ABSTRACT

Conservative Intervention through Changing Shoe Type to
Reduce Injury Risk Factors in Walking and Running

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Running and walking are associated with various injuries. Because the injury mechanisms for these injuries are mechanical in nature, a logical way to conservatively reduce injury risk is by wearing shoes that alter the individual's mechanics. This study is aimed at characterizing the effects that maximalist and minimalist shoes have on a fatigued runner, and interpreting how those effects may be beneficial or detrimental for running overuse injuries. Additionally, this study investigates the methodology of fatigue studies that utilize a treadmill and how its differences from over ground running may influence their results. Finally this study investigates which shoes may be best for preventing knee osteoarthritis progression in walking. Our findings suggest that different shoes may be beneficial and detrimental to different injuries, an acclimatization period should be included in fatigue studies, and there may be disadvantages to wearing maximalist shoes to reduce knee osteoarthritis progression.

Conservative Intervention through Changing Shoe Type to
Reduce Injury Risk Factors in Walking and Running

by

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A Thesis

Approved by the Department of Mechanical Engineering

Paul Ro, Ph.D., Chairperson

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DEDICATION

To my family and close friends.
Thank you for the endless support and for always believing in me.

CHAPTER ONE

Introduction

Altering Shoe Type to Alter Walking and Running Mechanics

Running and walking are very common forms of exercise, but are associated with a variety of injuries. Because the injury mechanisms for many of these injuries are mechanical in nature, a logical way to conservatively treat these injuries is to wear a shoe that beneficially alters the movement and loading profile during the activity. This thesis investigates the changed mechanics of walkers and runners while wearing different shoes, as well as the methodology of analyzing fatigued runners. The thesis is comprised of three separate and related studies: Differences between Maximalist and Minimalist Shoe Running Before and After a 5k Fatigue Protocol, The Potential Influence of Treadmill Running In Fatigue Studies, and The Effect of Shoes on Risk Factors Associated with Knee Osteoarthritis during Walking. This introduction will provide a brief overview of these projects. Further detail and supporting background will be provided in each chapter.

Differences between Maximalist and Minimalist Shoe Running Before and After a 5k Fatigue Protocol

Running has rapidly become the most common form of exercise since the spike in popularity in the 1970s. Despite the many benefits associated with running, it is also associated with a variety of overuse injuries. A common method to reduce the alarmingly high rate of overuse injuries in running is to alter the running shoe in order to alter the runner's mechanics. This thought process has resulted in a variety of running shoes that generally take one of two paths. One path is drastically reducing the amount of cushioning and trying to achieve the benefits associated with barefoot running while still protecting the foot with a shoe. The opposite path is to put excessive cushioning on the shoe to absorb impacts and control excessive motion at the ankle. There is a large amount of debate about which type of shoe will be most beneficial for overuse injuries, and it is, therefore, of interest to researchers to investigate how these shoes alter running mechanics. This topic will be further explained in Chapter Two. In order to investigate the shoes mechanics for interest in overuse injuries, a basic understanding of the overuse injuries must be achieved. The common overuse injuries that were investigated in this study included tibial stress fractures and patellofemoral pain syndrome. These injuries and their associated injury mechanisms will be covered in detail in Chapter Two. Additionally, it is reasonable to assume that many recreational runners are in a fatigued state during a large portion of their run, and it is, therefore, of interest to investigate how the shoes alter their mechanics while in a fatigued state. It is hypothesized that the effect of the shoe may differ depending on the fatigue status of the runner, and this hypothesis was investigated in Chapter Two of this thesis.

The Potential Influence of Treadmill Running In Fatigue Studies

In order to fatigue participants in the study in a way that is conducive to a research environment, a treadmill was utilized. While using a treadmill is a very common occurrence in fatigue studies, the potential influence of treadmill running needs to be addressed. Fatigue studies are necessary in research because athletes are generally in a fatigued state while participating in their athletic activity. For efficiency and simplicity, treadmills are commonly used in order to fatigue research participants that are participating in a fatigue study. There are many studies outlining differences between over ground running and treadmill running, and these studies are discussed in detail in Chapter Three, but this is frequently unaccounted for in fatigue studies. While there have been studies researching changes that occur when transitioning from over ground running to treadmill running, the changes that occur when transitioning from treadmill running back to over ground running remains largely uninvestigated. This occurs when data is collected on an over ground runway, but the runners are fatigued using a treadmill. Because studies utilize this methodology, differences while transitioning back to over ground were investigated in Chapter Three of this thesis. Additionally, because some studies to do not normalize shoe conditions in studies, it was investigated if the transition period would differ between maximalist and minimalist shoe conditions, since the overall compliance interaction between the shoe-treadmill and shoe-over ground will differ between shoe types.

The Effect of Shoes on Risk Factors Associated with Knee Osteoarthritis during Walking

In addition to the alteration of running mechanics due to varying shoe type, the alteration of walking mechanics due to varying shoe type is also of interest to researchers. Diseases such as knee osteoarthritis, which is discussed in Chapter Four of this thesis, have increased progression risk due to walking mechanics. Therefore, it is of interest if altering a patient's shoe type may reduce the progression of their disease by altering their walking mechanics. In this chapter, four different shoe conditions, as well as barefoot walking, were compared to see if shoe type would alter known risk factors for knee osteoarthritis progression. Of primary interest was the hypothesis that maximalist shoes, developed with foot-guidance technology, might reduce the knee adduction moment during walking.

Biomechanical Analysis Methods

The Baylor BioMotion Lab Instrumentation

The Baylor BioMotion Lab is located at the Baylor Research Innovation Collaborative (BRIC) in Waco, TX. The instrumentation used was consistent for all the studies described in this thesis. This lab utilizes fourteen Vicon Vantage Cameras collecting at 240 Hz (Vicon Motion Systems, LTD, Oxford, UK), three Advanced Mechanical Testing Inc. (AMTI) force plates collecting at 1680 Hz (Advanced Mechanical Testing Inc., Watertown, MA), and two high speed Bonita cameras collecting at 120 Hz (Vicon Motion Systems, LTD, Oxford, UK) that were placed around a 12.5 m runway. The runway surface was a raised surface made of hard metal tiling with a hard plastic coating. A Polar H7 Bluetooth heart rate monitor (Polar Electro Inc., Bethpage, NY) was used to measure heart rate of the subjects during the fatigue run. The treadmill that was used to fatigue participants for the studies in Chapter Two and Three and acclimatize patients to new shoes in Chapter Four was the Sole F80 treadmill (Sole Fitness, Tempe, AZ) as shown below in Figure 3.1. [1] The treadmill has 22” x 60” running surface and supports speeds from 0.5-12 mph. [1]

Figure 1.1: The Baylor Biomotion Lab, consisting of fourteen motion capture cameras, three force plates, and two high speed cameras.

Basic Protocol

Prior to collection, the subject gave their consent according to the IRB document of the study. The subjects also were asked basic demographic information including their race, age, lower limb injury history, and foot dominance. The subjects were provided running shorts when necessary, and the shorts were rolled up on the sides using Velcro straps. Their height, weight, leg length, ankle width, knee width, wrist width, elbow width, hand thickness, and shoulder offset were then measured and recorded. Reflective markers (10-mm spheres) were then placed on the subjects body in accordance to the Point Cluster Technique (PCT) marker set created by Andriacchi et al. [2], which is shown in Figure 1.2. Markers were placed by the same researcher, who had received proper training of marker placement, within each individual subject to ensure consistent placement of markers.

After marker placement, subjects were asked to stand in the center of the collection volume on one of the force plates so that a static calibration trial could be collected. The calibration trial gives an accurate way to capture the subject's neutral body position. After collecting the calibration trial, the RMMA, LMMA, RMTP, LMTP, RMFC, LMFC, RLTP, and LLTP markers that are displayed in Figure 1.2 were removed.

Marker Set

The marker set used for the studies contained in this thesis was a point cluster technique (PCT) marker set based on the marker method created by Andriacchi et al. in 1998. [2] The method utilizes a cluster of points uniformly distributed on to the segments of interest and a coordinate system is defined within the cluster. [2] This marker set has been shown to reduce the error associated with non-rigid movement of the skin due to soft tissue artifact, thus acting as a more accurate representation of the human motion while still being a non-invasive skin marker technique. The variation of this marker set that was used in this study is shown below in Figure 1.2.

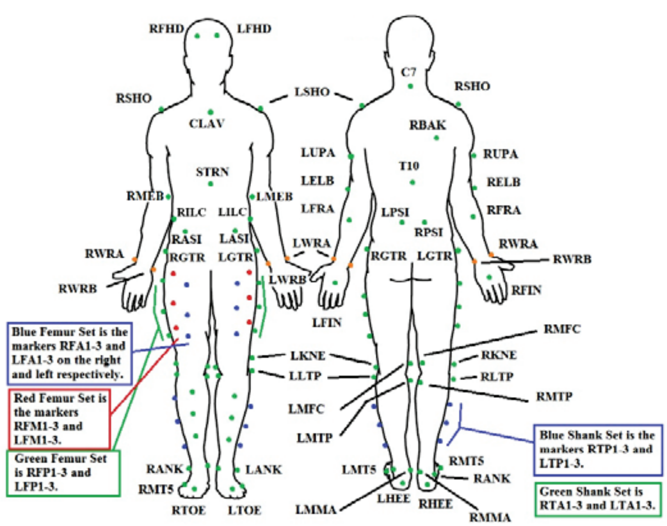

Figure 1.2: The marker set that was used for the studies in this thesis. It is a marker set that is based on the Point Cluster Technique (PCT) created by Andriacchi et al. [2]

Visual 3D Calculations

After collecting trials, the trials are gap filled within Vicon Nexus (Vicon Motion Systems, LTD, Oxford, UK). Trials were generally without major gaps, gap length of less than ten frames, and did not require a large amount of effort to fill. Gap filling is done to fill occlusions that occurred within the trial. Gap filling was done using spline filling if the gap was sufficiently small, otherwise pattern filling was used. Rigid body gap filling techniques were used for the pelvis markers. After gap filling the trials, they were exported as .c3d files so that they could be read by Visual3D (C-Motion Inc., Germantown, MD). This process is displayed in Figure 1.3.

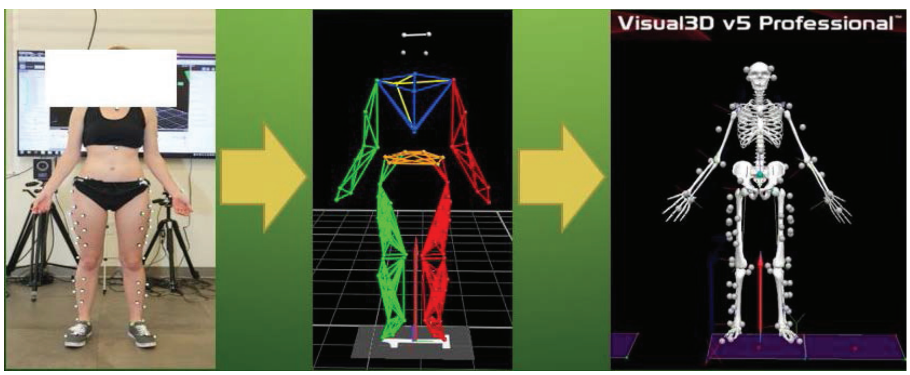

Figure 1.3: The flow of the processing. Capturing live human data and gap-filling within Vicon Nexus. After gap filling within Vicon, trials are exported into Visual3D in order to calculate the kinematics and kinetics from the trial.

Visual3D is arguably the most commonly used program to calculate biomechanical data in the field, and it allows for simple and quick analysis and processing. For these reasons, Visual3D was used to calculate the kinematics and kinetics of trials. The general methods Visual3D uses to accomplish this are described in the following paragraphs.

Kinematics. As mentioned when discussing the marker set, human skin in motion tracking is not generally rigid due to soft tissue artifact. While the PCT marker set reduces the errors associated with this, the calculations involved in this data still make an assumption of rigidity. *[3]* Each body segment that is modeled is defined by a local coordinate system (LCS) that moves correspondingly to the segment. *[3]* An example of a LCS being used to define a segment is shown in Figure 1.4, where the foot and shank both are shown to have a local coordinate system.

The coordinate axes and the origin for the LCS for each segment are found using calculations from individual markers that are dependent upon the marker set that you are using. The LCS axes for the PCT technique are based upon eigenvectors of the clusters and the center of mass to create orthogonal axes for each segment. The calculations for the segments used in this study are outlined in the article described earlier by Andriacchi et al. [2]

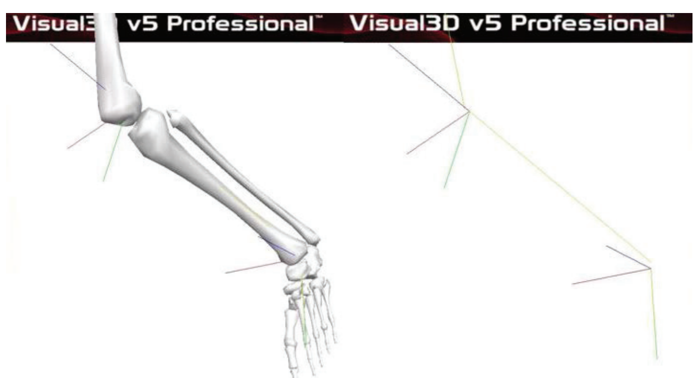

Figure 1.4: An example of body segments having local coordinate systems (LCS). The image displays then shank and foot LCS, each having independent coordinate axes.

It should be noted that it is generally difficult to estimate the origin of the hip joint, as discussed by Kainz et al. [4] Various methods exist in order to estimate the hip joint center, but the Harrington Regression Equations were utilized in all the studies in this thesis, since they have been shown to have greater repeatability and reliability compared to other methods. [4,5]

With each segment having a LCS, individual segment motions and accelerations may be calculated. In order to get joint angles, the orientation of the distal LCS with respect to the proximal LCS is calculated. [3] This is done using a Cardan sequence of rotations, or three successive rotations about each individual axis. [3] In biomechanics, the Cardan sequence XYZ of rotations is generally used because this is generally the order of largest change at a joint to smallest: flexion/extension (X), adduction/abduction (Y), and internal/external rotation (Z). [3] A graphical representation of this Cardan sequence used to find joint angles is displayed below in Figure 1.5. [3]

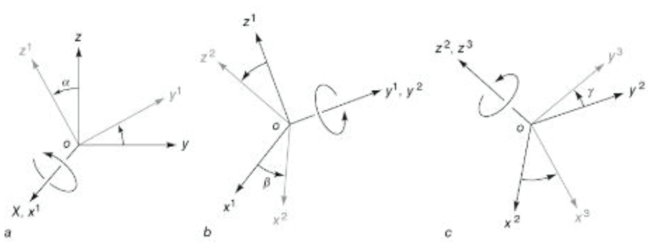

Figure 1.5: The Cardan sequence XYZ that is generally used in biomechanics that has a rotation about each individual axis to determine the joint angle for each axis. [3]

This is done at the ankle using the LCS of the foot and shank, at the knee using the LCS of the shank and thigh, and at the hip using the LCS of the thigh and pelvis. [3] Utilizing these methods, kinematics were calculated within Visual3D for this thesis.

Kinetics. In order to measure kinetics, methods based upon inverse dynamics are utilized. In order to do this, the ground reaction force at the bottom of the kinetic chain is measured using the force plates that were described earlier. In addition to the ground reaction force and moments, each segment's mass and inertial properties are required.

This is done using Hanavan's geometric model that was created in 1964, and this model is shown below in Figure 1.6. [6]

It should be noted that this model's regression equations have been updated throughout the years using cadavers and scanning techniques. [3] After these have been estimated, inverse dynamics may be done in order to get the segment and joint forces and moments. This methodology is displayed below in Figure 1.7. [7]

With these calculations, the kinematics and kinetics of each trial are calculated within Visual3D. Following calculations of these values, they are plotted and statistically analyzed using custom made MATLAB (MathWorks, Natick, MA) scripts. These outlined methods were used for all of the studies contained in this thesis.

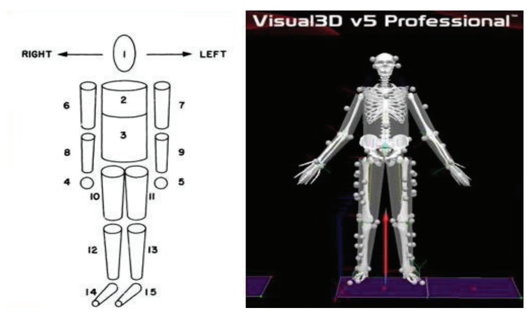

Figure 1.6: Hanavan's geometric model of the body, which is used to estimate the mass, center of gravity, and inertial properties of each individual body segment. [3,6]

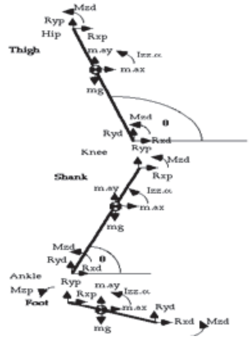

Figure 1.7: An example of the inverse dynamics done in order to calculate segment and joint moments and forces. [7]

Processing and Statistics

The trials were gap filled within Vicon Nexus. Gap filling is necessary due to any occlusions that occur during the trial due to the marker being slightly covered or moving extremely rapidly. Gap filling was done using spline filling if the gap was sufficiently small, otherwise pattern filling was used. Rigid body gap filling techniques were used for the pelvis markers. After gap filling the trials, they were exported as .c3d files so that they could be read by Visual3D (C-Motion Inc., Germantown, MD). Visual3D was used to calculate all kinetics and kinematics using the methods that are described in the Visual 3D Calculations section. The Harrington Regression Equations were used to estimate the hip joint center [5], as these have been shown to be the most accurate equations for the hip joint center. [4] The results were exported from Visual3D and analyzed using custom-made MATLAB (MathWorks, Natick, MA) scripts.

The methods used to calculate the vertical loading rate are consistent with those described by Willy and Davis [8], where the average slope of the vertical ground reaction force is extracted for 20% to 80% of the impact peak. Leg stiffness was calculated using the methods outlined by Farley et al. [9] Eversion velocity was calculated using the methods outlined by Oriwol et al. [10] Moments were normalized by the individual subject’s height and bodyweight and their ground reaction force was normalized by their body weight to highlight only differences of interest.

Statistics were performed using paired t-tests. This is a suitable statistical method because each subject was compared to themselves in two separate conditions, making the results dependent samples. Additionally, this method was chosen in order to be consistent with previous related studies for comparison.

CHAPTER TWO

Differences between Maximalist and Minimalist Shoe Running Before and After a 5k Fatigue Protocol

Introduction and Motivation

Altering Running Shoes for Overuse-Injury Prevention

Running is rapidly becoming the most popular form of exercise with an estimated 10 million runners in the US in 2016. [11] This is a great form of exercise that has many health benefits as well as mental benefits. Lee et al. performed a study that showed running, even 5 to 10 min/day, is associated with a notable decrease in risks of death from all causes of cardiovascular disease and results in multiple physiological benefits, which is displayed graphically below in Figure 2.1. [12]

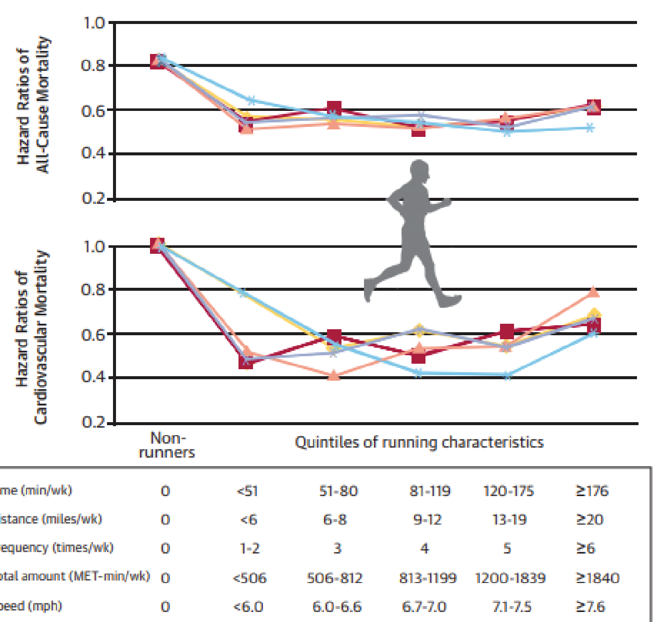

Figure 2.1: Lee et al.’s results showing that running can reduce mortality rates. [12]

While running has a lot of benefits, there are also many overuse injuries associated with this exercise. Various studies of recreational and competitive running have estimated that 70-80% of runners experience an overuse injury in a one year period. [13–15] Most of these injuries are fairly debilitating and will result in inconveniences in daily living as well as no longer being able to exercise easily. Ideally, a conservative method can be used in order to reduce the overuse injury rate and progression that is associated with running. Because the causes and risk factors of these overuse injuries are mechanical in nature, a common method used to attempt to reduce the alarming injury rate and progression is by altering the running shoe. This method of altering shoes in order to increase performance and also decrease the injury rate of runners has existed since the creation of the running shoe. Early research in the 1980s suggested that modifying running shoes may be a powerful tool to induce positive changes in running kinetics and kinematics and reduce injury rates, which sparked research and innovation in shoe technology. [16–18] Stemming from this ideology, multiple shoe types have emerged that can be mostly categorized into neutral shoes, stability shoes, motion control shoes, barefoot shoes, minimalist shoes, and maximalist shoes. [19] These shoe types are mostly a result of two different schools of thought. From the time of the running boom in the 1970s to up until 2009, running shoe construction had been progressing towards increased cushioning and stabilization. [14] Proponents of this school of thought believe that these features help prevent injuries in runners by controlling excessive motion and by absorbing more impact forces. More recently, however, there has been increasing support in the idea that the human foot is designed for running without the need of shoes or with shoes that have little cushioning. [14] This thought process aligns with the proponents of minimalist and barefoot shoes. This shoe attempts to promote a more natural foot strike, which is thought to reduce the ground reaction force. [14] There is an ongoing debate between these two ideologies, and there have been claims made for both. The minimalist and maximalist shoes epitomize these differing schools of thought and, because of this, they were chosen as the shoe conditions to investigate in this study.

Minimalist Shoes

Until recently, the modern running shoes was characterized by a large amount of cushioning under the heel. This large heel cushioning results in a large heel-toe drop, or the change in height from the heel to the toe within the shoe, of over 10 mm. This began changing around 2009, with a growing belief that humans were designed to be able to run without shoes or with shoes that mimic barefoot running with minimal protection. [14,20] There have even been studies that argue that running in barefoot and minimalist shoe conditions will result in a decrease in the frequency of overuse injuries. [21,22]. The belief behind this is centered on the fact that humans have been participating in endurance runs for thousands of years, but the modern running shoe, characterized by cushioning and motion control, was not invented until the running boom in the 1970s. [23] Despite the increasing technology of these shoes and adaptations of these shoes, running injuries have not experienced a decrease in frequency. [24] This is what resulted in the argument that running with the modern, heavily cushioned shoe may be resulting in unnatural kinematics and kinetics, which may be a cause of the high rate of injuries that runners experience today. [14] Due to this train of thought, extensive research comparing barefoot running to shod running has been performed. The most commonly reported benefit of running in barefoot and minimalist shoes is that they encourage a forefoot strike pattern. [14,22,25] This shift in strike pattern results in there being no impact peak in the vertical ground reaction force, allowing for a slower loading rate as well as a lower maximum vertical ground reaction force. [22,26–32] This is displayed graphically below in Figure 2.2, where the loading rate is the slope of the force curve leading up to the impact peak and the impact peak is the peak that results from foot strike. [14]

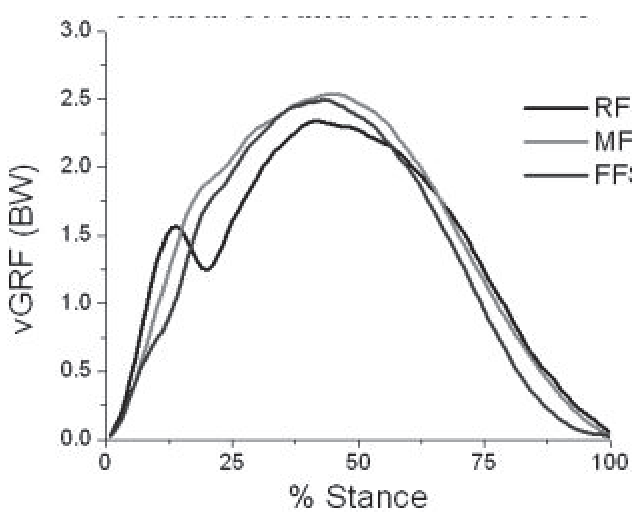

Figure 2.2: Vertical Ground Reaction Force graph showing the reduction or mitigation of the impact peak for forefoot strike patterns. [14]

This is a promising result for minimalist shoes because impact peak magnitude, loading rate, and tibial shock have been correlated with tibial stress fractures [33–37] as well as plantar fasciitis [38,39]. Both of these injuries are among the ten most common running overuse injuries reported. [40] Despite this frequently reported benefit, there are studies that reported a reduced, but present, impact peak in barefoot running [25] and even in some cases a much increased loading rate in barefoot running. [30] Additionally, there are also studies supporting the belief that adopting a forefoot strike does not reduce impact forces, loading rates, or the injury rate and progression of runners. [41] This contradicting evidence has resulted in a slight decrease in the popularity of minimalist shoes, and a growing interest in heavier cushioned, motion controlling shoes. If the minimalist shoes do reduce the ground reaction variables, they still may result in beneficial or detrimental effects on joint kinetics and kinematics. All of these variables are investigated in this study.

