algorithm creates multiple time delayed copies of the original time series data, and calculates the percentage of false nearest neighbours”. The appropriate embedding dimension is equal to the point at which the percentage of false nearest neighbours drops to zero. Figure 7.3a gives an example of false nearest neighbours in two dimension state space. When the distance between the neighbours in figure 7.3a is calculated the Euclidian distance is smaller than when the distance is calculated between the same neighbours in three dimension state space in 12b. This is an example of false nearest neighbours.

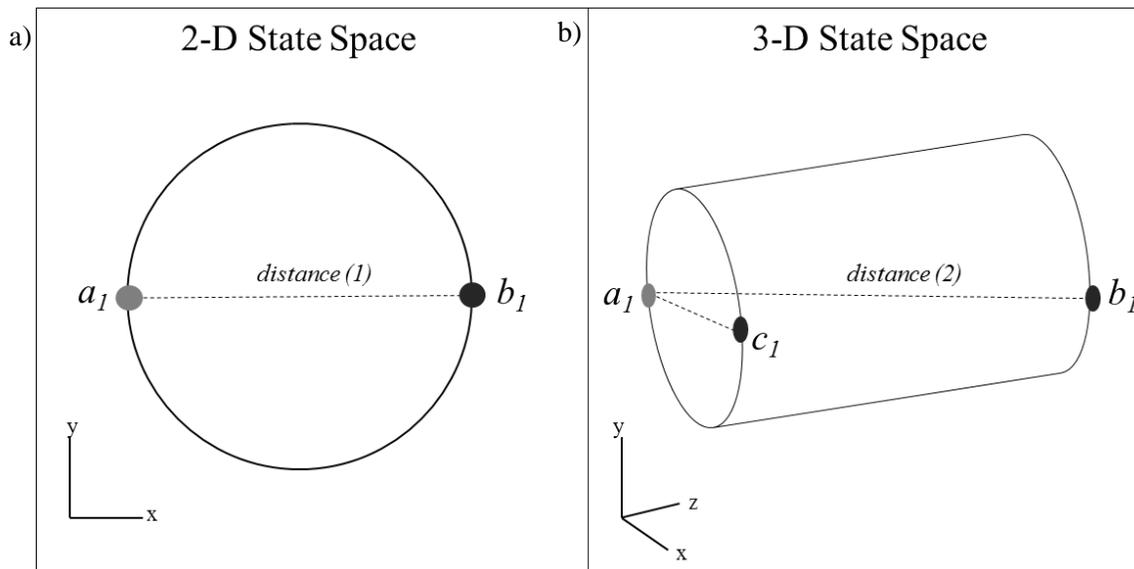


Figure 7.3. An example of a false nearest neighbor is presented in 7.3 a) where the distance between two points, a_1 and b_1 is calculated in 2D space. When an additional dimension is considered in 7.3 b), the Euclidian distance between points a_1 and b_1 is much larger. The nearest neighbor to point a_1 in 3D space would be point c_1 and not b_1 .

Wurdeman *et al.* (2012) have described the steps to calculate the LyE from Wolf’s algorithm in a way that is easy to understand for those who aren’t formally trained in

nonlinear analyses. The following sentences summarize their description of the steps required to estimate the LyE. The largest LyE represents the maximum rate of divergence between nearest neighbours in state space. A point on a reference trajectory is chosen and its nearest neighbour is determined by minimizing the distance between the two points. Once nearest neighbours are found the distance between them is calculated (d_t), the algorithm steps forward (k) data points and the distance is recalculated ($d_{t'}$). The algorithm continues to calculate the change in distance for each data point upon the reference trajectory. If the distance becomes large during recalculation, a new nearest neighbour is selected based on minimizing the distance and angle from the reference point (Wolf et al. 1985). The algorithm conducts these steps for each point, for the entire time series data. The LyE is the average rate of divergence or convergence from the running average of the differences in distances.

$$LyE = \frac{\log_2\left(\frac{d_{t'}}{d_t}\right)}{k} \quad \text{Eq. 3}$$

Where d_t is the initial distance between nearest neighbours, $d_{t'}$ is the final distance between nearest neighbours and k is the number of time steps taken between the first and second point. The value of k was set to 3 data points and is divided by the sampling rate to obtain a measure of time (Wurdeman, Myers & Stergiou 2012).

The Wolf algorithm requires several input parameters including, the number of steps ($k = 3$), the maximum angle (0.3 radians), the minimum scale length (0.0001) and the maximum scale length (0.1) for finding a replacement nearest neighbour (Wolf et al. 1985).

The values for the input parameters are based upon previous work with kinematic data (Wurdeman, Myers & Stergiou 2012, Wurdeman et al. 2012).

Since the LyE was calculated between novice and trained runners the same number of strides were analyzed for all participants (Wurdeman, Myers & Stergiou 2012).

Determination of the number of strides to use was done by counting the number of strides in each trial. The trial with the minimum number of strides was used and all other trials were cropped from the end to contain the same number of strides.

Three different signals with known LyE values were used to determine the efficacy of the data analysis procedure. A sine wave, the Lorenz attractor and random data were used. All data were sampled at 100 Hz, which was the same as the kinematic data. The sine wave had amplitude of ± 1 and frequency of 5 Hz. The Lorenz attractor had parameters of $\sigma = 16$, $\rho = 45.92$ and $\beta = 4$. The random signal was generated to have a mean of 0 and standard deviation of ± 1 . Reconstruction lag, embedding dimension and LyE were calculated for the three signals and results can be found on table 7.1.

Table 7.1. Three different signals with known properties were used to verify the results from the Wolf algorithm. The outcome for each signal matches exactly with the expected results.

Signal	Reconstruction Lag (τ)	Embedding Dimension	LyE (Bits/s)
Sine Wave	8	2	0.00
Lorenz Attractor	12	3	2.17
Random	1	4	37.76

For each running trial, the reconstruction lag and embedding dimension were calculated. Average values were calculated for the novice and trained running groups for the ankle, knee and hip. The average values were used for calculating the LyE for each trial.

Statistics

A three way mixed general linear model was used for statistical analysis. Independent variables included a within subject factor of material stiffness and midsole thickness and a between subject factor of group (novice or trained). For any significant interactions, paired t-tests were conducted to determine where the difference was significant. Significance was set to $p = 0.05$ prior to conducting the study. Heart rate data were averaged over the three minute running trial. Independent two tailed t-tests were used to compare average heart rate between each group, for each shoe.

Table 7.2. A three way mixed model ANOVA was used for each of the largest Lyapunov exponent in the sagittal plane for the ankle, knee and hip. This table outlines the three factors and each level associated with the factors.

