SENSORY FEEDBACK IN BAREFOOT RUNNING THEORY

BAREFOOT RUNNING: THE ROLE OF SENSORY FEEDBACK AND ITS THEORETICAL IMPLICATIONS

By

JODI GALLANT, BKin

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Master of Science

McMaster University

MASTER OF SCIENCE (2013) McMaster University

(Rehabilitation Science) Hamilton, Ontario

TITLE: Barefoot running: The role of sensory feedback and its theoretical implications

AUTHOR: Jodi Gallant, BKin (Brock University)

SUPERVISOR: Dr. Michael R. Pierrynowski

NUMBER OF PAGES: xi, 93

Abstract

Introduction: Barefoot running is growing in popularity as runners seek strategies to avoid running-related injuries (RRIs). A new theoretical perspective suggests that the improved cutaneous sensation during barefoot running results in a less injurious running style characterized by increased cadence, landing on the forefoot and more knee flexion. The mechanisms by which the barefoot running style may have an effect on RRIs are not well understood.

Purpose: Explore the new theoretical perspective on RRIs that supports the barefoot running style and investigate the effects of modified cutaneous sensation on the adaptation to and retention of the barefoot running style.

Methods: First, a scoping review was performed to identify implicit theory underlying both traditional shod and barefoot running research and practice. Second, a feasibility study investigated altered cutaneous sensation as a proposed mechanism by which a person learns and retains the skill of barefoot running. Sixteen participants ran shod on a treadmill then were randomized to receive one of four cutaneous sensation treatments. They then ran barefoot for the first time and 48 hours later. Changes in the cadences, foot angles and knee angles means and variations across runs and treatment groups were used to quantify learning and retention.

Results: The scoping review provided evidence that improved plantar cutaneous sensation, such as when one runs barefoot, could reduce the risk of RRIs. In the feasibility study, our findings suggest that barefoot compared to shod running increased plantar cutaneous sensory thresholds, and increased mean cadence and mean foot angle. Improved retention of the barefoot running style was shown in the treatment group with anaesthetic cream on their legs.

Conclusions: Plantar cutaneous sensation is proposed as an important factor when exploring the etiology of RRIs. This knowledge may influence an individual's risk of experiencing a running-related injury.

Acknowledgements

This thesis could not have been possible without the support and assistance of many people for whom I am sincerely grateful.

As a thesis supervisor, I could not have asked for a more dedicated, knowledgeable and accessible mentor than Dr. Michael Pierrynowski, who went above and beyond the call of duty to provide me with opportunities for a well-rounded, complete learning experience and modelled such a passion for learning and research that I couldn't help but enjoy the process.

I would like to express my sincere appreciation to my committee members, who provided a wide variety of expertise and were wonderful mentors in unique ways. Dr. Jae Patterson always provided thoughtful insight, positive feedback and enthusiasm in the face of challenges. Dr. Vickie Galea encouraged me to think critically and always provided honest and straightforward feedback. Dr. Joy MacDermid provided tools, resources and strong support for the project while setting a high standard for professionalism and hard work.

I am sincerely grateful to the REBP team for their assistance with recruitment and data collection and their enthusiasm for the project. Special thanks to the participants of my research study for making this work possible. I would also like to thank the McMaster School of Rehabilitation Science for providing me with financial support throughout the duration of my Master's training.

My graduate school experience was greatly enriched by the friendly and supportive crew in room 308. Their brilliant minds, warm hearts and encouraging words have made a solo journey feel like a team sport. I am especially grateful for the kindred spirit I have found in my friend, Andrea Cross. Her listening ear and motivating talks pushed me through the tough, final leg of this journey.

I would like to express my deepest thanks to my friends and family who provided me with extra grace and understanding during the busiest of times. Their encouragement, love, prayers, and support have gotten me through the peaks and troughs of this experience and have allowed me to keep it all in perspective. I feel truly blessed.

This work is dedicated to my husband Luke, who gave new meaning to the words 'unconditional support' throughout my Master's training. He was always willing to listen, to provide unending patience and to make extraordinary sacrifices that allowed me to pursue my passions. His ability to know what I needed to be productive and to do whatever it took to get us to the finish line has made me confident that I could not have completed this journey without him.

"And whatever you do or say, do it as a representative of the Lord Jesus, giving thanks through him to God the Father." Colossians 3:17

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Declaration of Academic Achievement

This paper is a sandwich thesis containing two original manuscripts. I, Jodi Gallant, wrote both manuscripts with assistance from Michael Pierrynowski and editorial input from Vickie Galea, Joy Macdermid, Jae Patterson, Laurie Wishart and Stephen Perry.

The first manuscript (Chapter 2) is a paper detailing the implicit theory behind the prevention and treatment of running-related injuries. An earlier version of this paper has been accepted for publication in the Journal of the American Podiatric Medicine Association (15 January 2013). Jodi Gallant performed the scoping review, defined and detailed the two opposing theories with assistance from Michael Pierrynowski. Laurie Wishart gave early editorial input. Vickie Galea, Joy MacDermid and Jae Patterson provided editorial assistance with the final manuscript preparation.

The second manuscript (Chapter 3) is a publishable paper detailing the background, methods, results and discussion of a feasibility study that was completed on the role of plantar cutaneous sensation while learning the novel task of barefoot running.

Jodi Gallant determined the research question, provided the overall study design, drafted the ethics submission, performed the data collection, interpreted the findings, and drafted the manuscript. Michael Pierrynowski assisted in reviewing the ethics application, refining the research question and study design, undertaking the analysis, interpreting the findings, and provided editorial assistance with manuscript preparation. Vickie Galea, Joy MacDermid, Jae Patterson and Stephen Perry provided editorial assistance with the final manuscript preparation.

CHAPTER 1: INTRODUCTION

Thesis Rationale and Overview

Despite substantial efforts, a relatively high rate of injury has been consistently reported in the running community over the last 40 years (Jenkins & Cauthon, 2011). As a result, a growing number of runners have recently embraced a new theoretical framework that supports the practice of barefoot running. Barefoot running may be defined as running while completely barefoot, with nothing separating the skin on the bottom of the foot from coming into contact with the running surface. This is in direct contrast to shod running which is defined as running while wearing any type of footwear.

The theoretical perspective behind barefoot running is emergent and represents a departure from the traditional framework for the prevention and treatment of running-related injuries, most notably that held by supporters of the modern running shoe. This emergent theory at present remains poorly defined, but is implicit in literature and proposes several new causal mechanisms leading to running-related injury. In addition, it proposes several mechanisms by which barefoot running is suggested to reduce an individual's risk of running-related injury. These proposed mechanisms command investigation in order to support or refute barefoot running as a strategy to avoid injury.

In order to investigate the proposed mechanisms, the theoretical perspective behind barefoot running must be explored and defined. As a result, this thesis consists of two manuscripts in order to first define the theoretical rationale for barefoot running and then to explore one of the proposed mechanisms by which it may be beneficial. A scoping review of the literature (Chapter 2) was performed in order to define, compare and contrast the opposing theories on the etiology of running-related injuries. Based on the results of this review, a feasibility study (Chapter 3) was undertaken to investigate one of the proposed mechanisms by which a person might adapt to and retain the barefoot running style.

Development of Research Question

Figure 1 provides a summary of the theoretical framework that is found implicit in the barefoot running literature. Central to this framework is the barefoot running style. The barefoot running style is perhaps the defining factor by which the practice of barefoot running is proposed to result in fewer injuries than shod running. It is characterized by changes in running kinematics and kinetics, such as increased cadence, initial contact with the ground by the forefoot or midfoot and an increase in knee flexion during the stance phase (Bishop, Fiolkowski, Conrad, Brun, & Horodyski, 2006; Divert et al., 2008; Lieberman et al., 2010; Squadrone & Gallozzi, 2009). This style is proposed to occur naturally as the body makes adjustments based on an increase in sensory feedback (somatosensation) as the feet come into direct contact with the running surface (Robbins & Gouw, 1991). For this reason, one element of somatosensation was investigated in this study. Plantar cutaneous sensation refers to the sensory information from the touch mechanoreceptors in the skin of the bottom of the feet that is received by the central nervous system as the skin is deformed by contact with a surface. This element of somatosensation was of interest because the defining characteristic of barefoot running -

the feet coming into direct contact with the running surface - should intuitively result in improved sensation. From this perspective, barefoot running may be seen as an intervention in itself, with the potential to have an effect on somatosensation and therefore alter the way that a person runs.

Based on this theoretical framework, the research question was determined to be: “What role does plantar cutaneous sensation play in the adaptation and retention of the barefoot running style?” For the purposes of this thesis, adaptation and retention refer to learning in specific ways. Adaptation refers to the relatively short-term changes that may occur during a person’s first attempt at a novel task, such as barefoot running. These changes are a response to the novel sensations and forces associated with the task. Learning will be inferred from a decrease in variability, representing adaptation to a task. Retention refers to a person’s ability to retain these changes over the relative long-term, so much so that they have made a permanent change in their running style.

Purposes and Significance

The purpose of the scoping review was to explore the theoretical rationale behind barefoot running as a background for investigating the mechanisms by which it is proposed to reduce the incidence of running-related injuries. The purpose of the feasibility study was to report potential trends and observations in the adaptation and retention of the barefoot running style as a result of a change in plantar cutaneous sensation. Overall, the papers contained in this thesis seek to inform researchers and novice runners of the importance of cutaneous sensation when learning the skill of barefoot running. This knowledge may influence an individual's risk of experiencing a running-related injury.

References

Bishop, M., Fiolkowski, P., Conrad, B., Brun, D., & Horodyski, M. (2006). Athletic footwear, leg stiffness, and running kinematics. *Journal of athletic training*, *41*(4), 387–392.

Divert, C., Mornieux, G., Freychat, P., Baly, L., Mayer, F., & Belli, A. (2008). Barefoot-shod running differences: shoe or mass effect? *International journal of sports medicine*, *29*(6), 512–8.

Jenkins, D. W., & Cauthon, D. J. (2011). Barefoot running claims and controversies: a review of the literature. *Journal of the american podiatric medical association*, *101*(3), 231–46.

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*, *463*(7280), 531–5.

Robbins, S. E., & Gouw, G. J. (1991). Athletic footwear: unsafe due to perceptual illusions. *Human performance*, *23*, 217–24.

Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of sports medicine and physical fitness*, *49*(1), 6–13.

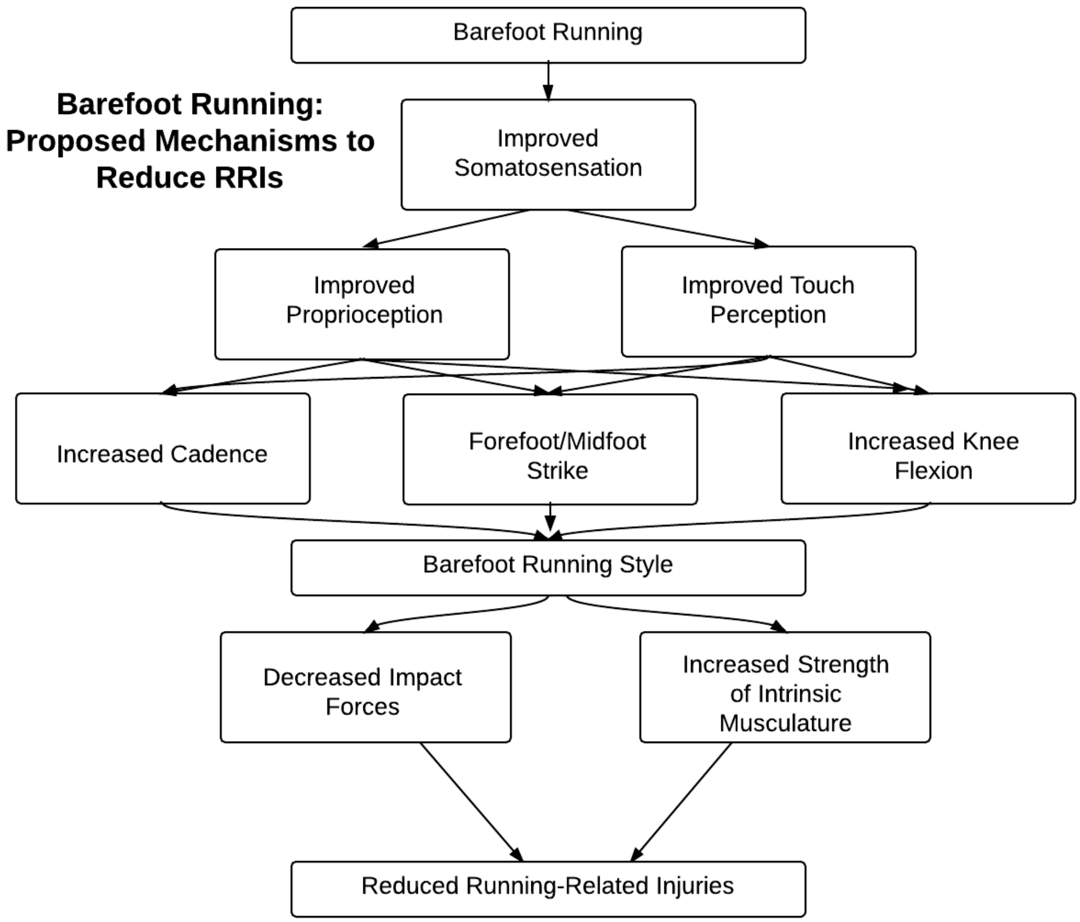

Figure 1 Summary of the proposed mechanisms by which barefoot running may reduce the risk of running-related injuries (RRIs).

CHAPTER 2: A THEORETICAL PERSPECTIVE ON RUNNING-RELATED INJURIES

Submitted earlier version for publication as:

Gallant, J.L., & Pierrynowski, M.R. (2013). A theoretical perspective on running-related injuries. *Journal of the American Podiatric Medicine Association, (In Press).*

Accepted for publication.

Permission to reprint is granted after publication.

Abstract

The etiology of running-related injuries remains unknown, however, an implicit theory underlies much of the conventional research and practice in the prevention of these injuries. This theory posits that the cause of running-related injuries lies in the high impact forces experienced between the foot and ground upon contact and the subsequent abnormal movement of the subtalar joint. The application of this theory is seen in the design of the modern running shoe with cushioning, support, and motion-control. However, a new theory is emerging which suggests that it is the use of these modern running shoes that has caused a maladaptive running style, which contributes to a high incidence of injury among runners. The suggested application of this theory is to cease use of the modern running shoe and transition to barefoot or minimalist running. This new running paradigm, which is at present inadequately defined, is proposed to avoid the adverse biomechanical effects of the modern running shoe. Future research should rigorously define then test both theories regarding their ability to discover the etiology of

running-related injury. Once discovered, the putative cause of running-related injury will then provide an evidence-based rationale for clinical prevention and treatment.

Introduction

Running is one of the most popular forms of exercise in North America, and its benefits to health and wellness are well-known. Despite evidence to suggest that running is one of the most effective ways to achieve fitness (Fields, Sykes, Walker, & Jackson, 2010), recent statistics suggest that it also involves a relatively high risk of injury. The results of several studies have found that anywhere between 11-85% of recreational runners experience a running-related injury (RRI) every year (Nielsen, Buist, Sorensen, & Lind, 2012) and 30-90% of injuries result in a reduction or stoppage of training (van Mechelen, 1992). The wide ranges in these statistics are largely due to varied definitions of the words 'runner' and 'injury'. For the purposes of this paper, a runner will be defined as anyone who self-identifies as such and runs a minimum distance per week on a regular basis for the purpose of physical fitness. A running-related injury will be defined as any musculoskeletal ailment of the lower extremities that is attributed to running and results in a reduction or stoppage in running mileage for at least one day. Considering the well-known health benefits of physical activity, any factor which causes a reduction or stoppage in physical activity should be viewed as a barrier to the health and wellness of North Americans. In this context, the etiology of RRIs must be well defined in order to develop effective modes of prevention and treatment and consequently improve the overall health status of North Americans.