Maximalist Shoes

Maximalist shoes, characterized by heavy cushioning and motion control, have not been as extensively researched as barefoot and minimalist running conditions. In 2009, at around the same time the minimalist shoes were growing in popularity, the company Hoka One One was founded. [42] They created the "maximalist shoe", which is characterized by a thick cushioning for the midsole as well as the heel. This results in a relatively small heel-toe drop of 4 mm due to the increased cushioning along the whole of the foot. [43] The thought process behind these shoes is that the increased cushioning will improve shock attenuation, or force reduction, and reduce the risk of injury. [44] Additionally, these shoes have a j-frame support that is intended to guide the foot through stance phase; this adds a motion control and stability aspect to the shoes that coincides with the extra cushioning. [45] The concept of 'motion control' shoes is centered on controlling excessive rear foot eversion and eversion velocity during running in order to reduce the incidence of overuse injury. [46–52] Rear-foot eversion is the motion of the foot away from the center of the body in the frontal plane, which is shown below in Figure 2.3. [53]

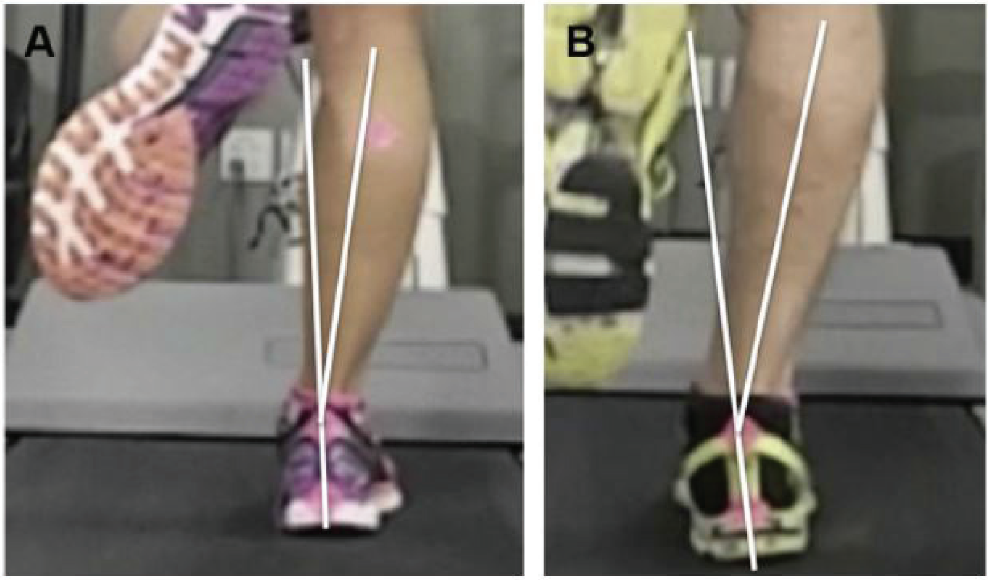

Figure 2.3: The image shows an increased eversion angle in runner B when compared to runner A while treadmill running. [53]

The Hoka maximalist shoes are also a "meta-rocker" shoe. [45] A rocker shoe is defined by a rounded shape bottom along the long side of the shoe that 'rocks' the foot through stance phase. Rocker shoes have been previously associated with multiple benefits, such as reduction in plantar-flexion moment, reduction of forefoot loading, and a reduction in stress fractures in the forefoot region without having a large effect on the kinetics and kinematics at the hip and knee. [54–56] Despite these benefits, rocker shoes have also been correlated with less energy efficiency while running, attributed to their increased mass. [57] With the combination of increased cushioning, motion control, and rocker technology, the maximalist shoe is the culmination of running trends and technology that occurred from the running boom in the 1970s up until the rise of minimalist shoes in 2009. Despite the maximalist shoe's growing popularity, research behind their effects on running remain limited. Sinclair et al. has researched the maximalist shoes in comparison to minimalist and found that maximalist shoes may be beneficial for patellofemoral pain symptoms and Achilles tendon pathology by reducing contact force and pressure in the patellofemoral joint and reducing Achilles tendon forces, but running in maximalist shoes also results in an increased tibial shock. [15,58,59]. Pollard et al. tested the maximalist shoes in comparison to a neutral shoe in a fatigued state and found a similar result to Sinclair et al.'s finding of the increased tibial shock experienced. They found that runners experienced increased impact peak loading and loading rates when running in the maximalist shoes, putting them at an increased risk of tibial stress fractures. [44] While some research has been done, the kinematic and kinetic effects of maximalist shoes remains limited. This study furthers research into maximalist shoes by fully describing the lower-limb, kinematic and kinetic effects of the maximalist shoes on fatigued runners.

Fatigue Running

Most previous shoe studies only investigated changes due to a change in shoe condition after a brief acclimatization period, but with the runner in a rested state. [15,46,54,58] While these trends and changes are of interest, regular runners are commonly running in a tired or fatigued state for a large portion of their runs. There have been reported changes in the kinematics and kinetics as a runner is fatiguing, making changes in a fatigued state of significance for investigation. [60–75]. Previous studies have reported that fatigue increases risk for tibial stress fractures by inducing increased shock, impact acceleration, free moments, rear-foot eversion, and vertical loading rate. [64,65,72,75] Also of interest, Dierks et al. investigated kinematic changes within runners with patellofemoral pain in a fatigued state and observed increased hip internal rotation, which is a risk factor of patellofemoral pain. [67,76] These changes of kinematics and kinetics within runners that occur in a fatigued state make it logical to perform a shoe study within a fatigued state. Also, it is reasonable to believe that the shoes may have an increased effect on a runner in a fatigued state, due to their muscles being fatigued and more easily influenced. Despite the rationale behind conducting a study of this nature, studies of this type are limited. Cheung et al. found that motion control shoes reduced fatigue of lower limb muscles, which should reduce and delay the kinematic and kinetic changes that occur in fatigue. [62] Mann et al. investigated the effects of fatigue in minimalist shoes versus neutral shoes on spatiotemporal variables and reported that runners maintained their running pattern in both shoe conditions and through the fatigue process. [71] It should be noted that this study was performed on a treadmill and running speed was controlled for individual subjects, but not across all subjects. Pollard et al. investigated changes in the maximalist running shoe when compared to a neutral shoe in a fatigued state and found that the maximalist shoe resulted in increased impact peaks and loading rates. [44] It should be noted that running speed was controlled for individual subjects, but not across all subjects. While these studies have reported useful results, there remains a lot of investigation that needs to be done to characterize the full kinetic and kinematic effects of various shoe types in a fatigued state. It is of particular interest to analyze how these changes may be beneficial or detrimental to the injury rate and progression of common running overuse injuries.

Tibial Stress Fractures

As mentioned previously, tibial stress fractures are among the ten most common running overuse injuries. [40] A stress fracture is the partial or complete fracture of a bone as a result of its inability to withstand repetitive or prolonged stresses and mechanical loading that results in structural fatigue. [34,77,78] Being the structural part of the body, the skeleton of an individual undergoes repetitive loading patterns based upon daily activities that they perform. These repetitive loading patterns result in small amounts of strain within the bone, on the order of 400-1500 microstrains, that are usually much lower than the ultimate tensile strain of bone, which is around 10,000 microstrains. [34] Despite being under the maximum strain, the bone will sustain a small amount of damage, referred to as microdamage, in a repetitive loading pattern with these straining conditions. [34,77] The reason for this is that bone is a viscoelastic material [79], and viscoelastic materials have a "memory"; this is described by Boltzmann Superposition Principle, which states that the stress-strain behavior of viscoelastic materials is a function of its entire loading history. [79,80] Simply put, each individual load put on the bone results in an independent and additive contribution to the bone's deformation. [79,80] Microdamage to the bone is not necessarily an undesirable occurrence though, as loading, straining, and damaging the bone is a natural part of bone remodeling. [34] The bone reformation process is displayed graphically below in Figure 2.4. [81]

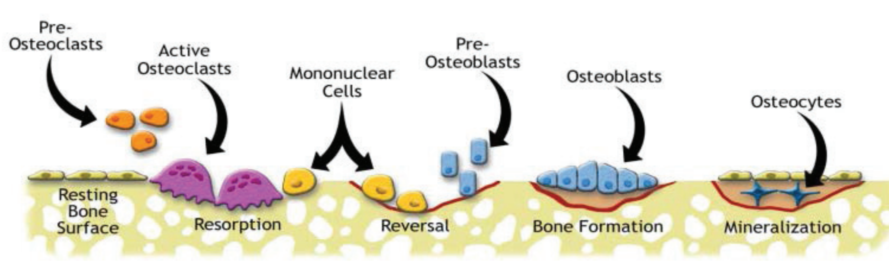

Figure 2.4: Graphical Representation of the Bone Remodeling Cycle [81]

A simplified description of the bone remodeling process is that osteoclasts resorb and remove damaged bone and osteoblasts subsequently replace it with new bone, that is stronger and denser, and these osteoblasts eventually mature into osteocytes. [77,79] Bone reformation is natural and healthy, as it allows for bones to adapt to mechanical loads that are imposed upon it to become stronger. [68,82] This phenomena can be described by Wolff's Law, which states that when the environmental loading on a bone is changed by trauma, pathology, or change in lifestyle, the bone remodels to counteract this new stress pattern. [82,83] Another describing principle was created by Carter et al., known as the stress stimulus equation, that shows that with increased tissue stress and strain there also comes an increase in bone growth. [84] The opposite holds true for this equation as well, where a decrease in daily stress and strain of the bone will result in increased resorption and a weakening of the bone. [84] This equation is shown in a simplified graphical form below in Figure 2.5. [85]

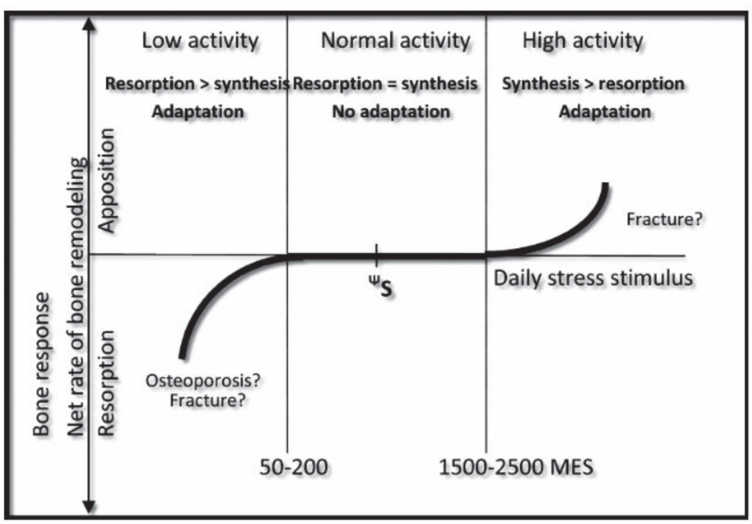

Figure 2.5: A simplified graphical presentation of Carter's Daily Stress Stimulus equation, displaying that decreased activity will result in increased bone resorption and increased activity will result in bone apposition.

Because of these principles, an increase in activity will allow for the growth of stronger and healthier bones and reduce the risk of osteoporosis, which can occur due to a sedentary lifestyle that results in increased osteolytic activity when compared to osteoblastic activity. [77,79] While bone reformation is healthy, there is a lag between increased osteoclastic activity and osteoblastic activity that results in the bone being in a weakened state, which may leave the bone susceptible to an accumulation of microdamage that can no longer be fixed by the bone remodeling process and eventually may lead to a stress fracture. [77] In order to reduce the risk of this common overuse injury, an understanding of their risk factors is necessary.

The risk factors for stress fractures are generally broken into either extrinsic or intrinsic risk factors. Extrinsic risk factors are factors that are external to the individual, such as equipment or environment, and intrinsic risk factors are internal to the individual, such as gender or age. Reported extrinsic factors that may result in an increased risk of tibial stress fractures include participation in exercise involving high magnitude loads and bursts [86], participation in exercise involving high load repetition resulting in cyclic overload [87], participation in an unfamiliar form of exercise that results in loads that your bones are unfamiliar with [88], running on an uneven and stiff surfaces [89–91], and footwear changes. [27,92] Reported intrinsic factors include the individual's bone mass, structure, and density [93], muscular fatigue status and strength [94], joint range of motion in order to propagate forces [95], physical fitness [96], gender (females are more susceptible) [77], and biomechanical factors such as vertical loading rate. [97] In our particular study, we are interested in being able to alter an individual's biomechanics, an intrinsic factor, by changing the individual's shoe, an extrinsic factor. Ideally, you would be able to study the direct effect of this change by limiting all other extrinsic and intrinsic factors so that the changed variables would be isolated. This is not always possible or realistic, particularly due to intrinsic factors, but reasonable measures should be taken by a researcher when possible.

In our study, we are focused on running overuse injuries, and the most common stress fracture for running injuries occur in the tibia. [40,78,98] This study is aimed to investigate how the changing of a runners shoe between two different extremes, minimalist and maximalist, will impact their risk factors for tibial stress fractures. As discussed, risk factors for stress fractures are based on mechanisms that result in microdamage to the bone.

The most commonly reported and measurable biomechanical variables that are risk factors for tibial stress fractures are the vertical ground reaction force, impact peak, and the instantaneous and average loading rates, which were displayed graphically in Figure 2.2. [33–35] This makes intuitive sense; the force the tibia receives will be directly related to the ground reaction force because the only joint absorbing force between the tibia and the ground is the ankle. The reason the impact force and peak ground reaction force are investigated are due to basic materials science and hooke's law with a stress strain curve; an increased force will result in an increased stress applied on the bone, both compressive and bending stresses. [79] The increased stress results in an increased strain of the bone, and this results in an increased amount of microdamage to the tibia, as discussed previously. [79] The reason we are interested in the impact peak and vertical loading rate, as opposed to just the peak force experienced, is due to the viscoelastic nature of bone. [34,79] Viscoelasticity is the study of a material that has both solid and fluid-like properties, and because of this these materials have properties that vary with time. [79,80] The important viscoelastic concept in order to understand the importance of the impact peak and loading rate is the dependence of viscoelastic materials on strain-rate. [80] An easy way to understand this principle is to visualize it with respect to silly putty. When silly putty is strained with a low strain rate, it behaves as a viscous material and with a very low modulus of elasticity. Conversely, when it is strained rapidly, it behaves as a more elastic material with an increased stiffness and fractures. [80] This easy to visualize example is displayed below in Figure 2.6. [99,100]

Figure 2.6: Silly putty exemplifying dependence of viscoelastic materials upon strain rate. The silly putty on the left was strained rapidly, resulting in elastic behavior and a low amount of strain before fracture. The silly putty on the right was strained slowly, resulting in viscous behavior and a large amount of strain before fracturing. [99,100]

Bone shows the same trend with changes in strain rate, although to a less extreme level. [79] With an increased strain rate, the bone will have a higher stiffness and behave as a more brittle material. [79] This dependence is shown in Figure 2.7 with actual plots of human bone strained at different rates. [101]

This increased strain rate results in the bone being more prone to microdamage. [34] The impact peak and loading rate have a direct effect on the strain rate because a larger impact peak and loading rate will result in a sharper increase in stress and a sharper increase in strain rate. Because of this, methods to reduce the injury risk of tibial stress fractures should at least consider reducing the impact peak and loading rate of the vertical ground reaction force.

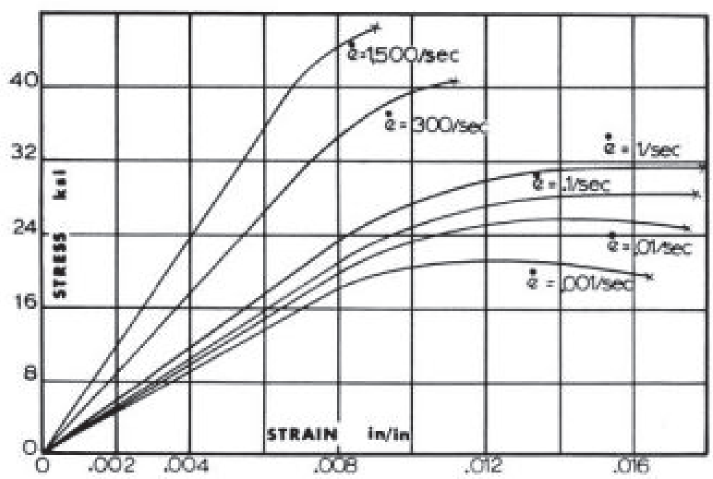

Figure 2.7: Stress-Strain curves of human bone strained at different strain-rates, performed by McElhaney. [101] It is observed that at a higher strain-rate, the bone fractures with a reduced ultimate strain and behaves more similarly to a stiff elastic material.

Another reported injury mechanism of tibial stress fractures is excessive rear foot eversion and eversion velocity. This is due to excessive eversion causing earlier onset of muscular fatigue. [51] As mentioned earlier, muscular fatigue status is an intrinsic risk factor for stress fractures because muscles and tendons are designed, in part, to protect bones by increasing shock attenuation of loads and absorb loads. [34,94] Muscular fatigue has been shown to result in increased strain rate for *in vivo* studies of both humans and dogs. [94,102,103] Because of this injury mechanism, methods to reduce the injury risk of tibial stress fractures in running should be aimed at controlling excessive eversion and eversion velocity in order to reduce muscular fatigue. Additionally, eversion results in a more horizontal alignment of the tibia, which is observed in Figure 2.3, and this alignment results in increased bending stress on the bone.

An additional reported injury mechanism associated with tibial stress fractures is malalignment at the hip and knee of the runner. [104] Milner et al. found that hip and knee abduction angles were significantly higher in runners with a history of tibial stress fractures, likely due to it increasing the bending stress put upon the tibia. [104] Bone is known to be much stronger in compression than in tension, by a factor of about 2 and this is displayed in Figure 2.8, [105] and the increased abduction of the hip and knee will result in increased tensile stress on the bone. [51]

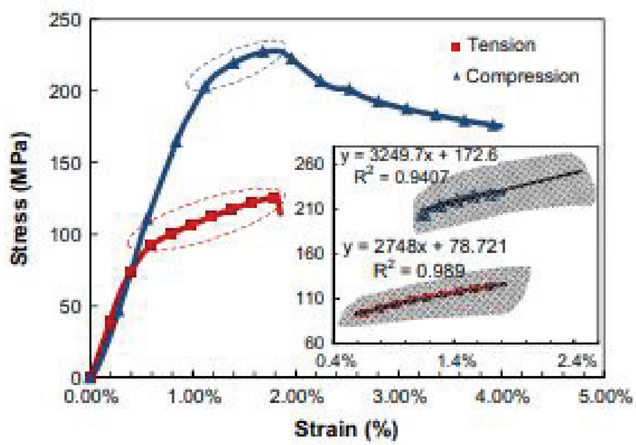

Figure 2.8: Bone displays around twice the ultimate strength in compression when compared to tension. [105]

Additionally, bone tissue is often exposed to torsional loading patterns, which results in shear stresses as well as tensile and compressive stresses. [106] Because bone is generally weak in shear and tension, torsional forces play a key factor in the pathology of stress fractures as well. [106] This mechanism is generally represented by the increased tibial stress fracture risk observed with an increased free moment [51,107] and hip external rotation. [108,109] An increase in free moment, which is the ground reaction torque along the vertical axis, or hip external rotation results in increased torsion of the leg. For these reasons, methods to reduce the injury risk of tibial stress fractures in running should be aimed at reducing the free moment and external rotation of the hip.

A final injury mechanism that is investigated in this study is the detrimental effect of restricting and reducing joint range of motion. A reduced range of motion of the lower body results in poor force attenuation by the leg, which in turn results in increased loading on the bones. [34,110] Seliktar et al. studied a group of patients who underwent a surgery that restricted the range of motion of the ankle joint, and found that this resulted in increased bone strain. [110] This injury mechanism is frequently represented by leg stiffness [34,35], which models the leg as a spring and is directly related to the leg's shock attenuation by bending. [91] This idea of modeling of the leg as a spring is displayed in Figure 2.9. [91]

Increased leg stiffness results in less shock attenuation and has been associated with an increased risk of tibial stress fractures. [51] Because of the mechanisms discussed, methods to reduce incidence of tibial stress fractures should be aimed at reducing leg stiffness.

As discussed, tibial stress fractures are a common overuse injury and injury mechanisms of interest for this study include increased vertical impact peaks, loading rates, eversion angles and velocity, hip external rotation angles, hip and knee abduction, free moments, and leg stiffness. These variables and their references are displayed below in Table 2.1.

Table 2.1: Tibial stress fracture risk factors and the corresponding references for each individual risk factor.

Risk Factor	References
Vertical Impact Peaks and Loading Rates	[29-31]
Eversion Angles and Velocity	[30,47]
Hip External Rotation Angles	[104,105]
Hip and Knee Abduction	[100]
Free Moments	[47,103]
Leg Stiffness	[30,31,106]

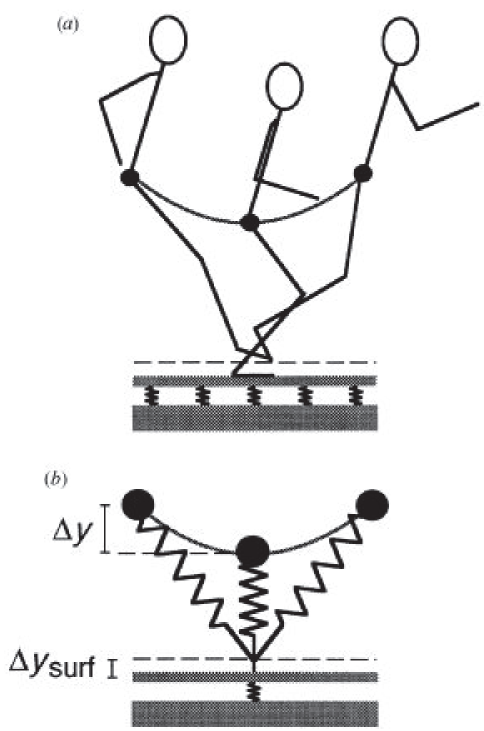

Figure 2.9: The representation of the leg as a spring that compresses during stance phase in order to attenuate shock. [91]

Patellofemoral Pain Syndrome

Patellofemoral pain syndrome is the most common running overuse injury and has been for over twenty years. [40] The patellofemoral joint itself consists of the patella, the distal and anterior parts of the femur, articular surfaces, and some surrounding supporting structures. [111] This patellofemoral joint and the location of the pain is shown below in Figure 2.10. [112]

Patellofemoral pain syndrome is an ambiguous way to describe pain in the anterior part of the knee and the term syndrome is used to encompass all signs and symptoms that occur and characterize this abnormality. [111]

Figure 2.10: The patellofemoral joint, consisting of the head of the femur, the patella, and surrounding articular cartilage. Patellofemoral Pain is occurring in the contact area between the head of the femur and the patella. [112]

Patellofemoral pain syndrome is difficult to define because a variety of symptoms can be associated with pain in the anterior part of the knee. Despite this ambiguity, most investigators agree that the injury mechanism for patellofemoral pain is, at least in part, due to flawed lower limb mechanics. [113] While there is not an established and agreed upon causality to patellofemoral pain, it is frequently reported to be due to increased contact forces between the patella and the distal end of the femur during activities such as climbing, squatting, running, and prolonged sitting, which was highlighted in Figure 2.10. [114,115] This increased, repetitive contact force can result in damage to the articular cartilage and result in pain in the exposed and innervated subchondral bone. [111,116,117] From this, it is of interest to researchers how it may be possible to alter a person's biomechanics in order to reduce their injury risk for patellofemoral pain.

While the patellofemoral joint is a part of the knee, proximal factors at the pelvis and hip are commonly reported because they influence the femur. One reported factor is weakness of hip abductor and external rotator muscle groups, which generally act to control excessive hip adduction and hip internal rotation during running. [115,118,119] Patients who are prone to patellofemoral pain syndrome typically display increased hip internal rotation and adduction. [120] Additionally, pelvic drop is a frequently reported risk factor for patellofemoral pain because it is a clinical sign of decreased hip abductor strength and activation and correlates with an increased hip adduction and rotation. [121] Pelvic drop is when the runner swings their hip excessively in the frontal plane, and is shown graphically in Figure 2.11. [122]

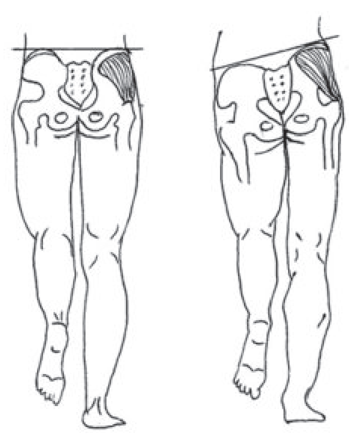

Figure 2.11: A graphical description of pelvic drop. [122] The runner on the right displays excessive pelvic drop while the runner on the left is running with a level pelvis.

The effect of this increased hip adduction and rotation has been studied in cadaveric studies. Huberti et al. performed a cadaveric study where they altered the q-angle during regular knee flexion and showed that increasing the hip adduction angle results in a 45% increase in peak pressures on the patella and thus significantly increases the contact forces between the patella and femur. [123] In a similar cadaveric study by Li et al., cadaveric knee specimens were flexed at varying angles and it was observed that an increased internal rotation of the hip and external rotation of the tibia resulted in increased contact pressure and forces between the patella and femur. [76] Li et al.'s results are displayed in a graphic representation in Figure 2.12. [76]

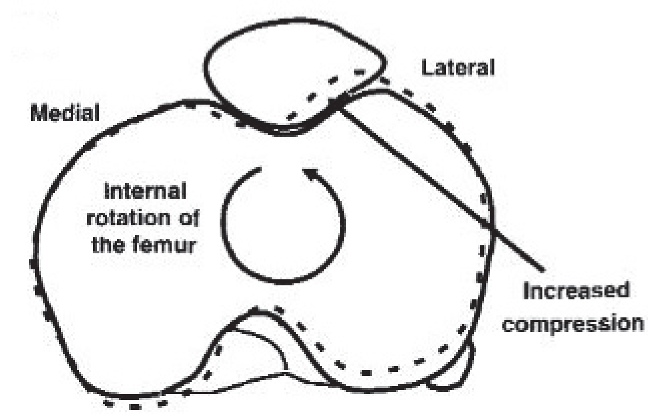

Figure 2.12: Li et al. found that increased internal hip rotation resulted in an increased contact force between the head of the femur and the patella. [76]

Both of these studies utilized cadaveric knee specimens and pressure sensors to measure changes in contact pressures between the head of the femur and patella, giving very useful insight into the mechanisms that result in patellofemoral pain. For the discussed reasons, it is recommended that intervention techniques to reduce the incidence of patellofemoral pain syndrome should be aimed at reducing excessive pelvic drop as well as internal hip rotation and adduction.

In addition to proximal injury mechanisms for patellofemoral pain syndrome, there are also associated risk factors distal to and at the knee joint. Knee valgus, has been shown to increase the lateral force acting on the patella which is attributed to both an increased hip adduction as well as an increased knee abduction. [115,124] Knee valgus is displayed in Figure 2.13 along with its associated characteristics. [125]

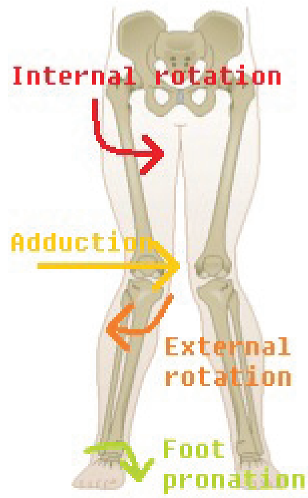

Figure 2.13: An image of the human lower body with knee valgus, with associated characteristics of hip internal rotation and adduction, knee external rotation and abduction, and eversion and external rotation. [125]

It is for this reason that researchers have associated excessive ankle eversion as a risk factor for patellofemoral pain, because knee valgus is common in people who have an increased eversion due to an increased medial displacement of the foot. [115,126] Based on this logical flow, the chain follows from ankle eversion increases the amount of knee abduction due to the medial displacement of the foot, and this in turn results in increased knee valgus. Increased knee valgus results in increased lateral contact forces between the patella and head of the femur, resulting in patellofemoral pain syndrome.

[124] Because of this injury mechanism, researchers should be focused on interventions that result in a decrease in excessive ankle eversion and knee abduction.

As discussed, patellofemoral pain syndrome is the most common overuse injury reported in running and injury mechanisms of interest for this study include increased hip internal rotation and adduction, pelvic drop, ankle eversion, and knee abduction.

Table 2.2: Patellofemoral Pain Syndrome Risk Factors and the corresponding references for each individual risk factor.

Risk Factor	References
Pelvic Drop	[117]
Hip Internal Rotation and Adduction	[72,111,114,115,119]
Knee Abduction	[111,120]
Ankle Eversion	[111,122]

Purpose

The purpose of this study was to compare the complete effect of maximalist shoes versus minimalist shoes on the kinetics and kinematics of the lower body of a fatigued runner. While similar studies exist, no previous studies have directly compared minimalist and maximalist shoes in a fatigued state. The most similar study to the one outlined in this thesis is a study performed by Pollard et al. that compared maximalist shoes to neutral shoes after running a 5 km run. [44] Our study is a step further than their study because they only reported vertical ground reaction and rear foot eversion changes between the shoes. [44] Additionally, they only controlled the speed of individual subjects instead of across all subjects, which has a direct impact upon vertical ground reaction forces. Finally, they did not acclimatize their subjects to over ground running after fatiguing, which allows for induced changes from treadmill running to be misinterpreted as fatigue changes. This possibility will be covered in the next chapter of this thesis. For these reasons, this thesis is a unique and powerful step forward in characterizing the effects of minimalist and maximalist shoes. This study provides a full characterization of kinematic and kinetic differences between maximalist and minimalist shoes that occur in a fatigued runner.

