Does Changing Step Width Alter Lower Extremity Biomechanics During Running?

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DEDICATION

This work is dedicated to my family and my fiancé. Your love, above all things, inspires me to pursue my passion.

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ABSTRACT

A large percentage of runners incur a running related injury, with injury occurring most frequently at the knee. Runners with the most common overuse knee injuries have associated biomechanics that differ from healthy runners. Altering step width while running may influence those associated biomechanics. The purpose of this study was to determine the biomechanical response of lower extremity joints in healthy runners to increasing and decreasing step width during running. A preferred step width condition was collected first, followed in randomized order by a narrow step width condition and a wide step width condition. Step width was decreased to 0% of participant's leg length during the narrow condition, and increased to 20% of participant's leg length during the wide condition. Step width, peak lower extremity angles, peak lower extremity moments, and knee abduction impulse were recorded. Step width changed successfully in all conditions, and was similar between genders with no interaction effect. Peak hip adduction angle decreased as step width increased from narrowest to widest, and was larger in women compared to men without an interaction effect. Peak hip internal rotation angle remained similar among step width conditions and genders, with no interaction effect. Peak knee internal rotation angle increased when step width increased from narrowest to widest, and was larger in women than men with no interaction effect. Peak knee abduction moment decreased when step width increased from narrowest to widest, and was larger in men than women with no interaction effect. Knee abduction angular impulse decreased when step width increased from narrowest to widest, and was larger in men than women, with no interaction effect. Peak rearfoot

eversion angle decreased when step width increased from narrowest to widest and was larger in women, with no interaction effect. Peak rearfoot inversion moment had a significant interaction effect, and decreased in male runners more than in female runners as step width increased from narrowest to widest. Findings suggest frontal plane biomechanics of healthy runners are influenced by step width.

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CHAPTER I

INTRODUCTION

Step Width during Running

Altering step width during running has been shown to change rearfoot kinematics in healthy runners (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). The knee and hip joints' response to altered step width during running have not been reported. Changes could also occur in knee and hip joint biomechanics when step width is altered during running. Injury to the knee is the most commonly reported overuse injury affecting runners (Taunton, et al. 2002; van Gent, et al. 2007). Runners with previous knee injury run with different biomechanics compared to healthy runners (Dierks, et al. 2011; Ferber, et al. 2010; Messier, et al. 1995; Noehren, et al. 2007; Souza & Powers 2009; Stefanyshyn, et al. 2006; Willson & Davis 2008). The response of the lower extremity joints to altering step width during running in healthy runners may reflect the biomechanics of runners with previous knee injuries. Women have different hip and knee joint biomechanics during running than men (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001). Therefore, there may be gender differences in the reaction to altered step width during running.

Step Width

Step width is a frontal plane spatio-temporal parameter. Research on the effects that altering step width during running has on lower extremity joint biomechanics is limited. The size of step width is different among ambulation tasks and individuals (Arellano &

Kram 2011; Donelan, et al. 2001; Owings & Grabiner 2003). During running, the amount of step width is chosen according to efficiency in metabolic cost (Arellano & Kram 2011). Only forefoot, rearfoot, and shank eversion, along with peak rearfoot angles have been reported with changes in step width during running (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). When step width is increased, rearfoot eversion excursion (Kersting & Neumann 1999) and peak rearfoot pronation decreases compared to preferred step width during running (Williams & Ziff 1991). When step width is decreased during running, peak rearfoot eversion angle (Pohl, et al. 2006), peak rearfoot pronation (Williams & Ziff 1991), and rearfoot eversion excursion increases compared to preferred step width (Kersting & Neumann 1999; Pohl, et al. 2006). Two methods to alter preferred step width during running have been reported. One method to alter step width is by use of a reference line (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). Instructions to increase or decrease step width is given in relation to a single line running down the center of the test runway. In another study, participants ran on a treadmill while watching their foot landing placement in vivo on a computer screen (Arellano & Kram 2011). Participants were instructed to land the mid heel of each foot on the designated virtual line(s) to increase or decrease their preferred step width during running. Both methods were able to successfully increase and decrease step width.