The etiology of running-related injuries has been a source of debate for many years. An RRI may occur as a result of any number of combinations of different factors, often unique to each individual. This multifactorial nature makes the prevention of RRIs challenging, and a simple, customizable system of prevention appealing. One of the most common methods of prevention is the prescription of running shoes based on foot type (Johnston, Taunton, Lloyd-Smith, & McKenzie, 2003). This is a widely accepted practice, and the design of the modern running shoe now appears to be technologically-advanced to address the problem of RRIs. However, despite each popular brand's claims for cushioning, support, and motion-control, a recent systematic review found that these shoes have never been tested in controlled clinical trials and so their effect on injury rates remains unknown (Richards, Magin, & Callister, 2009). In fact, a review of the literature on injury incidence has shown that RRIs have actually increased alongside the development of the modern running shoe over the last 40 years (Jenkins & Cauthon, 2011). As there remains no real consensus on what causes these injuries or how best to prevent them, the modern running shoe remains the gold standard and is consistently recommended to footwear prescribers for injury prevention (Johnston et al., 2003). A paradox now exists between evidence and practice as continued advances are made in cushioning, support and motion-control and injury rates continue to increase (Jenkins & Cauthon, 2011).

At the root of the paradox between evidence and practice is the widely accepted way of thinking about the causes of RRIs and the role of running shoes. This way of thinking may be considered a theoretical perspective as it is extremely prevalent and seems to have developed almost unknowingly and without being questioned for many years. Although it has never been formally presented or tested, it is widely accepted as fact. Due to its lack of testing and support of the use of running shoes for the prevention of RRIs, this perspective will be referred to as the 'Running Shoe Theory' for the purposes of this paper.

Based on the high injury rates associated with the use of shoes made with the Running Shoe Theory in mind, many are now questioning where this thinking came from and how helpful it really is to the health and wellness of those who run for exercise. It has recently been challenged by a wide variety of researchers, clinicians and runners alike, who suggest there may be an alternative way of thinking about the foot's function during running and the role that footwear plays in running-related injury (Jenkins & Cauthon, 2011; Lieberman, 2012; Robbins & Hanna, 1987). A new theory is emerging that supports the barefoot running movement as a more natural and potentially less injurious way to run. Despite having only a small amount of scientific evidence to support this new way of thinking, many runners have taken off their shoes and joined the movement based solely on the experiences of other runners who have done the same. They claim to experience less injuries and better performance, but many skeptics still hold to the traditional way of thinking and are waiting on solid evidence before changing their views. This emerging theory on the causes and prevention of RRIs will be referred to as the 'Barefoot Running Theory' for the purposes of this paper.

As research progresses and the running community reconsiders the etiology of RRIs, it is critical that these opposing theories be well defined and fully developed. Theory plays an important role in clinical decision-making and the development of new research programs, especially when there is a need for stronger evidence. This paper will outline both theories on the contributing factors to RRIs and summarize the available evidence to confirm or contradict their claims.

The objectives of this paper are to describe and discuss the theories behind running-related injury and footwear choice from the two opposing views. We will first describe the Running Shoe Theory of running-related injury which supports the use of cushioned, supportive, motion-controlling shoes. We will then summarize the evidence behind the application of this theory and the lack of evidence that has led many to question its usefulness. Principles and existing research of the emerging Barefoot Running Theory will then be discussed including the ways in which this theory addresses the problems of the opposing theory. Finally, the areas in which future research is needed and the challenges specific to this kind of research will be outlined.

Running Shoe Theory on the Cause of RRIs

Theory Development

Theory may be defined as a set of tested propositions to explain an observed phenomenon. When developing modes of prevention and treatment of injury where the ultimate cause is unknown, theory is critical for informing research and practice. This means that a theory should be thoughtfully developed and subject to continual testing against the latest evidence. Unfortunately, this does not always happen, as theory may develop alongside practice, based predominantly on the most prevalent way of thinking. Eventually they may become widely accepted without ever undergoing scientific testing. This seems to be the case when considering the ultimate cause of RRIs.

A recent systematic review by Richards, Magin and Callister (2009) found no studies that evaluated the effects of running shoes on injury or performance. They suggest that running shoes have therefore been prescribed as the gold standard for prevention and treatment of RRIs without scientifically proven benefit. If not based on evidence, it can be said that this practice, along with the design of the modern running shoe, is based on a perspective that is only theoretical in nature. The following sections will define and describe this theory, in order to better understand the paradigm that exists between current research and practice.

According to Robbins and Hanna (1987), the assumptions underlying the design of modern running shoes contend that feet are evolutionarily unsuccessful and inherently fragile; therefore the only way to prevent RRIs is to protect the foot by ‘packaging’ it in footwear that provides cushioning, support, and pronation control. For the purposes of this paper, these assumptions will be referred to as the ‘Running Shoe Theory’. The application of the Running Shoe Theory can be seen in a typical modern running shoe which has thick heel cushioning, firm arch support and a rigid heel counter to control motion at the subtalar joint. These shoes as a group are termed “pronation control, elevated cushioned heel” (PCECH) shoes (Richards et al., 2009) to reflect the different types of running shoes that are often prescribed after classifying an individual by foot type and arch structure. These shoes are designed to address the supposed causes of RRIs and therefore work to prevent injury. However, there is a lack of evidence that supports the use of PCECH shoes to prevent injury and therefore it is important to re-examine our theories on what causes RRIs. The following discussion will define and describe the two most common causes of injury, as held by the Running Shoe Theory of RRIs.

High Impact Forces (Kinetics)

The Running Shoe Theory on the cause of RRIs asserts that high impact forces experienced while running are one major cause of injury. This assumption is founded in logic and has been held for many years. In fact, twenty-five years ago, Robbins and Hanna (1987) described a general consensus that existed among sports medicine practitioners as to the ultimate cause of RRIs. It was understood that while running, the high rate and magnitude of loading (impact force) upon contact with the ground was the cause of RRIs. From a biomechanical perspective, Hreljac (2005) describes the stress-frequency curve which applies to all tissues of the body. Based on its physiology, each tissue has a different injury threshold which may be reached with either a high frequency or high stress (magnitude) of impact forces. From this standpoint, it is understandable that excessive force will inevitably result in injury (Richards et al., 2009) however this curve may be modified by many factors, making the relationship between impact and injury more complex.

Only recently have several observational studies actually linked these high impact forces to RRIs (Hreljac, 2005). As Hreljac (2005) summarizes, when comparing injured and non-injured runners, at least four published studies have found that injured runners had greater vertical impact forces than non-injured runners (Ferber, McClay-Davis, Hamill, Pollard, & McKeown, 2002; Grimston, Nigg, Fisher, & Ajemian, 1994; Hreljac, Marshall, & Hume, 2000; Stephen P Messier, Davis, Curl, Lowery, & Pack, 1991). In addition, one prospective study followed 240 female runners over two years and reported greater impact loading in the group of runners who sustained an injury during that time (Davis, Bowser, & Mullineaux, 2010). From these results it is suggested that high impact loading may increase the risk of running-related injuries.

It has also been argued that running on hard surfaces will increase impact forces and subsequently increase risk of injury. However, the evidence to support this assumption is weak (Richards et al., 2009). In fact, Ferris, Louie and Farley (1998) report that when running on hard surfaces, humans tend to land with a lesser amount of leg stiffness and therefore maintain the same peak ground reaction force, despite a change in surface stiffness. Nigg and Wakeling (2001) agree and suggest that the mechanism behind this adjustment involves muscle tuning in the locomotor system, consisting of precise changes to muscle activation patterns based on muscle spindle feedback, which occurs shortly before ground contact to prepare the body for landing. These findings put the Running Shoe Theory into question, as it seems that the body is capable of attenuating the high impact forces experienced on hard surfaces by decreasing leg stiffness through muscular activation patterns and therefore may not need any additional protection to avoid injury.

Although an association between high impact forces and RRIs is supported by the research, it is clear that hard surfaces do not directly increase these forces. More research is therefore needed to determine the cause of high impact forces and the best ways to attenuate them.

Abnormal Subtalar Motion (Kinematics)

A second factor that is often implicated as injury-causing by the Running Shoe Theory is based on what is considered to be abnormal motion at the subtalar joint (Johnston et al., 2003). Also known as the talocalcaneal joint, the subtalar joint occurs at the articulation between the talus and calcaneus bones and allows for pronation and supination of the foot during gait. Abnormal motion at the subtalar joint is proposed to consist of either overpronation or oversupination.

Pronation at the subtalar joint allows for the attenuation of impact forces over a longer period of time, preventing overloading of the lower extremity (Hreljac, 2005). It typically occurs during the first 25% of the stance phase and allows the foot to become flexible and adaptable to different types of terrain (Leung, Mak, & Evans, 1998). Normally, pronation ends as the foot approaches mid-stance and supination occurs to allow the foot to act as a rigid lever and propel the body forward. When pronation continues throughout this period, it may stretch the plantar ligaments and prolong the internal rotation of the leg, both of which may lead to pain and injury (Leung et al., 1998). This extended period of pronation is considered by supporters of the Running Shoe Theory to be abnormal and a potential cause of RRIs such as plantar fasciitis and ankle inversion sprains.

The idea that overpronation leads to injury is one that has been tested and resulted in conflicting reports. When measuring maximum pronation angles and maximum pronation velocities, Hreljac (2005) summarizes that injured runners have been reported in different studies to exhibit more pronation (Messier & Pittala, 1988; Milner, Hamill, & Davis, 2010), less pronation (Hreljac et al., 2000) and no difference in pronation (Messier et al., 1991) when compared to non-injured runners. Some researchers have even suggested that a larger amount of pronation is favourable during running, by facilitating force attenuation over a longer period of time, as long as it ends at mid-stance (Hreljac et al., 2000). Based on these reports, it is clear that no consistent association exists between overpronation and RRIs.

Oversupination, or underpronation, at the subtalar joint is less commonly mentioned in the literature, as it seems to be less prevalent in the general population. However, it is another classification of foot type that is often prescribed specific shoes to prevent supination which exceeds the 'normal' range (Johnston et al., 2003). This range, like that of overpronation, remains relatively undefined and we were unable to locate any controlled, clinical trials that examined the relationship between oversupination and RRIs.

Despite being commonly implicated as a major cause of injury in runners, no consistent association has been made between subtalar motion and RRIs. This finding, along with the lack of data on effectively attenuating high impact forces, brings into question the Running Shoe Theory on the cause of RRIs and with it, the design of the modern running shoe. The following discussion will address the application of this traditional theory, and consider the elements of PCECH shoes which are commonly believed to reduce the risk of injury, despite a lack of support in the scientific literature.

Application of Running Shoe Theory

According to Stewart (1972), the first shoes were worn primarily to protect the sole. Until the development of the modern running shoe in the 1970's, everyone ran either barefoot or in minimal shoes with little cushion and minimal heel lift (Lieberman, 2012). The PCECH shoe was developed as a natural application of what was thought to be the cause of RRIs. If injuries were thought to occur as a result of high impact forces and abnormal subtalar motion, then logically, a shoe that could attenuate these forces and prevent abnormal motion at the subtalar joint should prevent injuries. Although both of these proposed causes lack support in the scientific literature, PCECH shoes continue to be prescribed for the prevention of RRIs. In addition, the assumption that a shoe might effectively attenuate high impact forces and prevent abnormal subtalar motion remains unproven (Richards et al., 2009).

Richards, Magin, & Callister (2009) performed a review of the evidence for the prescription of PCECH shoes and list cushioning, an elevated heel, and motion-control systems as the three major features which have been typically incorporated in order to prevent injury. The following discussion will consider the two features of the PCECH shoe which have been designed to address the previously mentioned proposed causes of RRIs. More specifically, cushioning features to address high impact forces and motion-control systems to address abnormal subtalar motion. The lack of evidence for these strategies to effectively reduce the risk of RRIs will then be reviewed.

Cushioning

A typical PCECH shoe uses cushioning as a strategy to attenuate the high impact forces experienced while running. The Running Shoe Theory of RRIs behind this strategy views the foot as an inflexible lever, meaning it is therefore incapable of attenuating the high magnitude and rate of forces believed to be experienced when running on hard surfaces. The role of footwear, from this perspective, is to provide shock absorption through the use of cushioning in the midsole. Most commonly, ethylene vinyl acetate (EVA) foam is used but other technologies include air, gel, rubber, altered EVA and even springs (Kong, Candelaria, & Smith, 2009). However, the evidence is poor that supports the assertion that decreasing the stiffness of the interface between the foot and ground reduces impact forces or injury rates (Ferris et al., 1998). This is largely due to the observation that depending on the stiffness of the surface, muscle tuning appears to alter the stiffness of the leg just as the foot makes contact with the ground (Ferris, Liang, & Farley, 1999). In addition, a study by Kong, Candelaria and Smith (2009) compared the kinetics and kinematics of running in new cushioned shoes and worn shoes with degraded cushioning. They report no difference in maximum vertical active force or loading rate between new and worn shoes, but an increase in stance time in worn shoes. From these results they suggest that runners maintain constant impact loading by modifying their running form according to the amount of shoe cushioning (Kong et al., 2009).

The theoretical assumption that a cushioned shoe can reduce impact forces and reduce injuries appears to be contrary to the findings of aforementioned studies. In addition, as Richards, Magin and Callister (2009) suggest, cushioning itself may cause more harm than good by diminishing proprioception and providing the runner with a false sense of security against high impact forces. The proposed negative effects of PCECH shoes will be further discussed as it applies to the emerging Barefoot Running Theory of RRIs.

Motion-Controlling

Based on the theoretical assumption that abnormal motion at the subtalar joint contributes to RRIs, a typical PCECH running shoe includes features which are designed to prevent the subtalar joint from motion that exceeds the so-called 'normal' range. This most commonly refers to the prevention of overpronation, but may also include features to prevent oversupination. Features that are often advertised as being motion-controlling include a wedging or heel flare counter and the use of materials with different deformation rates in the lateral and medial midsoles (Cheung, Wong, & Ng, 2011). These features are designed to control motion by either restricting the subtalar joint's range of motion to that considered normal, or by directing motion from supination to pronation and back to supination.

Reports on the effectiveness of motion-control shoes on subtalar motion are conflicting. Some studies report that these shoes are capable of only small, subject-specific changes in running kinematics (Nigg & Wakeling, 2001). In contrast, a recent systematic review concluded that "motion control footwear is effective at reducing the amount of foot pronation and the vertical impact peak during running" (Cheung et al., 2011, p. 1317). However, this review did not find any evidence to suggest that motion control footwear is effective at controlling rotation at proximal segments such as the tibia and femur. As they explain, it is the rotation at the knee that is most often cited as the site of injury. In addition, one study found that a reduction of foot pronation during running actually increased impact loading (Perry & Lafortune, 1995). Although PCECH shoes may reduce foot pronation, it is unknown what impact this has on the risk of experiencing an RRI.

The theoretical assumption that motion control footwear is effective at altering subtalar motion is meaningless if abnormal subtalar motion does not contribute to RRIs. As previously mentioned, there has been no consistent link made between subtalar motion and injury rates (Richards et al., 2009). More research is needed to examine the effects of pronation and supination on the incidence of RRIs. Specifically, longitudinal trials which compare injury rates between runners wearing shoes with and without motion control systems are required to test this assumption (van Gent et al., 2007).

Although PCECH shoes are a common clinical application for the prevention of RRIs, there is a lack of support for this practice in the scientific literature. The design of a typical PCECH shoe relies upon two theoretical assumptions that remain unproven: that cushioning may effectively reduce high impact forces and therefore reduce injuries and that reducing the amount of abnormal subtalar motion while running will reduce injuries. Without support for these assumptions on its application, the validity of the Running Shoe Theory on the cause of RRIs must be called into question. It is here, in the shortcomings of its predecessor, that a new theory is emerging to explain the etiology behind running-related injuries and suggest new strategies for their prevention and treatment.