Hypothesis

Runners were tested before and after a fatigue protocol in both maximalist and minimalist shoes. It is hypothesized that the minimalist shoes will result in a reduction of ground reaction variables because that is their most commonly reported benefit. It is also hypothesized that the maximalist shoes will result in reduced ankle eversion and range of motion, due to their motion control technology. The maximalist shoes are also expected to reduce the plantar-flexion moment due to the rocker characteristics of the shoe.

Procedures and Methodology

All methods and analysis techniques are consistent with the ones outlined in Chapter One. The information below describes procedures and methodologies unique to this study.

Participants

A total of 12 participants were collected during this study. Of the 12 subjects, 4 of the participants were analyzed separately because they exhibited a forefoot strike pattern; a future study will expand this group and analyze. This resulted in 8 total subjects being investigated and analyzed. Strike pattern was analyzed post hoc using high speed video as well as dorsi-flexion angle at foot strike. Rear foot strikers that were analyzed maintained their strike pattern in both shoes and in both the pre-fatigue running condition as well as the fatigued running condition. Rear foot strikers were decided to be the focus of this study because an estimated 90% of recreational runners have a rearfoot strike pattern. [127] Subjects were also all male, and this was controlled due to reported differences in running and walking between males and females and because males have been studied less frequently in this particular research area. [128,129] Additional inclusion criteria were that subjects were within 18 and 55 years of age, had a BMI less than 30, ran at least one mile at least twice a week, and were able to complete a 5k fatigue run in less than a 12 min/mile pace, did not have any recent lower limb injuries or surgeries, and had shoe sizes consistent with the shoes that were available. Extended demographics are shown in Table 2.3. All participants signed an informed consent document that was approved by the Baylor Internal Review Board (IRB) on their first day of testing.

Table 2.3: Extended subject demographics. Standard deviation is included in parenthesis next to each value.

Demographic	Value
Age (years of age)	23.3 (2.3)
Height (cm)	178.1 (4.3)
Mass (kg)	71.6 (7.3)
Body-Mass-Index (kg/m^2)	22.6 (2.0)

Methods and Protocol

Subjects came to the BioMotion Lab for two separate sessions, spaced at least one week apart. For each individual session, the subject would wear either the minimalist (Nike Free) shoe shown in Figure 2.14 or the maximalist (Hoka One One Bondi 5) shoe shown in Figure 2.15. [130,131]

The Nike Free has a weight of 7.8 ounces and a heel-toe drop of 8 mm. [130] The Hoka One One Bondi 5 has a weight of 10 ounces and a heel-toe drop of 4 mm. [43] The initial shoe condition was randomized for each subject using a coin flip, where heads would result in the subject running in the maximalist shoe for their first session. The procedure and protocol was the same for both testing sessions, the only change being the shoe condition.

After the calibration trial described in Chapter One, subjects were tested along the runway at a 3.35 m/s ± 10 % pace (8 min/mile) prior to being fatigued (Pre-Fatigue condition). The speed was controlled to ensure that observed shoe and fatigue differences were not misinterpreted as the changes that can be induced by a change in speed. The subject was tested until they had completed five trials where the subject cleanly landed with their dominant foot on one of the force plates. The subjects were then asked to complete a 5k (3.1 mi) fatigue run on a treadmill inside the lab. The subject was allowed to run the 5k at whatever pace was comfortable with them, as long as it was faster than a pace of 12 min/mile.

Figure 2.14: The minimalist shoe used in this study, the Nike Free [130]

Figure 2.15: The maximalist shoe used in this study, the Hoka One One Bondi 5 [131]

To ensure fatigue, the subject was not allowed to stop running until they ran the 5k and satisfied one of two additional criteria. These criteria were that they either had reached 85% of their max heart rate based upon the age based max heart rate equation, or they had reached a 17 on the Borg Scale of Exertion shown below in Fig. 2.16. [132] The max heart rate was determined using the age-based estimated maximal heart rate, which is found by subtracting the individual subject's age from 220. [133] In the case that they did not meet one of the aforementioned conditions, the subjects pace was increased by 1 km/hr every two minutes until one of the criteria were reached. These additional criteria are consistent with previous fatigue studies [60,66,70,72], but it was decided to add the 5k distance run to increase the likelihood muscular fatigue as well as cardiovascular fatigue.

Rating	Perceived Exertion
6	No exertion
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 2.16: The Borg scale of perceived exertion [132]

The subjects were again tested immediately after completing the fatigue run and getting off the treadmill (Post-Immediate condition). These trials are not analyzed in this chapter, but will be the focus in Chapter Three of this thesis. The subject was again tested until five successful trials were completed. Immediately following these trials, as to not let the runner recover, the subject was instructed to run over ground in a provided space for 5 minutes in order to acclimatize to over ground running and reduce any influence from the treadmill running. This was done to avoid misinterpreting reported differences in treadmill running versus over ground running as results of fatigue. [89,91,134–136] After acclimatizing to over ground running, the subjects were tested a final time (Post-Fatigue condition). The Post-Fatigue and Pre-Fatigue conditions are the conditions analyzed within this chapter. The subject was tested until they had completed five trials where the subject cleanly landed with their dominant foot on one of the force plates.

Results

Pre-Fatigue Condition Results

The Pre-Fatigue sagittal plane kinematics and kinetics are plotted below in Figure 2.17. The peak flexion and extension values from these plots are shown numerically in Table 2.4. It should be noted that all plots are normalized to stance phase, and that the minimalist shoes generally had a reduced time of stance phase. The plots all have an area in early stance phase, around 25% of stance phase, boxed in order to highlight that the maximalist shoes appeared to have an effect at this point in stance phase in particular. It did not have this effect strongly in the sagittal plane, but more in the frontal and transverse planes.

In the sagittal plane, the ankle experienced a sustained decrease in the ankle dorsi-flexion moment with a peak difference of 1.4 percent of the subject's bodyweight multiplied by their height (%BW*H). Overall, there were no real differences seen in the sagittal plane.

The Pre-Fatigue frontal plane kinematics and kinetics are plotted below in Figure 2.18. The peak adduction and abduction values from these plots are shown numerically in Table 2.5. Within the frontal plane kinematics of the Pre-Fatigue results, the maximalist shoes resulted in a 1.2 degree increase in peak pelvic drop, a 2.0 degree decrease in peak knee abduction, and a 1.3 degree decrease in ankle eversion. For the ankle, there was also a 0.5 %BW*H reduction in the peak inversion moment for the maximalist shoes. There was also a decrease in knee adduction for the maximalist shoes of 2.2 degrees, showing that the knee range of motion in the frontal plane was not significantly higher when compared to the minimalist shoes. For the kinetics of the Pre-Fatigue results, the only change worth noting was a 0.5 %BW*H decrease in the ankle inversion moment.

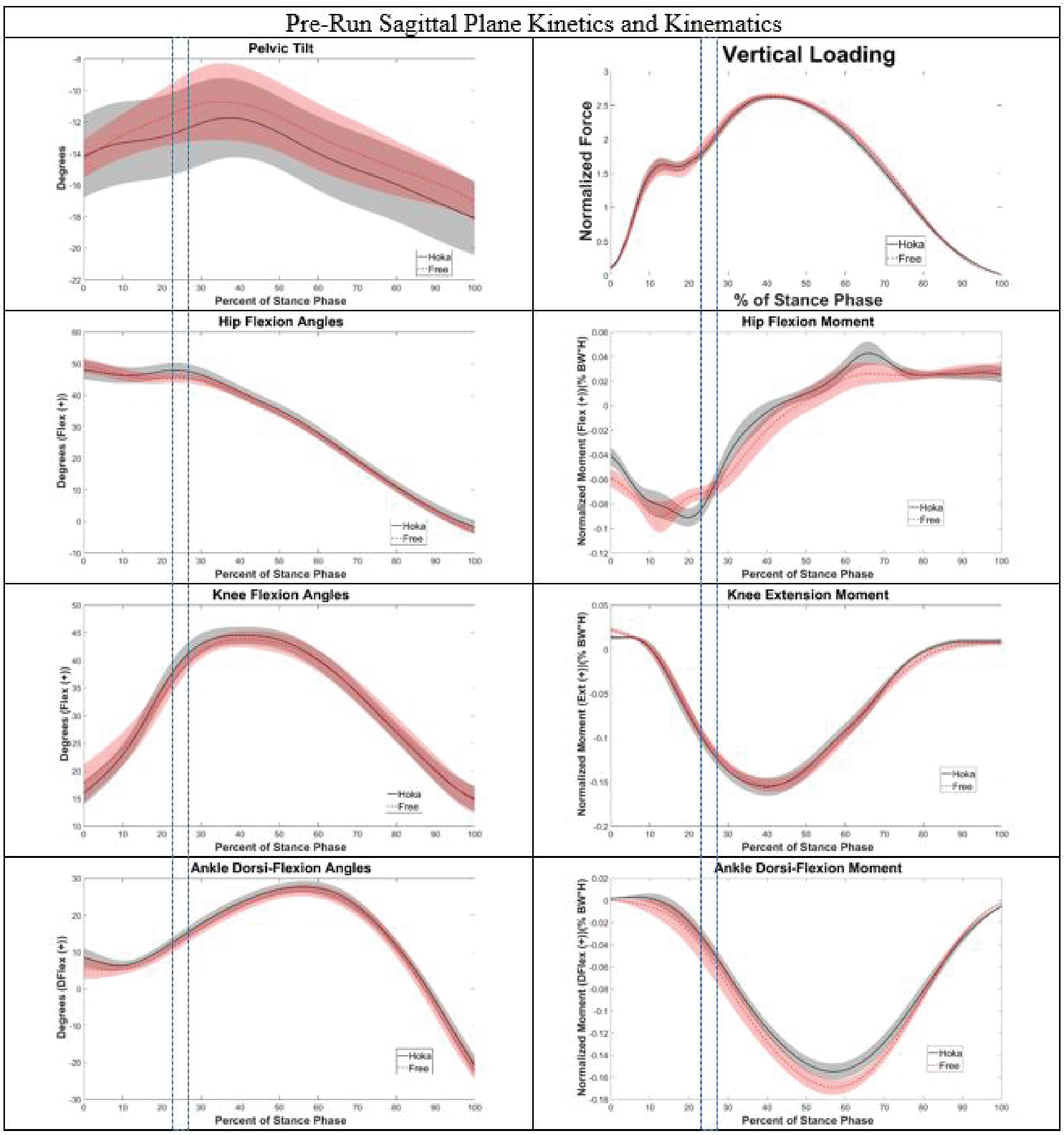

Figure 2.17: Sagittal Plane Kinematics and Kinetics for the Pre-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase.

Table 2.4: Peak flexion and extension moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Flexion (Degrees)	Peak Extension (Degrees)	Peak Flexion Moment (%BW*H)	Peak Extension Moment (%BW*H)
Pelvis	Free	9.7 (1.9)	17.8 (1.4)		
	Hoka	10.9 (1.3)	7.7 (0.5)		
	P-Value	0.69	0.82		
Hip	Free	50.2 (2.0)	3.0 (1.1)	4.1 (0.6)	10.3 (0.8)
	Hoka	49.8 (2.3)	1.8 (2.2)	5.1 (0.8)	9.9 (0.6)
	P-Value	0.85	0.55	0.28	0.52
Knee	Free	44.2 (1.5)	-12.1 (2.6)	15.5 (0.7)	2.3 (0.3)
	Hoka	44.9 (1.6)	-13.1 (2.2)	15.7 (1.0)	1.9 (0.2)
	P-Value	0.58	0.58	0.85	0.08
Ankle	Free	26.9 (1.6)	21.9 (2.6)	0.7 (0.3)	17.0 (0.7)
	Hoka	28.0 (1.7)	20.8 (2.8)	0.7 (0.2)	15.6 (0.7)
	P-Value	0.16	0.3	0.11	0.95

For the ankle, there was also a 0.5 %BW*H reduction in the peak inversion moment for the maximalist shoes. There was also a decrease in knee adduction for the maximalist shoes of 2.2 degrees, showing that the knee range of motion in the frontal plane was not significantly higher when compared to the minimalist shoes. For the kinetics of the Pre-Fatigue results, the only change worth noting was a 0.5 %BW*H decrease in the ankle inversion moment.

Around 25 % of stance phase, the maximalist shoes show a slight decrease in the hip abduction moment and eversion moment. This is observed to result in a reduced eversion, an increased pelvic drop, and increased knee adduction.

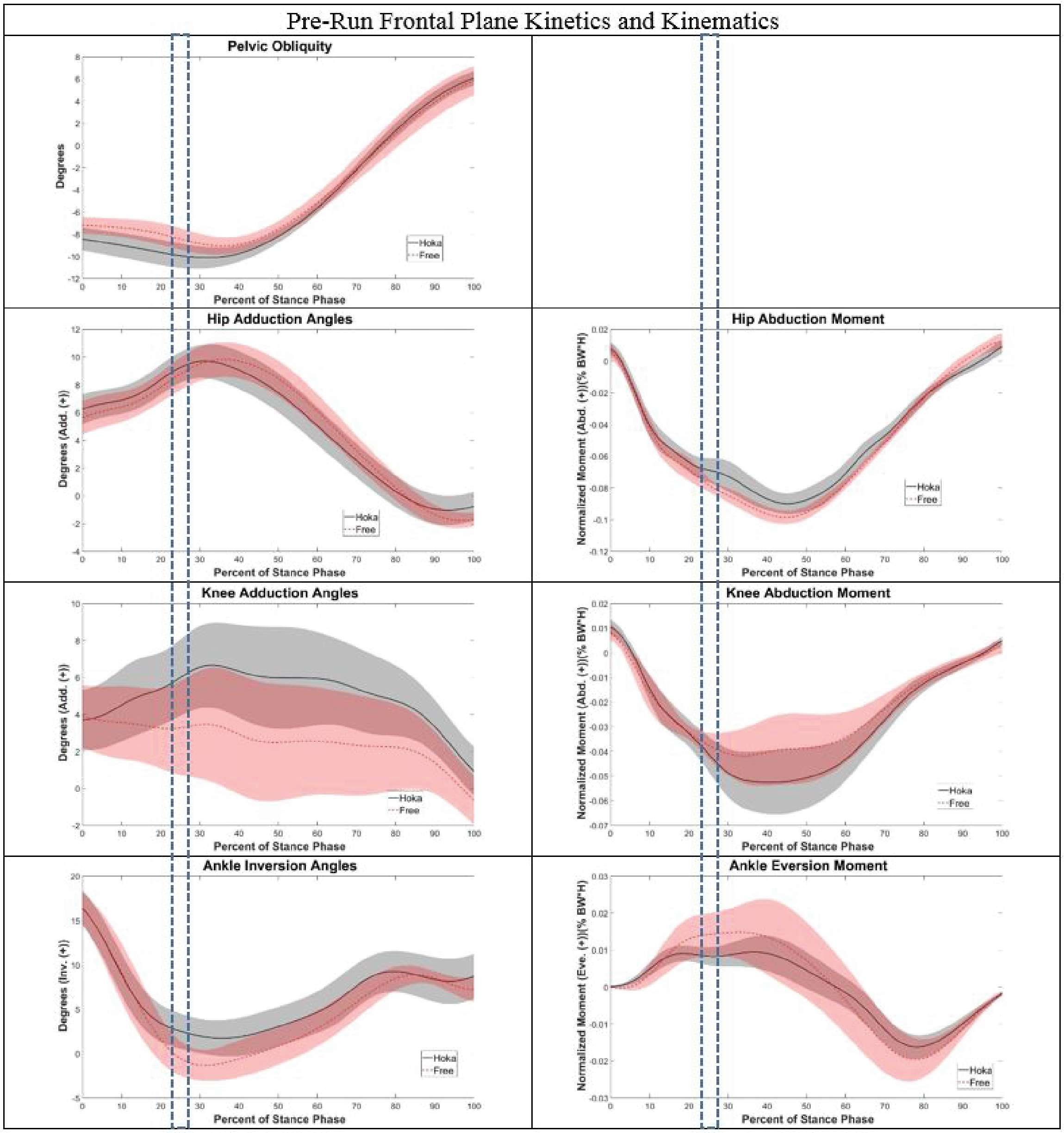

Figure 2.18: Frontal Plane Kinematics and Kinetics for the Pre-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase, since changes were seen in this region for the maximalist shoes in the frontal and transverse planes. They are included here for easy comparison across planes.

The Pre-Fatigue transverse plane kinematics and kinetics are plotted below in Figure 2.19. The peak external rotation and internal rotation values from these plots are shown numerically in Table 2.6.

Table 2.5: Peak adduction and abduction moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Adduction (Degrees)	Peak Abduction (Degrees)	Peak Adduction Moment (%BW*H)	Peak Abduction Moment (%BW*H)
Pelvis	Free	5.8 (1.3)	9.3 (0.8)		
	Hoka	6.1 (0.6)	10.5 (1.0)		
	P-Value	0.35	0.24		
Hip	Free	10.5 (1.1)	2.0 (0.5)	10.3 (0.4)	1.9 (0.4)
	Hoka	10.1 (1.3)	1.4 (1.0)	9.4 (0.6)	1.7 (0.3)
	P-Value	0.69	0.36	0.32	0.71
Knee	Free	6.4 (2.2)	2.1 (2.2)	5.5 (0.9)	1.2 (0.3)
	Hoka	9.0 (2.1)	-0.1 (1.6)	6.0 (1.1)	1.2 (0.3)
	P-Value	0.27	0.07	0.61	0.93
Ankle	Free	16.9 (1.6)	2.0 (1.9)	2.2 (0.7)	2.0 (0.9)
	Hoka	16.9 (1.8)	0.7 (2.1)	1.7 (0.3)	1.4 (0.4)
	P-Value	0.99	0.19	0.09	0.39

Within the transverse plane kinematics of the Pre-Fatigue results, the maximalist shoes resulted in a significant and sustained increase in internal hip rotation with a peak difference of 5.6 degrees. It also resulted in a decrease of peak hip external rotation by 5.2 degrees, meaning that it was a sustained increase in internal rotation that did not significantly alter the hip rotation range of motion. These result is fairly significant and is clinically relevant. Conversely, the maximalist shoes resulted in a sustained and significant decrease in internal ankle rotation with a peak difference of 5.7 degrees, which is a clinically relevant result. This change corresponded to a 3.7 degree increase in ankle external rotation, but still resulted in an increased external rotation throughout stance phase.

The free moment curve is observed to have a gradual rise and even levels out momentarily at 25% of stance phase. This result appeared in the kinetics, where a reduced ankle external rotation moment and hip internal rotation moment were seen at 25 % of stance phase as well. This corresponded on the kinematic graphs with the maximalist shoes displaying increased pelvic rotation, hip internal rotation, and ankle rotation, particularly at 25% of stance phase.

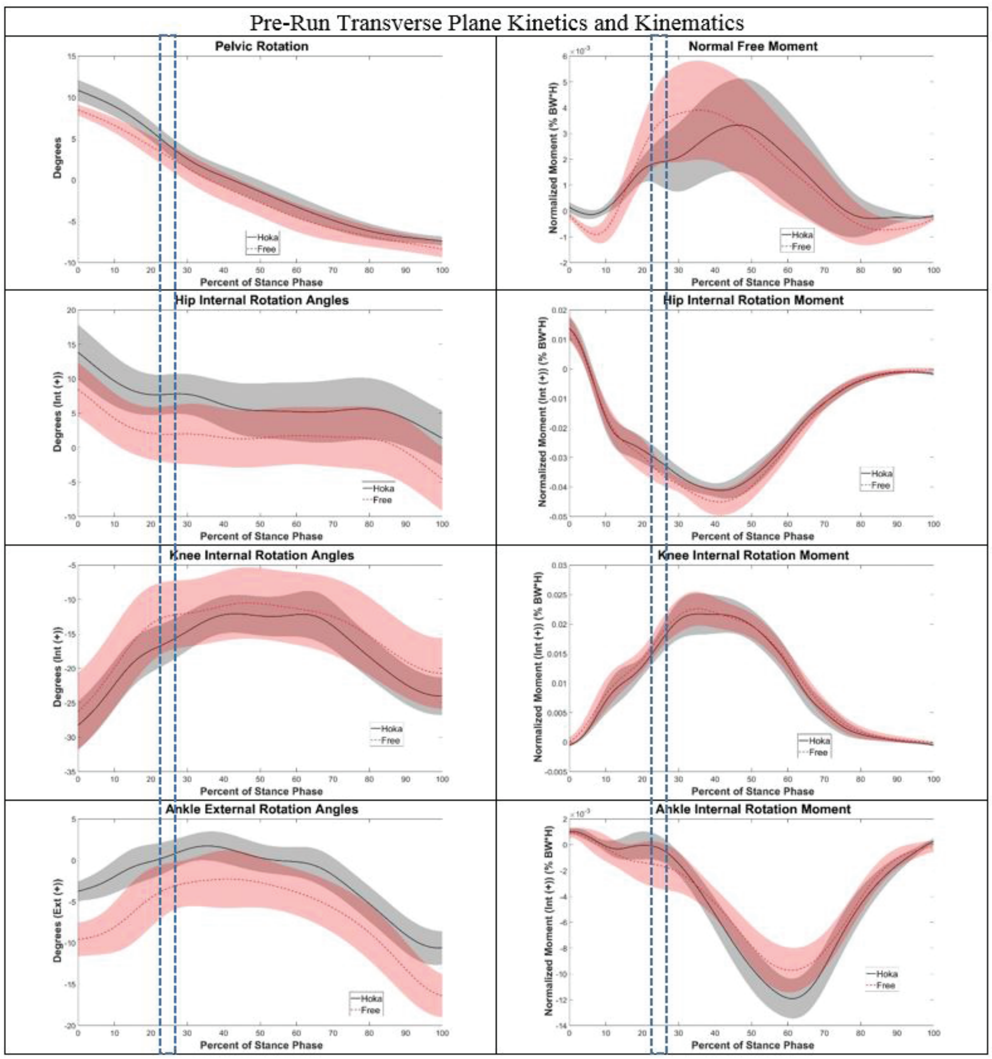

Figure 2.19: Transverse Plane Kinematics and Kinetics for the Pre-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase.

Table 2.6: Peak internal rotation and external rotation moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Internal Rotation (Degrees)	Peak External Rotation (Degrees)	Peak Internal Rotation Moment (%BW*H)	Peak External Rotation Moment (%BW*H)
Pelvis	Free	8.5 (0.6)	8.5 (1.0)		
	Hoka	10.9 (1.3)	7.7 (0.5)		
	P-Value	0.21	0.52		
Hip	Free	9.1 (3.8)	4.7 (4.6)	1.4 (0.4)	4.8 (0.4)
	Hoka	14.7 (3.7)	-0.5 (4.2)	1.4 (0.4)	4.4 (0.3)
	P-Value	0.05*	0.07	0.97	0.52
Knee	Free	-8.9 (5.2)	26.9 (5.4)	2.3 (0.3)	0.1 (0.1)
	Hoka	-10.2 (3.2)	28.9 (3.3)	2.3 (0.4)	0.2 (0.03)
	P-Value	0.58	0.49	0.83	0.75
Ankle	Free	16.5 (2.6)	-1.0 (3.3)	0.3 (0.03)	1.1 (0.1)
	Hoka	10.8 (2.0)	2.7 (1.9)	0.2 (0.1)	1.3 (0.2)
	P-Value	0.05*	0.12	0.58	0.65

The Pre-Fatigue vertical ground reaction data as well as the peak free moment data are shown below numerically in Table 2.7. The plots were included in the previous figures. There was no significant change in the force plate data in the Pre-Fatigue condition results, although the maximalist shoes were shown to increase the vertical impact peak slightly. Additionally, there were no significant differences in the peak free moment, but it should be noted that the rate of increase in the free moment was much more gradual in the maximalist shoes when compared to the minimalist shoes.

Additional variables of interest that were investigated include leg stiffness and eversion velocity, which are shown below in Table 2.8. There was a 365 kN/m decrease in leg stiffness for the maximalist shoes and a substantial reduction in average eversion velocity with a decrease of 114.4 degrees per second.

Table 2.7: Vertical Ground Reaction Force (VGRF), Vertical Impact Peak (VIP), Vertical Average Loading Rate (VALR), Vertical Instantaneous Loading Rate (VILR), the peak free moment, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Condition	VGRF (N/BW)	VIP (N/BW)	VALR (N/BW*s)	VILR (N/BW*s)	Free Moment (%BW*H)
Free	2.66 (0.05)	1.59 (0.16)	68.99 (8.94)	114.07 (9.61)	0.55 (0.14)
Hoka	2.66 (0.04)	1.68 (0.11)	70.18 (11.14)	113.21 (8.57)	0.45 (0.13)
P-Value	0.98	0.34	0.85	0.91	0.36

Table 2.8: Leg stiffness, average eversion velocity, maximum eversion velocity, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Condition	Leg Stiffness (N/m)	Average Eversion Velocity (°/s)	Max Eversion Velocity (°/s)
Free	8571 (317)	355.6 (41.1)	590.3 (65.1)
Hoka	8206 (299)	241.2 (38.0)	444.2 (65.1)
P-Value	0.17	0.06	0.17

In summary, the primary results for Pre-Fatigue are that the maximalist shoes resulted in a slight reduction of the plantar-flexion moment, a sustained reduction of knee abduction, a reduction of peak ankle eversion and eversion velocity, a sustained increase in hip internal rotation, and a sustained increase in ankle external rotation.

Post-Fatigue Results

The Post-Fatigue sagittal plane kinematics and kinetics are plotted below in Figure 2.20. The peak flexion and extension values from these plots are shown numerically in Table 2.9. Once again, all plots are normalized to stance phase, and it should be noted that the minimalist shoes generally had a reduced time of stance phase. The plots all have an area in early stance phase, around 25% of stance phase, boxed in order to highlight that the maximalist shoes appeared to have an effect at this point in stance phase in particular. It did not have this effect strongly in the sagittal plane, but more in the frontal and transverse plane.

In the kinematics in the sagittal plane, the maximalist shoes resulted in a 1.9 degree increase in hip extension during stance phase as well as an overall sustained increase in hip extension, which did not occur in the Pre-Fatigue condition. Also, the peak ankle dorsi-flexion angles were no longer different between the two shoe conditions, but instead there was of increase of 1.5 degrees of plantar-flexion for the maximalist shoes. For the kinetics, there was a 1.0 %BW*H reduction in the peak hip extension moment at early stance that also did not occur prior to the fatigue protocol. Additionally, there was not as significant of a decrease in the peak plantar-flexion moment for the maximalist shoes when compared to the change that was seen in the Pre-Fatigue condition.

The Post-Fatigue frontal plane kinematics and kinetics are plotted below in Figure 2.21. The peak adduction and abduction values from these plots are shown numerically in Table 2.10. Within the frontal plane kinematics of the Post-Fatigue results, the maximalist maintained their increase in pelvic drop that was seen in the Pre-Fatigue condition, but also resulted in a greater pelvic height at the start of stance phase. This means that the pelvic range of motion in the frontal plane was significantly greater for the maximalist shoes when compared to the minimalist shoes.