Independent Variables		Dependent Variables	Statistical Model
Factor	Level		
Running Group (Between Subjects Factor)	Novice vs. Trained	LyE _{ankle} LyE _{knee} LyE _{hip}	3 Way Mixed General Linear Model
Midsole Thickness (Within Subjects Factor)	Traditional vs. Minimal		
Material Stiffness (Within Subjects Factor)	Soft vs. Hard		

7.3 Results

Participants in the trained running group ran 61.7 km/week on average. The novice running group confirmed that they ran less than a total of 10 km in the past year. Demographic results can be found on Table 7.3. Running speed determined from the warm

up trial, was 11.2 (1.35) km/hr for the trained running group and 8.5 (0.8) km/hr for the novice running group.

Table 7.3. Participant demographics

	Novice	Trained
Age (Y)	21.5 (2.71)	23.3(5.82)
Height (m)	1.77 (0.06)	1.75(0.05)
Weight (Kg)	75.8 (9.8)	68.3(5.1)
Weekly Mileage (km/week)		61.7(28.2)
Easy Training Pace (min/km)		4:37(0:23)
Hard Training Pace (min/km)		3:36(0:20)

Heart rate values were not significantly different ($p > 0.41$) between groups for all shoe conditions. The trained and novice groups had average heart rate values of 140 bpm and 144 bpm for the minimal soft shoe ($t(22) = 0.85, p = 0.41$). While running in the minimal hard shoe, average heart rate values for the trained and novice groups were the same at 142 bpm ($t(22) = 0.18, p = 0.86$). Average heart rate values were 142 bpm and 146 bpm for the trained and novice groups while running in the traditional soft shoe ($t(22) = 0.68, p = 0.50$). Average heart rate values for the trained and novice groups were 142 bpm and 145 bpm while running in the traditional hard shoe and were not statistically different ($t(22) = 0.43, p = 0.67$). Figure 7.4 shows time series data for all shoe conditions and has been averaged across all participants. Heart rate trends in both the novice and trained running groups were very similar.

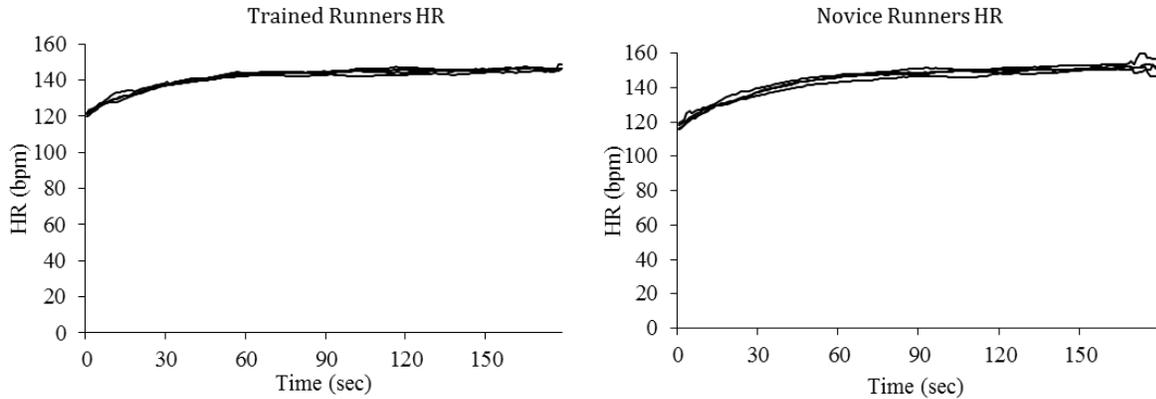


Figure 7.4. Heart rate data were averaged over each three minute trial for both groups. All four footwear conditions are plotted showing the same heart rate activity across shoe conditions and between groups.

Input Parameters

Table 7.4 displays the average embedding dimension and reconstruction lag that were found for each joint within each group. The same values were used across all four shoe conditions for each joint within each group.

Table 7.4. Average reconstruction lag (τ) and embedding dimension ($d_{(e)}$) used for each joint.

	Trained			Novice		
	Ankle	Knee	Hip	Ankle	Knee	Hip
τ	11	8	15	14	10	19
$d_{(e)}$	7	6	6	7	6	6

Ankle LyE

A main effect of group was observed for the LyE from the ankle joint ($F_{1,21} = 13.64, p = 0.001$). Novice runners had significantly larger LyE values compared to trained runners (Figure 7.5a). There were no significant interactions or main effects for midsole thickness or material stiffness for the ankle LyE.

Knee LyE

The LyE for the knee was greater in novice runners compared to trained runners ($F_{1,21} = 31.61, p < 0.001$). Similar to the ankle, there were no differences in LyE for the knee across shoe conditions.

Hip LyE

The LyE for the hip had a significant interaction between running group and midsole thickness ($F_{1,21} = 4.79, p = 0.04$). *Post hoc* analysis revealed that the novice running group had larger LyE values at the hip in traditional shoes compared to minimal shoes ($t(9) = 2.60, p = 0.029$). In the trained running group, there were no differences between shoes with differing midsole thickness. The trained running group had significantly lower LyE values for the hip across all shoe conditions ($F_{1,21} = 21.83, p < 0.001$). Results from all three joints can be found in Table 7.5.

Table 7.5. Mean (SD) rate of divergence of nearby trajectories (Bits/s) for the ankle, knee and hip in the sagittal plane.

	Trained				Novice				Sig.
	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	Soft Minimal	Hard Minimal	Soft Traditional	Hard Traditional	
Ankle	1.21	1.21	1.22	1.25	1.49	1.47	1.49	1.42	c
S.D	(0.26)	(0.29)	(0.16)	(0.27)	(0.13)	(0.09)	(0.09)	(0.18)	
Knee	0.74	0.75	0.78	0.72	1.22	1.23	1.25	1.25	c
S.D	(0.19)	(0.19)	(0.20)	(0.16)	(0.24)	(0.24)	(0.23)	(0.22)	
Hip	0.63	0.63	0.64	0.63	1.17	1.16	1.18	1.19	c, e
S.D	(0.27)	(0.27)	(0.26)	(0.28)	(0.30)	(0.26)	(0.32)	(0.31)	

a denotes a main effect of thickness ($p < 0.05$)

b denotes a main effect of stiffness ($p < 0.05$)

c denotes a main effect of group ($p < 0.05$)

d denotes a stiffness x thickness interaction ($p < 0.05$)

e denotes a group x thickness interaction ($p < 0.05$)