Barefoot Running Theory on the Cause of RRIs

Theory Development

Within the larger North American running community, there is a growing movement of barefoot runners. While supporters of the practice have always been around, it is only in the last decade that it has substantially grown, in large part due to the publicity from both scientific and non-scientific sources. Beginning with the trailblazing work of Robbins and Hanna in the late 1980's (Robbins & Hanna, 1987) and gaining more public attention with Lieberman's 2010 study (Lieberman et al., 2010), a scientific basis for the practice of barefoot running is now growing. Many attribute the recent surge in popularity of barefoot running to the publication of Christopher McDougall's book, Born to Run. This best-selling book promotes the practice while telling the story of the author's own journey in learning to run long distances without injury (McDougall, 2009). Throughout both the book and the scientific literature, a new way of thinking about what does and does not cause RRIs is presented, and a new theory on their prevention is steadily being built.

The emerging theory behind the barefoot running movement is based on what are considered to be the reasons for the large incidence in RRIs with the use of PCECH shoes. Several researchers have implicated these shoes for causing detrimental side effects which may contribute to RRIs (Lieberman, 2012; Richards et al., 2009; Robbins & Gouw, 1991; Robbins & Hanna, 1987). According to this Barefoot Running Theory, the foot is a dynamic, flexible system that attenuates high impacts with the downward deflection of the medial longitudinal arch (Ker, Bennett, Bibby, Kester, & Alexander, 1987). It is capable of rehabilitation and avoids injury when allowed to function according to its physiological design (Robbins & Hanna, 1987). Running-related injuries occur when the foot is forced to function unnaturally, that is, confined within a PCECH shoe, and the body maladapts to this condition (Lieberman, 2012). These maladaptations, or side effects, of the PCECH shoe have been proposed to cause injury, often based more on a lack of support for the Running Shoe Theory than on experimental evidence showing their detriment. Considering the limited body of evidence in support of this emerging theory, the following discussion will concentrate on the three most commonly cited side effects of PCECH shoes: atrophy of the intrinsic foot musculature, diminished somatosensation and an abnormal gait (Lieberman et al., 2010; Robbins, Waked, Allard, McClaran, & Krouglicof, 1997; Robbins & Hanna, 1987). Although other factors, such as running economy, are mentioned in the literature, these three have been chosen based on the amount of currently available evidence.

Atrophy of Intrinsic Foot Musculature

As early as 1972, Stewart (1972) proposed that the solution to foot ailments lies in using them in a more natural physiological way. His observations of the Army Shoe Board led him to believe that the foot's arch is maintained not only by bones and ligaments but also by strong intrinsic musculature. In order to maintain the arch, these intrinsic foot muscles must be strong, and to be strong they must be used. The Running Shoe Theory of RRIs assumes that the typical rigid foot with its relatively unyielding arch is beyond rehabilitation (Robbins & Hanna, 1987). It is therefore packaged into a shoe with a large amount of shock-absorbing material surrounding it. This tightly packed shoe does not require much, if any, muscular support to maintain the medial longitudinal arch as it is firmly supported. The Barefoot Running Theory of RRIs hypothesizes that intrinsic foot musculature may atrophy as a result of the use of tightly packed, cushioned shoes, and cause many common foot ailments seen today.

As a result of the PCECH shoe's tight fit, little intrinsic muscle activation is required for locomotion. It is therefore proposed that runners who wear PCECH shoes may develop weak intrinsic foot musculature which may lead to a decrease in medial longitudinal arch height and subsequent injuries. These injuries may include plantar fasciitis, one of the most commonly experienced conditions in sports involving running and jumping (Robbins & Hanna, 1987). Although a PCECH shoe treats the symptoms of plantar fasciitis by providing support for the medial longitudinal arch, it does nothing to treat the cause and therefore nothing to alleviate the symptoms of plantar fasciitis experienced when not wearing PCECH shoes. For example, a person who suffers from plantar fasciitis may find that a new pair of PCECH shoes alleviates the pain normally felt while shod, but they still suffer from pain and discomfort while at home and unshod. Robbins and Hanna (1987) propose that strengthening intrinsic foot musculature may spare the fascia by giving it support during impact. More research is required to compare intrinsic muscle strength between habitually shod and habitually barefoot runners. Based on Davis' Law (Davies & Ellenbecker, 1999), it is reasonable to suppose that the use of a PCECH shoe which provides enough support to the medial longitudinal arch without much muscular support may lead to atrophy of these muscles. This side effect is therefore proposed to contribute to an increased risk of injury.

Diminished Somatosensation

The Barefoot Running Theory of RRIs proposes that sensory feedback between the peripheral and central nervous systems is critical in the avoidance of injury. Somatosensation from the foot is provided in large part by proprioception and touch. Proprioception in this context refers to a kinesthetic sense of foot position. McCloskey (1978) defines kinesthetic sensations as those perceived about the "static position or velocity of movement of those parts of the body moved by skeletal muscles and perceived sensations about the forces generated" (p. 763). Touch refers to the information provided by mechanoreceptors on the plantar surface of the foot. Robbins and Waked (1998) proposed that footwear attenuates plantar tactile events, thus preventing normal stimulation of the foot's mechanoreceptors. It is these plantar surface mechanoreceptors that respond to plantar deformations and, in combination with muscle spindle fibres, provide the body with directional sensibility to allow for rapid changes in foot position in order to avoid injury (Robbins & Gouw, 1991). According to this finding, exposure of the plantar skin's mechanoreceptors to the ground surface is critical to provide the body with accurate feedback in order to function optimally and avoid injury.

Based on one study of young men in barefoot and shod conditions, errors in foot position sense increased by more than 4^{o} when in the shod condition (Robbins, Waked, & McClaran, 1995). Additionally, a similar study done in older men found an increase in foot position sense errors in conditions with softer, thicker soles when compared to firm, thinner soles (Robbins et al., 1997). The danger in these errors in foot position sense lies in their correlation to ankle injuries when running. According to Robbins and Waked (1998), impaired proprioception results in inadequate use of anticipatory muscular movements during dynamic situations. These anticipatory muscular movements are what the body relies on to prevent injury when there is not enough time to respond to a loading event, such as when landing on an uneven surface.

Robbins and Hanna (1987) suggest that the modern running shoe has placed the runner in a vulnerable state by diminishing sensory feedback without diminishing the injury-causing impact. Injuries occur due to the lack of protective actions, normally stimulated by sensory feedback, and the appearance of protection provided by a heavilycushioned running shoe. This is referred to as the “discomfort-impact illusion”, whereby injury is inevitable as a result of footwear that provides the wearer with plantar comfort despite the large vertical impact upon landing (Robbins & Gouw, 1991). On account of the perceived impact being therefore lower than the actual impact, the body responds with inadequate anticipatory muscular movements to moderate the impact and subsequent injury occurs (Robbins & Gouw, 1991). According to the Barefoot Running Theory of RRIs, the PCECH shoe wearer believes that the cushioning in their shoe has decreased their risk of injury by attenuating the impact experienced at heel strike, but in reality it has only diminished their somatosensation of the impact. This side effect is therefore proposed to contribute to an increased risk of injury.

Unnatural Running Form

In addition to weakened foot musculature and diminished sensory feedback, the Barefoot Running Theory of RRIs proposes that PCECH shoes may contribute to injury by facilitating an unnatural running form while running. This concept has developed in large part from the work of Harvard physical anthropologist, Dr. Daniel Lieberman. Lieberman (2012) suggests that running in shoes with elevated heels promotes a landing which is characterized by a heel (or rearfoot) strike. From an evolutionary perspective, this landing is unnatural because the foot is a product of eons of adaptations to different conditions and environments, all experienced until recently, completely barefoot.

The Barefoot Running Theory of RRIs proposes that our feet and bodies have maladapted to wearing shoes that offer a cushioned, elevated heel. Previous work found that those runners who rearfoot strike produce a spike in the magnitude and rate of loading on a vertical ground-reaction force-time curve that is not present in those runners who forefoot strike (Lieberman et al., 2010). This spike is frequently referred to as the 'impact transient' and has been commonly implicated as injury-causing (Robbins & Hanna, 1987). Lieberman (2012) suggests that our feet have maladapted to wearing shoes and that this injury-causing impact transient is a result. In fact, he suggests that the pain experienced when landing with a rearfoot strike while running barefoot may serve as a warning signal that we are running in a way that may lead to chronic overloading of tissues and subsequent injury. The pain would therefore force our bodies to find a running form that generates a smaller impact peak, such as that of a forefoot or midfoot strike (Lieberman, 2012). By wearing a PCECH shoe, the Barefoot Running Theory proposes that the wearer is ignoring the body’s natural adaptive processes and instead adapting to a running form which increases the impact forces experienced at foot-ground contact. More research is required to support this relatively new concept, however, it is reasonable to propose that running with a form which results in higher impact peaks may lead to an increased risk of injury.

In summary, the Barefoot Running Theory of RRIs proposes that running-related injuries are the result of side effects experienced from the use of PCECH shoes. This includes weakened intrinsic foot musculature leading to a decrease in medial longitudinal arch height, decreased somatosensation leading to more foot position sense errors and an altered running form that results in large impact peaks upon contact with the ground. In order to avoid RRIs, this theory must be applied and practical steps must be outlined to prevent and/or reverse the side effects of PCECH shoes.

Application of Barefoot Running Theory

Based on the proposed injury-causing side effects associated with PCECH shoes, the Barefoot Running Theory of RRIs suggests that barefoot running will avoid the negative effects of running whilst wearing PCECH shoes. Many authors and clinicians familiar with podiatry report that the foot ailments commonly seen in the shod population are absent in barefoot populations (Rao & Joseph, 1992; Squadrone & Gallozzi, 2011; Stewart, 1972). Therefore, it is proposed that running barefoot allows for several positive changes to occur, and that these changes may reduce the risk of certain RRIs.

By transitioning to barefoot running or even incorporating it into a runner's training schedule, it is proposed that the risk of RRIs may be decreased through three specific changes. These changes are an increase in strength of the intrinsic foot musculature, an improvement in somatosensation and a shift to a lower-impact running form. Current evidence in support of these hypotheses will be presented in the following sections.

Improve Intrinsic Foot Muscle Action

Much anecdotal evidence from clinicians and researchers report a rare incidence of flat feet in barefoot populations (Stewart, 1972; Rao & Joseph, 1992). This has led to the hypothesis that barefoot activity may improve the action of the intrinsic foot musculature, especially that required to maintain the medial longitudinal arch.

A study done by Robbins and Hanna (1987) was one of the first to analyze changes in the medial longitudinal arch as a result of increased barefoot activity. Using foot imprints and x-rays, they measured changes in the medial longitudinal arch span of 17 recreational runners. The experimental group was told to increase their barefoot weight-bearing activity over approximately four months and encouraged to walk or run barefoot when possible. They found a mean change (representing either a shortening (+) or lengthening (-) of the medial longitudinal arch) of +4.7 mm in the experimental group and -4.9 mm in the control group, suggesting that an increase in barefoot activity activates the normally inactive musculature while weight-bearing (Robbins & Hanna, 1987). Although this study demonstrated significant change between the two groups, it faced criticism because of its small sample size and the lack of regulation of dosage.

No published studies have yet reported a reduction in RRIs as a result of increased intrinsic muscle action. Although it would be reasonable to suppose that a stronger foot may provide protection and support against injuries of the bones and joints of the foot, more research is required to investigate the effect of increased intrinsic muscle action on the incidence of RRIs.

Facilitate Somatosensation

By running barefoot, the foot is able to make direct contact with the ground surface. Consequently, this allows the mechanoreceptors on the foot's plantar surface to directly receive sensory feedback. This information is used to properly position the foot, minimize forces and command muscular support, all while preventing overloading to the ligaments (Robbins & Waked, 1998). As Lieberman (2012) hypothesizes, barefoot runners are more likely to adjust their gait or muscular support accordingly as they sense damaging rates and magnitudes of loading. This is especially important in the prevention of ankle sprains, which are reported to have a lower incidence in barefoot populations (Robbins & Waked, 1998).

A recent study by Squadrone and Gallozzi (2011) had participants estimate treadmill surface slope while in either a minimalist shoe or a standard, cushioned running shoe. A minimalist shoe is meant to provide the benefits of barefoot running while still offering some plantar protection. They report that while running, treadmill surface slope was significantly better estimated by runners when wearing a minimalist shoe than when wearing a standard, cushioned running shoe (Squadrone & Gallozzi, 2011). In this case, treadmill surface slope is an outcome measure of proprioception and the results suggest that a minimalist shoe facilitates better proprioception than a PCECH shoe. The main limitation to this study is that its generalizability to barefoot running is poor. As Jenkins and Cauthon (2011) explain minimalist shoes may provide the runner with a false sense of security, allowing them to run at an intensity that the natural barefoot would not allow. Additionally, many varieties of minimalist shoes are becoming available with unique characteristics and therefore need to be tested individually to determine their effectiveness. This study provides promising results for an improvement in somatosensation with the practice of barefoot running, as sound reasoning would suggest that the results might be amplified as closer contact between the sensory tactile sensors and ground surface is made.

Sufficient somatosensation allows the body to carefully monitor and limit the intensity of a run in order to prevent chronic overloading of the tissues. This means that injuries are prevented by paying attention to pain and limiting intensity accordingly, possibly leading to less running overall. Considering that training intensity is one of the only modifiable factors with a strong association to injury (van Gent et al., 2007), barefoot running could result in less RRIs simply because it limits the intensity that a person can run at. More research is needed to determine exactly what effect barefoot running has on somatosensation and the impact this may have on the incidence of RRIs.

Promote Better Running Form

The Running Shoe Theory on the cause of RRIs proposes that the impacts experienced during running should be minimized using a cushioned heel. In contrast, the Barefoot Running Theory suggests that these impacts can be minimized or even avoided by running with a different form, specifically by landing on either the forefoot or midfoot rather than the rearfoot (Lieberman et al., 2010). This form is distinguished by several characteristics that include a shorter stride, a high cadence (>170 steps/minute), a landing on the ball of the foot below the 4^{th} and 5^{th} metatarsal heads and a loose, aligned upper body (Lieberman, 2012). In fact, the Barefoot Running Theory proposes that this running form is a result of the body's adaptation to the painful impacts experienced during running with a heel strike.

A recent retrospective study compared injury rates and severities of collegiate-level distance runners based on foot strike (Daoud et al., 2012). They found that those runners who habitually ran with a rearfoot strike had approximately twice the rate of repetitive stress injuries than those who habitually ran with a forefoot strike. There were several limitations to this study, including a lack of measurement of footwear type and a relatively small, homogenous sample. Although the results of this study provide some support for the theory that a runner's form may contribute to the incidence of RRIs, more well-designed, prospective studies are needed to investigate the link between foot strike and injury incidence.

Future Research Directions

This review has summarized several studies that suggest that running barefoot may increase intrinsic musculature, improve somatosensation and promote better running form (Lieberman et al., 2010; Robbins & Hanna, 1987; Squadrone & Gallozzi, 2011). One study has explored the differences in injury rates between forefoot and rearfoot-striking runners (Daoud et al., 2012) but more prospective research is needed. Specifically, future research should address the effectiveness of barefoot running on somatosensation and intrinsic muscle action. Additionally, the links between better somatosensation and RRIs and increased muscle action and RRIs need to be investigated.

Ideally, a prospective study which compared injury rates and severities between habitually barefoot and habitually shod runners is needed to test the merit of this emerging theory and provide evidence for both research and practice.