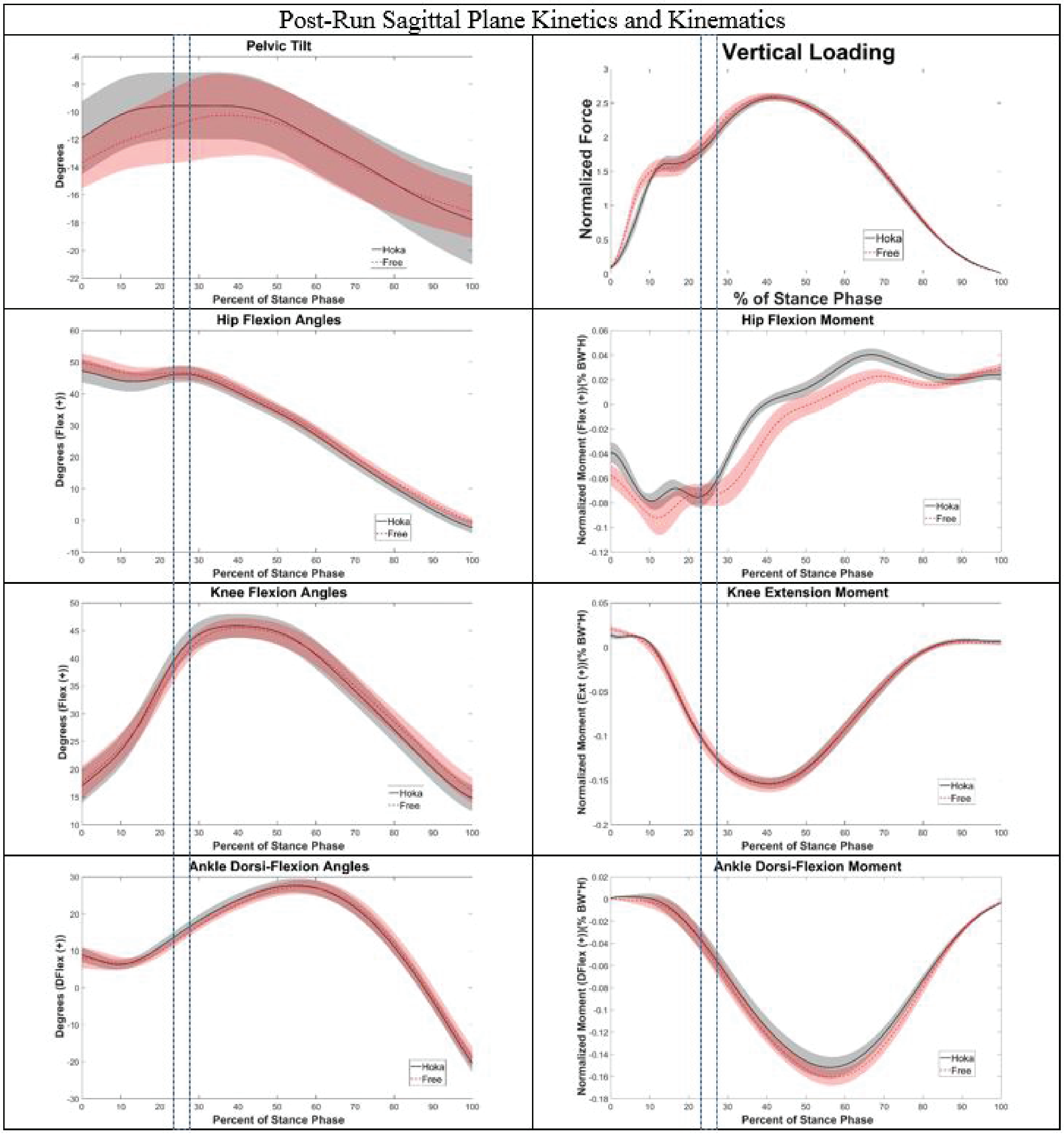

Figure 2.20: Sagittal Plane Kinematics and Kinetics for the Post-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase.

Additionally, there was still an increase in knee adduction of 2.2 degrees and a reduction in knee abduction of 1.8 degrees, showing the same trend in the frontal plane that was observed in the Pre-Fatigue condition.

Table 2.9: Peak flexion and extension moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Post-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Flexion (Degrees)	Peak Extension (Degrees)	Peak Flexion Moment (%BW*H)	Peak Extension Moment (%BW*H)
Pelvis	Free	8.9 (2.2)	17.9 (2.1)		
	Hoka	8.6 (2.5)	18.1 (3.1)		
	P-Value	0.93	0.96		
Hip	Free	51.0 (2.5)	0.4 (1.3)	3.7 (0.7)	10.6 (0.7)
	Hoka	48.8 (3.2)	2.3 (1.7)	4.3 (0.5)	9.6 (0.4)
	P-Value	0.36	0.24	0.25	0.05*
Knee	Free	45.8 (1.8)	-14.5 (2.5)	15.7 (0.9)	2.1 (0.3)
	Hoka	46.0 (2.2)	-13.4 (2.4)	15.5 (0.6)	1.8 (0.3)
	P-Value	0.74	0.39	0.81	0.34
Ankle	Free	27.4 (1.9)	18.9 (2.8)	0.6 (0.3)	16.2 (0.7)
	Hoka	27.8 (1.9)	20.4 (2.5)	0.7 (0.2)	15.2 (1.0)
	P-Value	0.73	0.21	0.65	0.3

The ankle peak eversion reduction was maintained in the maximalist shoes with a reduction of 2.0 degrees and corresponded to a 0.6 %BW*H reduction in the peak inversion moment. For kinetic differences, a significant difference in peak hip adduction moment that was not present in the Pre-Fatigue condition was present in the Post-Fatigue, with a difference of 1.2 %BW*H. The reduction of peak inversion moment at the ankle was maintained in the Post-Fatigue condition with a decrease of 0.6 %BW*H.

Similar to what was observed in the Pre-Fatigue condition, there were differences seen in the maximalist shoes at 25 % of stance phase. For the kinetics, there was a reduced slope seen in each joint at 25 % of stance phase. In the kinematics, there was an increased pelvic drop, hip adduction, knee adduction, and ankle eversion. The knee adduction curve had a brief decrease at 25% of stance phase that corresponded to the kinetic curve.

The Post-Fatigue transverse plane kinematics and kinetics are plotted below in Figure 2.22. The peak external rotation and internal rotation values from these plots are shown numerically in Table 2.11.

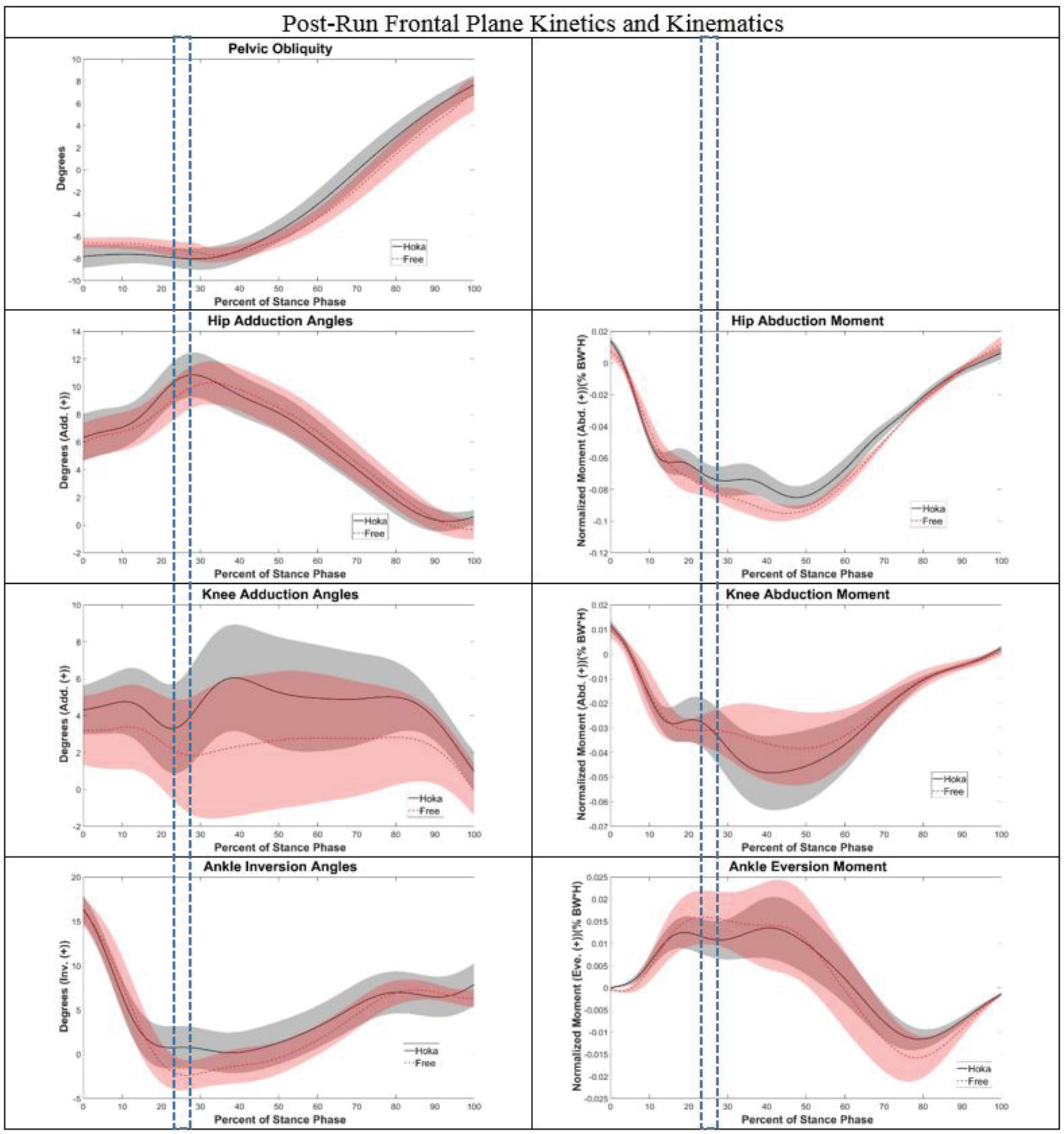

Figure 2.21: Frontal Plane Kinematics and Kinetics for the Post-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase.

Table 2.10: Peak adduction and abduction moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Post-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Adduction (Degrees)	Peak Abduction (Degrees)	Peak Adduction Moment (%BW*H)	Peak Abduction Moment (%BW*H)
Pelvis	Free	6.7 (1.4)	8.2 (0.5)		
	Hoka	7.7 (0.9)	9.5 (0.8)		
	P-Value	0.19	0.33		
Hip	Free	10.8 (1.5)	0.8 (0.8)	10.2 (0.5)	1.9 (0.3)
	Hoka	11.0 (1.6)	0.1 (0.6)	9.0 (0.7)	1.7 (0.2)
	P-Value	0.79	0.26	0.05*	0.43
Knee	Free	6.1 (2.6)	2.0 (2.6)	5.1 (1.1)	1.5 (0.4)
	Hoka	8.3 (2.3)	0.2 (1.7)	5.5 (1.3)	1.3 (0.2)
	P-Value	0.36	0.23	0.67	0.57
Ankle	Free	16.3 (1.5)	2.9 (1.8)	1.9 (0.4)	2.1 (0.9)
	Hoka	16.4 (1.6)	0.9 (2.3)	1.3 (0.2)	1.8 (0.6)
	P-Value	0.95	0.24	0.06	0.44

Within the transverse plane kinematics of the Pre-Fatigue results, the maximalist shoes maintained their sustained increase in internal hip rotation with a peak difference of 5.9 degrees. It also maintained the decrease of hip external rotation with a peak difference of 4.5 degrees, once again signifying that it was a sustained increase in internal rotation that did not significantly alter the hip rotation range of motion in the transverse plane. Also, the maximalist shoes maintained the sustained decrease in internal ankle rotation with a peak difference of 3.6 degrees. This change corresponded to a 2.5 degree increase in ankle external rotation, and thus didn't result in a significant change in the range of motion.

At the highlighted 25 % stance phase, the same gradual rise of the free moment is observed. This corresponded to a slight leveling out in the knee and ankle rotation moment curves. The hip rotation moment saw a short drop in the external rotation moment.

The Post-Fatigue vertical ground reaction data as well as the peak free moment data are shown below numerically in Table 2.12. The plots were included in the previous figures.

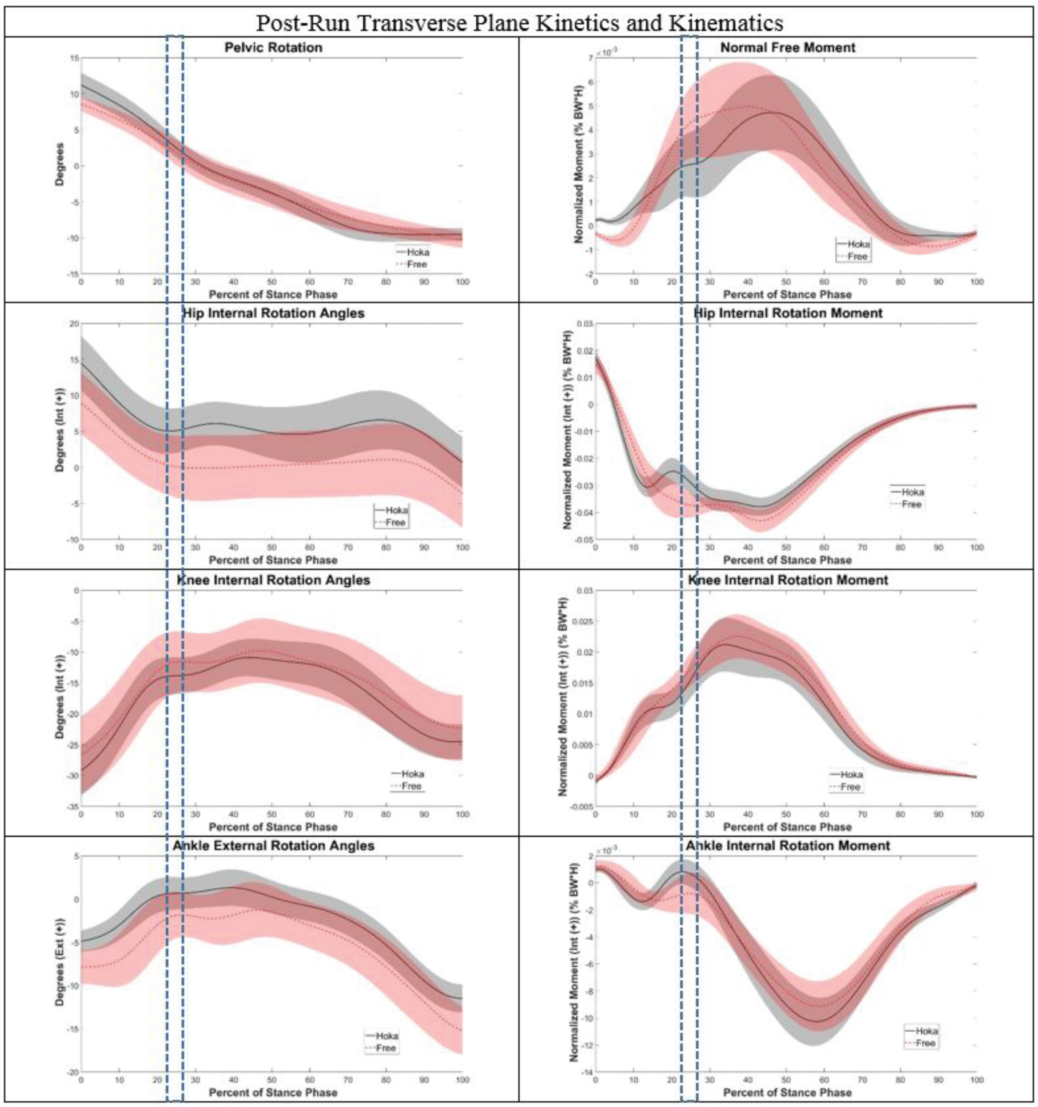

Figure 2.22: Transverse Plane Kinematics and Kinetics for the Post-Fatigue condition in the maximalist shoes (Hoka) and the minimalist shoes (Free). The moments are normalized to the individual subject's body weight multiplied by their height. The trials were normalized to stance phase. Early stance is boxed, around 25% of stance phase.

Table 2.11: Peak internal rotation and external rotation moments, angles, and the paired t-test p-value comparing the two shoe conditions are shown for the Post-Fatigue condition during stance phase. The standard error is included in parenthesis.

Joint	Condition	Peak Internal Rotation (Degrees)	Peak External Rotation (Degrees)	Peak Internal Rotation Moment (%BW*H)	Peak External Rotation Moment (%BW*H)
Pelvis	Free	8.6 (1.0)	10.5 (1.1)		
	Hoka	11.2 (1.7)	10.6 (1.2)		
	P-Value	0.28	0.97		
Hip	Free	9.3 (4.2)	4.5 (4.8)	1.5 (0.3)	4.8 (0.5)
	Hoka	15.2 (3.5)	-0.0 (3.5)	1.7 (0.3)	4.1 (0.3)
	P-Value	0.08	0.18	0.35	0.33
Knee	Free	-8.3 (5.1)	27.6 (6.0)	2.4 (0.3)	0.2 (0.1)
	Hoka	-9.9 (3.1)	29.7 (3.6)	2.2 (0.4)	0.2 (0.1)
	P-Value	0.52	0.44	0.51	0.55
Ankle	Free	15.3 (2.8)	-0.2 (3.1)	0.3 (0.1)	1.0 (0.2)
	Hoka	11.7 (1.6)	2.3 (2.0)	0.3 (0.1)	1.1 (0.2)
	P-Value	0.19	0.16	0.33	0.46

Similarly to the Pre-Fatigue results, there was no significant change in the force plate data in the Post-Fatigue condition results, although the maximalist shoes were again shown to increase the vertical impact peak slightly. Similar to the Pre-Fatigue condition, there were no significant differences in the peak free moment, but it is once again noted that the rate of increase in the free moment was much more gradual in the maximalist shoes when compared to the minimalist shoes in the Post-Fatigue condition as well.

The same additional variables of interest that were investigated in Pre-Fatigue were once again investigated in Post-Fatigue and are shown below in Table 2.13.

Table 2.12: Vertical Ground Reaction Force (VGRF), Vertical Impact Peak (VIP), Vertical Average Loading Rate (VALR), Vertical Instantaneous Loading Rate (VILR), the peak free moment, and the paired t-test p-value comparing the two shoe conditions are shown for the Post-Fatigue condition during stance phase. The standard error is included in parenthesis.

Condition	VGRF (N/BW)	VIP (N/BW)	VALR (N/BW*s)	VILR (N/BW*s)	Free Moment (%BW*H)
Free	2.62 (0.05)	1.63 (0.12)	70.41 (10.39)	115.85 (7.42)	0.63 (0.13)
Hoka	2.60 (0.05)	1.70 (0.12)	70.54 (5.79)	113.90 (8.57)	0.57 (0.12)
P-Value	0.62	0.36	0.99	0.85	0.3

There was less of a difference in in leg stiffness for the maximalist shoes in the Post-Fatigue condition, but the substantial reduction in eversion velocity was maintained from Pre-Fatigue. The reduced stiffness change is due to the leg stiffness in the minimalist condition remaining fairly stable, but the leg stiffness in the maximalist condition having an increased stiffness compared to the Pre-Fatigue condition.

Table 2.13: Leg stiffness, average eversion velocity, maximum eversion velocity, and the paired t-test p-value comparing the two shoe conditions are shown for the Pre-Fatigue condition during stance phase. The standard error is included in parenthesis.

Condition	Leg Stiffness (N/m)	Average Eversion Velocity (°/s)	Max Eversion Velocity (°/s)
Free	8548 (384)	381.3 (49.2)	519.3 (85.9)
Hoka	8379 (416)	302.9 (49.3)	636.0 (79.2)
P-Value	0.62	0.06	0.02*

In summary, the Post-Fatigue results of interest are a slight reduction in the plantar-flexion moment, a reduction of the hip flexion moment, a reduction of the hip abduction moment, a sustained reduction of knee abduction, reduced ankle eversion and velocity, a sustained increase in internal hip rotation, and a sustained increase in ankle external rotation when compared to the minimalist shoes.

It should also be noted that spatiotemporal variables were also investigated for both shoes in the Pre-Fatigue and Post-Fatigue conditions. There were no significant differences in step length or width between the shoes in either condition, but the minimalist shoes resulted in a slightly reduced stride length and a correlating slight increase in stride frequency in both conditions.

In summary, the reduced plantar-flexion moment observed in the maximalist shoes decreased in significance after fatigue. There was a reduction of the hip flexion moment after fatigue that did not occur in Pre-Fatigue for the maximalist shoes. There was also a reduced peak hip adduction moment in the maximalist shoes in the Post-Fatigue condition that was not significant in Pre-Fatigue for the maximalist shoes. There was a sustained decrease in knee abduction in the maximalist shoes that became slightly more significant after fatigue for the maximalist shoes. There was a reduced peak eversion angle, reduced inversion moment, and reduced eversion velocity both before and after fatigue for the maximalist shoes. There was a sustained increase in hip internal rotation and ankle external rotation that became more significant after fatiguing for the maximalist shoes. The maximalist shoes also resulted in a reduced leg stiffness compared to the minimalist shoes that was less significant in the Post-Fatigue condition compared to the Pre-Fatigue Condition.

Discussion and Conclusions

Discussion

Our primary hypothesis was that the minimalist shoes would result in a reduction of ground reaction variables because that is their most commonly reported benefit. Additionally, it was hypothesized that the maximalist shoes will result in reduced ankle eversion and range of motion, due to their motion control technology. The maximalist shoes were also expected to reduce the plantar-flexion moment due to the rocker characteristics of the shoe.

There were not a lot of substantial differences between the shoes in the sagittal plane in the Pre-Fatigue or the Post-Fatigue condition. There was an increased dorsi-flexion in Pre-Fatigue for the maximalist shoes as well as a decrease in the dorsi-flexion moment, as was hypothesized. This can be attributed to their meta-rocker characteristics. The reduced dorsi-flexion moment is in good agreement with a study done by Boyer and Andriacchi et al. and shows that the maximalist meta-rocker characteristics are inducing changes similar to rocker shoes. [56] The reduction is because the rocking shape of the shoe propels the foot through stance phase and, in turn, requires less push off. These changes were seen to diminish slightly with fatigue, but the trends remained in the same direction. Additionally, there was a small sustained increase in hip extension and flexion moment that was seen in Post-Fatigue for the maximalist shoes when compared to the minimalist shoes that did not occur in the Pre-Fatigue condition. This likely played a part in why the change in leg stiffness was not as substantial in the Post-Fatigue condition, because the minimalist leg stiffness did not change with fatigue. Despite the reduced change, the maximalist shoes displayed a reduced stiffness when compared to the minimalist shoes in both the Pre-Fatigue and Post-Fatigue conditions. This difference in leg stiffness may be attributed to the meta-rocker aspect of the shoe as well, because the rocker shoe is allowing for greater shock attenuation through stance phase by guiding the foot through stance phase in the sagittal plane. As discussed previously, an increased leg stiffness is an injury mechanism for tibial stress fractures. Therefore, this result could be used as an argument in favor of the maximalist shoes. But the difference became fairly insignificant with fatigue.

There were notable changes of interest within the frontal and transverse planes. Following the logic that everything starts from the reaction between the ground and the foot, it makes sense to start at the bottom. The ground reaction moment, represented by the free moment plots in Figure 2.19 and Figure 2.22, displays that the maximalist shoes allowed for a more gradual increase in the rotational moment induced on the leg. This resulted in a ripple effect throughout the transverse and frontal plane kinetics and kinematics and is why the early stance phase was highlighted in the plots. The corresponding reduction in almost all frontal and transverse plane joint moments that occurs at roughly 25% of stance phase can likely be attributed to this greater rotational force attenuation that is seen in the maximalist shoes. This may be a direct result of the motion control, j-frame technology that is advertised for the Hoka shoes, which is shown below in Figure 2.23. [45]

The j-frame technology is designed, similar to other common motion control shoes, to control excessive motion at the ankle by absorbing forces and guiding the foot through stance phase. In order to guide the foot through stance phase, increased cushioning is put on the inner and rear-foot part of the shoe. This is where the foot lands, and the extra force absorption allows for reduced eversion and better force attenuation. This goal of the j-Frame is consistent with our results, and may be a direct result of improved attenuation of rotational forces between the ground and the foot. This is seen in our free moment results and while it does not change the peak values of the free moment, it does allow for a more gradual application of torsional and bending forces to be put on the leg. As discussed, bone is a viscoelastic material and the overall damage to the bone is a function of the magnitude and rate at which the force is applied. Therefore, this result could be used as an argument in favor of the maximalist shoes.

Figure 2.23: The Hoka One One J-Frame Technology [45]

In addition to the change seen at early stance phase, there were also notable sustained and overarching differences between the shoes in the two conditions. As discussed, the maximalist shoes have a motion control aspect that is designed to reduce excessive ankle motion and mimic the benefits of other motion control shoes. This was seen in our results, as the maximalist shoes resulted in a reduced ankle eversion and eversion velocity in comparison to the minimalist shoes in both the Pre-Fatigue condition and the Post-Fatigue condition. As discussed previously, eversion and eversion velocity are risk factors for both tibial stress fractures and patellofemoral pain syndrome. This shows a benefit that maximalist shoes may induce when compared to minimalist shoes that is similar to the benefits described by motion control shoes. [46]

While the maximalist shoes were shown to reduce excessive eversion at the ankle, it was shown to result in abnormal kinematics at the knee and hip. Runners wearing the maximalist shoes saw a sustained increase in internal hip rotation through stance phase, an increase in peak hip adduction, and an increase in pelvic drop and range of motion in the frontal plane. These variables were discussed as risk factors for patellofemoral pain syndrome. This may play into the motion control aspect of the maximalist shoes, because Lafortune et al. previously found that shoes induced changes at the ankle, particularly rotation, were resolved at the hip. [137] In the maximalist shoes, for both Pre-Fatigue and Post-Fatigue, there was an increased external ankle rotation and an increased internal hip rotation, which is in good agreement with those findings. As discussed previously, these altered pelvic, hip, and knee kinematics will result in an increased contact pressure between the patella and head of the femur and could result in patellofemoral pain. These findings are particularly concerning because they were maintained in the fatigued state and are affecting runners for the entirety of a prolonged run. These results are consistent with Sinclair et al.'s findings, where they compared the peak contact force and pressure between minimalist, maximalist, and neutral shoes while running. [59] They reported a significantly greater patellofemoral contact force in the maximalist shoes when compared to the minimalist shoes, and therefore concluded that minimalist shoes may be able to reduce a runner's risk for patellofemoral pain syndrome. [59] Our study is in good agreement with Sinclair et al.'s findings and gives some insight into the kinematic causes that are resulting in this increased contact pressure and force for the maximalist shoes. Additionally, the ankle was seen to have a sustained increase in external rotation throughout stance phase. This can be attributed to the runners compensating for the increased hip internal rotation and knee adduction in order to stay balanced.