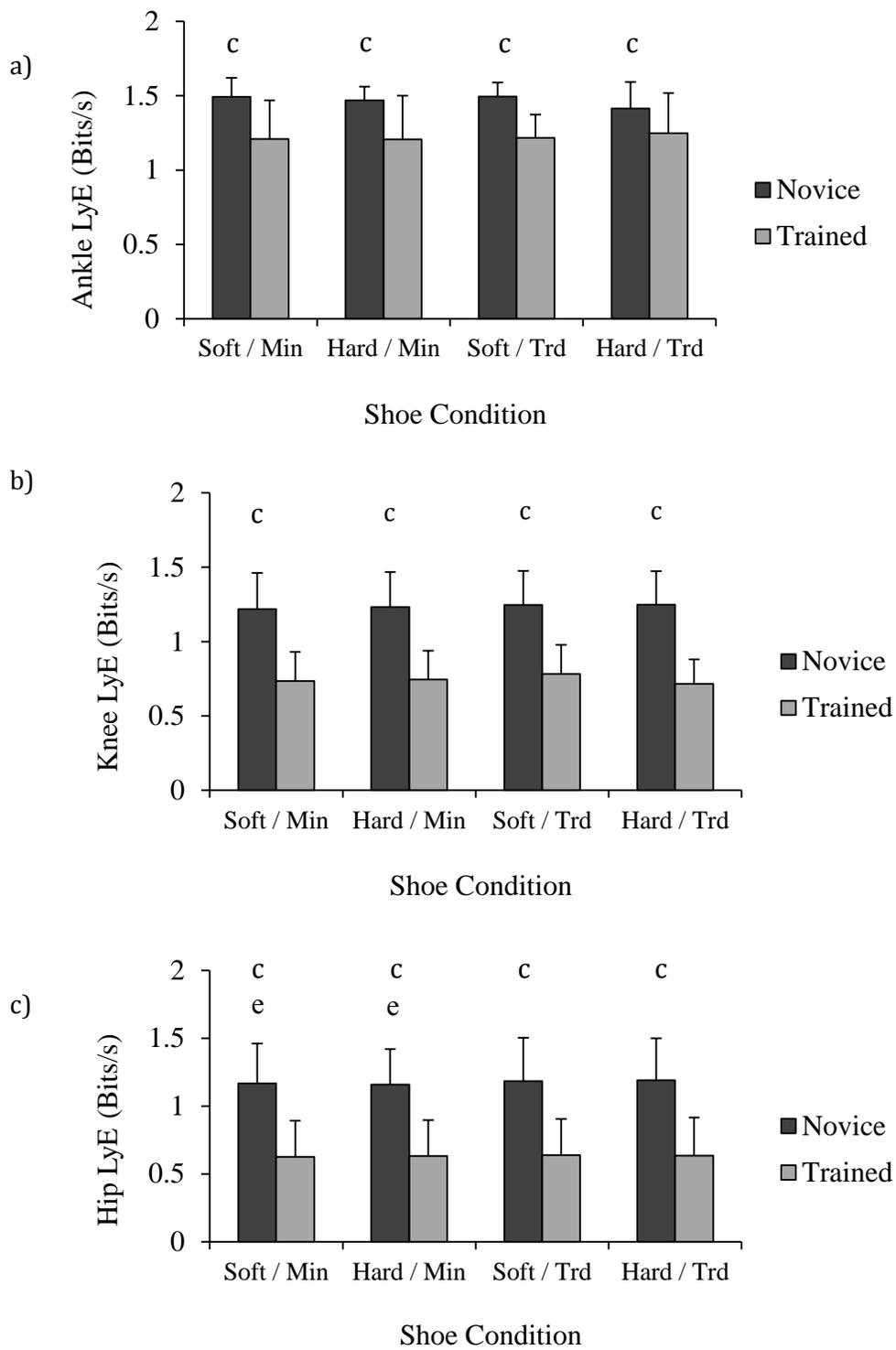


Figure 7.5. Mean values for the LyE for the ankle (a), knee (b) and hip (c). Group differences are denoted by 'c'. Across all three joints, trained runners displayed decreased attractor divergence. The letter 'e' denotes a group x thickness interaction.

7.4 Discussion

It was originally hypothesized that novice runners would be more variable compared to trained runners. The results from the LyE values at the ankle, knee and hip support this notion as trained runners displayed increased local dynamic stability across all shoe conditions tested. The second hypothesis of this study involved influencing local dynamic stability by manipulating material stiffness and midsole thickness. It was found, in both groups, that increasing both material stiffness and midsole thickness does not have an effect on local dynamic stability. The only significant interaction that existed was for the novice running group's divergence at the hip for traditional shoes compared to minimal shoes. In traditional shoes, there was decreased LDS compared to the thin, minimal shoes.

Group Comparisons

Trained runners displayed reduced attractor divergence at the ankle, knee and hip across all shoe conditions. Previous work has used other measures to compare variability between trained and novice runners (Nakayama, Kudo & Ohtsuki 2010). Coefficient of variation and detrended fluctuation analysis were used to determine how variable the stride interval was between runners and non-runners (Nakayama, Kudo & Ohtsuki 2010). The findings from this work show how the individual joints differ in local dynamic stability between trained and novice runners and support the findings of increased stride interval variability from Nakayama *et al.* (2010).

In relation to the optimal movement variability paradigm, novice runners are more variable than trained runners. Experience of a given activity appears to be an important determinant in the amount of local dynamic stability observed. With repeated exposure, it

is assumed that the body improves in motor output consistency which was seen in the trained runners compared to the novice runners. However, the boundaries of movement stability are still unknown in terms of how stable is too stable with respect to risk of overuse injuries. From these results it is clear that the novice runners operate on one side of the spectrum and that the trained runners are on the opposite side. However, it is still unknown how the trained runner's local dynamic stability compares to runners who have been injured. It may be that the trained runners included in this study display a healthy amount of variability; more work in this area is needed. It can be expected that a novice runner's local dynamic stability will decrease over time but the rate of this change, and the magnitude are still unknown and may be important in helping define who is a novice runner. Assessing the amount of stability in someone's running pattern may help identify how experienced they are. This information can potentially be useful for people who are learning to run or those who have a history of overuse injuries.