Many methodological challenges exist when designing a study to measure harm (Cardarelli & Seater, 2007). Despite yearly injury rates as high as 85% (Nielsen et al., 2012), the occurrence of an injury is still a rare event that would require both a large sample size and an extensive follow-up period to effectively capture (Cardarelli & Seater, 2007). Another difficulty becomes apparent when attempting to eliminate confounding variables. RRIs are multifactorial (Hreljac, 2005) and therefore could be the result of a number of unique combinations of factors, which could be different for each individual. When comparing barefoot to shod running, more specific challenges arise due to the practical differences between the two footwear conditions. To ensure equal treatment, adjustments must be made to correct for differences in shoe mass. Also, it is difficult to maintain equal dosages when the nature of barefoot running prevents novice runners from training at the same intensity and durations that are possible when shod. To further develop a theory behind the cause and prevention of RRIs, it is critical that future research studies find ways to address these challenges.

Conclusion

The high incidence of injuries in the running population is a barrier to physical activity and effective modes of treatment and prevention are essential for the health and wellness of runners everywhere. In the development of treatment and prevention modalities, both theories on the cause of RRIs should be examined and considered. The Running Shoe theory proposes high impact forces and abnormal subtalar motion to be the cause of RRIs. Therefore in order to prevent RRIs, it is recommended that runners use shoes which provide cushioning, support and motion-control. There is little research to support this practice and even some to suggest that these shoes may do more harm than good. Barefoot Running theory proposes that RRIs are a result of atrophy of the intrinsic foot musculature, diminished somatosensation and altered gait. Therefore it is recommended that runners transition to barefoot running in order to improve intrinsic foot muscle action, facilitate somatosensation and promote better running form.

To fully develop and define both theories, more research is needed to provide support to the assumptions made by both opposing views. Considering the lack of success in lowering the rate of RRIs with the application of the Running Shoe theory, it may be beneficial to focus future trials on the development and testing of new ways of thinking, such as that around barefoot running. Some promising evidence has been published to support the reduction of RRIs with barefoot running theory, but many questions are yet to be answered.

References

Cardarelli, R., & Seater, M. M. (2007). Evidence-based medicine, part 4. An introduction to critical appraisal of articles on harm. *The Journal of the American Osteopathic Association*, *107*, 310–314.

Cheung, R. T. H., Wong, M. Y. M., & Ng, G. Y. F. (2011). Effects of motion control footwear on running: a systematic review. *Journal of sports sciences*, *29*(12), 1311–9.

Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. a, & Lieberman, D. E. (2012). Foot strike and injury rates in endurance runners: a retrospective study. *Medicine and science in sports and exercise*, *44*(7), 1325–34.

Davies, G., & Ellenbecker, T. (1999). Focused exercise aids shoulder hypomobility. *Journal of biomechanics*, *6*, 77–81.

Davis, I., Bowser, B., & Mullineaux, D. (2010). Do Impacts Cause Running Injuries? A Prospective Investigation. *ASB*, 1335–1230.

Ferber, R., McClay-Davis, I., Hamill, J., Pollard, C., & McKeown, K. (2002). Kinetic variables in subjects with previous lower extremity stress fractures. *Medicine & Science in Sports & Exercise*, *34*(S5).

Ferris, D., Louie, M., & Farley, C. (1998). Running in the real world: adjusting leg stiffness for different surfaces. *The royal society*, *265*(1400), 989–994.

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, 32*(8), 787–794.

Fields, K. B., Sykes, J. C., Walker, K. M., & Jackson, J. C. (2010). Prevention of running injuries. *Current sports medicine reports*, *9*(3), 176–82.

Grimston, S. K., Nigg, B. M., Fisher, V., & Ajemian, S. V. (1994). External loads throughout a 45 minute run in stress fracture and non-stress fracture runners. *Journal of biomechanics*, *27*(6), 668.

Hreljac, A. (2005). Etiology, prevention, and early intervention of overuse injuries in runners: a biomechanical perspective. *Physical medicine and rehabilitation clinics of North America*, *16*(3), 651–67, vi.

Hreljac, A., Marshall, R. N., & Hume, P. A. (2000). Evaluation of lower extremity overuse injury potential in runners. *Medicine & Science in Sports & Exercise*, *32*, 1635–1641.

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

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*, *49*, 1101–1109.

Ker, R., Bennett, M., Bibby, S., Kester, R., & Alexander, R. (1987). The spring in the arch of the human foot. *Nature, 325*(8), 147-9.

Kong, P. W., Candelaria, N. G., & Smith, D. R. (2009). Running in new and worn shoes: a comparison of three types of cushioning footwear. *British journal of sports medicine*, *43*(10), 745–9.

Leung, A. K., Mak, A. F., & Evans, J. H. (1998). Biomedical gait evaluation of the immediate effect of orthotic treatment for flexible flat foot. *Prosthetics and orthotics international*, 22, 25–34.

Lieberman, D. E. (2012). What we can learn about running from barefoot running: an evolutionary medical perspective. *Exercise and sport sciences reviews*, *40*(2), 63–72.

Lieberman, D. E., Venkadesan, M., Werbel, W. a, Daoud, A. I., D'Andrea, S., Davis, I. S., Mang'eni, R. O., Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531–5.

McCloskey, D. I. (1978). Kinesthetic sensibility. *Physiological reviews*, *58*(4), 763–820.

McDougall, C. (2009). *Born to run: A hidden tribe, superathletes, and the greatest race the world has never seen*. New York: Knopf.

Messier, S. P., & Pittala, K. A. (1988). Etiologic factors associated with selected running injuries. *Medicine & Science in Sports & Exercise*, *20*, 501–505.

Messier, S. P., Davis, S. E., Curl, W. W., Lowery, R. B., & Pack, R. J. (1991). Etiologic factors associated with patellofemoral pain in runners. *Medicine Science in Sports Exercise*, *23*, 1008–1015.

Milner, C. E., Hamill, J., & Davis, I. S. (2010). Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. *The Journal of orthopaedic and sports physical therapy*, *40*(2), 59–66.

Nielsen, R. O., Buist, I., Sorensen, H., & Lind, M. (2012). Training errors and running related injuries: A systematic review. *Int J Sports Phys Ther*, *7*(1), 58–75.

Nigg, B. M., & Wakeling, J. M. (2001). Impact forces and muscle tuning: a new paradigm. *Exercise and sport sciences reviews*, *29*(1), 37–41.

Perry, S. D., & Lafortune, M. A. (1995). Influences of inversion/eversion of the foot upon impact loading during locomotion. *Clinical biomechanics, 10*(5), 253–257.

Rao, U. B., & Joseph, B. (1992). The influence of footwear on the prevalence of flat foot. A survey of 2300 children. *The Journal of bone and joint surgery British volume*, *74*, 525–527.

Richards, C. E., Magin, P. J., & Callister, R. (2009). Is your prescription of distance running shoes evidence-based? *British journal of sports medicine*, *43*(3), 159–62.

Robbins, S. E., & Gouw, G. J. (1991). Athletic footwear: unsafe due to perceptual illusions. *Human Performance*, *23*, 217–24.

Robbins, S. E., & Hanna, A. (1987). Running-related injury prevention through barefoot adaptations. *Medicine and science in sports and exercise*, *19*(2), 148–156.

Robbins, S. E., & Waked, E. (1998). Factors associated with ankle injuries: Preventive Measures. *Sports medicine*, *25*(1), 63–72.

Robbins, S. E., Waked, E., Allard, P., McClaran, J., & Krouglicof, N. (1997). Foot position awareness in younger and older men: the influence of footwear sole properties. *Journal of the American Geriatrics Society, 45*, 61–66.

Robbins, S. E., Waked, E., & McClaran, J. (1995). Proprioception and stability: foot position awareness as a function of age and footwear. *Age and Ageing*, *24*, 67–72.

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

Stewart, S. (1972). Footgear: Its history, uses and abuses. *Clinical Orthopaedics and Related Research*, *88,* 119-130.

Van Gent, R. N., Siem, D., van Middelkoop, M., van Os, A. G., Bierma-Zeinstra, S. M. A., & Koes, B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British journal of sports medicine*, *41*(8), 469–80; discussion 480.

Van Mechelen, W. (1992). Running injuries. A review of the epidemiological literature. *Sports medicine*, *14*(5), 320–35.

CHAPTER 3: EVALUATING THE BIOMECHANICAL EFFECTS OF ALTERED PLANTAR CUTANEOUS SENSATION ON THE ACQUISITION OF A BAREFOOT RUNNING STYLE

Abstract

Purpose: This feasibility study investigated the effect of plantar cutaneous sensation on the adaptation to and retention of the barefoot running style.

Methods: Sixteen healthy young adults ran shod on a treadmill for five minutes. They were then randomized to receive four different plantar cutaneous sensation treatments (anaesthetic cream on the feet; anaesthetic cream on the lower legs; anaesthetic cream on both the feet and lower legs; and placebo) before running barefoot on a treadmill for the first time (Session 1). Skill retention was measured by having participants run barefoot a second time, 48 h later (Session 2). The effect of the anaesthetic cream was assessed using Semmes-Weinstein cutaneous sensation testing of the leg and foot before and after each run. Motion capture and ground reaction force data were recorded for each five minute run, subdivided into early, middle and late epochs. Three biomechanical outcomes were considered. From the sequence of time instants the foot made contact with the treadmill belt, cadence was calculated and the foot-belt contact angle and knee angle at these time instants were extracted. The mean and variation of the biomechanical outcomes within each treatment group, running trial and epoch were calculated and compared to identify important trends. Three self-report outcomes were also collected and compared between groups: perceived running comfort, risk of injury and shod versus barefoot running difference.

Results: Differences were noted between mean cadence and mean foot angle at foot-belt contact when running barefoot compared to running shod. Variation in both cadence and foot angle were found to increase when participants tried barefoot running for the first time, but decreased throughout the trial and returned to shod levels at the end of their second barefoot run. Groups with anaesthetic cream on the legs demonstrated a more rapid and larger decrease in foot angle variation and cadence variation across trials and epochs. No difference in sensory threshold was found to occur in any of the four groups after anaesthetic cream application. A significant increase in sensory threshold was found after both barefoot runs.

Discussion: All participants demonstrated a change in their running style while running barefoot on a treadmill for the first time. In addition, a significant increase in plantar cutaneous sensory threshold was found after both barefoot runs. The application of anaesthetic cream on the legs, feet, and feet and legs, compared to non-anaesthetic cream, on four groups of four randomly allocated participants did not change their leg or foot sensory thresholds. However, the group that had anaesthetic cream on their legs (4 out of 16 participants) demonstrated a more rapid adaptation to and a better retention of the barefoot running style.

Significance: Future studies should consider the suggested protocol modifications. The findings of a larger, randomized controlled study should be able to inform novice runners on how to best learn and retain the skill of barefoot running. This knowledge may influence an individual's risk of experiencing a running-related injury.

Introduction

Barefoot Running

Barefoot running has been proposed as a less injurious running style when compared to running wearing shoes. The mechanisms by which this may occur remain relatively unknown, however several have been proposed. These proposed mechanisms are most often based on the kinetic and kinematic differences between barefoot and shod runners (Lieberman, 2012). Lieberman and colleagues (2010) compared footstrike patterns between habitually barefoot and habitually shod runners. They reported that barefoot endurance runners tended to land on their forefoot or sometimes midfoot, while shod runners most often landed on their rearfoot, as facilitated by shoes with cushioned, elevated heels. This difference was also reflected in altered foot-ground forces (ground reaction force: GRF), where runners who landed on their forefoot or midfoot had smaller GRF's during early foot-ground contact than those runners who landed on their rearfoot. It was proposed that the reduction in GRF was a result of an altered barefoot running style (Lieberman et al., 2010). The altered barefoot running style includes a higher stride rate (cadence), shorter stride length (Divert et al., 2008; Squadrone & Gallozzi, 2009), less ankle dorsiflexion and greater knee flexion at foot-ground contact (Bishop et al., 2006). In this study we propose that during barefoot running, compared to shod running, the foot would provide increased sensory feedback that facilitates the change in GRF and running style.

Learning

Anecdotal evidence suggests that barefoot running is growing in popularity ("What the barefoot running craze has done to the shoe industry - The Globe and Mail," 2012) and habitually shod runners are running barefoot for the very first time. The relative risk of injury when barefoot running has not been well-studied (Jenkins & Cauthon, 2011) and inherent risk of injury when learning a new motor skill is elevated. It is therefore of interest to examine the learning process as shod runners transition to barefoot running.

When learning a new motor skill, three stages of learning are proposed (Halsband & Lange, 2006). In the initial stage, learners establish a connection between their sensory cues and the correct motor commands. To establish this connection learners experience trial and error, resulting in high variability in the shape of movements and time of performance. During this stage they develop a sensorimotor map (Halsband & Lange, 2006). Performance at this stage is slow and largely guided by sensory feedback. In the intermediate learning stage, learners gradually alter the sensorimotor map. Increases in the speed of motor performance are expected (Halsband & Lange, 2006). In the advanced stage, the sensorimotor map is permanently stored in long-term memory, allowing for rapid and low variability performance with minimal sensory input (Halsband & Lange, 2006). Based on this model, learners with augmented sensorimotor cues should progress from the initial to intermediate learning stage more quickly than learners with typical or diminished cues. Learning of a novel task might therefore be characterized by the change from high to low relative variability as a learner becomes skilled at the task (Muller & Sternad, 2009).

Cutaneous Sensation

Temporary anaesthesia of the cutaneous surface of the forearm has been shown to improve sensory function of the ipsilateral hand in healthy adults (Björkman, Rosén, & Lundborg, 2004; Petoe, Molina Jaque, Byblow, & Stinear, 2012). The same group used functional magnetic resonance imaging to detect cortical changes during the period of forearm anaesthesia (Björkman, Weibull, Rosén, Svensson, & Lundborg, 2009). They reported that while the forearm was anaesthetized, the area in the cortex responsible for sensory feedback from the hand expanded over the cortical area responsible for the forearm, giving the hand more cortical surface to receive and process sensory information. It is likely that a similar cortical expansion of the feet would be observed when the cutaneous surface of the lower legs is anaesthetized. Conversely, when the cutaneous surface of the feet are anesthetised their space on the cortical map should decrease.

Hypotheses

The aim of this study was to explore trends in the rate at which a person acquires a barefoot running style while comparing groups with different levels of plantar cutaneous sensation. An anaesthetic cream was used to both heighten and diminish plantar cutaneous sensation before participants ran barefoot for the first time. We explored intra- and inter-trial changes in the mean and variation of biomechanical outcomes (cadence, foot angle at foot-belt contact and knee angle at foot-belt contact) using a motion capture system and force plate. We hypothesized that a person's level of plantar cutaneous sensation will have an effect on their ability to adapt to and retain a barefoot running style. Specifically, an improvement in sensation (reduction in sensory threshold) will result in an increased rate (decreased time) of adaptation and retention. Largely descriptive statistics are presented that focus on data trends; inferential statistics were avoided in this feasibility study as suggested by Leon, Davis, & Kraemer (2011).

Methods

Participants

A convenience sample of 16 healthy young adult volunteers was recruited for this study. All participants provided written informed consent that was approved by a University Ethics Review Board. Each participant had to be willing to run comfortably for 10 minutes on a treadmill, had no lower-limb fractures or sprains in the previous year, had no known adverse reactions to topical anaesthetic cream, had no previous experience with barefoot or minimalist running, and had no abnormal plantar or lower leg sensation. Participants were screened for contraindications to anaesthetic cream or barefoot running using a questionnaire.