Looking at the vertical impact peak results, our results did not display the commonly reported reduction in impact peak and loading rate that is a frequently associated benefit of the minimalist shoes. Pollard et al. recently published a study that compared the loading rate and eversion of maximalist shoes and neutral shoes before and after running a 5k. [44] They saw an increased loading rate and impact peak in the maximalist shoes, but there are some differences in our studies that may have resulted in this difference. Notable differences are that they had all female runners, they only controlled running speed for individual subjects but did not keep a consistent running speed across the study, and they did not acclimatize their runners to over ground running following the fatigue run on the treadmill. [44] Female runners are known to be more at risk of tibial stress fractures, which may have resulted in some differences compared to our all male study. [34] Because loading rate and impact peak are directly related to running speed, it is likely that this would result in differences between our data. While controlling the running speed for each individual subject may seem logical because it is the differences between the two conditions that are being compared as opposed to the exact values, this train of thought assumes that the relationship between running speed and these variables are perfectly linear and that amount of change will not be altered by changing the running speed. It is doubtful this is the case due to the complexity involved in the mechanics that make up human motion. Additionally, not controlling speed will result in an increased deviation in the reported results due to the results variability with speed. Also, treadmill running is associated with gradual changes in running mechanics that include ground reaction data [138], but this is to be covered more in the following chapter. Our study did, however, see a slight decrease in the vertical impact peak for the minimalist shoe condition that is consistent with previous studies [28] and the trend was maintained through fatigue, but our study showed no differences in loading rates between the shoes. With the slight reduction in impact peak, the minimalist shoes may reduce that risk factor for tibial stress fractures, and this may be attributed to the reduced weight of the shoe and reduced peak dorsi-flexion.

There were some limitations in this study. The most notable is that only 8 subjects were investigated, which reduces the statistical significance of many of the findings. Additionally, the subjects investigated did not have a history of patellofemoral pain syndrome or tibial stress fractures. Despite these limitations, the results still may be of clinical significance for reducing described risk factors.

Conclusions

The maximalist shoes were shown to have results similar to those of motion control shoes and rocker shoes, which it is advertised and designed to do. The maximalist shoe reduced ankle range of motion, and in turn ankle eversion and eversion velocity. Because eversion and eversion velocity are risk factors for common overuse injuries, this highlights a possible benefit of the maximalist shoes. But this reduction in ankle motion seemed to go hand in hand with abnormal kinematics at the pelvis, knee, and hip that could offset the benefits seen at the ankles. The minimalist shoes resulted in reduced hip internal rotation, knee abduction, and pelvic drop when compared to the maximalist shoes. These are known risk factors for patellofemoral pain syndrome and these differences highlight potential benefits of the minimalist shoes over the maximalist shoes. Additionally, the minimalist shoes were shown to slightly decrease the impact peak of the ground reaction force, which is of concern for tibial stress fractures. This study took a step forward in fully characterizing the changes in kinematics and kinetics that are a result of wearing minimalist and maximalist shoes and how fatigue may alter those changes. In the scope of common running overuse injuries, the conclusions show that shoe selection may be dependent upon which injuries the runner is more predisposed to, because the maximalist shoes control excessive ankle motion but the minimalist shoes showed a reduction in kinematic variables at the pelvis, hip, and knee that are frequently reported as injury mechanisms.

Future Works

A criteria to be included in this study was that the participant exhibited a rear foot strike pattern and maintained that strike pattern, for both shoes, through the fatigue protocol. The minimalist shoes, in many ways, were made for forefoot strikers and because of this it is hypothesized that the benefits of the minimalist shoes would be increased if the study was aimed at forefoot strikers. It would, therefore, be of interest to replicate this protocol in a group of forefoot strikers to investigate how this alters the results. With our already collected four forefoot strikers, it is of interest for our group to perform this study going forward once we get more forefoot participants.

A common occurrence for runners is to go to a running store and be prescribed a shoe type by the store based upon the runner's gait pattern and pain symptoms. I have met with a runner who had this happen and reported an increased pain at first with the prescribed shoes, but with the passing of time reported a significant decrease in pain compared to before running in that type of shoe. The ultimate study of interest for this area would be giving a subject a new shoe type and collect changes in their running mechanics intermittently over the course of a long period of time. The complications of this study would include ensuring that they run in that shoe for the entire time of the study, finding a large number of willing participants for the study, and getting the participant to come back for many collections. Despite the difficulty that would be associated with this type of study, it would be of great significance for shoe technology going forward.

Another study of interest would be seeing how these changes may be influenced if they were not in a lab setting. Comparing shoe types and how they may alter running mechanics while trail running with obstacles in your path may give a lot of insight for reducing injury mechanisms in a more common running setting. Complications that would be associated with this study would include getting kinetics in a real world setting as well as performing a motion capture study in general out in the real world.

Electromyography (EMG) and tibial acceleration data were collected in this study but not analyzed. This data will be analyzed to give a new scope on this study in the future. Additionally, more subjects will be added to this study in the future to add to the statistical and clinical significance of the findings.

There remain a large number of studies that are of interest to advance shoe technology in a way to better protect runners in the real world. Our study filled a gap and took a step forward in characterizing kinematic and kinetic changes that occur between maximalist and minimalist shoes for runners in a fresh and fatigued state.

CHAPTER THREE

The Potential Influence of Treadmill Running In Fatigue Studies

Introduction and Motivation

Fatigue Studies

As discussed in the previous chapter, there are various reasons to perform fatigue studies. The main reason is that most athletes in various settings are in a fatigued state for the vast majority of the time that they are engaging in the activity of interest. While performing studies in a rested state is still of interest and significance, it is still of interest, arguably greater, to investigate if the results are altered by the person's fatigue status. Due to the common overuse injuries associated with running that were discussed in the previous chapter, running is a frequently investigated activity in a fatigued state. Because there are various reported differences associated with fatigue running [66,69,70,74,139], it is of interest to researchers to perform their running studies with their subjects in a fatigued state. Some of the reported changes induced by fatigue are frequently investigated variables for a variety of injuries. Dierks et al. found that after their runners performed a prolonged fatigue run, they exhibited a significant increase in ankle eversion and knee internal rotation. [66] Ankle eversion, as discussed in the previous chapter, is a commonly investigated risk factor for a variety of overuse injuries, such as tibial stress fractures [52] and patellofemoral pain syndrome. [50] Samozino et al. found that their runners experienced a significant increased leg stiffness during a 24-h run [74], and, as we discussed in the previous chapter, increased leg stiffness is an injury mechanism for tibial stress fractures. [34] Ruiz et al. found that after fatiguing their participants with a series of running, stair climbing, and jumping activities that they exhibited a reduced loading rate and impact peak. [140] Gerlach et al. also found that after their subjects performed a fatigue run on a treadmill that they exhibited a decrease in impact peak and loading rate. [69] It should be noted that Clansey et al. found conflicting results, and reported an increase in loading rate as well as impact peak in fatigued runners. [64] Vertical loading rate and impact peak are reported to be associated with a variety of running overuse injuries and are thus very commonly investigated. [33] With it established that fatigue studies are of interest to be performed, the question now becomes how to fatigue the research participants in the study.

Fatigue Methods

A notable difficulty in performing fatigue studies is determining the methods and protocol to use in order to induce fatigue. A variety of methods have been used to attempt to induce fatigue in their participants, but these methods can mostly be split into two general categories. Some previous investigators have utilized a series of exercises such as jumping [73,140,141], squats [141,142], resistance exercises [63], or a combination of various exercises. [140,143] The other general category is to fatigue participants by having them run. [60–62,64–66,70–73,75,135,143–151] This category is of more interest to this study because it is ideal to fatigue the subjects in the setting that is of interest, which is running in this case. But even within this category, there are many different ways to perform this fatigue run for the participants. Ruder et al. [152], Jamison et al. [146], and Chan-Roper et al. [61] used runners that were participating in a race. This method has strengths in that it captures the runners in an extremely real environment and avoids any bias that may be caused by running in a lab setting or treadmill. These studies also generally have the inherent weakness of relying on two-dimensional kinematics that are found using high speed cameras and in turn only get the kinematics of one plane and some spatiotemporal variables; this how Ruder et al., Jamison et al. and Chan-Roper et al. performed their studies. [61,146,152] In order to overcome this and get three dimensional kinematics as well as kinetics with a force plate, researchers generally need to perform their study in a lab setting. One study performed by Kasmer et al. attempted to overcome the influence of a lab setting by testing the subjects on a treadmill prior to fatigue, then allow them to perform a 50k fatigue run outdoors, and finally bring them back into the lab to test a final time on the same treadmill. [147] This methodology has a strength in that you are able to fatigue the runners in an environment that is similar to the actual environment of interest, but it also has its own inherent weaknesses. The markers had to be removed after the pre-fatigue testing and replaced after completing the 50k fatigue run [147], which allows for various kinematic and kinetic errors and influence from marker placement to occur when doing three-dimensional kinematics and kinetics. Additionally, they did not completely avoid the influence of changing surfaces, because they still performed their actual motion capture collections on a treadmill. [147]

Because of all of the complications described in these previous studies, fatigue studies are most commonly done in a lab and subjects are fatigued on a treadmill. [60,62,64,65,67,70–72,72,73,75,135,143–145,150–153] These methods can prove to be quite powerful, because they allow data to be collected throughout the fatigue run in addition to just at the beginning and end. Of these studies, there are three different methodologies that are commonly seen to perform the fatigue treadmill run.

One of these methods is having the participants run a predetermined distance or time at a pre-determined and subject specific speed. [44,62,145,151] This method has strengths in that the researcher can attempt to ensure muscular fatigue in addition to cardiovascular fatigue by having a set distance or time criteria. The weakness of this method is that some subjects may not get fatigued by the set distance or time and others may be more fatigued; because there is no criteria other than distance or time, it is an unaddressed variable in the study.

Another method to perform these fatigue studies is by using blood lactate concentration or respiratory data, such as carbon dioxide pressure and oxygen consumption, in order to quantifiably ensure subject fatigue. [64,72,75,149,153] This method is quite powerful because it allows for a quantifiable way to ensure similar levels of fatigue across all subjects. The only weaknesses of these methods are availability of the required equipment and that the mask used for gathering respiratory data and the equipment used to sample blood from the subject's ear lobe may result in subject discomfort. Additionally, the blood lactate method requires the runner to stop intermittently in order for the blood to be tested and limits the number of people that are willing to participate in the study.

Due to the complications discussed with quantifying fatigue, the most common method used to perform these studies involve using a fatigue protocol where a set fatigue criteria is satisfied. [60,66,70,71,135,144,150] Two methods of performing this method are by having the subject run at a self-selected or predetermined pace [66,115,150], or by having them perform an incremental protocol until the fatigue criteria is satisfied. The most commonly used incremental treadmill fatigue protocols are modified versions of

Astrand and Bruce protocols. The Astrand protocol involves starting at a walking speed and incrementally increasing the speed of the treadmill, until the runner's average training speed is reached, and then incrementally increasing the grade (incline) until the runner is no longer able to continue. [154] The Bruce protocol follows a similar train of thought. The difference is that instead of increasing the speed and grade separately, the Bruce protocol simultaneously increases the speed and grade at each increment and also goes until the subject can no longer continue. [154] Many studies choose to use a 'modified' form of these protocols, by only increasing grade or speed instead of doing both. [60,70,144] Following this method exactly means that the fatigue protocol is continued until the individual is no longer able to continue, and some previous studies chose to keep this as their fatigue criteria. [65,144] The weakness of this method is that, while you may verbally encourage runners to keep going until exhaustion as Benjaminse et al. reported doing [144], it still relies on the subject's own judgement to decide when to stop and opens the door to subject induced bias in the study. To counter this problem, researchers commonly use other criteria to determine when to stop the subject's fatiguing activity. The most commonly used criteria are a combination of using a percentage of the subjects maximum heart rate as determined by the age based max-heart rate equation, which is the individual's age subtracted from 220 [133], and using a number on the Borg scale of perceived exertion that was shown in the previous chapter in Figure 2.16. [60,66,67,70] This method's strength is that it quantifies the subject's fatigue level in order to ensure that a similar level of fatigue is being achieved across the study. The weakness of this method is that its criteria are mostly focused on cardiovascular fatigue and may not be indicative of the athlete's real training environment if they are not running a similar distance to their standard distance in training. While all of these methods that occur within the lab setting have their strengths and weaknesses, they all generally utilize a treadmill. The use of the treadmill introduces a new variable that may need to be account for.

Treadmill Running

Fatiguing subjects on a force-plate embedded treadmill or testing over ground with force plates before and after fatiguing using a treadmill has its own inherent problems when attempting to draw conclusions about over ground running. There is a large amount of debate over the effects of treadmills on human motion mechanics, because there are researchers that believe they have no effect and there is no need to account for it and there are researchers that believe it does have an effect and measures need to be taken to minimize it. Studies that argue that the treadmill does not result in significant differences generally argue that if an acclimatization and familiarization period is done for the treadmill, then the differences in the mechanics will be reduced. [155,156] Despite these findings, there are still studies that find conflicting results. A recent study performed by Sinclair et al. in 2013 that included an acclimatization period for the treadmill still reported significant differences between over ground and treadmill running. [134] Because this is an ongoing debate, research still needs to be done in order to determine the best methodology to use in order to best analyze the targeted environment of the individual study. In order to investigate this, it is necessary to look at some commonly reported differences.

Some of the most commonly reported changes in treadmill running are spatiotemporal changes, particularly that treadmill running results in a decreased stride length and an increased stride frequency that is generally attributed to a fear of falling off of the treadmill. [157–160] It should be noted that there are some conflicting reports and Alton et al. actually reported an increase in stride length for his subjects. [136] This change may be dependent on the length of the treadmill if the cause is due to a fear of falling off, but it is reasonable to believe that the motion of the running surface may influence the results as well. For changes other than spatiotemporal variables, Sinclair et al. reported a reduced hip range of motion in the sagittal and transverse planes, knee flexion, and ankle eversion with treadmill running. [134] They attributed some of the sagittal plane change in kinematics to the different surface stiffness of the treadmill when compared to over ground [134], as an increased surface stiffness has been shown to result in an increased leg stiffness. [91] White et al. performed an interesting study using a treadmill with embedded force plates and displayed a linear decrease in the loading rate and impact force associated with the ground reaction force during a 20 minute run. [138] And this is in good agreement with a study performed by Milgrom et al. that found treadmill runners experienced a reduced tibial strain when compared to over ground runners. [89] Milgrom et al.'s study is quite powerful because they mounted strain gauges through bone staples directly into the tibia of their subjects in order to find the significantly reduced strains for treadmill running. [89] This is a particularly interesting finding because, as mentioned previously, Gerlach et al. found that a fatigue run on a treadmill resulted in a decrease in loading rate and impact peak and attributed this change to fatigue. [69] Ruiz et al. found the same results and induced fatigue without a treadmill [140], showing that both the treadmill and fatigue may share this induced change. But this may allow some insight into why Clansey saw conflicting results with fatigue runners. [64] With the overlap of an effect, this example shows how it may be easy to misinterpret data when a treadmill is involved.

Many biomechanical fatigue studies are performed solely on a force-plate embedded treadmill [62,65,66,70–72,115,135,145,149], but these types of treadmills may not always be readily available and, as discussed, may have differences in results when compared to over ground running. For these reasons, fatigue studies are sometimes conducted with an over ground testing condition but a treadmill fatigue protocol. [44,60,64,150] As discussed, research has been conducted and arguments have been made about using an appropriate acclimatization period when a runner begins running on a treadmill [155,156], but, to the author's knowledge, a study has never been performed describing an appropriate acclimatization period back to over ground running after prolonged running on a treadmill. If there is changes and acclimatization associated with transitioning from over ground running to treadmill running, then it makes intuitive sense that there would be similar changes and acclimatization associated with transitioning from the treadmill back to over ground running. Despite this logic, Pollard et al. [44], Clansey et al. [64], Brown et al. [150], and Anbarian et al. [60] did not account for this and immediately tested runners in an over ground setting after getting off the treadmill. It is, therefore, of interest if an acclimatization period back to over ground would result in any significant changes in the results.

Purpose

The purpose of this study was to investigate possible differences that may occur in over ground testing due to a fatigue protocol being performed on a treadmill. Because acclimatization studies have been done for adjusting from over ground to treadmill running, it is necessary to investigate if there is a similar adjustment period when transitioning back to over ground. This study also investigates if these changes are consistent between a maximalist and minimalist shoe condition, because some fatigue studies, such as Clansey et al. [64], did not control shoe conditions and it is of interest if this should be controlled in future studies for the reasons discussed in Chapter Two of this thesis. This study provides new insight into future methodology for fatigue studies that utilize a treadmill fatigue protocol, but perform testing over ground.

Hypotheses

Runners were tested immediately following a treadmill fatigue run and after an over ground acclimatization period. It is hypothesized that the participants will exhibit a reduced stride length and reduced stride width due to a fear of stepping off of the moving running surface. This is expected to result in altered kinetics and kinematics in the sagittal and frontal plane. It is also hypothesized that there will be differences in the ground reaction variables and stiffness, because these variables have been found to alter depending on the running surface. .

Procedures and Methodology

All methods and analysis techniques are consistent with the ones outlined in Chapter One. The information below describes procedures and methodologies unique to this study.

Participants

The participants in this chapter and their demographics are consistent with those described in Chapter Two.

Methods and Protocol

Subjects came to the BioMotion Lab for two separate sessions, spaced at least one week apart. For each individual session, the subject would wear either the minimalist (Nike Free) shoe shown in Figure 2.14 of the previous chapter or the maximalist (Hoka One One Bondi 5) shoe shown in Figure 2.15 of the previous chapter. [130,131] The treadmill used to fatigue is shown below in Figure 3.1.

Figure 3.1: The Sole F80 treadmill that was used in this study. [1]

The Nike Free has a weight of 7.8 ounces and a heel-toe drop of 8 mm. [130] The Hoka One One Bondi 5 has a weight of 10 ounces and a heel-toe drop of 4 mm. [43] The initial shoe condition was randomized for each subject using a coin flip, where heads would result in the subject running in the maximalist shoe for their first session. The procedure and protocol was the same for both testing sessions, the only change being the shoe condition.

The protocol used in this study is the same as the protocol described in Chapter Two. The difference is that this chapter focuses on the Post-Immediate and Post-Fatigue condition and not the Pre-Fatigue condition.

Results

All kinematics and kinetics were calculated for the hip, knee, and ankle in the sagittal, frontal, and transverse planes. Additionally, spatiotemporal and ground reaction forces and moments were investigated. All results are included in Appendix A, but only the variables where we saw substantial differences were included for discussion. These differences included the kinematics and kinetics of the hip in the sagittal, frontal, and transverse planes, the kinematics and kinetics of the knee in the frontal plane, the kinematics of the pelvis in the frontal plane, the vertical impact peak, the vertical loading rates, and spatiotemporal variables. A Pre-Fatigue line was included on the plots for visual comparison, but will not be discussed in this chapter.

Maximalist

The kinematics and kinetics of the hip in the sagittal, frontal, and transverse plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue conditions in the maximalist shoes are plotted below in Figure 3.2, 3.3, and 3.4, respectively. The kinematics and kinetics of the knee in the frontal plane for each condition are plotted below in Figure 3.5. The kinematics of the pelvis are plotted below in Figure 3.6. All plots are normalized to percent of stance phase and the standard error of the respective lines are represented by the corresponded shaded region. The maximum and minimum numerical values and the paired t-test p-values for all of these values are shown in Table 3.1.

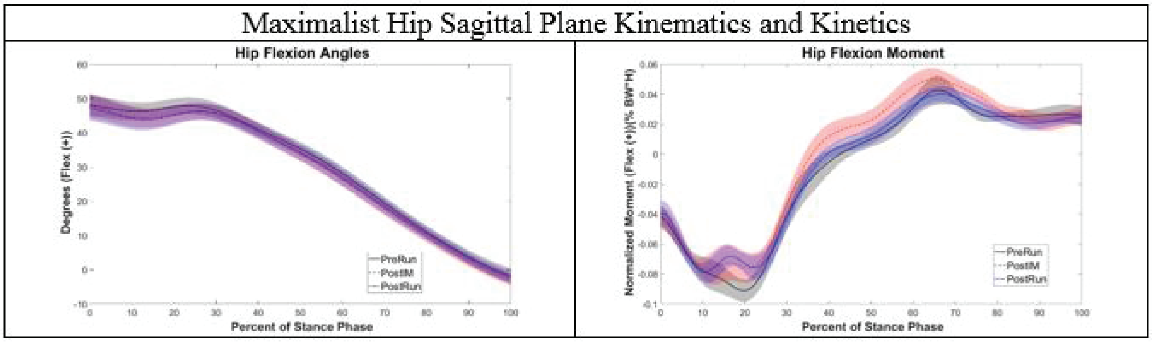

Figure 3.2: Hip kinematics and kinetics in the sagittal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the maximalist shoes. Hip flexion and the external hip flexion moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

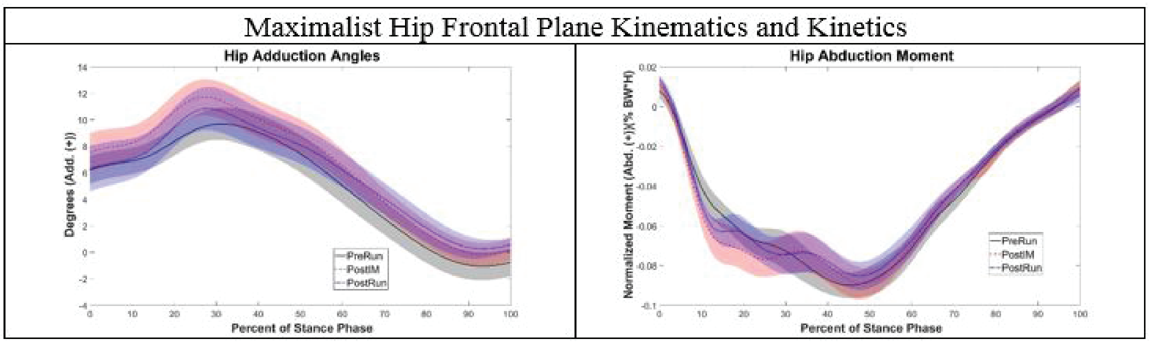

Figure 3.3: Hip kinematics and kinetics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the maximalist shoes. Hip adduction and the external hip abduction moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

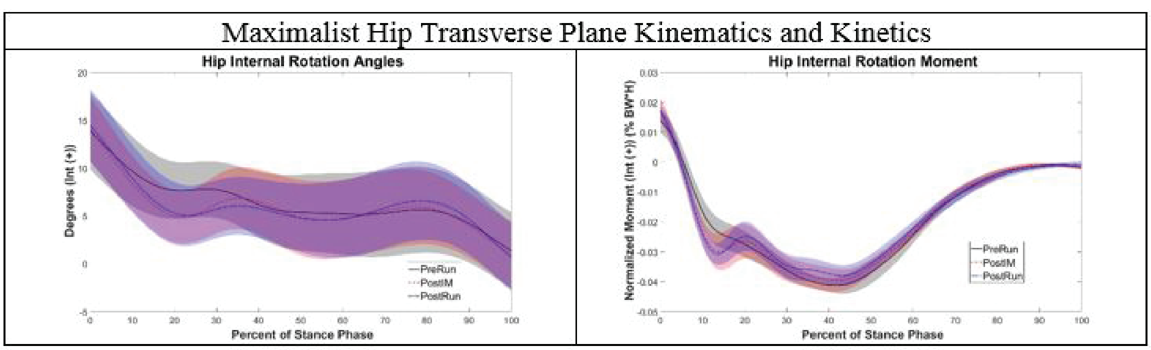

Figure 3.4: Hip kinematics and kinetics in the transverse plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the maximalist shoes. Hip internal rotation and the external hip internal rotation moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

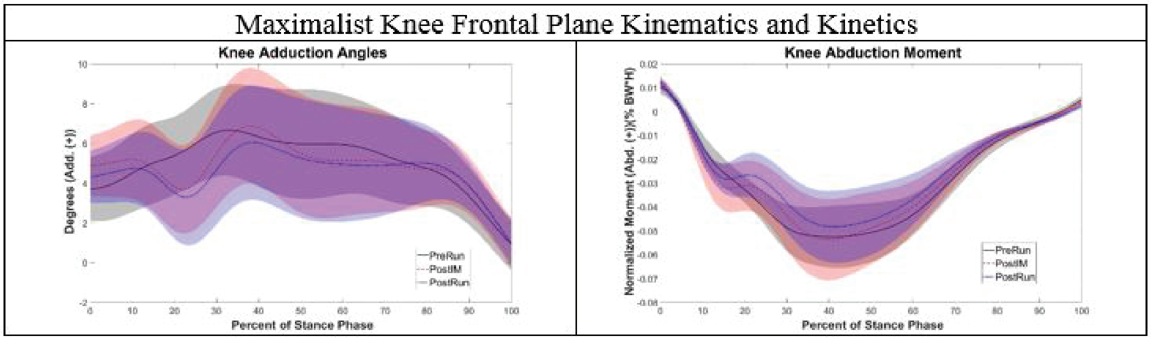

Figure 3.5: Knee kinematics and kinetics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the maximalist shoes. Knee adduction and the external knee abduction moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

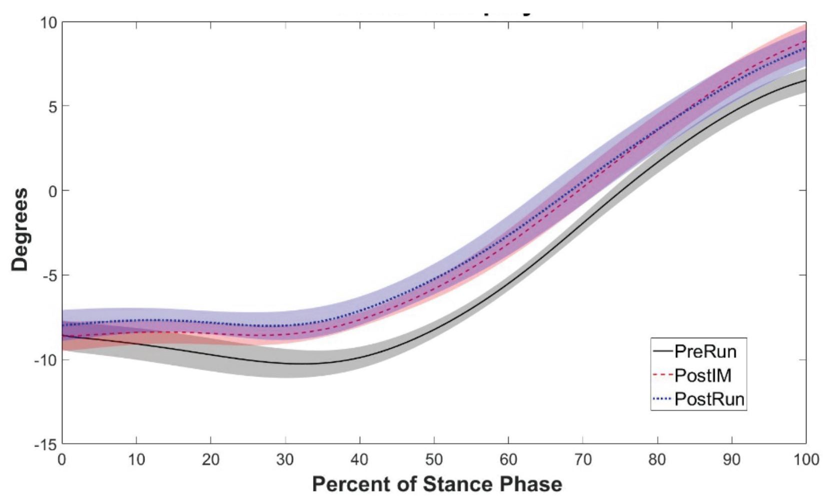

Figure 3.6: Pelvic kinematics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the maximalist shoes.

The acclimatization period resulted in a reduced hip flexion moment of 1.3 %BW*H. There was a decrease in knee adduction by 0.8 degrees; while statistically significant, it is still very small and likely not clinically relevant. There were no significant differences in the pelvic drop before and after the acclimatization period for the maximalist shoes.

Table 3.1: Maximum and minimum kinetics and kinematics for variables of interest and the paired t-test p-value comparing the Post-Immediate and Post-Fatigue condition values in the maximalist shoes during stance phase. The standard error is included in parenthesis.