Shoe Comparisons

Attractor divergence was consistent across all shoe conditions tested. The degree to which material stiffness and midsole thickness were manipulated, were not great enough to have an effect on local dynamic stability. The material stiffness's that were used in this study are fairly extreme with respect to typical durometers used in commercially available running footwear (50-55 Asker C), representing very hard and very soft midsoles. This means that altering midsole stiffness in a shoe will not help increase or decrease local dynamic stability. The innate pattern of running for all participants, regardless of experience was unaffected by the perception of different midsoles. This information is

useful as it eliminates the possibility that someone's local dynamic stability is related to the shoes they are wearing. It is someone's running experience that is related to the amount of stability in the lower limbs. Postural control research has found improved stability while barefoot (Rose et al. 2011). Other work has found increased variability while running barefoot compared to shod conditions (Stergiou, Decker 2011). An increase in variability while barefoot is presumed to be related to impact avoidance (Robbins, Hanna & Gouw 1988). The goal of the minimal shoes in this study was to decrease the amount of movement stability by increasing the perception of impact, as seen in barefoot research. However, the conditions that were used did not alter stability. This may be due to the fact that the minimal shoes used, are more similar to a traditional shoe than to a barefoot condition. Barefoot conditions allow direct information from the ground to the foot (Robbins, Hanna & Gouw 1988). In both the minimal and traditional shoe conditions tested, the foot laid on top of an insole which was on top of different midsoles, which is quite different than being barefoot. If one claim of minimal footwear is to improve stability, based on the minimal shoes tested in this study, the claim cannot be supported. Future work should include the comparison of barefoot local dynamic stability to shod local dynamic stability in order to accept or refute the fact that the quality of afferent feedback can manipulate stability while running.

Limitations

Several limitations in the current study should be noted. First, it has been shown that local dynamic stability is different between overground and treadmill walking (Dingwell et al. 2001). LyE is reduced while walking on a treadmill compared to

overground. It is unknown whether running or running experience alters attractor divergence between treadmill and overground testing. It is also known that the treadmill surface has compliance. A compliant surface may mask the differences in cushioning properties between shoe conditions. For this reason, the middle of the treadmill bed was reinforced to reduce the effect of bed compliance. Matching the intensity of running between groups of different fitness levels was a challenge. It was assumed that absolute heart rate would give the best indication of the effort for an individual. It is assumed that a trained runner would have a lower resting heart rate, and at 150 bpm, would be running at a preferred speed that was greater than a novice runner. The preferred running speed in the novice running group was slower and stability does change with preferred running speed (Jordan, Newell 2008). It is assumed that both groups were running at the same preferred pace for their given running experience. The reconstruction lag and embedding dimension were calculated for each person and the average values were used when estimating the LyE. There is potential for error to arise if an improper embedding dimension or reconstruction lag was used for a participant. Across all repeated measures, reconstruction lag and embedding dimension were held constant. If error were induced due to improper values, it would have been systematic across all shoe conditions.

Conclusions

The results from the current study examined the effects of running experience and midsole properties on local dynamic stability. Running experience was strongly associated with increased local dynamic stability at the ankle, knee and hip in the sagittal plane. It was also found that midsole material, for the most part, does not have an effect on local

dynamic stability. There was an interaction at the hip as novice runners displayed increased attractor divergence in thick soft shoes. This is important as the shoes that someone is wearing will not have an impact on their movement stability. It is their experience in conducting the movement that governs the amount of local dynamic stability. The rate of change in local dynamic stability is still unknown in novice runners. Identifying at which point a novice runner would be classified as a trained runner may be useful information in classifying at which point someone is trained.

CHAPTER 8.0 General Discussion

The intention for this final chapter is to synthesize the findings from both the overground running protocol and the treadmill protocol. The purpose of the overground protocol was to investigate differences kinetic and kinematic in novice and trained runners while wearing minimal and traditional shoes. The purpose of the treadmill protocol was to collect many consecutive strides in order to calculate attractor divergence in novice and trained runners. Combining the results from both studies yields an interesting story.

To summarize, it was found that midsole thickness influences the foot landing angle and the ankle angle. With thicker midsoles, trained and novice runners had increased dorsi-flexion; which is related to a heavier heel strike pattern. Material stiffness did not have an effect on landing kinematics, which is interesting because it is assumed that the perception of impact is greater with stiffer midsoles which would cause a change in kinematics, yet participants still landed in the same manner. The consequence for this is that for the same landing kinematics, vertical loading rates are higher in shoes with stiffer midsoles. Novice runners did not convert their strike pattern in minimal shoes and tend to use a rearfoot strike pattern a greater proportion of the time. Local dynamic stability results showed that trained runners have increased stability in comparison to novice runners, regardless of midsole construction.

These findings indicate that changing the way in which someone runs affects the loading experienced by the body, but is not related to a change in the stability of the movement. However, running experience influences local dynamic stability but does not affect landing kinematics at the ankle or hip. The novice runners were found to land with

increased knee extension compared to the trained runners. It is assumed that the local dynamic stability at the knee is not related to the differences in kinematics. Altering material stiffness and midsole thickness has the ability to change the way in which someone runs and the loading placed on the body, but not the stability of the movement.

There are several research questions that arise from this work that remain to be answered. It appears that there is a threshold in surface stiffness whereby strike patterns are altered to regulate the amount of impact to the body. Running over concrete has been shown to convert 43% of rearfoot strikers to midfoot or forefoot strikers (Gruber et al. 2013). However, on any surface that is somewhat cushioned, specifically in the range of manufactured midsoles, it seems as though converting one's strike pattern to regulate impact forces is rare. Furthermore, studies that have increased midsole thickness (Horvais, Samozino 2013) also change midsole stiffness by way of making the material thicker. By making several shoe conditions with the same overall material stiffness and manipulating the thickness and elastic modulus proportionally it may be seen that running kinematics do or do not change with thickness.

It was also shown that local dynamic stability in the sagittal plane is increased with running experience. Some important questions arise when trying to define or categorize who is a trained runner and who is a novice runner. Knowing how local dynamic stability increases as running experience improves in novice runners may help classify at which point someone is "a runner".

The results from the overground running portion of this thesis form an interesting framework which can be seen in Figure 8.1. In Novice runners, who use a rearfoot strike

pattern a majority of the time, it is recommended that softer midsoles be used. This recommendation is inconsequential in affecting the landing kinematics yet reduces vertical loading rates placed on the body. If the goal for a consumer is to land with a flatter landing angle, thinner midsoles with lower heel to toe offsets should be used. This work did not attempt to assess Achilles tendon strain, which is presumed to increase while landing with a flatter foot-landing angle due to increased plantar flexion early in stance. The minimal shoes used in this thesis were able to cause a change in landing kinematics, but this change was not great enough to convert one's strike pattern. Interestingly, kinematic changes that were caused by differences in midsole thickness were observed.