Experimental Design

Figure 1 summarizes the design of the experiment, which required two sessions, 48 hours apart. Participants were scheduled either one-at-a-time or in pairs with a staggered start. All testing took place indoors in a movement laboratory. The laboratory housed a treadmill (True 500 Soft, True Fitness Technology, St. Louis, MO), AMTI (Advanced Mechanical Technology Inc., Model OR6-7, Watertown, MA) force platform and motion capture system (Vicon MX +40, Denver, CO). During the first session, anthropometrics (age, height, mass, leg lengths, inter ASIS distance, knee widths and ankle widths) and running experience data (frequency of runs per week, average duration of run) were collected to determine any confounding variables and to calculate biomechanical outcomes. Body Mass Index (BMI) was calculated using each participant's height and mass. Self-selected pace was then determined by having participants familiarize themselves with the treadmill and choose a speed that was comfortable. Participants were instructed to choose a speed that they felt could be sustained comfortably both shod and barefoot for five minutes. They were cautioned that barefoot running would be a new task and so might require a slight decrease from their typical shod pace.

Sensory measurements were taken immediately before and after each run using Semmes-Weinstein monofilaments. The first of these measurements was used to test participant eligibility and provide a baseline measure, while the remaining measurements were used to monitor any sensory changes that may have occurred as a result of running, the anaesthetic cream and the passage of time. Sensory testing occurrences were labeled pre-shod (T1), post-shod (T2), pre-bare (T3), and post-bare (T4) for the first session, and pre-bare (T5) and post-bare (T6) for the second session. Timeline of sensory testing occurrences are detailed in Figure 1.

Participants performed their first five-minute run on the treadmill while wearing their own typical running shoes and at their self-selected pace. All participants' typical running shoes were classified as 'traditional running shoes' due to characteristics such as elevated heels, cushioning, and motion control systems.[1] To minimize the treadmill motor-induced acceleration period, participants stepped onto the treadmill after it attained the pre-selected speed. This allowed for their first strides on the treadmill to be at a constant speed. After five minutes, the participants were instructed to stop the treadmill motor and then slow to a walk then quietly stand as the treadmill belt came to a full stop.

Following the shod run, participants were block randomized to receive one of four sensory treatments (Group names): 1) placebo cream applied to both the feet and lower legs (None), 2) anaesthetic cream applied to the lower legs and placebo cream on the feet (Legs), 3) anaesthetic cream applied to the plantar and dorsal aspects of the feet and placebo cream on the lower legs (Feet), 4) anaesthetic cream applied to both the feet and lower legs (Both). Creams were applied liberally to the feet and lower legs and were occluded with plastic wrap for 30 minutes immediately following application. Components of anaesthetic cream are described in detail below.

After removing the occlusive wrap and cream, the participants performed their second run on the treadmill at the same self-selected pace, this time while barefoot. At the end of the first session, participants were cautioned of the possible residual effects of

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[1] Traditional running shoes are defined relative to barefoot or minimalist footwear. Barefoot or minimalist footwear are listed in Appendix A. Participants with experience running in minimalist footwear were excluded from the study.

anaesthesia and asked to refrain from any non-typical physical activity before returning for their second session.

During the second session, 48 hours later, participants ran for five minutes on the treadmill at their self-selected pace while barefoot with no sensory treatment.

Location

Although people run on a variety of surfaces, treadmill running was selected in order to control ambient temperature, humidity, wind and running speed. When measuring cutaneous sensation, changes in skin temperature have been found to alter sensory threshold (Nurse & Nigg, 2001). A consistent belt speed for each participant removed speed as a confounding factor when comparing shod to barefoot running. The laboratory also allowed for the use of a force plate and motion capture system that were not available in an outside environment.

Sensory Treatments (Interventions)

A topical anaesthetic cream [2.5% prilocaine + 2.5% lidocaine in a Pluronic Lecithin Organogel (PLO)] was used to both heighten and diminish plantar cutaneous sensation. To diminish plantar cutaneous sensation, anaesthetic cream was applied to the plantar and dorsal aspects of the feet while a placebo cream (PLO cream) was applied to the lower legs (Feet).[2] To heighten plantar cutaneous sensation, anaesthetic cream was

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[2] Although the intention was to alter plantar cutaneous sensation, anaesthetic cream was applied to both the plantar and dorsal surfaces of the feet to ensure complete coverage of any involved mechanoreceptors. Due to variability between subjects, identifying borders of plantar cutaneous innervations would be impractical.

applied to the lower legs while a placebo cream was applied to the feet (Legs).[3] Normal plantar cutaneous sensation was expected to remain in the placebo condition that received placebo cream on both the lower legs and feet (None). Finally the effect of anaesthetic cream applied to both the lower legs and feet is unknown (Both).

Both participants and researchers were blinded to the group allocations by having a pharmacist compound and package the placebo and anaesthetic creams into identical containers that were labelled C, D, E, and F. The placebo and anaesthetic creams were identical in colour, odour and texture. Participants were instructed not to inform the researchers if they thought they felt any effects of the cream.

Sensory Measurements

To test cutaneous sensation, a modified Semmes-Weinstein monofilament (SWM) test was used. This equipment uses 8 monofilaments (#1-8) of varying thickness (marked from 1.65 to 6.65), representing a logarithmic force on a base of 10 needed to bend the monofilament. Greater values indicate reduced sensation. See Table 1 for monofilament testing sizes, applied force and applied pressure.

There is no consensus on the location or exact procedures for SWM testing (Lee et al., 2003). In this study, five locations were tested: three areas on the plantar surface of the foot (third metatarsal head, lateral longitudinal arch and heel) and two on the lower leg (upper and lower) of the participant's dominant leg. These locations are diagrammed

[3] This assumption is based on the results of studies on the upper body by Björkman, Rosén, & Lundborg, (2004) and Petoe, Molina Jaque, Byblow, & Stinear, (2012).

in Figure 2. Care was taken to avoid any abnormal skin surfaces such as callouses, warts or cuts/bruises.

Sensory testing had the participant prone on a plinth with eyes closed. They were instructed to relax and to focus only on the testing being done. The researcher then identified each testing area by name while touching it with the largest monofilament (#8). Then starting with the smallest monofilament (#1), one of the five randomly selected sites was touched for approximately 1.5 seconds, by applying the monofilament perpendicular to the skin's surface with just enough pressure to cause the monofilament to bow. Three consecutive touches were performed and a positive test was recorded when at least two touches at the correct site were reported by the participant. All of the five sites were tested with the smallest monofilament. After testing each site with the smallest monofilament, those sites that were not detected were randomly tested with the second smallest monofilament (#2). Testing proceeded, with successively larger monofilaments until all sites were detected. The smallest monofilament size detected at each site determined sensory threshold and this data were used for subsequent analysis (see Appendix B).

Motion Capture System

To obtain kinematic data, sixteen reflective markers (14 mm hemispherical, 4 grams, MoCap Solutions, Huntington Beach, CA) were applied bilaterally to the participant's pelvis, legs and feet. Locations included anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), mid-lateral thigh, lateral epicondyle of the femur (knee), mid-lateral shank, lateral malleolus, heel and second metatarsal head. Due to the challenges of keeping the markers on throughout a run that often resulted in perspiration on the skin's surface, and the presence of residual cream, several methods were used to adhere the markers to their respective locations. If needed, the skin was swabbed with rubbing alcohol to dry the surface on which to apply the marker. Markers were then adhered to the skin and/or shoe's surface using a combination of electrode washer double adhesive, moleskin, Topstick™ (Vapon Inc., Fairfield, NJ), a double-sided tape typically used for hairpieces, athletic tape and waterproof tape.

The motion of the 16 reflective markers was collected at 100 Hz using an eight-camera motion capture system (Vicon MX 40+, Denver, CO). Commercial software (Vicon Nexus, v1.8) was used to synchronize acquisition of kinematic and force plate data. Motion capture data were processed using the Vicon Plug-in Gait Model. The relatively rare and short blocks of missing marker data were interpolated and smoothed using a quintic spline routine from the same software (Vicon Nexus, v1.8).

Running Style Outcomes

The three outcomes of interest in this study were cadence, knee angle at foot-belt contact and foot angle at foot-belt contact. Vertical GRF data were collected at 100 Hz by placing the rear right treadmill footpad on the force plate. Approximately 1/4 of the treadmill's weight was transmitted through this footpad. Gait events were detected when a foot made contact with the treadmill surface, causing vertical GRF to exceed set threshold (4% above body weight in addition to treadmill tare weight). Right and left foot-belt contacts were identified from kinematic data by which the heel marker at the lowest height at foot-belt contact determined which foot was contacting the belt. Cadence was calculated from the sequence of foot-belt contact times at each foot-belt contact and reported in strides per minute. The first and last eight events were deleted from each running trial to remove acceleration and deceleration effects when transitioning from standing to running and from running to walking.

Both foot and knee angle at foot-belt contact were calculated using the trajectories of the reflective markers applied to the participant's body. Using the sagittal plane projections of the thigh, knee and lower leg markers on one side of the body, the planar knee angle between these markers was calculated. A fully extended knee was defined as zero degrees. Using the sagittal plane projection of the metatarsal and heel markers on one side of the body, the foot angle between these markers and a horizontal plane was calculated. When the participant stood comfortably these markers were applied at constant height above the ground and therefore defined zero degrees. These angles were then extracted at each foot-belt contact event. Positive foot angle values indicated dorsiflexion relative to standing position while negative foot angle values indicated plantarflexion. Since some foot and lower leg markers fell off during some running trials, the data from the right or left side of the body was selected for analysis based on the side that had the most complete trajectory data.

Adaptation to the novel task of barefoot running was quantified by dividing each run into three epochs of 16 consecutive strides. A stride was defined as the time between two consecutive foot-belt contacts made by the same foot. The first 16 strides of a run were defined as the early epoch, the middle 16 strides were defined as the middle epoch and the last 16 strides were defined as the late epoch. Within these three epochs, the mean and standard deviation (SD) for cadence, knee angle and foot angle were calculated. Therefore for every participant, three runs were divided into three epochs, with six biomechanical outcomes (mean and SD of cadence, foot angle and knee angle, respectively).

Self-Reported Comfort, Risk of Injury and Difference in Running Style

After both sessions, participants were asked to rate their perceived comfort and risk of injury by using a seven-point Visual Analogue Scale. They were asked to rate their perception of the running style difference between running shod and barefoot (after Session #1) and between their barefoot runs on Session #1 and Session #2 (after Session #2) using a four- or seven- point Visual Analogue Scale. The questions asked were:

1 "When running barefoot, compared to running wearing shoes, was it _______ " (1-very uncomfortable, 4-neither comfortable nor uncomfortable 7-very comfortable)

2 "When running barefoot, compared to running wearing shoes, did you feel that you were ___________ to injure yourself?" (1-very unlikely, 4-neither likely nor unlikely, 7-very likely).

3a (Session 1) "When running barefoot, compared to running wearing shoes, did you feel that you ran _______ " (1-the same, 2-a little differently, 3-fairly differently, 4-extremely differently).

3b (Session 2) "When running barefoot **today**, compared to running barefoot during the first session, did you feel that you ran _______ " (1-the same, 2-a little differently, 3-fairly differently, 4-extremely differently).

This was followed with the question:

4 "If it felt different, how?" at which point participants were given blank space to use their own words to describe the experience (see Appendix C).

Data Analysis

Descriptive statistics (means, standard deviations, standard errors) were used for demographic values (age, height, weight, etc.) and all three biomechanical outcome measures. A three-way (group, trial, epoch) repeated measures for trial and epoch analysis of variance (ANOVA) was used to identify trends in the outcome measures. Due to the feasibility nature of this study, statistical analyses focused on outcomes approaching significance (i.e. significant at $p < 0.10$) and trends in the data.

Sensory data were analyzed to determine the effects of group and time of testing. Sensory measurements provided ordinal data with a limited number of discrete values. These data were analyzed using the non-parametric Wilcoxon Rank Sum Test. Group (4) by time (3) interaction effects were also explored using an ANOVA despite violating assumptions by using ordinal data with very few non-equal interval steps.

Descriptive statistics were used on the quantitative aspects of the participant questionnaire data. The qualitative questionnaire data were not formally analyzed, but was interpreted to inform discussion of results.

Results

Participants

Nine females and seven males met inclusion criteria and gave consent to be included in the study. Participants' ages ranged from 23 to 32 years (mean (SD) 24.9(2.4)) with BMI ranging from 19.2 to 26 kg/m^2 (mean (SD) 22.5(2.5)). Participants had varying amounts of running experience, quantified by the weekly frequency and duration of their runs. None of the participants wore custom foot orthoses. There were no significant differences in baseline values between the four treatment groups and no adverse events. All participants were able to complete the study protocol. See Table 2 for participant demographics.

Sensory Measurements

No statistically significant difference in sensory threshold for the combined three testing sites on the foot was found in any of the four treatment groups between T1 and T2: pre and post shod run ($W= 962, p=0.72$) or between T2 and T3: pre and post cream application ($W=876, p=0.23$). A statistically significant increase in sensory threshold was found between T3 and T4: pre and post first barefoot run ($W=224, p<0.0001$) and between T5 and T6: pre and post second barefoot run ($W=444, p<0.001$).

No significant difference in sensory threshold was found at the five testing locations between any of the four groups ($F_{3,12} < 1.58$, $p > 0.24$) and between T2 and T3: pre and post cream application ($F_{1,15} < 4.29$, $p > 0.06$). We note that only the arch site approached statistical significance ($p=0.06$). See Table 3 for a summary of sensory results.

Running Style Outcomes

Cadence

All groups behaved similarly with an increased mean cadence during both barefoot runs across epochs when compared to the shod run (see Figure 3). During the shod run, all groups behaved similarly with a trend towards a decrease in cadence variation (SD) across epochs. A 3 to 6 strides per minute variation in cadence was observed in all four intervention groups. Note the elevated variation in the Legs group was due to one participant who suddenly changed her running pattern halfway through the shod run (middle Epoch). Across trials, the Legs group was found to have the highest cadence (see Figure 3 – Mean).

During participants' first barefoot run, the Feet, Both and None groups had a decrease in cadence variation during the middle epoch followed by an increase in cadence variation in the late epoch. This late increase in variation may be related to the increased sensory threshold that we observed after the barefoot runs. The Legs group had a decline in cadence variation across epochs. Overall, the None group had a greater cadence variation than the other three groups indicating a trend toward decreased cadence variation with the use of anaesthetic cream, regardless of where it was applied.

During the second barefoot run, the Feet, Legs and None groups all demonstrated a trend toward an increase in cadence variation across epochs. Again this increase in cadence variation may be related to the increase in sensory threshold and that this occurred sooner in the second barefoot run. The Both group demonstrated a decrease in cadence variation across Epochs. Once again, the None group had the greatest amount of cadence variation (see Figure 3 – SD).

Foot Angle

During the shod run, the four groups demonstrated 12.2^{o} to 15.3^{o} of mean dorsiflexion at foot-belt contact, indicating a rearfoot strike. A trend was observed towards a linear decline in mean foot angle across Epochs in the shod run (see Figure 4 – Mean). All groups had a decreased mean dorsiflexed foot angle of 1.6 to 6.7^{o} during both barefoot runs compared to the shod run. The smallest mean foot angles were observed in the Legs (1.6^{o}) and None (2.8^{o}) groups, while the two groups that had cream on the feet (Feet, Both) had larger degrees of dorsiflexion than those without cream on the feet (Legs, None) (see Figure 4-Mean).

During the shod run, all groups demonstrated a decline in foot angle variation across epochs, possibly indicating an accommodation to the treadmill. Approximately 5.7^{o} variation in foot angle at foot-belt contact was observed in all four groups.

The foot angle variation across all groups was smaller during the first barefoot run than during the shod run (see Figure 4-SD). The smallest magnitudes of foot angle variation were observed in the Legs and Feet groups, while the largest variation was seen in the None group, followed by the Both group. Those with cream on the legs (Legs and Both groups) demonstrated a decline in foot angle variation across epochs in the first barefoot run, while the Feet and None groups demonstrated a decrease in the middle epoch and an increase in the late epoch. Note the elevated variation in the Both group due to one participant who had a high amount of foot angle variation at the beginning of his first barefoot run.