		Post-Immediate		Post-Fatigue		P-Value	
Joint	Variable	Peak Positive	Peak Negative	Peak Positive	Peak Negative	Peak Positive	Peak Negative
Hip	Flexion Angle (Degrees)	49.2 (2.8)	-2.8 (1.8)	48.8 (3.2)	-2.3 (1.7)	0.75	0.19
	Flexion Moment (%BW*H)	5.6 (0.8)	-9.9 (0.5)	4.3 (0.5)	-9.0 (0.5)	0.005*	0.3
	Adduction Angle (Degree)	11.9 (1.4)	-0.5 (0.9)	11.0 (1.6)	-0.0 (0.6)	0.14	0.34
	Abduction Moment (%BW*H)	1.8 (0.2)	-9.4 (0.9)	1.7 (0.2)	-9.0 (0.7)	0.54	0.43
	Int. Rotation Angle (Degree)	14.9 (3.2)	-0.1 (3.5)	15.2 (3.5)	0.0 (3.5)	0.65	0.88
	Ext. Rotation Moment (%BW*H)	1.8 (0.4)	-4.4 (0.4)	1.7 (0.3)	-4.1 (0.3)	0.61	0.28
Knee	Adduction Angle (Degree)	9.1 (2.3)	-0.2 (1.8)	8.3 (2.3)	-0.2 (1.7)	0.02*	0.73
	Abduction Moment (%BW*H)	1.5 (0.3)	-5.9 (1.4)	1.3 (0.2)	-5.5 (1.3)	0.09	0.35
Pelvis	Obliquity (Degrees)	8.9 (1.0)	-9.7 (0.7)	8.4 (1.1)	-9.4 (0.7)	0.69	0.55

Additional variables of interest include the vertical impact peak and loading rates, leg stiffness, and spatiotemporal variables, and these are shown and compared with paired t-test p-values in Table 3.2. The vertical ground reaction curve is shown below in Figure 3.6.

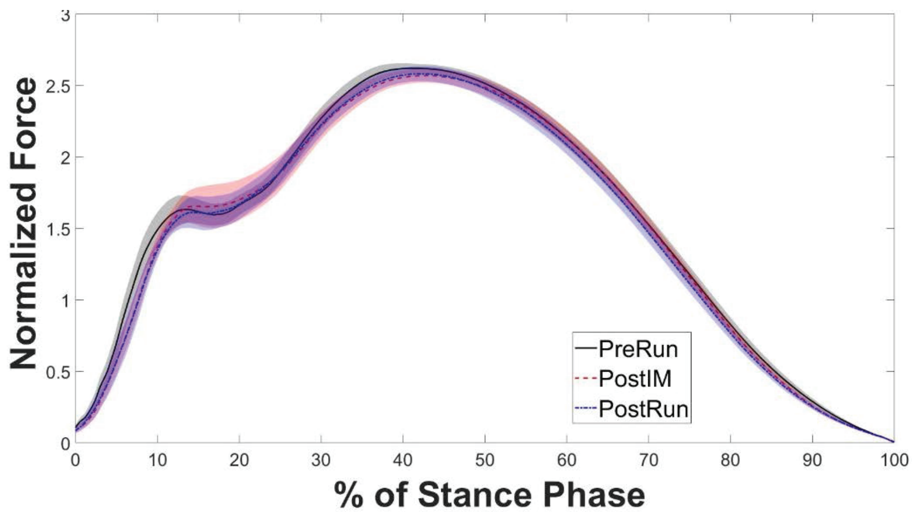

Figure 3.7: The vertical ground reaction curves for the Pre-Fatigue, Post-Immediate, and Post-Fatigue conditions in the maximalist shoes, normalized to stance phase.

There was a slight increase in the average loading rate after the acclimatization for the maximalist shoes. Leg stiffness increased, but not significantly. The step width decreased significantly following the over ground acclimatization. There was also a substantial decrease in stride length without a substantial increase in cadence, but both running speeds were still within 10% of the target speed.

Table 3.2: Values for variables of interest and the paired t-test p-value comparing the Post-Immediate and Post-Fatigue condition values in maximalist shoes during stance phase. The standard error is included in parenthesis.

Variable Type	Variable	Post-Immediate	Post-Fatigue	P-Value
Ground Reaction Force	VIP (N/BW)	1.71 (0.13)	1.70 (0.12)	0.91
	VALR (N/BW*s)	65.6 (9.3)	70.5 (5.8)	0.46
	VILR (N/BW*s)	113.1 (5.1)	113.9 (8.6)	0.93
Leg Stiffness	Stiffness (N/m)	8194 (280)	8526 (460)	0.4
Spatiotemporal Variables	Stride Length (m)	2.93 (0.09)	2.74 (0.12)	0.08
	Step Width (cm)	3.3 (1.0)	4.7 (0.8)	0.01*
	Cadence (steps/s)	2.9 (0.1)	2.8 (0.1)	0.53

Minimalist Shoes

The kinematics and kinetics of the hip in the sagittal and frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue conditions in the minimalist shoes are plotted below in Figure 3.7 and 3.8, respectively. The kinematics and kinetics of the knee in the frontal plane for each condition are plotted below in Figure 3.9. The kinematics of the pelvis are plotted below in Figure 3.10. All plots are normalized to percent of stance phase and the standard error of respective lines are represented by the corresponding shaded region. The maximum and minimum numerical values and the paired t-test p-values for these variables are shown in Table 3.3.

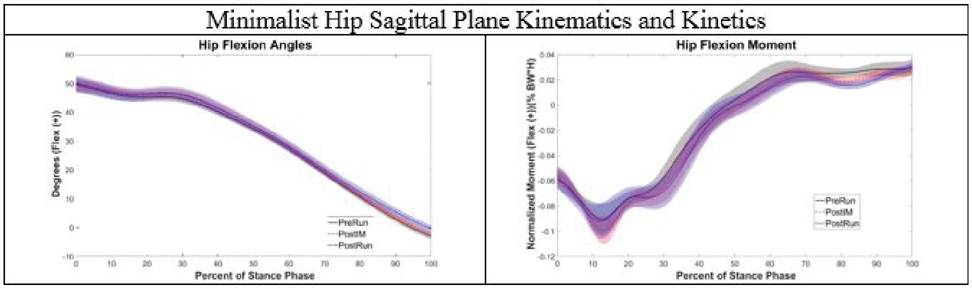

Figure 3.8: Hip kinematics and kinetics in the sagittal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the minimalist shoes. Hip flexion and the external hip flexion moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

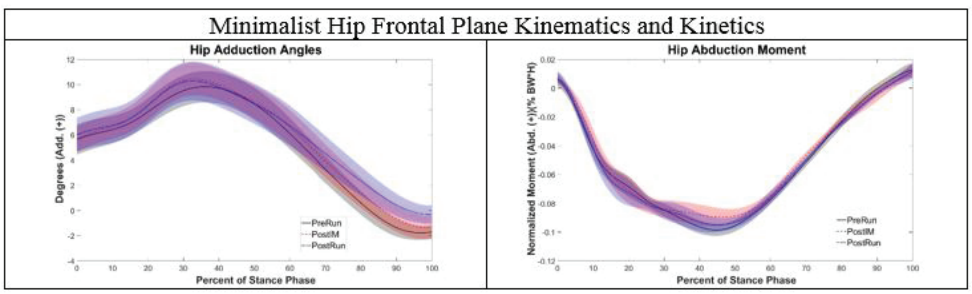

Figure 3.9: Hip kinematics and kinetics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the minimalist shoes. Hip adduction and the external hip abduction moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

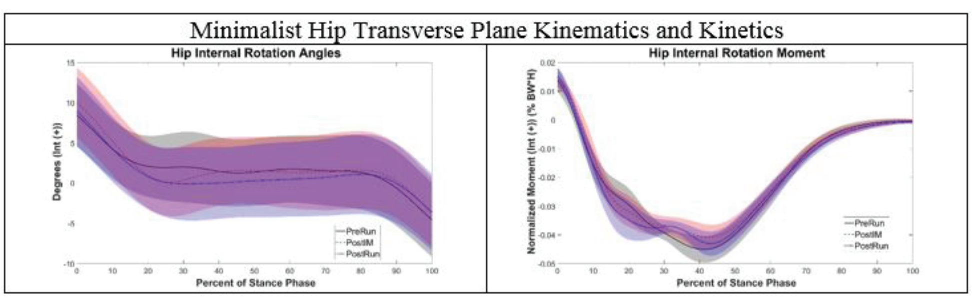

Figure 3.10: Hip kinematics and kinetics in the transverse plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the minimalist shoes. Hip internal rotation and the external hip internal rotatoin moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

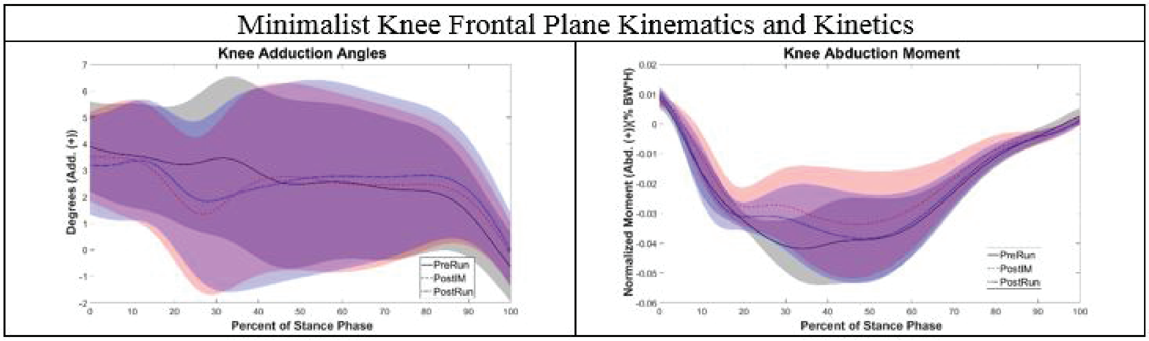

Figure 3.11: Knee kinematics and kinetics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the minimalist shoes. Knee adduction and the external knee abduction moment are positive in the respective plots. The moments were normalized by the individual runner's bodyweight (BW) multiplied by their height (H).

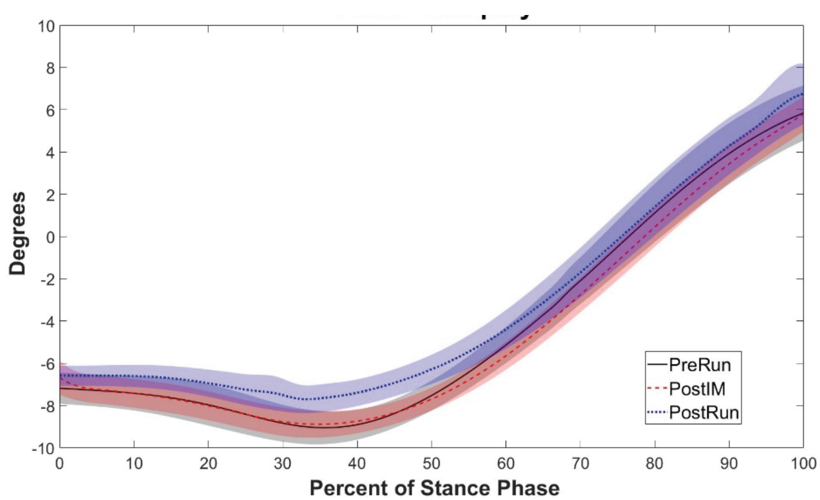

Figure 3.12: Pelvic kinematics in the frontal plane for the Pre-Fatigue, Post-Immediate, and Post-Fatigue condition in the minimalist shoes.

For the minimalist shoes, there was a significant decrease in hip extension of 1.8 degrees following the acclimatization period, which was more substantial than the change seen in the maximalist shoes. This did not correspond to a kinetic change at the hip in the sagittal plane.

Table 3.3: Maximum and minimum kinetics and kinematics for variables of interest and the paired t-test p-value comparing the Post-Immediate and Post-Fatigue condition values in minimalist shoes during stance phase. The standard error is included in parenthesis

		Post-Immediate		Post-Fatigue		P-Value	
Joint	Variable	Peak Positive	Peak Negative	Peak Positive	Peak Negative	Peak Positive	Peak Negative
Hip	Flexion Angle (Degrees)	50.4 (1.9)	-2.2 (0.8)	51.0 (2.5)	-0.4 (1.3)	0.58	0.03*
	Flexion Moment (%BW*H)	3.6 (0.3)	-10.8 (0.6)	3.7 (0.3)	-10.6 (0.7)	0.43	0.52
	Adduction Angle (Degree)	10.9 (1.2)	-1.7 (0.9)	10.8 (1.5)	-0.8 (0.8)	0.64	0.004*
	Abduction Moment (%BW*H)	1.7 (0.3)	-9.7 (0.7)	1.9 (0.3)	-10.2 (0.5)	0.54	0.28
	Int. Rotation Angle (Degree)	10.5 (4.2)	-4.3 (4.4)	9.3 (4.2)	-4.6 (4.8)	0.03*	0.64
	Ext. Rotation Moment (%BW*H)	1.5 (0.2)	-4.5 (0.4)	1.5 (0.23)	-4.8 (0.5)	0.97	0.08
Knee	Adduction Angle (Degree)	6.2 (2.4)	-2.0 (2.4)	6.1 (2.6)	-2.0 (2.6)	0.68	0.97
	Abduction Moment (%BW*H)	1.8 (0.6)	-4.9 (1.1)	1.5 (0.4)	-5.1 (1.1)	0.36	0.38
Pelvis	Obliquity (Degrees)	7.5 (1.9)	-9.2 (0.6)	7.9 (1.7)	-8.3 (0.5)	0.72	0.002*

There was also a significant decrease in hip abduction of 0.9 degrees for the Post-Fatigue condition. This did not correspond to any significant kinetic changes. There was a significant reduction in peak internal rotation angle with a difference of 1.2 degrees following the acclimatization period. This corresponded to an increase of 0.3 %BW*H in the internal rotation moment. There were no significant changes at the knee between the Post-Immediate and Post-Fatigue conditions for the minimalist shoes, which was different from what was seen in the maximalist shoe. There was a significant decrease in pelvic drop of 0.9 degrees for the Post-Fatigue condition. While these changes showed statistical significance, they are all relatively small changes that may not be clinically relevant.

Additional variables of interest include the vertical impact peak and loading rates, leg stiffness, and spatiotemporal variables, and these are shown and compared with paired t-test p-values in Table 3.4. The vertical ground reaction curve is shown below in Figure 3.11.

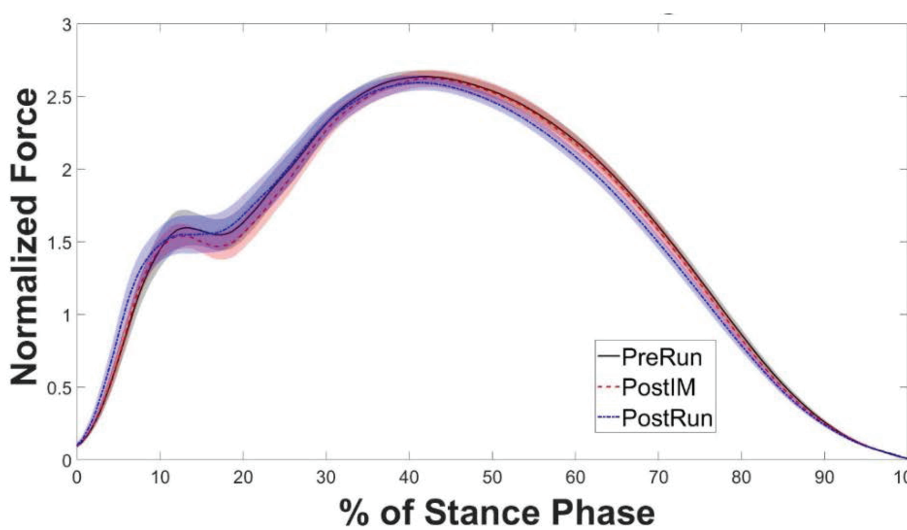

Figure 3.11: The vertical ground reaction curves for the Pre-Fatigue, Post-Immediate, and Post-Fatigue conditions in minimalist shoes, normalized to stance phase.

Table 3.4: Values for variables of interest and the paired t-test p-value comparing the Post-Immediate and Post-Fatigue condition values during stance phase in the minimalist shoe. The standard error is included in parenthesis.

Variable Type	Variable	Post-Immediate	Post-Fatigue	P-Value
Ground Reaction Force	VIP (N/BW)	1.56 (0.09)	1.61 (0.11)	0.57
	VALR (N/BW*s)	57.1 (7.3)	71.0 (10.9)	0.09
	VILR (N/BW*s)	113.1 (3.8)	115.9 (7.4)	0.65
Leg Stiffness	Stiffness (N/m)	8346 (354)	8548 (383)	0.25
Spatiotemporal Variables	Stride Length (m)	2.92 (0.08)	2.76 (0.10)	0.11
	Step Width (cm)	4.2 (1.1)	5.3 (1.1)	0.16
	Cadence (steps/s)	2.9 (0.1)	2.9 (0.1)	0.95

There was an increase in average loading rate following the over ground acclimatization for the minimalist shoes. There was also an increase in step width and leg stiffness following the over ground acclimatization, similar to the results of the maximalist shoes. There was also a decrease in stride length without a substantial increase in cadence, but both running speeds were still within 10% of the target speed.

Discussion and Conclusions

Discussion

It was hypothesized that a fear of falling off of the moving running surface would reduce the step width and length, and this would result in kinetic and kinematic changes. It was also hypothesized that stiffness and ground reaction variables would change due to previously reported differences with treadmill running. Because most previous studies focus on the strict differences between over ground running and treadmill running or on the gradual and transitional changes that occur when a runner begins running on a treadmill, it is hard to directly compare to previous studies. It is expected that the changes will occur in the same planes within the same joints when transitioning back to over ground, but not necessarily in the same direction. Following this thought process, most comparisons of over ground and treadmill running report that stride length decreased and cadence increased. [158,160] Both maximalist and minimalist shoes exhibited a higher stride length in the Post-Immediate condition when compared to the Post-Fatigue condition. This change was not statistically significant, but was still a notable trend. This may be a result of transitioning from a running surface that is moving to a stable and hard surface. The tread on the belt is moving in the opposite direction from the direction that the foot is trying to accelerate in, which may result in an increased push off force forward immediately after getting off the treadmill. This is consistent with the results seen in the hip sagittal plane results, with the increased flexion external moments seen at the hip in the maximalist shoes for the Post-Immediate condition and the increased extension seen in the minimalist shoes.

There was an observed increase in leg stiffness that occurred following the over ground acclimatization period for both shoes tested. This change was, again, not statistically significant but was still a notable change. It is hypothesized that this is an effect from transitioning from a less stiff surface to a stiffer surface; due to the unfamiliarity with a stiff surface, the subjects exhibited a rapid reduction in leg stiffness that disappears with a transition period. Corresponding to this result, there was also a reduced average loading rate in the Post-Immediate results compared to the Post-Fatigue results for both shoe conditions. This is hypothesized to be a result of the reduced leg stiffness resulting in more shock attenuation in the leg. This difference was seen to be much more substantial in the minimalist shoes, which may give some insight for the differences observed between the results presented in Chapter Two of this thesis and the results seen by Pollard et al. [44]; Pollard et al. saw a reduced average loading rate in their neutral shoes after fatigue compared to their maximalist shoes, but did not include this acclimatization period. Our Post-Immediate results were similar to Pollard et al.'s, but the difference disappears after acclimatization to over ground running.

Within the frontal plane, there were interesting changes that are all believed to be a result of the reduced step width of the Post-Immediate condition compared to that of the Post-Fatigue condition. It is hypothesized that the reduced step width is a direct result of a fear of running outside of the tread of the running surface. This fear may have resulted in the increase in knee adduction and hip adduction observed in the maximalist shoe in the Post-Immediate condition. Interesting, maximalist shoes had the same reduced step width in the Post-Immediate condition, but responded slightly differently. They did not see and change in the knee angle, but still exhibited a change in hip angle as a result of the reduced step width. An additional notable change in the frontal plane was the increase in pelvic drop in the Post-Immediate condition for the minimalist shoe, which is hypothesized to be, again, a result of the change in step width.

Comparing our transverse plane results to previous studies, Sinclair saw an increased hip movement in the transverse plane in over ground runners compared to treadmill runners [134], but the minimalist shoe results showed an increased hip internal rotation for the minimalist shoes in the Post-Immediate condition. Because of this difference, it may be a transition effect as opposed to the exact differences in treadmill and over ground running. In the maximalist shoes, there were no significant changes at the hip in the transverse plane, which is consistent with the results of Schache et al. [161] and Fellin et al. [162]. For our results, the change in the hip internal rotation seen for early stance phase in the minimalist shoes can be attributed to the increased pelvic drop that occurred at around the same point in stance phase. Pelvic drop is, as mentioned in the previous chapter, generally seen in conjunction with increased hip internal rotation and adduction. [67] This is consistent with changes seen at the hip and pelvis for the minimalist shoes.

There were statistically significant changes observed, but most of the kinematics and kinetics changed only a small amount. Most of these changes are clinically insignificant and if the possibility of these changes are accounted for when drawing conclusions, it is unlikely to significantly affect results in future studies.

There were some limitations in this study. A notable weakness is that only one treadmill was investigated, and it is likely that the results will change significantly depending on the treadmill. Another limitation is that only 8 subjects were investigated, which reduces the statistical significance of many of the findings. Despite the reduced statistical significance, the results still may hold significance for future methodology in studies that utilize treadmills. An additional limitation is that the subject's fatigue levels between Post-Immediate and Post-Fatigue were not quantitatively compared, but it is reasonable to say they were of similar levels of fatigue because they were not allowed to rest between the two testing periods. Immediately after testing the Post-Immediate condition, participants ran laps on a hard surface for five minutes and were immediately tested a final time.

Conclusions

This study investigated if it is necessary to acclimatize runners back to over ground running after treadmill running. From our results, it is shown that there are changes in running kinematics and kinetics when transitioning to over ground running after treadmill running. These changes seem to be a result of changes in stride length and width. The change in stride width is hypothesized to be due to a fear of stepping off of the running surface. If this is this case, this may be able to be countered by having a sufficiently wide running surface. The change in stride length is hypothesized to be due to transitioning from a moving surface to a static surface. Because differences were observed, it is recommended for researchers to include a sufficiently acclimatize their subjects back to over ground running after fatiguing on a treadmill if testing is being done on over ground. Additionally, the differences observed were similar between shoe conditions, but not completely the same. It is, therefore, recommended that running fatigue studies normalize shoe conditions.

Future Works

This study, to the author's knowledge, is the first that investigated the changes that occur when transitioning back to running over ground after treadmill running. Because this is a scenario that occurs in research environments, it is of interest to investigators if there are altered mechanics associated with this transition. While we did show there were differences after a five minute acclimatization period, previous studies investigating a similar transition period in treadmills studied what amount of time was a sufficient amount of time to transition. [156] It is, therefore, recommended that a future study be done to determine what amount of time is sufficient in order to acclimate to over ground running.

As mentioned, a weakness of this study was only investigating one treadmill. It is of interest to investigators what length and width of a treadmill is sufficient to reduce the changes that occur in running. Treadmills also have varying surface stiffness, and it is also of interest what stiffness of the running surface is necessary to reduce the changes in ground reaction forces and leg stiffness. It is, therefore, recommended that future studies be done to investigate changes in running pattern due to treadmill length, width, and stiffness.

CHAPTER FOUR

The Effect of Shoes on Risk Factors Associated with Knee Osteoarthritis during Walking

Introduction and Motivation

Knee Osteoarthritis Progression during Walking

Osteoarthritis (OA) is a leading cause of pain and injury in elderly people; twenty-three percent of people over the age of eighteen in the United States are reported to have doctor-diagnosed arthritis. [163] A large portion of those afflicted by OA experience it in the form of knee OA. [164] The growing problem of osteoarthritis has been attributed to the growing obesity problem in today's society, and this has been particularly associated with knee OA. [165] This relationship is due to obesity resulting in increased forces in the knee, and knee OA most commonly is agreed to be a result of overloading of the medial compartment in the knee that causes damage and loss of joint cartilage. [166–168] This joint cartilage damage is illustrated in Figure 4.1 below, with an x-ray image of a patient with knee OA in both knees. [169]

Because the cause and progression of knee OA is reported to be due to a local mechanical load environment at the knee, it is common to attempt to take a conservative biomechanical approach to reduce this risk and progression. [168] In order to evaluate the effectiveness of conservative strategies, it is necessary to first have an understanding of the biomechanical variables that result in an increased loading of the medial compartment in the knee. The medial compartment of the knee is focused on because knee OA is more commonly seen in the medial than lateral compartment. [170]

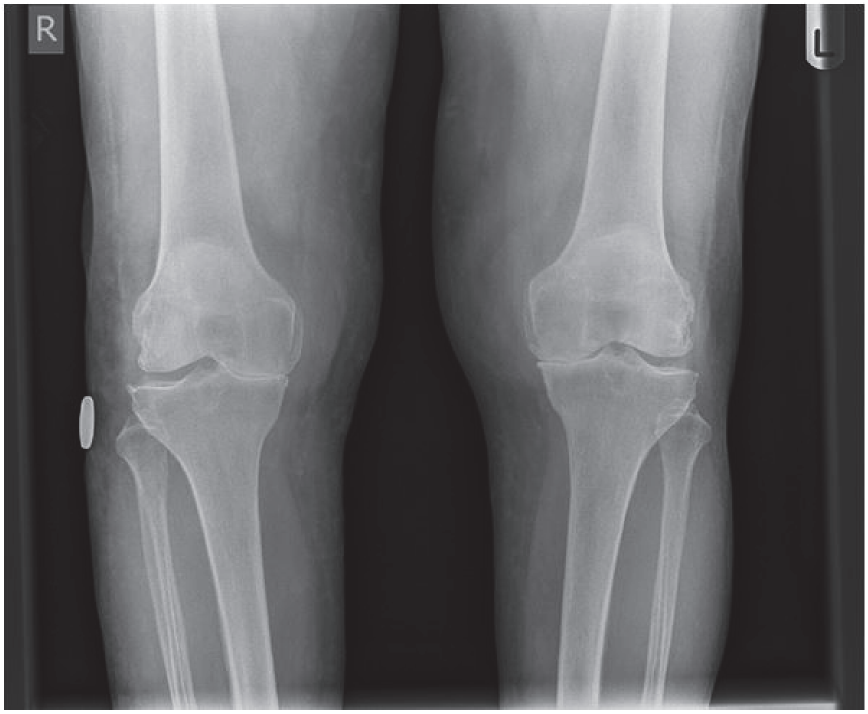

Figure 4.1: An x-ray of a patient with knee OA in both knees. [169] A loss of joint cartilage on the medial side of both knees is clearly shown as a loss of joint space.

Risk Factors for Knee OA

Because it is extremely difficult to get an exact measurement of contact pressure in the medial compartment of the knee using non-invasive methods, generally researchers use biomechanical factors that attribute to an increased contact force. The most commonly investigated variable as a risk factor of knee OA is looking at the external knee adduction moment. [168,171–174] An increased knee adduction moment results in increased compression in the medial compartment of the knee and an increased varus alignment in the knee, as shown below in Figure 4.2. [168]

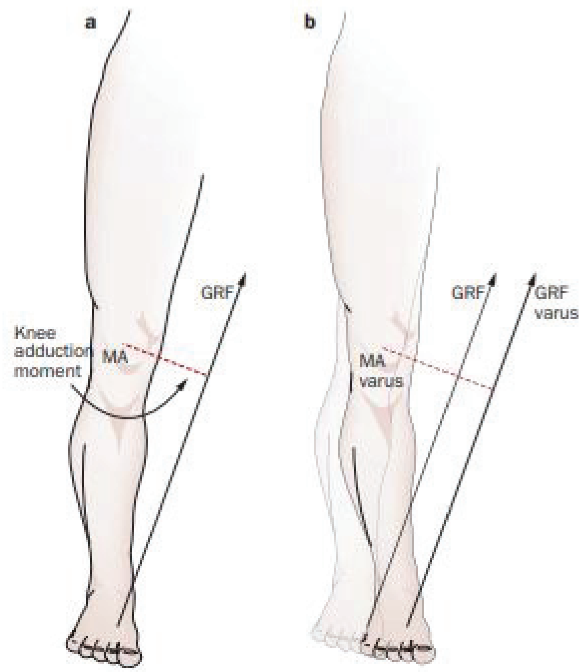

Figure 4.2: A graphical representation of the ground reaction force resulting in an increased knee adduction moment and in turn increased varus alignment and medial compartment compressive forces at the knee. [168]

When the external knee adduction moment is analyzed, researchers generally only report the peak value for comparison. While the peak knee adduction moment may be a direct representation of the maximum medial joint load experienced at any point of time during walking, it is not representative of the full loading throughout the entirety of stance phase. [172] Because of this, the knee adduction moment impulse, or the time integral of the knee adduction moment over stance phase, has become a frequently assessed variable as a risk factor for knee OA. [172] Analyzing the knee adduction moment impulse allows for the comparison of not just the peak load experienced, but also the cumulative and sustained loading pattern experienced by the knee during stance phase. [172] While analyzing conservative biomechanical methods, researchers aim to reduce the overall and sustained loading of the medial knee by reducing the knee adduction moment impulse during stance phase.