Knee Injuries in Runners

The most common running related knee injuries are patellofemoral pain (PFP) and iliotibial band syndrome (ITBS) (Taunton, et al. 2002; van Gent, et al. 2007). Previous

research has compared the lower extremity biomechanics of runners with current PFP or a history of ITBS to healthy runners. Discovering biomechanics that are specific to runners with current PFP or a history of ITBS may give insight to the injury mechanisms. At the hip joint, runners with PFP display both larger and smaller peak adduction angles compared to healthy runners (Dierks, et al. 2011; Willson & Davis 2008). Runners with a history of ITBS elicit larger peak hip adduction angles compared to healthy runners (Ferber, et al. 2010; Noehren, et al. 2007). Runners with PFP display both larger and smaller peak hip internal rotation angles when compared with healthy runners (Souza & Powers 2009; Willson & Davis 2008). At the knee joint, differences exist between healthy runners and runners with PFP or with a history of ITBS during running (Dierks, et al. 2011; Ferber, et al. 2010; Noehren, et al. 2007; Stefanyshyn, et al. 2006; Willson & Davis 2008). In the frontal plane, runners with PFP have larger knee abduction impulses compared to healthy runners (Stefanyshyn, et al. 2006). In the transverse plane, runners with PFP display larger knee external rotation angles at the time of peak knee extension moment than healthy runners (Willson & Davis 2008). Runners with previous ITBS displayed larger peak knee internal rotation angles than healthy runners (Ferber, et al. 2010; Noehren, et al. 2007). Peak knee flexion angle during running was also shown to be smaller in runners with PFP compared to healthy runners (Dierks, et al. 2011). Differences have also been reported in rearfoot biomechanics between healthy runners and runners with PFP or previous ITBS. Runners with PFP have a smaller rearfoot pronation change at the beginning of stance compared to healthy runners (Duffey, et al. 2000). Runners with previous ITBS have a smaller calcaneal to vertical touchdown angle compared to healthy runners (Messier, et al. 1995).

Gender Differences in Running Kinematics

Studies comparing the biomechanics of men and women during running have reported kinematic differences in the hip and knee joint (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001). At the hip joint, women exhibit a larger peak hip adduction angle and adduction excursion compared to men during the stance phase of running (Chumanov, et al. 2008; Ferber, et al. 2003). Women also run with a larger peak hip internal rotation angle and hip external rotation excursion compared to men (Chumanov, et al. 2008; Ferber, et al. 2003). At the knee joint, women have a larger peak knee adduction angle during the stance phase of running compared to men (Ferber, et al. 2003; Malinzak, et al. 2001). A smaller peak knee flexion angle has also been reported in women compared to men while running (Malinzak, et al. 2001).

Purpose

The purpose of this study is to determine the biomechanical response of the lower extremity to altering step width during running in healthy runners.

Hypotheses

1. Peak hip adduction angle during running will be similar among the step width conditions and genders.
2. Peak hip internal rotation angle during the stance phase of running will be similar among the step width conditions and genders.

3. Peak knee internal rotation angle during the stance phase of running will be similar among the step width conditions and genders.
4. Peak knee abduction moment during the stance phase of running will be similar among the step width conditions and genders
5. Knee abduction angular impulse during the stance phase of running will be similar among the step width conditions and genders.
6. Peak rearfoot eversion angle during the stance phase of running will be similar among the step width conditions and genders.
7. Peak rearfoot inversion moment during the stance phase of running will be similar among the step width conditions and genders.