During the second barefoot run, all groups ended their run with equal or lesser foot angle variation than they had during the Shod run. The Legs groups demonstrated the smallest variation in foot angle, followed by the Both group. Again note the elevated variation in the Both group due to one participant who had a high amount of foot angle variation at the beginning of his first barefoot run (see Figure 4 – SD).

Knee Angle

All four groups demonstrated 5.2^{o} to 9.6^{o} of mean knee flexion at foot-belt contact when running shod with a slight increase in mean knee flexion across epochs. The Legs group demonstrated the lowest amount of knee flexion during the shod run. No change in the trends in mean knee flexion at foot-belt contact was observed during either barefoot run when compared to the shod run. During the second barefoot run, the None and Legs group had greater degrees of mean knee flexion than the Feet and Both groups (see Figure 5-Mean).

During the shod run, 1.8^{o} to 4.7^{o} variation in knee angle at foot-belt contact was observed across all four groups. All groups demonstrated similar trends with no change across epochs.

During the first barefoot run, a trend was observed across all groups to decrease knee angle variation during the middle epoch and increase variation in the late epoch. This is similar to the trend observed in cadence variation during barefoot runs and could be related to the increase in sensory threshold that occurs after a barefoot run.

During the second barefoot run, an increase in knee angle variation was observed across epochs for all four groups. Overall, groups had larger knee angle variation values during the second barefoot run than during the shod or first barefoot runs. No differences in knee angle variation were observed between groups in any of the three runs (see Figure 5 – SD).

Self-Reported Comfort, Risk of Injury and Difference in Running Style

No trends were evident between participants' self-reported comfort, risk of injury or difference in running style when comparing groups or sessions (see Table 4). Three participants noted better body awareness and eight described landing more on their toes or forefoot while barefoot. After their second barefoot run, seven participants felt they had more control and that barefoot running felt more natural or comfortable during the second session. These participants were equally distributed across the four groups (see Table 5).

Discussion

This study intended to use an adaptive design with the purpose of determining how many blocks of four participants in each of four experimental groups were required to achieve adequate statistical power to detect differences in the ability of the four experimental groups to adapt to and retain the skill of running barefoot. However, due to unexpected challenges such as marker loss, the scope of the study was altered. It became a feasibility study in order to identify modifications to the original protocol and to detect trends in the response pattern of the four experimental groups.

Cutaneous Sensation

No change in sensory threshold was observed as a result of the use of anaesthetic cream. There are at least three possible explanations for this lack of effect. The first explanation is that the anaesthetic cream did not change plantar cutaneous sensation. It is possible that the cream was not left on the skin long enough for an effect to take place or that a higher concentration of anaesthesia was needed to permeate the thick skin on the legs and feet. The second possible explanation is that it is possible that the SWM test was not sensitive enough to detect the small changes in plantar cutaneous sensation that occurred as a result of the cream. This is unlikely since a change was detected as a result of the barefoot runs. Finally, it is possible that the SWM test detects changes in touch fibres, while the anaesthetic cream used affects changes in pain fibres. In this case, the wrong measurement tool was used and as a result we were unable to detect the changes in plantar cutaneous sensation that occurred as a result of the anaesthetic cream. This would explain why the four treatment groups behaved differently despite having similar sensory threshold results.

An unexpected change in sensory threshold was observed as a result of barefoot running during both Session 1 and Session 2. One possible explanation for this result may be that sensory threshold increased in order to modulate the repeated stimuli of the plantar foot's touch mechanoreceptors while barefoot on the treadmill for the first time. Shear forces from the plantar skin coming into contact with the treadmill may have also had a negative impact on sensory threshold. A study by Dai, Li, Zhang, and Cheung (2006) reported that the shear forces acting on the foot are affected by the friction between the foot-shoe interface. Based on this finding, it is expected that individuals would encounter different shear forces while running on a treadmill when compared to overground running. More research is needed to confirm these hypotheses.

Barefoot Running Style

During the shod run, all participants demonstrated a running style that was consistent with that of a habitually shod runner. This included a relatively small amount of mean knee flexion at foot-belt contact (7.7^{o}), a moderate amount of dorsiflexion at foot-belt contact (13.8^{o}) and a mean cadence of 80 strides per minute. Our foot angle results differ from those reported by Lieberman and colleagues (2010), who found habitually shod runners demonstrated a mean plantar foot angle of $28.3^{o} \pm 6.2^{o}$ of dorsiflexion and mean knee angle of $9.1^{o} \pm 6.4^{o}$ while running shod. One possible explanation for this difference may be in how foot angle was determined in the two studies. The Lieberman (2010) study describes the plantar foot angle as being the angle of the plantar surface of the foot relative to earth horizontal. Our foot angle was defined as the angle between the sagittal plane projection of the metatarsal and heel markers on one side of the body and the horizontal plane. It is possible that foot deformation during foot-ground contact could explain the increase in Lieberman's dorsiflexion angle compared to our findings.

During the first and second barefoot runs our participants ran with the stereotypical barefoot running style when compared to running shod (increased cadence and decreased foot-floor angle). These findings indicate that the participants both adapted and retained a new running style while running barefoot for the first and second times. It should be noted that the relationship between increased cadence and risk of RRI remains unknown. Although an increase in cadence has been associated with decreased loading forces of the lower limb (Hobara, Sato, Sakaguchi, Nakazawa, & Functions, 2012), it will also result in a greater number of foot-floor contacts for a given distance. This increase in number of steps taken will increase the accumulated force load and perhaps contribute to an increased risk of injury. More research is needed to determine whether an increase in cadence may increase or decrease one's risk of experiencing an RRI.

A small increase in knee flexion was found by Lieberman and colleagues (2010) when habitually shod runners tried barefoot running. This change in knee angle was not observed in our study. The lack of change in knee angle between trials raises the question of the suitability of our measure of knee angle since knee angle at the instant of foot-belt contact does not adequately capture the change that occurs when adapting to a barefoot running style. Based on the closed kinetic chain of the lower extremity, a person running with a higher cadence with shorter strides, and landing on their forefoot, would naturally require more knee flexion. Therefore, the range of motion of the knee joint during the weight acceptance phase may be a better outcome to quantify shod to barefoot running style change.

Learning

Lower magnitudes of variation in running style outcomes were thought to represent a learned running style (Muller & Sternad, 2009). Following this hypothesis, we expected that all participants would have a relatively low amount of variation during their shod run, since all were familiar with treadmill running. In contrast, both cadence and foot angle variation were found to decrease across epochs during the five minute shod run. Despite participants' experience with treadmill running, this decrease in variation may represent a period of accommodation to the treadmill. Lavcanska, Taylor, & Schache (2005), reported that inexperienced treadmill runners took approximately six minutes to familiarize themselves with treadmill running. It is possible that the participants in this study required more than five minutes to accommodate to treadmill running.

Large variations in the outcome measures, relative to the shod run, were expected when the participants ran barefoot on a treadmill for their very first time. An increase in variation did occur in knee angle and cadence at the beginning of the first barefoot run but foot angle variation decreased when compared to the shod run. During the second barefoot run, cadence variation was similar to the shod run. Knee angle variation increased across epochs in the second barefoot run while foot angle variation reached its lowest value at the end of the last epoch. The different pattern of change in variation between the three outcome measures makes it difficult to determine if true adaptation and retention of the barefoot running style occurred as defined by our hypothesis.

Trends were observed in foot angle variation and cadence variation when considering the influence of anaesthetic cream on an individual's adaptation and retention of the barefoot running style. According to these measures, groups with anaesthetic cream on their legs (Legs and Both) demonstrated adaptation to the barefoot running style at a faster rate than those groups without cream on the legs. The group with anaesthetic cream only on their lower legs (Legs) also demonstrated retention of the barefoot running style based on their low foot angle variation and cadence variation. Therefore, the effect of anaesthetic cream applied to the lower legs on adaptation and retention of the barefoot running style should be further investigated in future studies.

Self-Reported Comfort, Risk of Injury and Difference

Despite different biomechanical responses to shod and barefoot running, the participant's questionnaire data did not indicate any trends in comfort, risk of injury or perceived differences in running patterns between the four groups. This may reflect that each participant's experience with shod and barefoot running was relatively unique, having some participants find it more comfortable than others and some feeling more hesitant due to their perceived risk of injury. Additional questions regarding why a participant may or may not embrace barefoot running should be considered in future studies.

Limitations

One major limitation to this feasibility study is the small sample size that limits the conclusions that can be drawn from the results. To address this limitation, we have chosen to focus our analysis on trends in the data. Limited statistics are presented in order to avoid inferential conclusions. According to Leon et al. (2011), feasibility studies are especially helpful when introducing a novel intervention, such as the use of anaesthetic cream before running on a treadmill. Although inappropriate to be used for sample size determination or inferential statistics, well-conceived feasibility studies such as this one may reduce the risk of problems that are common in full-scale clinical trials (Leon et al., 2011).

Another potential limitation is the challenge that exists when studying running patterns. It became clear that each runner has his or her own unique running style that makes it difficult to capture patterns. In addition, a recent study has found that not all barefoot runners use a forefoot strike and that many factors, such as running speed and training level, contribute to each runner’s foot strike pattern (Hatala, Dingwall, Wunderlich, & Richmond, 2013). A homogenous sample would be advantageous but is not representative of the general running population and would therefore limit generalizability. Participants also had wide variations in self-selected speed, which could influence running strategies and biomechanics. Self-selected speed was chosen over one constant speed in order to best capture each participant's natural style and reflect the way they most typically ran.

Finally, some limitations are due to unexpected results, such as wide variations that were found in participants' sensory thresholds and responses to anaesthetic cream. Additionally, the study was limited by the effectiveness of the anaesthetic cream to change plantar cutaneous sensation and by the effectiveness of the SWM test to detect this change.

Future Directions

To answer the original research question, modifications are recommended to the experimental protocol.

When considering outcome measures, our results suggest that cadence and foot angle may best represent changes in barefoot running style, while knee angle may not be as important. Removing knee angle at foot-belt contact as an outcome measure would improve testing efficiency and reduce participant burden, as a lesser number of reflective markers would be required.

Due to the wide variation in running shoes available, it would beneficial to standardize the shoes that participants wear during their shod run. Despite the fact that all of our participants ran in what was considered a traditional running shoe, the specific features of each participant's shoes may vary and therefore may have varying effects on their running style. It is recommended that future studies provide participants with a standardized running shoe several weeks before baseline testing in order to allow participants to become accustomed to these shoes before baseline testing.

Following the assumption that anaesthetic cream affects pain fibres, it would be beneficial to use a pin prick test to look for changes before and after cream application. A stronger intervention may also be needed to significantly alter plantar cutaneous sensation. In order to achieve this, the anaesthetic cream could be left on for a longer period of time, perhaps up to an hour, in order to increase effects. However, this modification should only be made after careful consideration of the cream's potential toxic effects. Alternative anaesthetic interventions should also be considered including vibration, hypothermia and transdermal anaesthesia. To better monitor the change in plantar cutaneous sensation and ensure blinding, future studies could also designate a third-party researcher to administer cutaneous anaesthesia and perform sensory testing to monitor true sensory threshold change.

Our results presented a trend in cadence and foot angle means that were consistent with our hypothesis on learning; that those with cream on the legs would adapt and retain the barefoot running style at the fastest rate, followed by the group with no cream, then the group with cream on both the feet and legs and finally the group with cream on the feet. Variation was chosen as the indicating measure of learning, however the variation in outcome variation measures did not reflect this trend. This raises the question of whether variation is a true measure of learning or retention during a continuous task such as running. Despite the findings that inexperienced runners are less economical (Lees 1994), variability in a continuous task may also indicate a type of neural flexibility to the environment. It is possible that outcome means may provide a better indication of learning during a continuous task when there is a specific biomechanical pattern change expected.

Contamination may also have occurred between participants whose testing sessions were done at the same time. Observation of others has been found to be a confounding factor when learning a new skill (Wulf, Shea, & Lewthwaite, 2010). In addition, participant's level of attention during the SWM test may have affected results. It may therefore be of benefit to limit testing to one participant at a time.

Markers falling off during a running trial contributed to shorter unilateral biomechanical data. Simultaneously collected bilateral data could be maximized if stronger adhesives were used to attach the markers to the participant's body. In addition, those markers on the lower legs and feet which were most vulnerable to falling off due to inertial forces, which are proportional to weight, suggest the use of lower mass reflective markers to reduce marker loss. As previously mentioned, the exclusion of knee angle as an outcome measure would also reduce the risk of marker loss as fewer markers would be required.

Finally, it would be beneficial to complete a similar study in an outdoor location in order to improve generalizability to the wider recreational running community. This modification would bring about added challenges, such as how to regulate running speed and ground temperature, but would allow for more application to runners considering making the transition to barefoot.

Clinical Implications

The results of this study require larger, randomized controlled follow-up trials in order to make definitive recommendations to coaches, clinicians and runners on the best way in which to transition to barefoot running. However, this study does provide some evidence that sensory threshold should be considered before running barefoot. Participants with plantar sensory deficits should be cautioned of the further decrease in sensation that may result from running barefoot and of the increased risk of injury this may pose. When transitioning to barefoot running, careful attention should be paid to the body's own sensory feedback in order to avoid pain and injury, rather than focusing on the adaptation of a desired running style. The accumulated effects of long-term barefoot running on plantar cutaneous sensation remain unknown, therefore barefoot runners should exercise caution, monitor any suspected changes in sensation, and seek medical attention when necessary.

Conclusion

This feasibility study provides insight into how to design a randomized controlled trial that would examine how novice barefoot runners adapt to and retain the skill of barefoot running. Adaptation is demonstrating that one can perform a new skill within the first learning session, whereas retention is the ability of the learner to perform the skill at a later point in time. In this study, 16 of 16 participants demonstrated a change in their running style, as measured with an increased cadence and foot-ground plantarflexion, and most had an increased knee flexion, when barefoot compared to when shod. These findings are consistent with previous studies (Bishop et al., 2006; Lieberman et al., 2010; Squadrone & Gallozzi, 2009). Consistent with these biomechanical findings, a significant increase in plantar cutaneous sensory threshold was found after both barefoot runs as measured using the SWM test. The application of anaesthetic cream on the legs, feet, and feet and legs, compared to non-anaesthetic cream, on four groups of four randomly allocated participants did not change their leg or foot sensory thresholds, as measured by the SWM test. However, the group that had anaesthetic cream only on their legs (4 out of 16 participants) demonstrated a more rapid adaptation to and a better retention of the barefoot running style. These results are conflicting since the SWM test showed no difference in sensory threshold, but a change in biomechanics did occur based on the group allocation. Future studies should consider using a pin prick test to measure pain and having a separate researcher monitor sensory threshold. It may also be beneficial to test one participant at a time and use lightweight and fewer markers. Finally, future studies should consider alternative methods for measuring learning during running and exclude knee angle as a valuable outcome measure. The findings of the randomized controlled study should be able to inform novice runners on how to best learn and retain the skill of barefoot running. This knowledge may influence an individual's risk of experiencing a running-related injury.

References

Bishop, M., Fiolkowski, P., Conrad, B., Brun, D., & Horodyski, M. (2006). Athletic footwear, leg stiffness, and running kinematics. *Journal of athletic training*, *41*(4), 387–392.

Björkman, A., Rosén, B., & Lundborg, G. (2004). Acute improvement of hand sensibility after selective ipsilateral cutaneous forearm anaesthesia. *The European journal of neuroscience*, *20*(10), 2733–6.

Björkman, A., Weibull, A., Rosén, B., Svensson, J., & Lundborg, G. (2009). Rapid cortical reorganisation and improved sensitivity of the hand following cutaneous anaesthesia of the forearm. *The European journal of neuroscience*, *29*(4), 837–44.