The external knee adduction moment is the most commonly investigated biomechanical variable, but recent studies have shown that a significant reduction in the moment does not always correspond to a significant reduction in the medial contact force in the knee. [174] Walter et al. reported this finding, and stated that the reduced medial contact force due to a reduction in knee adduction moment may be mitigated by a corresponding increase in the external knee flexion moment. [172,174] This is because the knee flexion moment is correlated to the net muscle contraction during early stance phase, and these muscle contractions correspond to large compressive forces at the knee. [173] Chehab et al. further tested this hypothesis by analyzing the knee flexion and adduction moments in conjunction with magnetic resonance imaging (MRI) within their patients for five years in order to see the significance of each individual variable. [173] They found that the knee adduction moment had a greater influence on the femoral cartilage and the knee flexion moment had a greater influence on the tibial cartilage, signifying that both variables should be considered when analyzing the effectiveness of interventions. [173] It should be noted that some studies support that the knee flexion moment does not correlate to medial knee OA progression, such as the one performed by Chang et al., and that targeting only the knee adduction moment is the best representation of the medial contact force. [172] Chang et al. analyzed 204 patients and used MRI to correlate knee adduction and flexion moments to cartilage damage, giving a lot of power to their study; they found no correlation between knee flexion moment and knee OA progression. [172] Despite Chang et al.'s findings, knee flexion moment was investigated in this study in addition to the knee adduction moment and moment impulse. These variables have been shown to correlate to increased medial contact forces, which results in damage to the medial cartilage in the knee. These variables of interest are shown below in Figure 4.3.

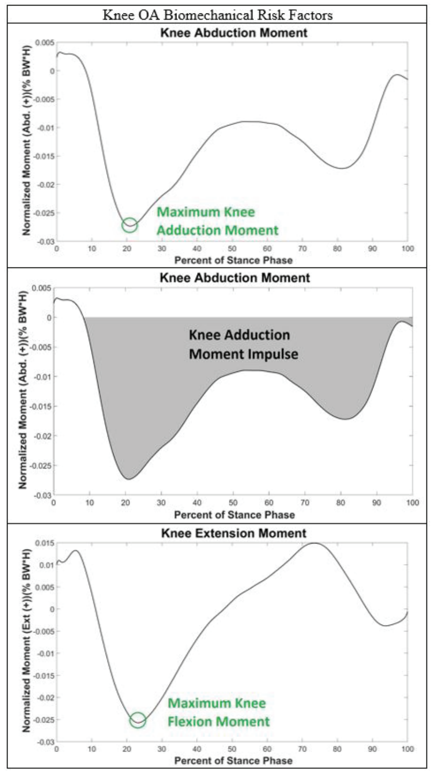

Figure 4.3: The risk factors for knee OA, including the peak external knee adduction and flexion moments and the knee adduction moment impulse. The knee adduction moment impulse is the time integral of the knee adduction moment during stance phase.

Biomechanical intervention methods are aimed at reducing these three variables. Commonly seen methods to accomplish this include changing footwear and orthotics. [168]

Previous Intervention Studies

A common intervention method for knee OA progression is through the use of orthotics in the form of a lateral wedge insole inside the shoe. Several studies aimed at reducing the knee adduction moment have utilized lateral wedge orthotics to reduce the varus alignment of the leg. [168,175–178] This lateral wedge insole has been shown to induce a knee adduction moment reduction of 4-14 percent in a number of studies. [168,175–178] Orthotics are an interesting and seemingly effective method to conservatively reduce the risk factors of knee OA, but another conservative method of interest is through the changing of the shoe itself.

Following the ideology of the lateral wedge, variable stiffness shoes have been investigated for potential benefits for knee OA progression as well. [179] Variable stiffness shoes with an increased lateral sole stiffness induced a significant reduction of the knee adduction moment, and is shown to replicate the effect of the lateral wedge orthotics. [179]

A number of studies have displayed the benefits of barefoot walking for the risk factors of knee OA when compared to walking in shoes. [171,180–183] Kemp et al. found that walking barefoot significantly reduced the medial knee joint load, but did not control the shoe condition, or use only one shoe for all subjects, and called for a future study to be done to compare the various shoe types in the scope of knee OA. [171] Studies have been done to try to fill this knowledge gap, such as Kerrigan et al. showing the drastic reduction of the knee adduction moment in barefoot walking in comparison to high-heels, showing the dangers of common women's footwear. [181] Shakoor et al. has investigated stability shoes, flat walking shoes, clogs, and flip flops and reported that there were no statistical differences between flip-flops, flat-walking shoes, and barefoot walking, but the other shoes resulted in varying increases in the knee adduction moment. [183] Shakoor et al. also found that specialized, light-weight mobility shoes performed similarly to barefoot walking, showing that they may be beneficial in reducing the risk factors associated with knee OA. [182] Despite the amount of research that has been done, additional research is needed to fully investigate the effects of shoe type on the progression of knee OA, particularly with the increased popularity of the maximalist shoe that was discussed in Chapter 2 of this thesis.

Purpose

The purpose of this study was to analyze and compare the effect of varying shoe types on commonly reported risk factors for knee OA. While the benefits of barefoot walking have been researched and are mostly agreed upon, walking barefoot is an impractical solution for most people. For this reason, it is necessary to investigate altered mechanics that are induced by various shoe type and find which shoe reduces the many risk factors associated with knee OA progression. Of primary interest are the minimalist shoe, which might replicate some aspects of barefoot walking, and the maximalist shoe, which has an active guiding frame and might replicate some of the benefits seem with wedged orthotics.

Hypothesis

Participants were tested while walking in maximalist, minimalist, stability, and neutral shoes as well as in barefoot. Maximalist and minimalist shoes were focused upon because they haven't been investigated in this scope. It is hypothesized that the maximalist shoes will perform similarly to the stability shoes due to their similarities, but the maximalist shoes will perform better by reducing varus alignment. It is also hypothesized that the minimalist shoes will replicate the benefits of barefoot walking and reduce the risk factors, because they are designed to replicate barefoot walking.

Procedures and Methodology

All methods and analysis techniques are consistent with the ones outlined in Chapter One. The information below describes procedures and methodologies unique to this study.

Participants

A total of 20 participants were collected during this study. Of the 20 subjects, 11 were male and 9 were female. The subjects were separated by gender due to known and reported differences between the genders in walking, and also analyzed all together as well. [129] Subjects in this study were relatively young, age of 28.05 ± 1.73 (ages 18-46), since they were also asked to run in multiple types of shoes as part of another project. However, their age and health ensured that the participants were able to walk in multiple types of shoes for an extended period of time without pain or without getting fatigued. Therefore, these participants represent a pilot study aimed at understanding the mechanical influence of the shoes without concern for complicating health factors. Future studies can use the results of this study to better design a clinical trial intervention study within patients with early stage medial knee OA. All participants signed an informed consent document that was approved by the Baylor Internal Review Board (IRB) on their first day of testing.

Methods and Protocol

Subjects came to the BioMotion Lab for one session where they were tested in five different shoe conditions: Maximalist (Hoka One One Bondi 5), Minimalist (Nike Free), Stability (Nike Structures), Neutral (Nike Pegasus), and barefoot. Images of the minimalist and maximalist shoes used are shown in Figures 2.14 and 2.15 in Chapter 2 of this thesis. [130,131] The minimalist Nike Free has a weight of 7.8 ounces and a heel-toe drop of 8 mm. [130] The maximalist Hoka One One Bondi 5 has a weight of 10 ounces and a heel-toe drop of 4 mm. [43] The stability Nike Structures has a weight of 10.4 ounces and a heel-toe drop of 10 mm. [184] The neutral Nike Pegasus has a weight of 9.9 ounces and a heel-toe drop of 10mm. [185]

After the calibration trial, described in Chapter One, subjects were asked to run for two minutes on the treadmill to acclimatize to the new shoe condition. Following acclimatization, subjects walked across the lab floor at a self-selected pace. The subject was tested until they had completed five trials where the subject cleanly landed with their dominant foot on one of the force plates. This procedure was repeated for all shoe conditions. The participants always started in the neutral shoe condition, but the order of the following four conditions were randomized for each participant.

Results for Male Subjects

For reasons discussed in the introduction, external knee adduction and flexion moments were analyzed in this study. Additionally, the knee adduction moment impulse was analyzed, and is the time integral of the knee adduction moment curve. The plots for the knee adduction and flexion moment normalized by subject body weight (BW) and height (H) are shown in Figures 4.5 and 4.6, respectively. Plots are normalized to percent of stance phase. The peak adduction moment, peak flexion moment, and knee adduction moment impulse as well as the paired t-test value versus the neutral shoe condition are presented in Table 4.1.

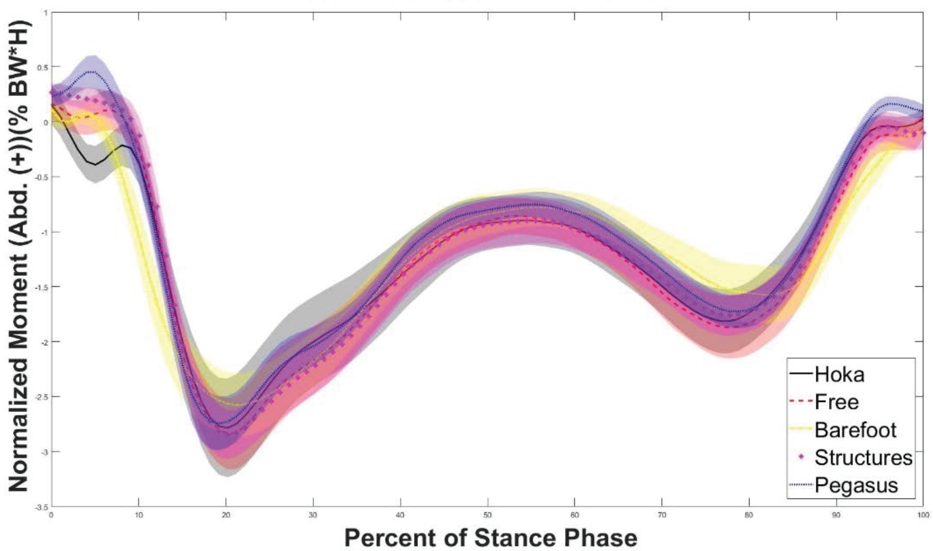

Figure 4.5: The external knee abduction moment for male subjects normalized by subject body weight multiplied by their height. External knee adduction is negative.

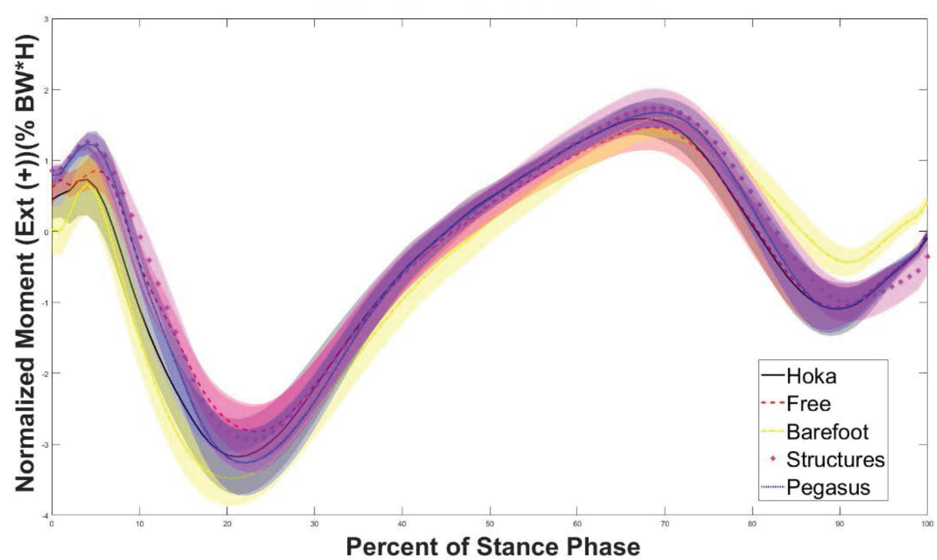

Figure 4.6: The external knee extension moment for male subjects normalized by subject body weight multiplied by their height. External knee flexion is negative.

Table 4.1: Peak knee adduction and flexion moments and the knee adduction moment impulse for male subjects, all normalized by the subject's body weight multiplied by their height. The paired t-test p-value comparing the condition to the neutral shoe condition are shown below each value. The standard error is included in parenthesis.

Variable	Value Type	BareFoot	Min.	Max.	Structures	Neutral
Peak Knee Adduction Moment %(BW*H)	Average	2.9 (0.3)	3.1 (0.4)	3.3 (0.4)	3.1 (0.2)	3.0 (0.3)
	P-Value	0.48	0.61	0.48	0.48	
Peak Knee Flexion Moment %(BW*H)	Average	3.8 (0.4)	3.2 (0.4)	3.7 (0.5)	3.2 (0.4)	3.5 (0.4)
	P-Value	0.19	0.34	0.52	0.37	
Knee Adduction Moment Impulse %(BW*H*s)	Average	0.7 (0.1)	0.9 (0.1)	0.8 (0.1)	0.8 (0.1)	0.8 (0.1)
	P-Value	0.20	0.50	0.76	0.79	

There were no substantial differences when comparing between the shoe conditions for male subjects. It is noted that the maximalist shoes did result in a slight increase of peak knee adduction and flexion moment and the minimalist shoes performed similarly to the neutral shoe condition.

Results

Results for Female Subjects

The plots for the knee abduction and extension moment normalized by subject body weight (BW) and height (H) are shown in Figures 4.7 and 4.8, respectively. Plots are normalized to percent of stance phase. The peak adduction moment, peak flexion moment, and knee adduction moment impulse as well as the paired t-test value versus the neutral shoe condition are presented in Table 4.2.

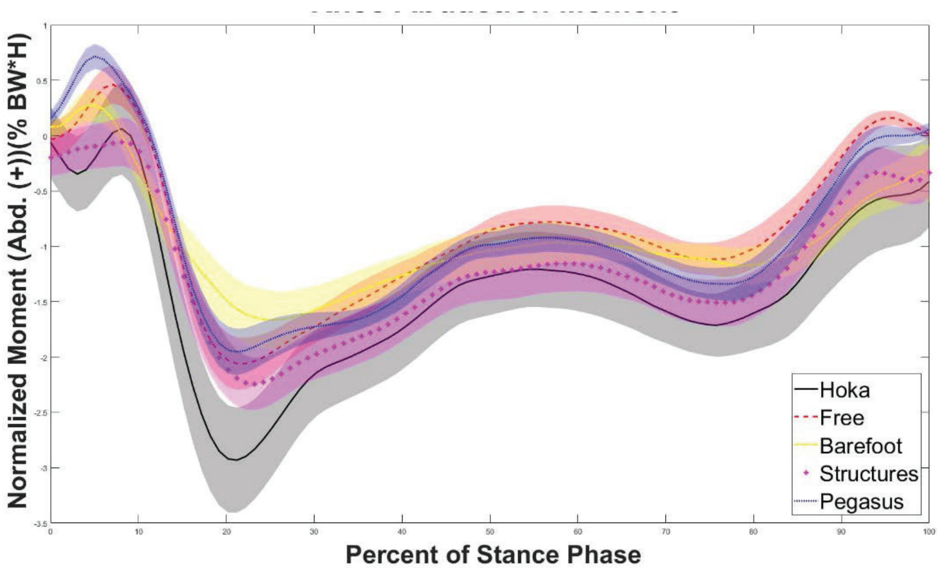

Figure 4.7: The external knee abduction moment for female subjects normalized by subject body weight multiplied by their height. External knee adduction is negative.

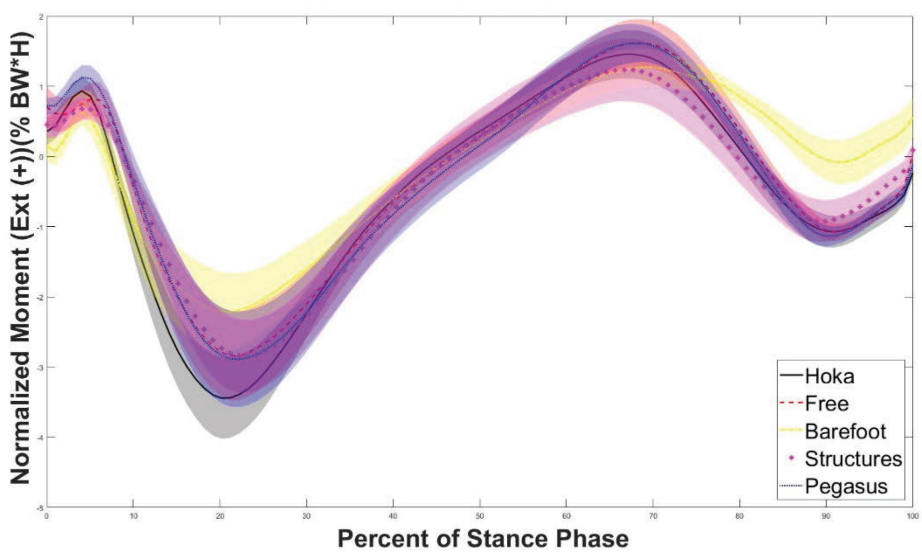

Figure 4.8: The external knee extension moment for female subjects normalized by subject body weight multiplied by their height. External knee flexion is negative.

Table 4.2: Peak knee adduction and flexion moments and the knee adduction moment impulse for female subjects, all normalized by the subject's body weight multiplied by their height. The paired t-test p-value comparing the condition to neutral are shown below each value. The standard error is included in parenthesis.

Variable	Value Type	BareFoot	Min.	Max.	Structures	Neutral
Peak Knee Adduction Moment %(BW*H)	Average	2.2 (0.2)	2.4 (0.2)	3.1 (0.5)	2.6 (0.2)	2.3 (0.2)
	P-Value	0.68	0.45	0.07	0.11	
Peak Knee Flexion Moment %(BW*H)	Average	2.5 (0.5)	3.2 (0.6)	3.6 (0.6)	3.2 (0.5)	3.3 (0.7)
	P-Value	0.10	0.86	0.40	0.85	
Knee Adduction Moment Impulse %(BW*H*s)	Average	0.6 (0.1)	0.6 (0.1)	0.8 (0.1)	0.7 (0.1)	0.6 (0.1)
	P-Value	0.19	0.39	0.20	0.27	

There were no statistically significant differences for female subjects, but there were much more substantial differences than the ones seen for the male subjects. The maximalist shoe condition was seen to increase the knee adduction moment by 0.8 %BW*H when compared to neutral and increase the knee adduction moment impulse by 0.2 %BW*H*s. The minimalist shoes were, again, seen to perform similarly to the neutral condition.

Results for All Subjects Analyzed Together

The plots for the knee abduction and extension moment normalized by subject body weight (BW) and height (H) are shown in Figures 4.9 and 4.10, respectively. Plots are normalized to percent of stance phase. The peak adduction moment, peak flexion moment, and knee adduction moment impulse as well as the paired t-test value versus the neutral shoe condition are presented in Table 4.3.

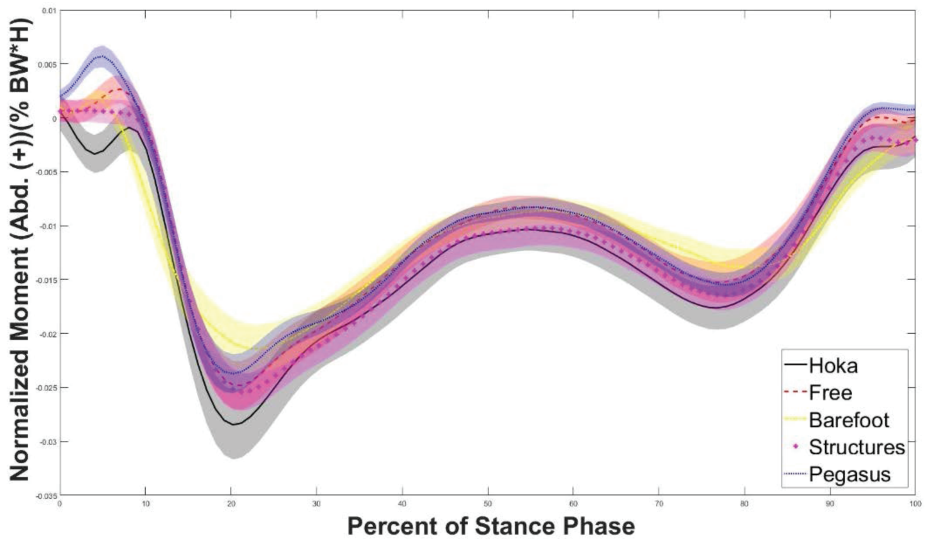

Figure 4.9: The external knee abduction moment for all subjects normalized by subject body weight multiplied by their height. External knee adduction is negative.

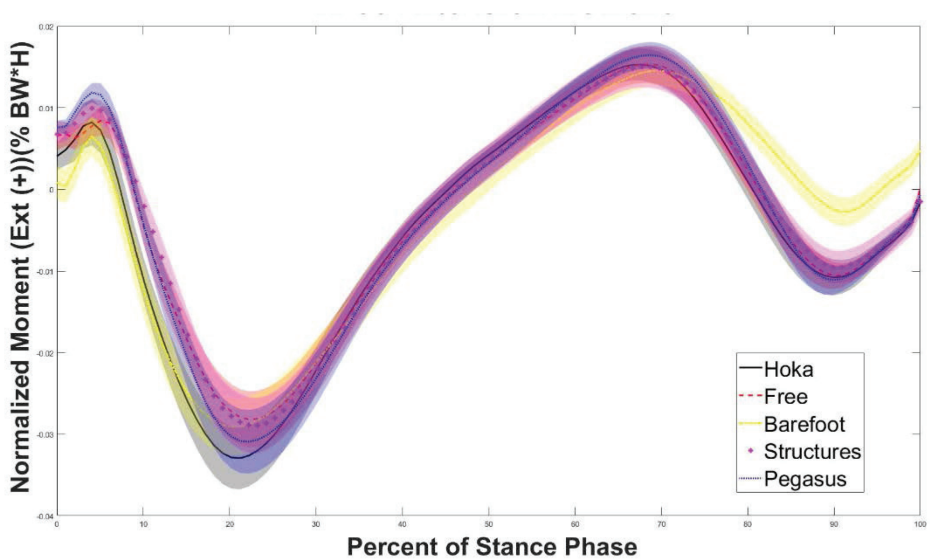

Figure 4.10: The external knee extension moment for all subjects normalized by subject body weight multiplied by their height. External knee flexion is negative.

Table 4.3: Peak knee adduction and flexion moments and the knee adduction moment impulse for all subjects, all normalized by the subject's body weight multiplied by their height. The paired t-test p-value comparing the condition to neutral are shown below each value. The standard error is included in parenthesis.

Variable	Value Type	BareFoot	Min.	Max.	Structures	Neutral
Peak Knee Adduction Moment %(BW*H)	Average	2.6 (0.2)	2.8 (0.2)	3.2 (0.3)	2.9 (0.2)	2.6 (0.2)
	P-Value	0.45	0.44	0.08	0.10	
Peak Knee Flexion Moment %(BW*H)	Average	3.2 (0.4)	3.2 (0.3)	3.6 (0.4)	3.2 (0.3)	3.4 (0.4)
	P-Value	0.60	0.43	0.30	0.40	
Knee Adduction Moment Impulse %(BW*H*s)	Average	0.7 (0.1)	0.7 (0.1)	0.8 (0.1)	0.8 (0.1)	0.7 (0.1)
	P-Value	0.06	0.80	0.26	0.30	

There were, again, no statistically significant differences for all the subjects when analyzed together, but some of the substantial differences seen in the female data still remained. The maximalist condition was still seen to increase all risk factors for knee OA. The stability shoes were also seen to increase the peak knee adduction moment. The minimalist shoes were, again, seen to perform similarly to the neutral condition.

Discussion and Conclusions

Discussion

It was hypothesized that the maximalist shoes would perform similarly to stability shoes and that the minimalist shoes would replicate the benefits of barefoot walking. The maximalist shoes were actually shown to perform worse when compared to the stability shoes and the minimalist shoes did not replicate the benefits of barefoot walking.

The barefoot walking data presented in this study are consistent with previous studies, in that barefoot walking reduced the risk factors for knee OA [171,180], but not nearly as significantly. This may be due to our subjects being young and healthy, making the trends less significant. Additionally, Shakoor et al. previously investigated stability shoes and they increased the peak knee adduction moment when compared to barefoot walking, which is consistent with the results seen in this study. [183] Following the comparison with previous studies that did utilize patients with knee OA, it is hypothesized that the trends in this study may be of clinical interest but will not be as significant as they would be in knee OA patients.

The main focus of this study was on maximalist and minimalist shoe conditions, because they have not been investigated heavily in this setting previously and there are reasons to think that the minimalist shoe would induce movements similar to barefoot walking and the maximalist shoes would possibly induce changes similar to a wedged orthotic due to the active j-frame technology. The maximalist shoes were shown to result in increases in all the risk factors for knee OA in both genders. It is hypothesized that this is due to the same reasons that were discussed in Chapter 2 of this thesis. These reasons are that the maximalist shoes reduce and control motion at the ankle, but this change corresponds to increased motion higher up the kinetic chain of the leg. The j-frame technology displayed in Figure 2.23 [45] may be more designed for running, but in walking it seems to unintentionally act as a medial wedge. It resulted in reduced eversion in running that was not replicated in walking. Opposite to the lateral wedge discussed in the introduction, this medial wedge may be inducing varus alignment when walking that is causing an increased knee adduction moment. This is interesting, because in the running data discussed in Chapter 2 of this thesis it had the opposite effect. This is due to the j-frame being designed to attenuate the shock from foot strike and then guide the foot through the remaining part of the stance phase. However, in walking, there is a reduced ground reaction force and instead of the increased cushion absorbing the force, it seems to induce an increased varus alignment that results in the observed increased knee adduction moment.

On the opposite side of the shoe spectrum, the minimalist shoes did not behave as hypothesized and did not replicate the benefits of barefoot walking. They seemed to closely resemble the results seen in the stability and neutral shoes. This is a bit counter-intuitive because they are designed to replicate barefoot conditions, but they instead seem to model a modern neutral shoe that has a decently large amount of cushion. It is hypothesized that the minimalist shoe isn't replicating the barefoot conditioning because it still has cushioning, even if it is a relatively smaller amount of cushioning. The cushioning is still enough to result in a rear foot strike pattern and thus many of the benefits associated with barefoot walking are lost.