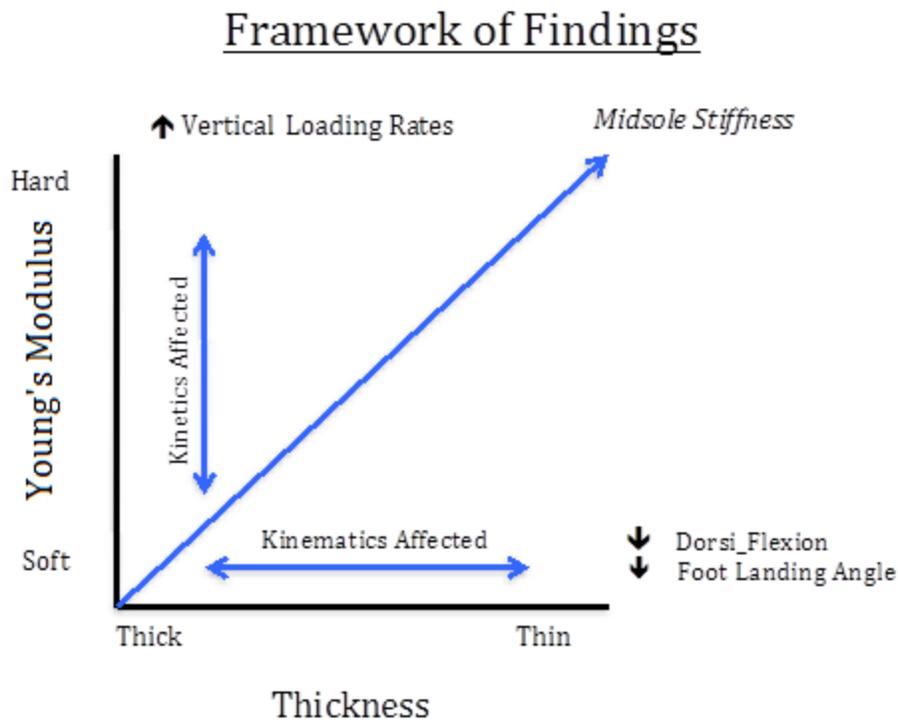


Figure 8.1. A conceptual framework of the findings is presented. Along the x-axis it is shown that ankle and foot landing kinematics are affected by midsole thickness. Along the y-axis it is shown that vertical loading rates are affected by Young's modulus. Overall midsole stiffness is affected by both midsole thickness and Young's modulus.

REFERENCES

- Abarbanel, H.D.I. & Kennel, M.B. 1993, "Local false nearest neighbors and dynamical dimensions from observed chaotic data", *Physical Review E*, vol. 47, no. 5, pp. 3057.
- Abarbanel, H.D.I. 1996, *Analysis of Observed Chaotic Data: Springer Study Edition*, Springer Verlag.
- Altman, A. & Davis, I. 2011, "Do Barefoot Runners Display More Variability in Footstrike Mechanics Than Shod Runners?", *35th Annual Meeting of the American Society of Biomechanics*.
- Altman, A. & Davis, I.S. 2012, "A kinematic method for footstrike pattern detection in barefoot and shod runners", *Gait & posture*, vol. 35, no. 2, pp. 298-300.
- Barak, M.M., Lieberman, D.E. & Hublin, J. 2011, "A Wolff in sheep's clothing: Trabecular bone adaptation in response to changes in joint loading orientation", *Bone*, vol. 49, no. 6, pp. 1141-1151.
- Bartlett, R., Wheat, J. & Robins, M. 2007, "Is movement variability important for sports biomechanists?", *Sports Biomechanics*, vol. 6, no. 2, pp. 224-243.
- Bertelsen, M.L., Jensen, J.F., Nielsen, M.H., Nielsen, R.O. & Rasmussen, S. 2012, "Footstrike patterns among novice runners wearing a conventional, neutral running shoe", *Gait & posture*, .
- Boling, M.C., Padua, D.A., Marshall, S.W., Guskiewicz, K., Pyne, S. & Beutler, A. 2009, "A Prospective Investigation of Biomechanical Risk Factors for Patellofemoral Pain Syndrome The Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) Cohort", *The American Journal of Sports Medicine*, vol. 37, no. 11, pp. 2108-2116.
- Bonacci, J., Vicenzino, B., Spratford, W. & Collins, P. 2013, "Take your shoes off to reduce patellofemoral joint stress during running", *British journal of sports medicine*, .
- Borg, G. 1982, "Psychophysical Bases of Perceived Exertion", *Medicine and science in sports and exercise*, vol. 14, no. 5, pp. 377-381.
- Bovens, A., Janssen, G., Vermeer, H., Hoerberigs, J., Janssen M. & Verstappen, F. 1989, "Occurrence of running injuries in adults following a supervised training-program", *International Journal of Sports Medicine*, vol. 10, pp. S186-S190.
- Buist, I., Bredeweg, S.W., Lemmink, K.A.P.M., van Mechelen, W. & Diercks, R.L. 2010, "Predictors of Running-Related Injuries in Novice Runners Enrolled in a Systematic Training Program", *The American Journal of Sports Medicine*, vol. 38, no. 2, pp. 273-280.