Dai, X.-Q., Li, Y., Zhang, M., & Cheung, J. T.-M. (2006). Effect of sock on biomechanical responses of foot during walking. *Clinical biomechanics (Bristol, Avon)*, *21*(3), 314–21.

Divert, C., Mornieux, G., Freychat, P., Baly, L., Mayer, F., & Belli, A. (2008). Barefoot-shod running differences: shoe or mass effect? *International journal of sports medicine*, *29*(6), 512–8.

Halsband, U., & Lange, R. K. (2006). Motor learning in man: a review of functional and clinical studies. *Journal of physiology, Paris*, *99*(4-6), 414–24.

Hatala, K. G., Dingwall, H. L., Wunderlich, R. E., & Richmond, B. G. (2013). Variation in foot strike patterns during running among habitually barefoot populations. *PloS one*, *8*(1), e52548.

Hobara, H., Sato, T., Sakaguchi, M., Nakazawa, K., & Functions, M. (2012). Step frequency and lower extremity loading during running. *International Journal of Sports Medicine, 33*, 310–313.

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

Lavcanska, V., Taylor, N. F., & Schache, A. G. (2005). Familiarization to treadmill running in young unimpaired adults. *Human movement science*, *24*(4), 544–57.

Lee, S., Kim, H., Choi, S., Park, Y., Kim, Y., & Cho, B. (2003). Clinical usefulness of the two-site Semmes-Weinstein monofilament test for detecting diabetic peripheral neuropathy. *Journal of Korean medical science*, *18*(1), 103–7.

Leon, A., Davis, L., & Kraemer, H. (2011). The role and interpretation of pilot studies in clinical research. *Journal of psychiatric research*, *45*(5), 626–629.

Lieberman, D. E. (2012). What we can learn about running from barefoot running: an evolutionary medical perspective. *Exercise and sport sciences reviews*, *40*(2), 63–72.

Lieberman, D. E., Venkadesan, M., Werbel, W. a, Daoud, A. I., D'Andrea, S., Davis, I. S., Mang'eni, R. O., Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531–5.

Muller, H., & Sternad, D. (2009). Motor Learning: Changes in the Structure of Variability in a Redundant Task. *Advances in experimental medicine and biology, 629*, 439-456.

Nurse, M. A., & Nigg, B. M. (2001). The effect of changes in foot sensation on plantar pressure and muscle activity. *Clinical biomechanics*, *16*(9), 719–27.

Petoe, M. A., Molina Jaque, F. A., Byblow, W. D., & Stinear, C. M. (2012). Cutaneous anesthesia of the forearm enhances sensorimotor function of the hand. *Journal of neurophysiology, 109*(4), 1091-1096.

Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of sports medicine and physical fitness*, *49*(1), 6–13.

What the barefoot running craze has done to the shoe industry - The Globe and Mail. (2012). Retrieved July 27, 2013, from http://www.theglobeandmail.com/life/health-and-fitness/fitness/running/what-the-barefoot-running-craze-has-done-to-the-shoe-industry/article4186746/

Wulf, G., Shea, C., & Lewthwaite, R. (2010). Motor skill learning and performance: a review of influential factors. *Medical education*, *44*(1), 75–84.

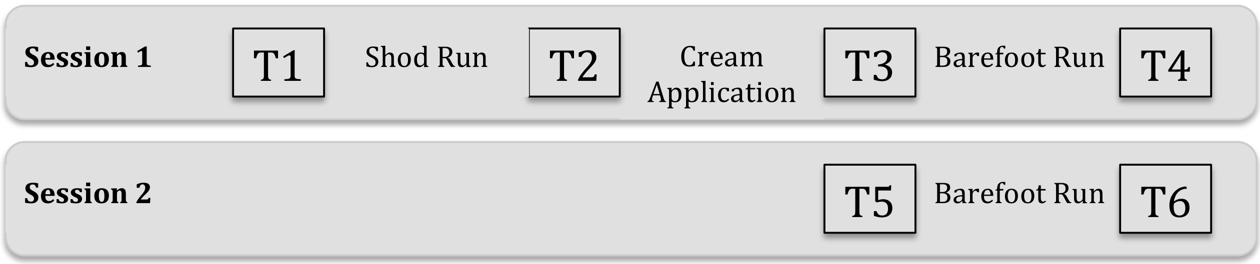

Figure 1 Timeline of sensory testing occurrences. During the first session, sensory measurements were taken pre-shod run (T1) and post-shod run (T2) and pre-barefoot run (T3) and post-barefoot run (T4). During the second session, sensory measurements were taken pre-barefoot run (T5) and post-barefoot run (T6).

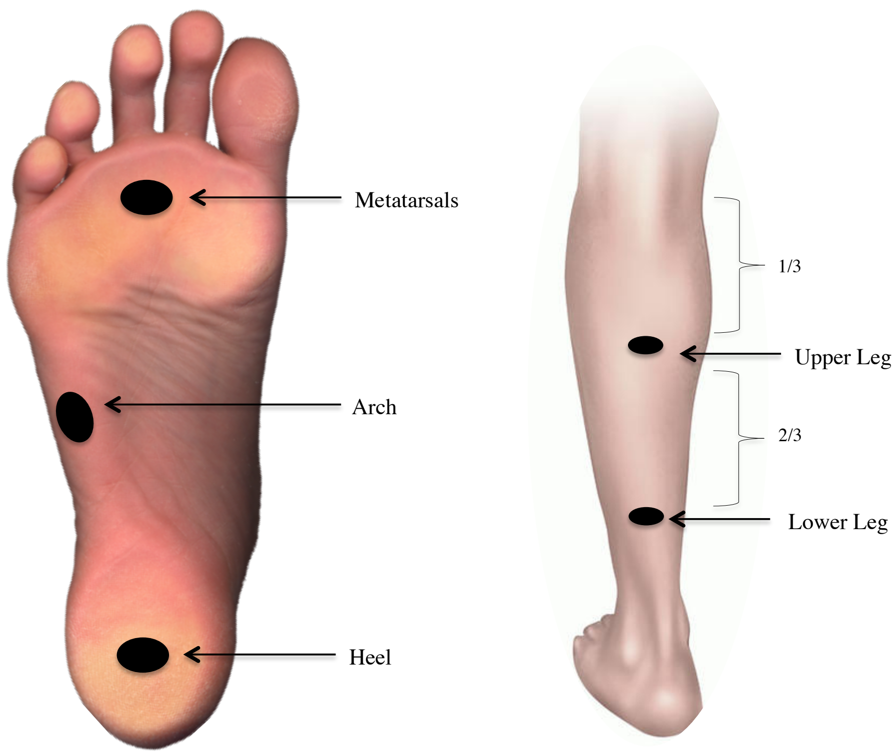

Figure 2 Locations of Sensory Testing. Images retrieved from: http://www.advancedfoottexas.com/2011/02/pain-in-the-ball-of-the-foot/ and https://www.healthtap.com/#topics/lower-calf-stretches

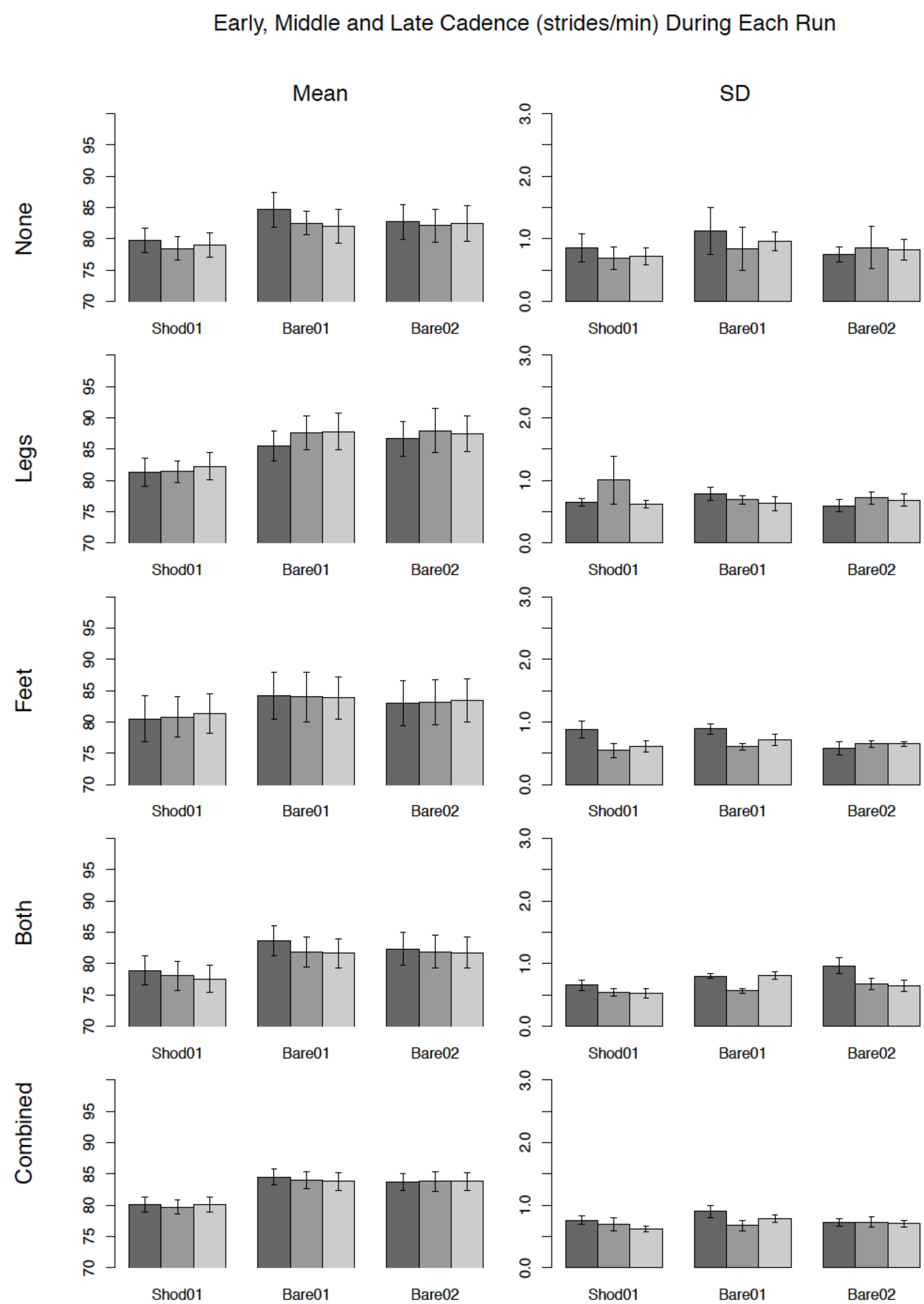

Figure 3 Mean cadence (left) and cadence variation (right), in strides per minute, for all four groups during all three runs (Shod01, Bare01, Bare02) during Early (dark grey), Middle (medium grey) and Late (light grey) epochs.

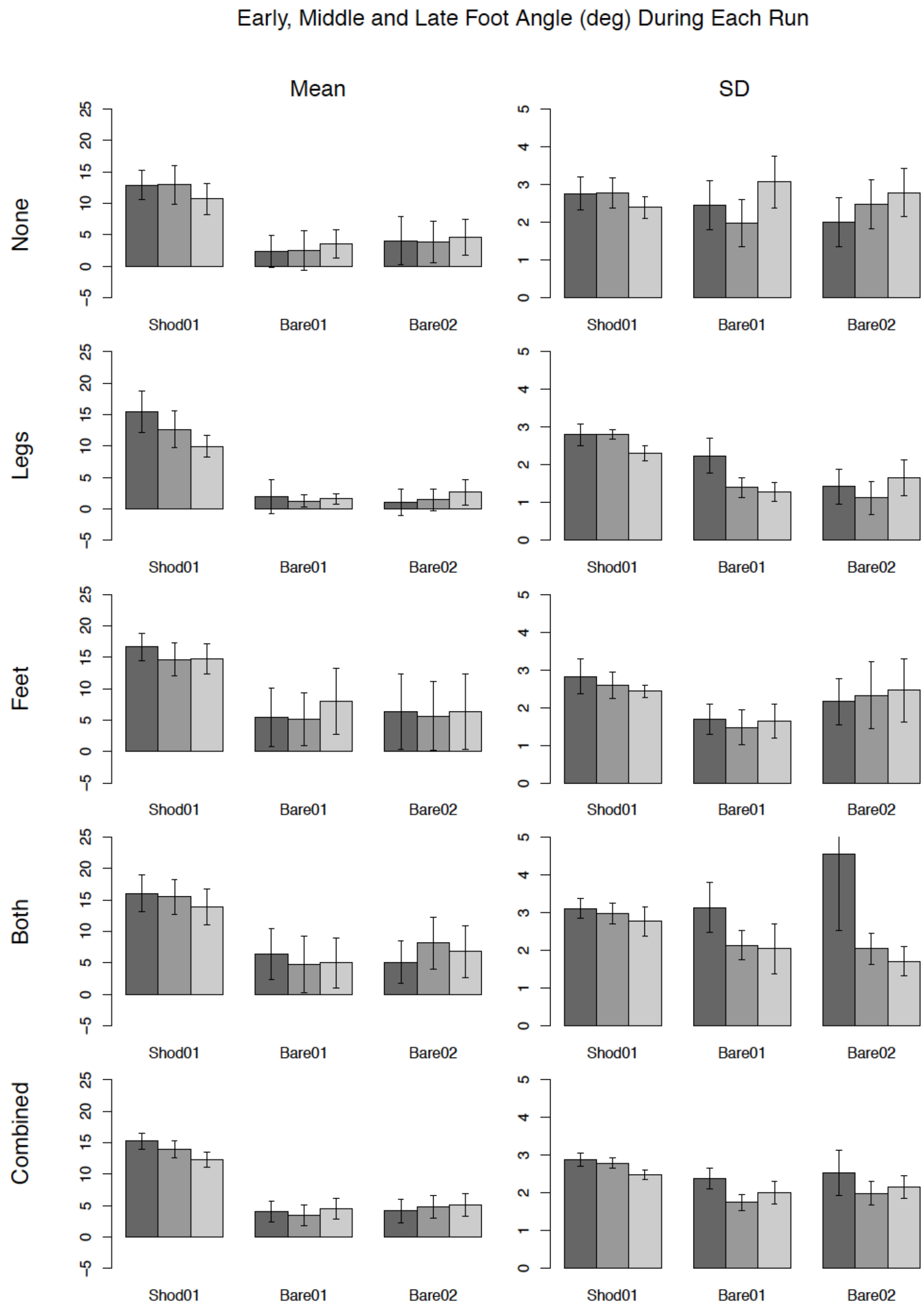

Figure 4 Mean foot angle (left) and foot angle variation (right), in degrees, for all four groups during all three runs (Shod01, Bare01, Bare02) during Early (dark grey), Middle (medium grey) and Late (light grey) epochs.