The female subjects were seen to have more substantial changes across shoe conditions when compared to the male subjects. This was an interesting and unexpected finding that shows that females may be more mechanically influenced by a changed shoe condition. In general, females have a wider pelvis and a different frontal plane alignment of their body (q-angle) which might partially explain the different frontal plane kinetics observed in this study.

This study was done post hoc using unprocessed and unanalyzed walking data collected by Taveres et al. [186] The main limitation with this study is that it is only a pilot study that enrolled young and healthy subjects when investigating a painful condition that generally afflicts elderly individuals. Studying young and healthy individuals allows us to identify the mechanical changes caused by the shoes without concern for outside factors like pain or fatigue. While it is hypothesized that the trends observed in this pilot study will stay in the same direction and be more significant in knee OA patients, future studies are needed to confirm this hypothesis. Despite these limitations, this pilot data should serve as reference data for a follow-up study aimed patients with knee OA. The results of this study indicate that a maximalist shoe with an opposing j-frame might provide the cushioning needed for comfortable walking and might guide the foot away from the undesirable knee kinetics observed in this study. A future clinical trial aimed at conservative treatments for knee OA should probably not include the maximalist shoes unless there are future studies involving knee OA patients to support their inclusion or unless some changes are made to the underlying guidance technology.

Conclusion

Various shoe types were investigated for their mechanical effect on the risk factors for knee OA. The maximalist and minimalist shoes were focused on because their influence on these risk factors were largely uninvestigated and there were reasons to believe that these should could be beneficial. Maximalist shoes were shown to result in increased knee adduction and flexion moment as well as an increase in the knee adduction moment impulse, and this is attributed to the j-frame acting as a medial wedge.

The minimalist shoes were shown to perform similarly to the neutral and stability shoes and did not replicate barefoot walking. This was a pilot study that utilized young and healthy subjects, but may provide some reference data for future studies.

Future Works

It is recommended that a future study be aimed at investigating the influence of maximalist and minimalist shoes on the risk factors for knee OA using patients afflicted with knee OA. It is very possible the results may have increased trends or be significantly different from the results of this study. Of particular interest would be to develop a shoe that has a j-frame in the opposite configuration to see if this alteration would reduce the risk factors. This shoe might be ideal for the older knee OA patients since it would provide cushioning and foot stability, but possible reduce the risk factors for knee OA progression.

It is also suggested that a future study be done that compares how shoe influence may alter due to gender. This study presented results suggesting that females were more susceptible to mechanical changes due to altering shoe type, but with only nine females and eleven males, it is inconclusive. Therefore, it is recommended that a study recruit more male and female subjects and investigate if females do in fact experience greater changes due to altering shoe type.

CHAPTER FIVE

Conclusions

Differences between Maximalist and Minimalist Shoe Running Before and After a 5k Fatigue Protocol

A study was performed comparing the lower limb mechanics of runners while wearing maximalist and minimalist shoes following a fatigue protocol. The purpose of this study was to analyze the potentially beneficial or detrimental effects of these opposing shoe types on the kinetics and kinematics of fatigued runners. Decreased range of motion at the ankle and increased range of motion at the hip was observed in the maximalist shoes when compared to the minimalist shoes, which may put the individual at greater risk for patellofemoral pain syndrome. The maximalist shoes were shown to decrease excessive eversion, which may result in a decreased risk of tibial stress fractures compared to the minimalist shoes. Because of this, it is advised that running shoe type should be dependent upon what injuries a runner is historically more susceptible to develop. This study grants greater understanding of altered kinematics and kinetics in fatigued runners that result from commonly used running shoes. This allows for better shoe advisement and help guide future research in shoe technology. Future research should focus on how these results may change for forefoot strikers, for runners running on an uneven terrain, and for runners over a longer period of time running in the same shoe.

The Potential Influence of Treadmill Running In Fatigue Studies

A study was performed comparing the kinematics and kinetics of runners immediately after treadmill running and kinematics and kinetics after reacclimatizing to over ground running. The purpose of this study was to analyze the potential influence of treadmill running on over ground testing in research. This is a common occurrence for researchers that perform fatigue studies using a treadmill but perform testing over ground. Differences were found between trials that were collected immediately following the fatigue treadmill run and trials that were collected after a five minute over-ground acclimatization period. The acclimatization period resulted in a significant increase in the step width and a slight reduction in the step length in both the maximalist shoes and minimalist shoes. This resulted in an increased knee adduction, a reduced hip extension moment, and a slight increase to the leg stiffness in the maximalist shoes. The changes seen in the minimalist shoes were a decreased in hip abduction, a decrease in hip internal rotation, a decrease in pelvic drop, and a slight increase in loading rate. While some of these results showed statistical significance, they were small changes and may not hold clinical or research significance. It is therefore advised that an acclimatization period be included for studies with an interest in these changed variables and for the potential influence of the treadmill to be addressed when drawing conclusions in fatigue studies. Additionally, because it was found that different shoes respond differently to this transition period, shoe type should be controlled if they are not the variable of interest in the fatigue study. Future research should be done to investigate what length of an acclimatization period is necessary in order to eliminate influence from treadmill running.

Future research should also investigate how treadmills with increased length and width may reduce the changes observed in the running pattern.

The Effect of Shoes on Risk Factors Associated with Knee Osteoarthritis during Walking

A post hoc study was performed comparing the effect of maximalist, minimalist, stability, and neutral shoes as well as barefoot on knee OA progression risk factors while walking. The purpose of this study was to analyze if maximalist and minimalist shoes are detrimental or beneficial for knee OA progression. Minimalist and maximalist shoes were focused on because they are largely uninvestigated in this scope and may have potential benefits. Maximalist shoes are designed to reduce rear foot eversion, and may, therefore, reduce the varus alignment of the knee. Minimalist shoes are of interest because they are designed to replicate barefoot, which has been shown to have many benefits for knee OA. Maximalist shoes were shown to be detrimental to knee OA progression, and this is attributed to the j-frame behaving as a medial wedge and inducing increased varus alignment in walking and increasing risk factors. Minimalist shoes were shown to not replicate the benefits of barefoot walking like they were hypothesized to, and instead behaved similar to the neutral shoes. Therefore, it was found that the maximalist shoes were detrimental to knee OA progression and the minimalist shoes performed similarly to cushioned shoes instead of barefoot. Additionally, changes were seen to be more significant for female participants, likely due to their different frontal plane alignment (increased q-angle). This study was limited because it was performed on young and healthy subjects without knee OA symptoms, but this allowed for testing of all shoe conditions within one testing session without resulting in pain to participants. It is hypothesized that the trends observed in this study would stay in the same direction and be more significant for knee OA patients because of the similarities seen in the stability and barefoot conditions, but future studies are needed to confirm this hypothesis. Future studies should also investigate how this j-frame technology may be beneficial if it was placed laterally instead of medially. This may allow for the benefits of the maximalist shoe, increased cushioning and stability, while also reducing knee OA progression risk factors. Additionally, a study should recruit more females and males for an intervention study to confirm if females are more responsive to intervention techniques.

Significance

This thesis reported the differences in running mechanics resulting from altering shoe type in fatigued runners, particularly as these differences pertain to tibial stress fractures and patellofemoral pain syndrome. This will allow for better shoe recommendation to reduce running overuse injuries and better direct future shoe technology. This thesis also showed that it may be necessary to acclimatize runners back to over ground running after treadmill running if particular variables such as hip and knee adduction, hip internal rotation, vertical loading rate, hip extension moment, or leg stiffness are important to the study, because there may be altered running mechanics leftover from treadmill running. Finally, this thesis provided pilot data to show changes in knee OA risk factors due to varying shoe types, particularly maximalist and minimalist shoes. The findings suggest that the increasingly popular maximalist shoes may result in detrimental effects to knee OA progression by increasing the varus alignment of the knee. The findings also show that minimalist shoes do not replicate barefoot walking, but instead have similar effects to neutral shoes.

APPENDICES

APPENDIX A

All Post-Immediate Data

Minimalist Post-Immediate Data

Table A.1: Maximum, minimum, and range of motion angles and the associated standard error for the Post-Immediate condition in the minimalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase. Values are in degrees.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	27.9	-19.4	47.2	1.6	2.7	1.9	0.452	0.606	0.320
	Inversion	16.6	-3.2	19.7	1.7	2.6	1.7	0.699	0.845	0.656
	External Rotation	-0.6	-15.5	14.9	3.2	2.8	1.7	0.183	0.400	0.611
'Knee'	Flexion	45.9	13.3	32.6	1.4	1.8	0.9	0.904	0.254	0.174
	Adduction	6.2	-2.0	8.2	2.4	2.4	1.3	0.677	0.970	0.570
	Internal Rotation	-8.5	-28.4	20.0	5.0	6.1	2.2	0.798	0.285	0.394
'Hip'	Flexion	50.4	-2.2	52.6	1.9	0.8	1.8	0.575	0.027	0.312
	Adduction	10.9	-1.7	12.6	1.2	0.9	1.1	0.636	0.004	0.019
	Internal Rotation	10.5	-4.3	14.8	4.2	4.4	1.4	0.026	0.637	0.230
'Pelvic'	Tilt	-8.1	-17.8	9.7	1.4	1.4	0.8	0.406	0.780	0.259
	Obliquity	7.5	-9.2	16.7	1.9	0.6	2.0	0.716	0.002	0.653
	Rotation	8.6	-10.8	19.4	0.8	1.2	1.2	0.466	0.614	0.654

Table A.2: Maximum and minimum moments and the associated standard error for the Post-Immediate condition in the minimalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase. Values are %BW*H.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	0.47%	-16.8%	0.23%	0.79%	0.427	0.098
	Eversion	2.31%	-1.88%	1.02%	0.46%	0.562	0.947
	Internal Rotation	0.45%	-1.02%	0.16%	0.24%	0.368	0.852
'Knee'	Extension	2.34%	-15.6%	0.24%	1.09%	0.497	0.823
	Abduction	1.79%	-4.86%	0.64%	1.13%	0.357	0.378
	Internal Rotation	2.19%	-0.17%	0.32%	0.04%	0.133	0.447
'Hip'	Extension	3.56%	-10.8%	0.33%	0.64%	0.430	0.515
	Abduction	1.73%	-9.73%	0.26%	0.65%	0.542	0.283
	Internal Rotation	1.49%	-4.46%	0.23%	0.40%	0.973	0.078
'FreeMoment'		0.58%	-0.19%	0.15%	0.06%	0.248	0.326

Table A.3: Additional variables investigated and their associated standard error for the Post-Immediate condition in the minimalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	1.46	0.04	0.02	0.01	0.108	0.156
'Cadence'	time/step	0.35	s	0.01		0.951	
'K_Leg'	Stiffness	8345.52	kN*m	354.31		0.247	
VGRF	Max Force	2.64	N/BW	0.06		0.492	
VIP	Impact Force	1.56	N/BW	0.09		0.567	
VALR	AverageRate	57.05	N/BW*s	7.29		0.087	
VILR	Max Rate	113.08	N/BW*s	3.77		0.653	

Maximalist Post-Immediate Data

Table A.4: Maximum, minimum, and range of motion angles and the associated standard error for the Post-Immediate condition in the maximalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	27.6	-20.7	48.3	1.8	2.5	2.2	0.639	0.761	0.894
	Inversion	16.4	-1.0	17.4	1.7	2.3	1.8	0.997	0.869	0.908
	External Rotation	2.2	-11.5	13.7	2.0	2.0	1.4	0.880	0.685	0.523
'Knee'	Flexion	46.7	13.3	33.3	2.2	2.5	1.2	0.485	0.857	0.281
	Adduction	9.1	-0.2	9.3	2.3	1.8	1.4	0.022	0.734	0.084
	Internal Rotation	-9.7	-29.6	19.9	3.0	3.2	1.6	0.654	0.800	0.996
'Hip'	Flexion	49.2	-2.8	52.0	2.8	1.8	1.4	0.745	0.186	0.475
	Adduction	11.9	-0.5	12.4	1.4	0.9	0.9	0.138	0.340	0.192
	Internal Rotation	14.9	-0.1	15.0	3.2	3.5	1.3	0.651	0.878	0.776
'Pelvic'	Tilt	-10.0	-19.1	9.0	1.1	1.4	0.7	0.576	0.627	0.964
	Obliquity	8.9	-9.7	18.6	1.0	0.7	1.4	0.689	0.552	0.464
	Rotation	10.2	-10.1	20.3	1.4	0.9	1.0	0.655	0.223	0.016

Table A.5: Maximum and minimum moments and the associated standard error for the Post-Immediate condition in the maximalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	0.80%	-15.0%	0.18%	0.93%	0.524	0.380
	Eversion	1.73%	-1.43%	0.39%	0.21%	0.863	0.173
	Internal Rotation	0.30%	-1.18%	0.04%	0.20%	0.318	0.536
'Knee'	Extension	1.93%	-16.3%	0.28%	0.82%	0.301	0.166
	Abduction	1.49%	-5.93%	0.26%	1.44%	0.087	0.352
	Internal Rotation	2.37%	-0.18%	0.43%	0.04%	0.238	0.988
'Hip'	Extension	5.64%	-9.88%	0.75%	0.48%	0.005	0.304
	Abduction	1.83%	-9.35%	0.19%	0.90%	0.545	0.431
	Internal Rotation	1.79%	-4.38%	0.36%	0.37%	0.610	0.281
'FreeMoment'		0.551%	-0.17%	0.134%	0.068%	0.809	0.175

Table A.6: Additional variables investigated and their associated standard error for the Post-Immediate condition in the maximalist shoes, and the paired t-test p-value comparing the values to the Post-Fatigue condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	1.47	0.03	0.05	0.01	0.083	0.011
'Cadence'	time/step	0.35	s	0.01		0.531	
'K_Leg'	Stiffness	8193.63	kNm	280.03		0.405	
VGRF	Max Force	2.60	N/BW	0.05		0.810	
VIP	Impact Force	1.71	N/BW	0.13		0.915	
VALR	AverageRate	65.58	N/BW*s	9.33		0.461	
VILR	Max Rate	113.05	N/BW*s	5.13		0.932	

APPENDIX B

All Walking Data

Minimalist Walking Data

Table B.1: Maximum, minimum, and range of motion angles and the associated standard error in the minimalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	13.4	-18.3	31.7	0.8	1.6	1.1	0.433	0.188	0.365
	Inversion	15.9	3.3	12.6	1.3	1.1	0.8	0.532	0.669	0.609
	External Rotation	-2.3	-17.7	15.4	1.1	1.3	0.7	0.050	0.191	0.577
'Knee'	Flexion	42.1	-0.7	42.9	1.4	0.8	1.3	0.148	0.569	0.128
	Adduction	3.9	-1.6	5.5	0.8	0.6	0.4	0.470	0.416	0.851
	Internal Rotation	-16.0	-30.0	14.0	1.7	1.4	0.9	0.923	0.391	0.171
'Hip'	Flexion	33.7	-7.2	40.9	1.7	1.3	1.3	0.098	0.652	0.201
	Adduction	7.9	-6.2	14.1	0.4	0.7	0.7	0.999	0.501	0.560
	Internal Rotation	9.8	-2.9	12.7	1.5	1.6	0.6	0.737	0.755	0.952
'Pelvic'	Tilt	-8.3	-12.7	4.4	1.3	1.2	0.4	0.366	0.436	0.271
	Obliquity	6.2	-7.6	13.8	0.7	0.6	0.8	0.264	0.215	0.427
	Rotation	6.0	-8.7	14.7	1.3	0.6	1.1	0.251	0.166	0.625

Table B.2: Maximum and minimum moments and the associated standard error for the minimalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	1.21%	-8.45%	0.15%	0.18%	0.853	0.791
	Eversion	0.56%	-1.72%	0.08%	0.16%	0.335	0.722
	Internal Rotation	0.23%	-0.81%	0.03%	0.06%	0.793	0.623
'Knee'	Extension	1.20%	-3.20%	0.11%	0.34%	0.095	0.431
	Abduction	0.65%	-2.77%	0.08%	0.22%	0.255	0.443
	Internal Rotation	0.76%	-0.74%	0.07%	0.05%	0.683	0.998
'Hip'	Extension	6.43%	-4.86%	0.39%	0.35%	0.208	0.691
	Abduction	0.95%	-5.24%	0.11%	0.20%	0.026	0.568
	Internal Rotation	0.63%	-1.75%	0.06%	0.14%	0.973	0.078

Table B.3: Additional variables investigated and their associated standard error for the minimalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	0.74	0.09	0.04	0.01	0.985	0.213
'Speed'	Walking Pace	1.39	m/s	0.04		0.055	
'Cadence'	time/step	0.49	s	0.02		0.637	
'K_Leg'	Stiffness	5553.53	kNm	285.57		0.003	

Table B.4: Maximum, minimum, and range of motion angles and the associated standard error for maximalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	12.4	-13.7	26.1	1.0	1.5	1.3	0.027	0.035	0.007
	Inversion	15.5	4.8	10.7	1.2	1.1	1.0	0.248	0.243	0.006
	External Rotation	-2.0	-16.1	14.1	2.1	1.9	0.7	0.417	0.953	0.051
'Knee'	Flexion	42.5	0.6	41.8	2.3	1.1	2.1	0.485	0.104	0.159
	Adduction	5.0	-1.2	6.3	0.8	0.8	0.5	0.147	0.849	0.028
	Internal Rotation	-17.7	-29.7	12.0	2.4	2.1	1.0	0.402	0.757	0.141
'Hip'	Flexion	34.3	-5.9	40.2	1.8	1.3	1.6	0.558	0.154	0.228
	Adduction	7.5	-5.4	12.9	0.5	0.7	0.7	0.319	0.049	0.077
	Internal Rotation	9.2	-2.1	11.3	1.6	1.7	0.6	0.463	0.263	0.095
'Pelvic'	Tilt	-8.5	-12.7	4.2	1.3	1.2	0.5	0.506	0.509	0.803
	Obliquity	5.2	-7.5	12.8	0.9	0.5	0.8	0.655	0.398	0.398
	Rotation	5.9	-8.8	14.7	1.4	0.8	1.0	0.335	0.420	0.754

Table B.5: Maximum and minimum moments and the associated standard error for the maximalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	1.25%	-8.17%	0.14%	0.40%	0.587	0.435
	Eversion	0.76%	-1.67%	0.14%	0.19%	0.014	0.948
	Internal Rotation	0.25%	-0.88%	0.03%	0.08%	0.204	0.583
'Knee'	Extension	1.11%	-3.64%	0.20%	0.35%	0.281	0.298
	Abduction	0.52%	-3.23%	0.13%	0.31%	0.136	0.079
	Internal Rotation	0.88%	-0.77%	0.10%	0.07%	0.190	0.675
'Hip'	Extension	6.14%	-4.88%	0.34%	0.48%	0.844	0.875
	Abduction	0.96%	-5.51%	0.15%	0.37%	0.184	0.310
	Internal Rotation	0.75%	-1.89%	0.09%	0.21%	0.373	0.399

Table B.6: Additional variables investigated and their associated standard error for the maximalist shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	0.72	0.09	0.02	0.01	0.136	0.842
'Speed'	Walking Pace	1.41	m/s	0.04		0.327	
'Cadence'	time/step	0.35	s	0.01		0.951	
'K_Leg'	Stiffness	5797.44	kNm	505.69		0.045	

Table B.7: Maximum, minimum, and range of motion angles and the associated standard error for barefoot, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	12.0	-16.5	28.6	0.7	1.4	1.3	0.001	0.732	0.122
	Inversion	18.2	3.2	15.0	1.4	1.3	1.2	0.324	0.660	0.091
	External Rotation	0.8	-15.2	16.0	1.2	1.1	0.8	0.328	0.425	0.910
'Knee'	Flexion	32.6	1.6	31.0	1.9	0.8	1.6	0.000	0.001	0.000
	Adduction	4.4	-1.3	5.7	0.8	0.6	0.4	0.477	0.765	0.476
	Internal Rotation	-17.7	-32.5	14.8	1.7	1.6	0.8	0.217	0.008	0.025
'Hip'	Flexion	33.2	-5.0	38.2	1.7	1.5	1.3	0.095	0.043	0.010
	Adduction	7.7	-4.0	11.7	0.4	0.7	0.7	0.619	0.000	0.001
	Internal Rotation	9.0	-2.1	11.1	1.5	1.7	0.6	0.315	0.287	0.048
'Pelvic'	Tilt	-8.7	-12.8	4.1	1.3	1.3	0.3	0.540	0.409	0.529
	Obliquity	4.0	-7.5	11.4	0.7	0.7	0.7	0.037	0.094	0.013
	Rotation	6.6	-8.5	15.1	1.2	0.7	1.0	0.947	0.919	0.875

Table B.8: Maximum and minimum moments and the associated standard error for barefoot, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	0.64%	-7.76%	0.09%	0.37%	0.000	0.046
	Eversion	0.48%	-1.70%	0.08%	0.18%	0.746	0.909
	Internal Rotation	0.21%	-0.82%	0.03%	0.08%	0.492	0.916
'Knee'	Extension	0.98%	-3.24%	0.21%	0.35%	0.052	0.597
	Abduction	0.62%	-2.55%	0.05%	0.20%	0.110	0.447
	Internal Rotation	0.75%	-0.62%	0.08%	0.05%	0.490	0.010
'Hip'	Extension	4.76%	-4.73%	0.33%	0.40%	0.001	0.641
	Abduction	0.90%	-4.95%	0.12%	0.21%	0.029	0.349
	Internal Rotation	0.60%	-1.60%	0.07%	0.13%	0.424	0.178

Table B.9: Additional variables investigated and their associated standard error for barefoot, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	0.69	0.09	0.03	0.01	0.136	0.842
'Speed'	Walking Pace	1.33	m/s	0.04		0.003	
'Cadence'	time/step	0.51	s	0.01		0.132	
'K_Leg'	Stiffness	7917.17	kNm	566.19		0.000	

Table B.10: Maximum, minimum, and range of motion angles and the associated standard error for the stability shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)			P-Value (Paired t-test)		
		Max	Min	ROM	Max Error	Min Error	ROM Error	Max	Min	ROM
'Ankle'	Dorsi-flexion	13.7	-15.1	28.8	0.7	1.4	1.2	0.794	0.088	0.052
	Inversion	15.8	3.6	12.2	1.7	1.3	0.9	0.592	0.922	0.296
	External Rotation	-0.5	-15.3	14.9	1.2	1.5	0.9	0.873	0.464	0.242
'Knee'	Flexion	41.4	-1.1	42.5	1.9	0.7	2.0	0.171	0.723	0.200
	Adduction	4.1	-1.4	5.5	0.7	0.6	0.5	0.862	0.932	0.815
	Internal Rotation	-15.5	-28.7	13.2	1.6	1.6	0.8	0.414	0.475	0.951
'Hip'	Flexion	33.6	-6.5	40.1	1.7	1.5	1.6	0.246	0.654	0.168
	Adduction	7.5	-6.0	13.5	0.4	0.7	0.8	0.238	0.382	0.115
	Internal Rotation	8.7	-3.6	12.3	1.4	1.5	0.7	0.095	0.383	0.341
'Pelvic'	Tilt	-8.7	-12.6	3.8	1.2	1.2	0.3	0.635	0.276	0.125
	Obliquity	4.9	-7.8	12.7	0.6	0.5	0.7	0.482	0.646	0.336
	Rotation	5.8	-9.0	14.8	1.3	0.6	1.2	0.157	0.354	0.670

Table B.11: Maximum and minimum moments and the associated standard error for the stability shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)		P-Value (Paired t-test)	
		Max	Min	Max Error	Min Error	Max	Min
'Ankle'	Plantar-Flexion	1.24%	-8.25%	0.11%	0.29%	0.565	0.432
	Eversion	0.54%	-1.56%	0.07%	0.16%	0.573	0.351
	Internal Rotation	0.22%	-0.87%	0.03%	0.06%	0.987	0.404
'Knee'	Extension	1.21%	-3.19%	0.09%	0.31%	0.129	0.395
	Abduction	0.48%	-2.88%	0.07%	0.17%	0.003	0.100
	Internal Rotation	0.77%	-0.77%	0.08%	0.06%	0.822	0.503
'Hip'	Extension	6.17%	-4.44%	0.43%	0.35%	0.919	0.102
	Abduction	0.85%	-5.32%	0.13%	0.16%	0.015	0.253
	Internal Rotation	0.63%	-1.68%	0.05%	0.10%	0.321	0.646

Table B.12: Additional variables investigated and their associated standard error for the stability shoes, and the paired t-test p-value comparing the values to the neutral condition during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	0.73	0.10	0.02	0.01	0.359	0.513
'Speed'	Walking Pace	1.39	m/s	0.04		0.109	
'Cadence'	time/step	0.53	s	0.01		0.203	
'K_Leg'	Stiffness	5472.50	kNm	232.16		0.029	

Table B.13: Maximum, minimum, and range of motion angles and the associated standard error for the neutral shoes during stance phase.

Variable	Positive Orientation	Value (Degrees)			Error (Degrees)		
		Max	Min	ROM	Max Error	Min Error	ROM Error
'Ankle'	Dorsi-flexion	13.8	-17.0	30.8	0.9	1.4	1.1
	Inversion	16.7	3.8	12.9	1.1	0.9	0.8
	External Rotation	-0.3	-16.2	15.9	1.0	1.1	0.7
'Knee'	Flexion	44.0	-0.9	44.9	1.3	0.9	1.3
	Adduction	4.2	-1.4	5.6	0.7	0.5	0.5
	Internal Rotation	-16.1	-29.3	13.2	1.6	1.6	0.9
'Hip'	Flexion	34.9	-6.9	41.8	1.7	1.4	1.2
	Adduction	7.9	-6.4	14.4	0.5	0.5	0.6
	Internal Rotation	9.6	-3.1	12.7	1.5	1.5	0.7
'Pelvic'	Tilt	-8.6	-12.9	4.3	1.2	1.2	0.4
	Obliquity	5.7	-7.9	13.6	0.5	0.6	0.8
	Rotation	6.2	-8.8	15.1	1.5	0.7	1.0

Table B.14: Maximum and minimum moments and the associated standard error for the neutral shoes during stance phase.

Variable	Positive Orientation	Value (Degrees)		Error (Degrees)	
		Max	Min	Max Error	Min Error
'Ankle'	Plantar-Flexion	1.18%	-8.52%	0.09%	0.18%
	Eversion	0.51%	-1.68%	0.06%	0.15%
	Internal Rotation	0.22%	-0.83%	0.02%	0.06%
'Knee'	Extension	1.36%	-3.38%	0.10%	0.40%
	Abduction	0.74%	-2.64%	0.06%	0.18%
	Internal Rotation	0.79%	-0.74%	0.07%	0.06%
'Hip'	Extension	6.20%	-4.95%	0.37%	0.37%
	Abduction	1.19%	-5.11%	0.11%	0.16%
	Internal Rotation	0.67%	-1.72%	0.06%	0.12%

Table B.15: Additional variables investigated and their associated standard error for the neutral shoes during stance phase.

Variable	Variable Type	Value		Error		P-Value (Paired t-test)	
'Step'	Length & Width (m)	0.73	0.10	0.02	0.01	0.359	0.513
'Speed'	Walking Pace	1.39	m/s	0.04		0.109	
'Cadence'	time/step	0.53	s	0.01		0.203	
'K_Leg'	Stiffness	5472.50	kNm	232.16		0.029	

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