- Buist, I., Bredeweg, S.W., van Mechelen, W., Lemmink, K.A.P.M., Pepping, G. & Diercks, R.L. 2008, "No Effect of a Graded Training Program on the Number of Running-Related Injuries in Novice Runners", *The American Journal of Sports Medicine*, vol. 36, no. 1, pp. 33-39.
- Callaghan, J.P. & McGill, S.M. 2001, "Intervertebral disc herniation: studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive force", *Clinical Biomechanics*, vol. 16, no. 1, pp. 28-37.
- Cavagna, G.A., Franzetti, P., Heglund, N.C. & Willems, P. 1988, "The determinants of the step frequency in running, trotting and hopping in man and other vertebrates.", *The Journal of physiology*, vol. 399, no. 1, pp. 81-92.
- Cavanagh, P.R. & LaFortune, M.A. 1980, "Ground reaction forces in distance running", *Journal of Biomechanics*, vol. 13, no. 5, pp. 397-406.
- Cignetti, F., Schena, F. & Rouard, A. 2009, "Effects of fatigue on inter-cycle variability in cross-country skiing", *Journal of Biomechanics*, vol. 42, no. 10, pp. 1452-1459.
- Cignetti, F., Decker, L.M. & Stergiou, N. 2012, "Sensitivity of the Wolf's and Rosenstein's algorithms to evaluate local dynamic stability from small gait data sets", *Annals of Biomedical Engineering*, vol. 40, no. 5, pp. 1122-1130.
- Dalleau, G., Belli, A., Bourdin, M. & Lacour, J. 1998, "The spring-mass model and the energy cost of treadmill running", *European journal of applied physiology and occupational physiology*, vol. 77, no. 3, pp. 257-263.
- Daoud, A.I., Geissler, G.J., Wang, F., Saretsky, J., Daoud, Y.A. & Lieberman, D.E. 2012, "Foot Strike and Injury Rates in Endurance Runners: A Retrospective Study", *Medicine & Science in Sports & Exercise*, vol. 44, no. 7, pp. 1325-1334.
- Davis, I.F.A.C.S.M., Milner, C.E. & Hamill, J.F.A.C.S.M. 2004, "Does Increased Loading During Running Lead to Tibial Stress Fractures? A Prospective Study", *Medicine & Science in Sports & Exercise*, vol. 36, no. 5) (Supplement, pp. S58.
- De Clercq, D., Aerts, P. & Kunnen, M. 1994, "The mechanical characteristics of the human heel pad during foot strike in running: An in vivo cineradiographic study", *Journal of Biomechanics*, vol. 27, no. 10, pp. 1213-1222.
- De Wit, B., De Clercq, D. & Aerts, P. 2000, "Biomechanical analysis of the stance phase during barefoot and shod running", *Journal of Biomechanics*, vol. 33, no. 3, pp. 269-278.
- Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R. & Sternad, D. 2001, "Local Dynamic Stability Versus Kinematic Variability of Continuous Overground and Treadmill Walking", *Journal of Biomechanical Engineering*, vol. 123, no. 1, pp. 27-32.

- Divert, C., Baur, H., Mornieux, G., Mayer, F. & Belli, A. 2005a, "Stiffness adaptations in shod running", *Journal of Applied Biomechanics*, vol. 21, pp. 311-321.
- Divert, C., Mornieux, G., Baur, H., Mayer, F. & Belli, A. 2005b, "Mechanical comparison of barefoot and shod running", *International Journal of Sports Medicine*, vol. 26, no. 7, pp. 593-598.
- Dusing, S.C. & Harbourne, R.T. 2010, "Variability in postural control during infancy: implications for development, assessment, and intervention", *Physical therapy*, vol. 90, no. 12, pp. 1838-1849.
- Enders, H., von Tscherner, V. & Nigg, B.M. 2012, "Damped tissue vibrations during shod and barefoot running; strike pattern vs. running condition", *17th Biennial Conference for the Canadian Society for Biomechanics*.
- Ericsson, K.A. 2004, "Deliberate practice and the acquisition and maintenance of expert performance in medicine and related domains", *Academic Medicine*, vol. 79, no. 10, pp. S70-S81.
- Farley, C.T., Glasheen, J. & McMahon, T.A. 1993, "Running springs: speed and animal size", *Journal of Experimental Biology*, vol. 185, no. 1, pp. 71-86.
- Ferber, R., Hreljac, A. & Kendall, K.D. 2009, "Suspected Mechanisms in the Cause of Overuse Running Injuries: A Clinical Review", *Sports Health: A Multidisciplinary Approach*, vol. 1, no. 3, pp. 242-246.
- Ferris, D.P., Liang, K. & Farley, C.T. 1999, "Runners adjust leg stiffness for their first step on a new running surface", *Journal of Biomechanics*, vol. 32, no. 8, pp. 787-794.
- Frederick, E.C. 1984, "Physiological and ergonomics factors in running shoe design", *Applied Ergonomics*, vol. 15, no. 4, pp. 281-287.
- Frost, H. 1990, "Structural adaptations to mechanical usage (SATMU)1. Redefining Wolff's law: the bone modeling problem", *Anatomical Record*, vol. 226, pp. 403-413.
- Frost, H. 1987, "Bone "mass" and the "mechanostat" a proposal", *Anatomical Record*, vol. 219, no. 1, pp. 1-9.
- Goldmann, J., Potthast, W. & Brüggemann, G. 2013, "Athletic training with minimal footwear strengthens toe flexor muscles", *Footwear Science*, vol. 5, no. 1, pp. 19-25.
- Goss, D.L., Lewek, M.D., Yu, B. & Gross, M.T. 2012, "Accuracy of self-reported footstrike patterns and loading rates associated with traditional and minimalist running shoes", *American Society of Biomechanics*.

- Goss, D.L. & Gross, M.T. 2012, "Relationships Among Self-reported Shoe Type, Footstrike Pattern, and Injury Incidence", *U.S.Army Medical Department journal*, , pp. 25-30.
- Gruber, A.H., Silvernail, J.F., Brueggemann, P., Rohr, E. & Hamill, J. 2013, "Footfall patterns during barefoot running on harder and softer surfaces", *Footwear Science*, vol. 5, no. 1, pp. 39-44.
- Hamill, J., Russell, E.M., Gruber, A.H. & Miller, R. 2011, "Impact characteristics in shod and barefoot running", *Footwear Science*, vol. 3, no. 1, pp. 33-40.
- Hamill, J., van Emmerik, R.E., Heiderscheit, B.C. & Li, L. 1999, "A dynamical systems approach to lower extremity running injuries", *Clinical biomechanics (Bristol, Avon)*, vol. 14, no. 5, pp. 297-308.
- Hamill, J., Haddad, J. & McDermott, W. 2000, "Issues in quantifying variability from a dynamical systems perspective", *Journal of Applied Biomechanics*, vol. 16, no. 4, pp. 407-418.
- Hanson, N.J., Berg, K., Deka, P., Meendering, J.R. & Ryan, C. 2010, "Oxygen cost of running barefoot vs. running shod", *International Journal of Sports Medicine*, vol. 32, no. 6, pp. 401-406.
- Hardin, E.C., Van Den Bogert, A.J. & Hamill, J. 2004, "Kinematic Adaptations during Running: Effects of Footwear, Surface, and Duration", *Medicine & Science in Sports & Exercise*, vol. 36, no. 5, pp. 838-844.
- Hasegawa, H., Yamauchi, T. & Kraemer, W. 2007, "Foot strike patterns of runners at the 15-km point during an elite-level half marathon", *The Journal of Strength & Conditioning Research*, vol. 21, no. 3, pp. 888-893.
- Heidenfelder, J., Sterzing, T. & Milani, T.L. 2010, "Systematically modified crash-pad reduces impact shock in running shoes", *Footwear Science*, vol. 2, no. 2, pp. 85-91.
- Hennig, E.M., Valiant, G. & Liu, Q. 1996, "Biomechanical variables and the perception of cushioning for running in various types of footwear", *Journal of Applied Biomechanics*, vol. 12, pp. 143-150.
- Hennig, E.M. 2011, "Eighteen years of running shoe testing in Germany – a series of biomechanical studies", *Footwear Science*, vol. 3, no. 2, pp. 71-81.
- Horvais, N. & Samozino, P. 2013, "Effect of midsole geometry on foot-strike pattern and running kinematics", *Footwear Science*, vol. 5, no. 2, pp. 81-89.
- Johnston, C.A.M., Taunton, J.E., Lloyd-Smith, D.R. & McKenzie, D.C. 2003, "Preventing running injuries. Practical approach for family doctors.", *Canadian Family Physician*, vol. 49, no. 9, pp. 1101-1109.