PART 1

CHAPTER II – III

LITERATURE REVIEW, MATERIALS AND METHODS

ABSTRACT

Runners with either of the two most common running injuries, PFP or ITBS, have different lower extremity biomechanics during running than healthy runners. Altering step width during running in healthy runners may change the lower extremity biomechanics that are associated with PFP and ITBS. This study observed the effect of changing step width during running in healthy runners on lower extremity biomechanics. Participants ran in three step width conditions: preferred, narrow, and wide step width, at a standardized running velocity. The preferred step width condition was collected first, collection of the narrow and wide step width proceeded in randomized order. Tape, attached to the ground, was positioned along the runway in the testing apparatus to alter step width based on the participant's leg length. A nine camera motion capturing system (Vicon, Oxford, UK), and a synchronized force plate (Advanced Mechanical Technology, Inc., Watertown, MA) recorded trial data. Trial data were processed in Visual 3D (C-Motion, Germantown, MD), and custom matlab software (MathWorks, Natick, MA) was used to extract the dependent variables. The dependent variables were analyzed statistically using a 2 x 3 mixed model ANOVA (SPSS Inc, Chicago Ill.). Differences were considered significant if $p < 0.05$

CHAPTER II

LITERATURE REVIEW

The popularity of running in the United States is evident in the average annual increase of 17,300 marathon participants over the last seven years (Lamppa 2010). Since 2004, estimated participation in the marathon has grown from 386,000 runners to 507,000 runners in 2010 (Lamppa 2010). Details of running biomechanics can be examined through kinematic and kinetic results, as well as spatio-temporal parameters. The influence of spatio-temporal parameters, specifically step width, on running kinematics is only partially documented in the literature. The effects of altering preferred step width during running have only been reported for rearfoot kinematics (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). The biomechanics of runners with and without running related injuries have been compared in an attempt to find possible explanations for these injuries. Differences in lower extremity biomechanics have been found between healthy and injured runners (Dierks, et al. 2011; Duffey, et al. 2000; Ferber, et al. 2010; Messier, et al. 1995; Noehren, et al. 2007; Souza & Powers 2009; Stefanyshyn, et al. 2006; Willson & Davis 2008). Running related injuries occur most commonly at the knee joint and include patella-femoral pain (PFP) and iliotibial band syndrome (ITBS) (Taunton, et al. 2002; van Gent, et al. 2007). It's estimated that 42.1% of all running related injuries occur at the knee, and 46% of those were classified as PFP (Taunton, et al. 2002). The biological mechanism for PFP is unknown, currently it is thought that a combination of factors, including biomechanics, lead to the overuse injury (Duffey, et al. 2000). PFP involves pain in the anterior aspect of the patella that worsens with running (Dierks, et al. 2011). ITBS is a painful inflammatory response to

repeated friction of the iliotibial band against the lateral femoral epicondyle (Whiting & Zernicke 2008). The iliotibial band starts to create friction against the lateral femoral epicondyle around 30° of flexion (Orchard, et al. 1996). ITBS is the second most frequent occurring injury to runners (Taunton, et al. 2002). Step width is a frontal plane spatio-temporal parameter. Altering the preferred step width in runners may yield beneficial results that will counter the biomechanics seen in runners with a history of knee injuries. Gender differences in running biomechanics may influence the response to step width changes during running. This chapter will focus on reviewing the literature in these three main areas – step width during running, knee injuries in runners, and gender differences in running biomechanics.

Step Width during Running

Spatio-temporal parameters variables are used commonly to describe gait characteristics. Step width is one spatio-temporal parameter that has been observed in all types of participants and locomotion tasks. Step width has been defined as the medio-lateral distance between contra-lateral heels (Arellano & Kram 2011), contra-lateral ankle joints (Williams & Ziff 1991), as well as contra-lateral toes (Pohl, et al. 2006) at initial ground contact.

Influence of Step Width on Gait

Step width values may vary between individuals while performing similar locomotion task (Owings & Grabiner 2003). Likewise, different sized step widths are found among

different locomotion tasks (Arellano & Kram 2011; Donelan, et al. 2001). The average step width during running, ~3.95% of leg length (Arellano & Kram 2011), is smaller than the average step width during walking, ~12% of leg length (Donelan, et al. 2001), in humans. Currently, no study exists that focuses on how altering step width during running influences hip and knee joint biomechanics. Some studies, however, have reported the effects of altering step width during running in forefoot, rearfoot, and shank variables (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991).