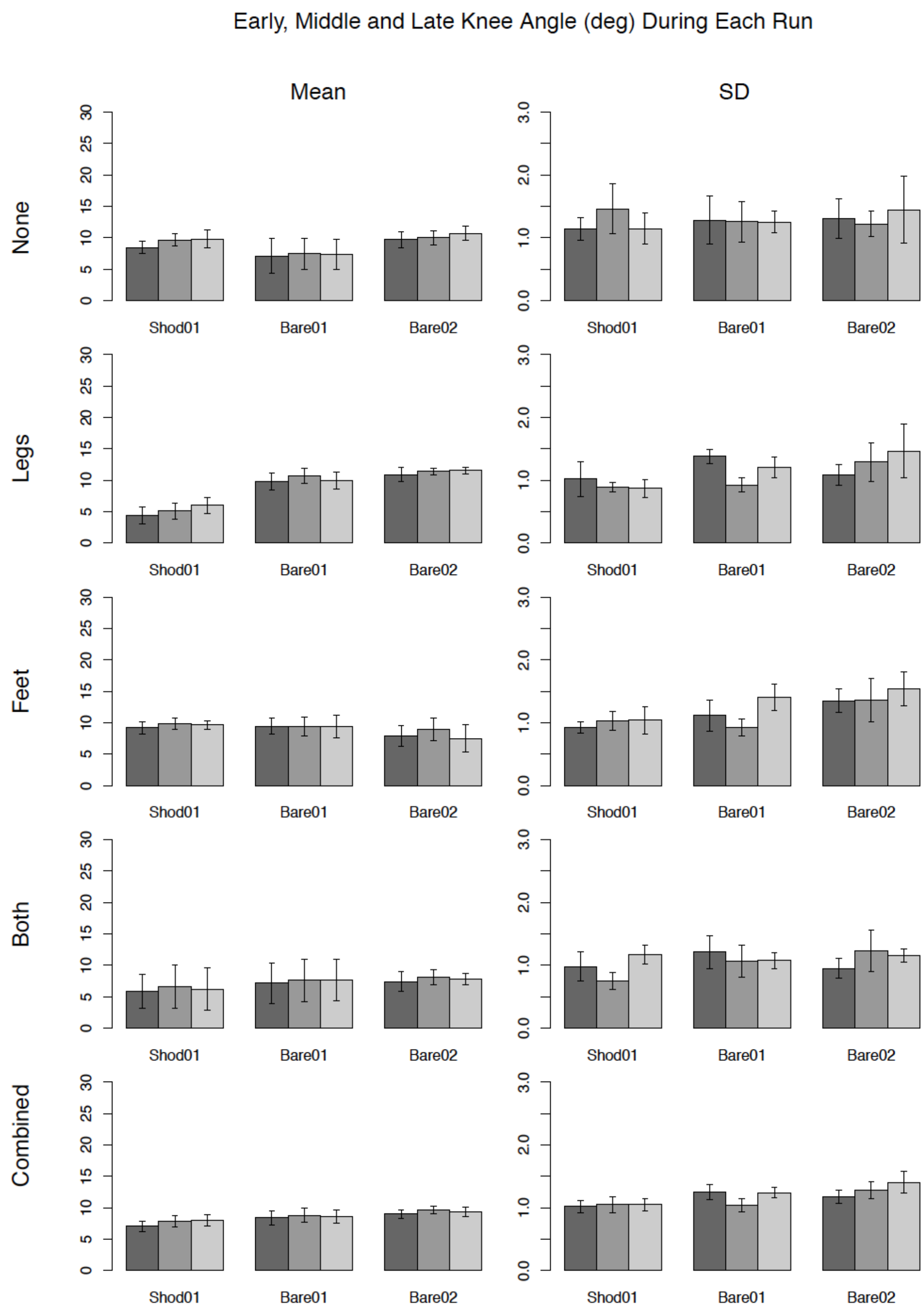

Figure 5 Mean knee angle (left) and knee angle variation (right), in degrees, for all four groups during all three runs (Shod01, Bare01, Bare02) during Early (dark grey), Middle (medium grey) and Late (light grey) epochs.

Table 1 Semmes-Weinstein monofilament testing sizes. Adapted from http://www.ncmedical.com/wp-content/uploads/2011/07/Touch-Test-Sensory-Evaluator_11_web.pdf.

Number	Monofilament Size	Target Force (g)	Pressure (g/mm^2)	Plantar Thresholds
1	2.83	0.07	5.53	Normal
2	3.61	0.4	16.1	
3	4.08	1	24.4	Diminished Light Touch
4	4.31	2	27.4	
5	4.56	4	40.3	Diminished Protective Sensation
6	5.07	10	68.3	Loss of Protective Sensation
7	5.46	26	106	
8	6.65	300	292	Deep Pressure Sensation only

Table 2 Group demographics.

	None (n=4)	Legs (n=4)	Feet (n=4)	Both (n=4)	F	p
Sex	1 male, 3 female	2 male, 2 female	1 male, 3 female	3 male, 1 female		
Age (years)	25.8 (4.3)	25 (1.8)	23.8 (2.5)	25 (2.2)	0.40	0.75
BMI (kg/m²)	21.9 (2.9)	22.3 (2.3)	22.4 (2.4)	23.7 (3.1)	0.36	0.78
Average Running Frequency (runs/week)	2.5 (0.6)	1.3 (1.0)	1.6 (1.1)	1.5 (1.3)	1.14	0.37
Average Running Duration (minutes/run)	35 (12.3)	22.5 (15)	28.8 (2.5)	40 (28.3)	0.78	0.53
Self-Selected Running Speed (kilometres/hour)	9.3 (1.7)	8.3 (1.6)	8.9 (1.8)	9.2 (1.5)	0.26	0.85

Values are presented as Mean (SD)

Table 3 Sensory measurements (by number) for the four intervention groups at each of the six measurement times.

	T1	T2	T3	T4	T5	T6
None	3 (0.9)	2.7 (1.1)	3 (0.8)	2.9 (1.0)	2.5 (1.1)	2.8 (0.9)
Legs	2.6 (0.8)	2.6 (0.9)	2.6 0.8)	2.7 (0.8)	2.5 (0.8)	3 (0.9)
Feet	2.8 (1.0)	2.8 (1.0)	2.6 (0.8)	3 (0.9)	3 (0.9)	3 (1.0)
Both	2.2 (0.9)	2.5 (0.9)	2.5 (0.9)	2.7 (0.9)	2.5 (1.0)	2.6 (1.1)

Values are presented as Mean(SD)

Table 4 Questionnaire results from sessions 1 and 2. Scale represented by 1 being very uncomfortable and 7 being very comfortable (Comfort); 1 being very unlikely to injure yourself and 7 being very likely to injure yourself (Perceived Risk of Injury); 1 being 'felt the same as running shod' and 4 'felt extremely different from running shod' (Perceived Difference-Session #1); 1 being 'felt the same as first barefoot run' and 4 being 'felt extremely different from first barefoot run' (Perceived Difference-Session #2).

	Session #1 (Relative to Shod Run)			**Session #2 (Relative to First Barefoot Run)**		
	Comfort	Perceived Risk of Injury	Perceived Difference	Comfort	Perceived Risk of Injury	Perceived Difference
None	4.5 (1.3)	3.5 (1.0)	2.8 (1.0)	4.3 (1.0)	3.8 (1.0)	2.0 (0.8)
Legs	3.4 (0.8)	3.3 (1.7)	3 (0.8)	3.5 (1.3)	3.5 (2.1)	2.3 (0.5)
Feet	4.3 (1.0)	4.3 (1.0)	2.5 (0.6)	4.8 (1.0)	3.8 (0.5)	2.0 (0.8)
Both	5.3 (0.5)	2.3 (0.5)	3.0 (0)	5.0 (0)	2.5 (0.6)	2.0 (0.8)

Values are presented as Mean (SD)

Table 5 Participant comments on the perceived difference between their first barefoot run and running shod (Session #1) and between their second and first barefoot runs (Session #2).

		Session #1 (Relative to Shod Run)	Session #2 (Relative to First Barefoot Run)
None	1	better awareness of my toes to the ground	n/a
	2	striking the ground harder	more natural; little steadier
	3	felt imprints of treadmill but not really my toes; surprisingly comfortable	same; feel more; more control
	4	ran on my toes; felt like I was running faster	felt lighter on my feet
Legs	5	changed the timing of my stride, felt foot flopped more	a little more comfortable
	6	a little apprehensive	first session I was running on my toes, this session I ran more evenly on my feet
	7	ran on toes when barefoot because it felt more comfortable. Didn't run on toes with shoes on	little harder to run on toes because calves felt a little more sore
	8	avoided heel strike; tried to reduce impact	hard to tell; slightly more forefoot than heelstrike
Feet	9	more awareness of intrinsic muscles/proprioception, pushoff felt different, dorsiflexors not working as hard	same
	10	more unsteady, felt like I had to run more on my toes	easier to get into the 'barefoot groove' and feel as though I was running normally and consistently the same way through entire 5 minutes
	11	like my foot was wider, at first went harder on my heel	more toe-off, more intrinsic foot muscle activation, more calf use
	12	more on forefoot; burning sensation, esp. big toe, but better 15 minutes later	no burning sensation; felt more natural stride and tempo, more comfortable, more on toes
Both	13	more force through heels , left foot pronating more	less foot pounding/slapping, more weight through toes vs arch
	14	greater impact on my forefoot and midfoot, arch felt more rigid	more in control of my lower extremities
	15	like my toes were gripping the mat; more stable	n/a
	16	on toes with more control; less worry of knocking ankles	calves/achilles tendon slightly sore; more relaxed stride

CHAPTER 4: DISCUSSION AND CONCLUSIONS

Overview of Major Findings and Contributions

The purpose of this thesis was to explore the theoretical rationale behind barefoot running and investigate the role of plantar cutaneous sensation in the adaptation and retention of the barefoot running style.

The traditional and emerging theories on the etiology of running-related injuries have been described and contrasted. The Running Shoe theory supports the use of shoes with motion-control, cushioning and elevated heels in an attempt to attenuate high impact forces and limit abnormal subtalar motion. The Barefoot Running theory proposes that many injuries result from the use of traditional running shoes and suggests running barefoot in order to increase foot muscle activation, facilitate somatosensation and promote the barefoot running style. Both theories require rigorous testing of the mechanisms by which RRIs are caused, and ultimately prevented.

The barefoot running style is proposed to be a result of the foot functioning according to its physiological design, receiving feedback from plantar mechanoreceptors that allow for rapid changes in foot position. This style has been described as having a higher cadence, greater knee flexion and a forefoot landing and is the goal of many runners who have joined the barefoot running movement. We hypothesized that plantar cutaneous sensation may have an effect on the rate at which novice barefoot runners might adapt to and retain the barefoot running style.

A feasibility study (Chapter 3) was designed to answer the research question: "What role does plantar cutaneous sensation play in the adaptation and retention of the barefoot running style?" A change in running style was observed in the study when participants ran barefoot for the first time. This finding supports the idea that running barefoot causes a person to run differently than when they are shod, possibly due to the rapid feedback received from the foot's plantar mechanoreceptors. Future research is required to support these findings and determine if this new running style might prevent running-related injuries. The application of anaesthetic cream was not found to alter sensory thresholds, however, those participants with anaesthetic cream on the legs were found to adapt to and retain the barefoot running style at a faster rate than those without cream on the legs.

From these findings, it is clear that novice runners adapt to and retain a different running style when barefoot compared to when shod. This change may result from improved somatosensation. This improved somatosensation is only one mechanism by which barefoot running is proposed to reduce the risk of running-related injuries.

The results of this thesis add to the current literature by further defining and contrasting the implicit theories behind the prevention and treatment of running-related injuries and by providing further insight into the change in running style that occurs when running barefoot.

In conclusion, the results of this thesis provide promising support for barefoot running as a means by which runners may adjust their running style and potentially avoid running-related injuries. Future trials will confirm the role of plantar cutaneous sensation and how runners might best adapt to and retain this style. Larger studies are required in order to capture and compare injury incidence in the barefoot and shod running populations. As limited success is observed in preventing running-related injuries with the use of the traditional running shoe, barefoot running should be considered as an alternative strategy by which runners might better attend to the body's natural mechanisms to detect risk and avoid injury.

APPENDIX A: Examples of Popular Minimalist Footwear (Spring 2013)

Vibram Five Fingers
Invisible Shoe Huaraches
Inov8 Evoskin, Bare X,
New BalanceMinimus
BrooksPure
FilaSkele-Toes
AdidasAdipur
Luna Sandals
SauconyHattori
Vivo Barefoot
Terra plana Vivo Barefoot
MerrellTrue/Pace/Trail/Road/
Sonic Glove
Zemgear Split toe Low

FeelmaxKuusaa,Osma, Niesa
SockwaAmphibian
LeguanoPremium
KigoDrive, Shel
TevaNilch, Zilch
SomnioNada
StemOrigins
AltraAdams, Samson, Provision,
Instinct, Intuition
Topo AthleticRT
SkoraBase
DunlopVolleys shoes
CusheShucoon
NewtonMV2

From http://www.therunningclinic.ca/en/runners-information/recommended-shoes.php

Four Elements to Minimalist Shoes
A sufficiently wide toe box to allow for natural toe splay
No heel elevation (i.e., a shoe that is completely flat from heel to toe)
No or little toe spring (i.e., a minimal or non-existent "toe ramp")
Soles that can easily be bent or twisted

From: http://www.naturalfootgear.com/why-many-minimalist-shoes-are-not-truly-minimalist/

For more info: http://naturalrunningcenter.com/shoe-reviews/

APPENDIX B: Sensory Measurement Protocol

1. Participant lays prone on plinth with eyes closed and feet and lower legs exposed.
2. Identify the five testing areas to the participant by touching each with the largest monofilament (Orange, 6.65) and naming each one respectively (i.e. upper leg, lower leg, heel, arch, 'toes').

   Note: Avoid abnormal skin surfaces such as callouses, warts, cuts or bruises.
3. Explain that you will randomly be touching one of the five areas up to three times in a row with the monofilaments. The participant is to indicate when they feel a touch and identify the testing area where they felt it and how many times (one to three).
4. Begin testing with smallest monofilament (Green, 2.83) and gently press monofilament perpendicular against skin surface just until filament bows.
5. Hold pressure for 1.5 seconds then remove.
6. Repeat at same site two more times.
7. If participant correctly identifies testing area at least two of three times:

   →RECORD AS SENSORY LEVEL FOR THIS TESTING AREA

	Green (1)	Blue (2)	Purple (3)	Pink (4)	Red (5)	Brown (6)	Yellow (7)	Orange (8)	Sensory Level (1-8)
Upper Leg	X								1
Lower Leg	X								1
Heel			X						3
Arch	X								1
Metatarsals	X								1

   If participant fails to identify testing area (or only identifies one of three):

   →CONTINUE TEST AT NEXT TESTING AREA
8. Repeat procedure with smallest monofilament at all five testing areas in random order.

9. For those sites that have not yet been identified, repeat procedure with next largest monofilament until sensory levels have been determined for all five testing areas. Note: Keep participants unaware of correct or incorrect detections.

APPENDIX C: Questionnaires

After Session 1: **Code: __________**

Please respond by circling one of the numbers (1 to 7):

"When running barefoot, compared to running wearing shoes, was it ______ "

1	2	3	4	5	6	7
Very uncomfortable			Neither uncomfortable nor comfortable			Very comfortable

Please respond by circling one of the numbers (1 to 7):

"When running barefoot, compared to running wearing shoes, did you feel that you were __________ to injure yourself?"

1	2	3	4	5	6	7
Very unlikely			Neither unlikely nor likely			Very likely

Please respond by circling one of the numbers (1 to 4):

"When running barefoot, compared to running wearing shoes, did you feel that you ran ______ "

1	2	3	4
The same	A little differently	Fairly differently	Extremely differently

If it felt different, how?

____

____

____

After Session 2: **Code: __________**

Please respond by circling one of the numbers (1 to 7):

"When running barefoot, compared to running wearing shoes, was it ______ "

1	2	3	4	5	6	7
Very uncomfortable			Neither uncomfortable nor comfortable			Very comfortable

Please respond by circling one of the numbers (1 to 7):

"When running barefoot, compared to running wearing shoes, did you feel that you were __________ to injure yourself?"

1	2	3	4	5	6	7
Very unlikely			Neither unlikely nor likely			Very likely

Please respond by circling one of the numbers (1 to 4):

"When running barefoot **today**, compared to running barefoot during the first session, did you feel that you ran ______ "

1	2	3	4
The same	A little differently	Fairly differently	Extremely differently

If it felt different, how?

____

____

____