- Jordan, K., Challis, J.H., Cusumano, J.P. & Newell, K.M. 2009, "Stability and the time-dependent structure of gait variability in walking and running", *Human movement science*, vol. 28, no. 1, pp. 113-128.
- Jordan, K. & Newell, K.M. 2008, "The Structure of Variability in Human Walking and Running is Speed-Dependent", *Exercise & Sport Sciences Reviews*, vol. 36, no. 4, pp. 200-204.
- Kram, R. & Franz, J. 2012, "Is Barefoot Running More Economical?", *International Journal of Sports Medicine*, vol. 33, no. 3, pp. 249.
- Kram, R., Franz, J., Tung, K. & Wierzbinski, C. 2012, "Energetic advantages and disadvantages of running shoes", *Conference for the Canadian Society for Biomechanics*.
- Kurz, M.J. & Stergiou, N. 2003, "The spanning set indicates that variability during the stance period of running is affected by footwear", *Gait & posture*, vol. 17, no. 2, pp. 132-135.
- Lake, M.J. & LaFortune, M.A. 1998, "Mechanical inputs related to perception of lower extremity impact loading severity.", *Medicine and science in sports and exercise*, vol. 30, no. 1, pp. 136.
- Lieberman, D.E., Venkadesan, M., Werbel, W.A., Daoud, A.I., D'Andrea, S., Davis, I.S., Mang/Eni, R.O. & Pitsiladis, Y. 2010, "Foot strike patterns and collision forces in habitually barefoot versus shod runners", *Nature*, vol. 463, no. 7280, pp. 531-535.
- Luo, G., Stergiou, P., Worobets, J., Nigg, B. & Stefanyshyn, D. 2009a, "Improved footwear comfort reduces oxygen consumption during running", *Footwear Science*, vol. 1, no. 1, pp. 25-29.
- McDougall, C. 2009, *Born to Run: A hidden tribe, superathletes, and the greatest race the world has never seen*, Knopf.
- McGill, S., Cholewicki, J. & Peach, J. 1997, "Methodological considerations for using inductive sensors (3space isotrak) to monitor 3-D orthopaedic joint motion", *Clinical Biomechanics*, vol. 12, no. 3, pp. 190-194.
- McGill, S.M. 1997, "The biomechanics of low back injury: Implications on current practice in industry and the clinic", *Journal of Biomechanics*, vol. 30, no. 5, pp. 465-475.
- Meardon, S.A., Hamill, J. & Derrick, T.R. 2011, "Running injury and stride time variability over a prolonged run", *Gait & posture*, vol. 33, no. 1, pp. 36-40.
- Milani, T.L., Hennig, E.M. & LaFortune, M.A. 1997, "Perceptual and biomechanical variables for running in identical shoe constructions with varying midsole hardness", *Clinical Biomechanics*, vol. 12, no. 5, pp. 294-300.

- Mundermann, A., Stefanyshyn, D.J. & Nigg, B.M. 2001, "Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors", *Medicine & Science in Sports & Exercise*, vol. 33, no. 11, pp. 1939-1945.
- Nakayama, Y., Kudo, K. & Ohtsuki, T. 2010, "Variability and fluctuation in running gait cycle of trained runners and non-runners", *Gait & posture*, vol. 31, no. 3, pp. 331-335.
- Nielsen, R.O., Buist, I., Parner, E.T., Nohr, E.A., Sørensen, H., Lind, M. & Rasmussen, S. 2013, "Foot pronation is not associated with increased injury risk in novice runners wearing a neutral shoe: a 1-year prospective cohort study", *British journal of sports medicine*, .
- Nielsen, R.O.P.T., Cederholm, P., Buist, I.P.D., Sorensen, H.P.D., Lind, M.P.D. & Rasmussen, S.M.D. "Can GPS be used to detect deleterious progression in training volume among runners?", *Journal of Strength & Conditioning Research*, .
- Nigg, B.M., Bahlsen, H.A., Luethi, S.M. & Stokes, S. 1987, "The influence of running velocity and midsole hardness on external impact forces in heel-toe running", *Journal of Biomechanics*, vol. 20, no. 10, pp. 951-959.
- Nigg, B.M. & Wakeling, J.M. 2001, "Impact Forces and Muscle Tuning: A New Paradigm", *Exercise & Sport Sciences Reviews*, vol. 29, no. 1, pp. 37-41.
- Nigg, B.M. & Gérin-Lajoie, M. 2011, "Gender, age and midsole hardness effects on lower extremity muscle activity during running", *Footwear Science*, vol. 3, no. 1, pp. 3-12.
- Nigg, B. 2009, "Biomechanical considerations on barefoot movement and barefoot shoe concepts", *Footwear Science*, vol. 1, no. 2, pp. 73-79.
- Perl, D.P., Daoud, A.I. & Lieberman, D.E. 2012, "Effects of Footwear and Strike Type on Running Economy", *Medicine & Science in Sports & Exercise*, vol. 44, no. 7, pp. 1335-1343.
- Perry, S.D., Radtke, A. & Goodwin, C.R. 2007, "Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination", *Gait & posture*, vol. 25, no. 1, pp. 94-98.
- Potthast, W., Braunstein, B., Niehoff, A. & Bruggemann, G. 2005, "The choice of training footwear has an effect on changes in morphology and function of foot and shank muscles.", *International Society of Biomechanics in Sports*.
- Riccio, G. 1993, "Information in movement variability: About the qualitative dynamics of posture and orientation." in *Variability and Motor Control* K.M Newell & D.M Corcos, , pp. 317-357.

- Ridge, S.T., Johnson, A.W., Mitchell, U.H., Hunter, I., Robinson, E., Rich, B.S., Brown, S.D. & Ridge, S. 2013, "Foot Bone Marrow Edema after 10-week Transition to Minimalist Running Shoes", *Medicine & Science in Sports & Exercise*, .
- Robbins, S.E., Hanna, A.M. & Gouw, G.J. 1988, "Overload protection avoidance response to heavy plantar surface loading", *Medicine and science in sports and exercise*, vol. 20, no. 1, pp. 85-92.
- Rocchi, L., Chiari, L. & Horak, F. 2002, "Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease", *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 73, no. 3, pp. 267-274.
- Rose, W., Bowser, B., McGrath, R., Salerno, J., Wallace, J. & Davis, I. 2011, "Effect of footwear on balance", *Proceedings of the American Society of Biomechanics, Long Beach (CA)*, .
- Rosenstein, M.T., Collins, J.J. & De Luca, C.J. 1993, "A practical method for calculating largest Lyapunov exponents from small data sets", *Physica D: Nonlinear Phenomena*, vol. 65, no. 1-2, pp. 117-134.
- Rothschild, Carey, P.T., Dpt & Cscs 2012, "Running Barefoot or in Minimalist Shoes: Evidence or Conjecture?", *Strength & Conditioning Journal*, vol. 34, no. 2, pp. 8-17.
- Schmit, J.M., Regis, D.I. & Riley, M.A. 2005, "Dynamic patterns of postural sway in ballet dancers and track athletes", *Experimental Brain Research*, vol. 163, no. 3, pp. 370-378.
- Schwartz, M.H. & Rozumalski, A. 2005, "A new method for estimating joint parameters from motion data", *Journal of Biomechanics*, vol. 38, no. 1, pp. 107-116.
- Shorten, M. & Mientjes, M. 2003, "The effects of shoe cushioning on impact force during running", *6th FBS*, .
- Shorten, M. & Mientjes, M.I.V. 2011, "The 'heel impact' force peak during running is neither 'heel' nor 'impact' and does not quantify shoe cushioning effects", *Footwear Science*, vol. 3, no. 1, pp. 41-58.
- Sinclair, J., Greenhalgh, A., Brooks, D., Edmundson, C.J. & Hobbs, S.J. 2013, "The influence of barefoot and barefoot-inspired footwear on the kinetics and kinematics of running in comparison to conventional running shoes", *Footwear Science*, vol. 5, no. 1, pp. 45-53.
- Squadrone, R. & Gallozzi, C. 2009, "Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners", *Journal of Sports Medicine and Physical Fitness*, vol. 49, no. 1, pp. 6-13.
- Stefanyshyn, D. & Fusco, C. 2004, "Athletics", *Sports Biomechanics*, vol. 3, no. 1, pp. 55-66.
- Stergiou, N. 2004, *Innovative analyses of human movement*, Human Kinetics Publishers.

- Stergiou, N. & Decker, L.M. 2011, "Human movement variability, nonlinear dynamics, and pathology: Is there a connection?", *Human Movement Science*, vol. 30, no. 5, pp. 869-888.
- Stergiou, N., Harbourne, R.T. & Cavanaugh, J.T. 2006, "Optimal movement variability: a new theoretical perspective for neurologic physical therapy", *Journal of Neurologic Physical Therapy*, vol. 30, no. 3, pp. 120.
- Sterzing, T., Schweiger, V., Ding, R., Cheung, J.T. & Brauner, T. 2013, "Influence of rearfoot and forefoot midsole hardness on biomechanical and perception variables during heel-toe running", *Footwear Science*, vol. 5, no. 2, pp. 71-79.
- Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R. & Zumbo, B.D. 2002, "A retrospective case-control analysis of 2002 running injuries", *British journal of sports medicine*, vol. 36, no. 2, pp. 95-101.
- Tenbroek, T. 2011, *Adaptations to Running While Footwear Cushioning and Surface are Manipulated*, University of Massachusetts - Amherst.
- TenBroek, T.M., Rodrigues, P., Frederick, E.C. & Hamill, J. 2013, "Effects of unknown footwear midsole thickness on running kinematics within the initial six minutes of running", *Footwear Science*, vol. 5, no. 1, pp. 27-37.
- Turner, C.H. 1998, "Three rules for bone adaptation to mechanical stimuli", *Bone*, vol. 23, no. 5, pp. 399-407.
- van Wegen, E.E.H. 2000, "On Variability and Stability in Human Movement", *JAB*, vol. 16, no. 4.
- von Tscherner, V. 2000, "Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution", *Journal of Electromyography and Kinesiology*, vol. 10, no. 6, pp. 433-445.
- Wakeling, J.M. & Nigg, B.M. 2001, "Modification of soft tissue vibrations in the leg by muscular activity", *Journal of applied physiology*, vol. 90, no. 2, pp. 412-420.
- Wakeling, J.M., Pascual, S.A. & Nigg, B.M. 2002, "Altering muscle activity in the lower extremities by running with different shoes", *Medicine & Science in Sports & Exercise*, vol. 34, no. 9, pp. 1529-1532.
- Wells, R. & Winter, D. 1980, "Assessment of signal and noise in the kinematics of normal, pathological and sporting gaits", *Human locomotion*, vol. 1, pp. 92-93.
- Williams, K. 1993, "Biomechanics of distance running", *Current issues in biomechanics*, , pp. 3-32.

- Williams, D.S., McClay, I.S. & Manal, K.T. 2000, "Lower extremity mechanics in runners with a converted forefoot strike pattern", *Journal of Applied Biomechanics*, vol. 16, no. 2, pp. 210-218.
- Wolf, A., Swift, J.B., Swinney, H.L. & Vastano, J.A. 1985, "Determining Lyapunov exponents from a time series", *Physica D: Nonlinear Phenomena*, vol. 16, no. 3, pp. 285-317.
- Wolff, J. 1986, *The law of bone remodelling*, Springer - Verlag, Berlin and New York.
- Woollacott, M.H., Shumway-Cook, A. & Nashner, L.M. 1986, "Aging and posture control: changes in sensory organization and muscular coordination", *The International Journal of Aging and Human Development*, vol. 23, no. 2, pp. 97-114.
- Wurdeman, S.R., Myers, S., Jacobsen, A. & Stergiou, N. 2012, "Prosthesis preference is related to stride-to-stride fluctuations at the prosthetic ankle", *J.Rehabil.Res.Dev.* ,
- Wurdeman, S.R., Myers, S.A. & Stergiou, N. 2012, "Transtibial Amputee Joint Motion has Increased Attractor Divergence During Walking Compared to Non-Amputee Gait", *Annals of Biomedical Engineering*, , pp. 1-8.
- Zadpoor, A.A. & Nikooyan, A.A. 2011, "The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review", *Clinical Biomechanics*, vol. 26, no. 1, pp. 23-28.