Biomechanics of Altered Step Widths during Running

In the current literature, only rearfoot, forefoot, and shank kinematic responses to altered step width during running have been reported (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). When runners increase their preferred step width, decreases are seen in rearfoot eversion excursion (Kersting & Neumann 1999) and peak rearfoot eversion angle (Williams & Ziff 1991). In one study, peak rearfoot eversion, rearfoot eversion excursion, forefoot abduction and dorsiflexion angles did not change as the preferred step width was increased (Pohl, et al. 2006). Running with a crossover step width is defined as landing with the lateral borders of each foot just inside the mid-line of progression (Pohl, et al. 2006). In the crossover condition, subjects ran with a greater rearfoot eversion excursion than running with a preferred step width (Kersting & Neumann 1999; Williams & Ziff 1991). Peak rearfoot eversion angle also increased during the crossover condition compared to running with a preferred step width (Pohl, et al. 2006; Williams & Ziff 1991). Reports also note that rearfoot eversion excursion, and forefoot dorsiflexion excursion increase while forefoot

abduction excursion decreases with a crossover step width (Pohl, et al. 2006). No changes have been reported in shank internal rotation excursion in response to an increased or crossover step width (Pohl, et al. 2006). Lower extremity kinematics in response to altered step width during running is scarce due to a limited amount of literature available on this topic. Furthermore, several different methods of manipulating running step width have been reported in the literature (Arellano & Kram 2011; Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991).

Methods to Alter Preferred Step Width during Running

In each reported attempt to manipulate step width during running, a visual marker was employed and verbal directions were given (Arellano & Kram 2011; Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). A reference line down the middle of a running surface was the visual marker for the studies that reported kinematics (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). In one study, subjects were instructed to run with a step width 5cm greater than their preferred step width for the increased condition (Kersting & Neumann 1999). In that study, the reported crossover condition instructions for subjects was to cross the midline (Kersting & Neumann 1999). It is unclear whether step width increased or decreased in this study as the change in step width among conditions was not reported. In a different study, subjects were instructed to run with normal, wide, and cross-over step widths according to a reference line on the floor (Pohl, et al. 2006). During the wide step width condition, subjects were instructed to keep their right and left feet to the corresponding sides of the reference line (Pohl, et al. 2006). For the cross-over step width condition, subjects

were instructed to land the lateral borders of each foot inside the line (Pohl, et al. 2006). Subjects were also instructed to run along the reference line during the normal step width condition (Pohl, et al. 2006). The subject's change in step width during running was significant between conditions (Pohl, et al. 2006). During running, participant's average wide step width was 0.11m, their average crossover step width was -0.07m, and their average normal step width was 0.05m (Pohl, et al. 2006). A third study utilized a reference line on a treadmill belt to manipulate step width while running (Williams & Ziff 1991). Participants were instructed to crossover the midline, run on the midline, and increase step width for the crossover, middle (normal), and wide step width conditions respectively (Williams & Ziff 1991). Step width changed significantly between the wide (4.2cm), middle (1.0cm), and crossover (-1.9cm) conditions using this method (Williams & Ziff 1991). Altered step width was also reported in a study that examined the effects of altered running parameters on energy consumption (Arellano & Kram 2011). While running on a treadmill, a monitor displayed in vivo foot placement via virtual markers that were positioned on the feet (Arellano & Kram 2011). Two virtual lines positioned along the anterior-posterior axis of the feet were also displayed on the monitor (Arellano & Kram 2011). The subjects were told to land the feet with the heel marker images on the virtual lines during running (Arellano & Kram 2011). The virtual lines were adjusted to 0%, 15%, 20% and 25% of the subject's leg length while running (Arellano & Kram 2011). The average step width during running was reported as 3.95% of leg length (Arellano & Kram 2011). It was noted that virtual lines were indistinguishable when distanced less than 13% of leg length apart (Arellano & Kram 2011). For this reason, step width during running was first increased to 15% of leg length (Arellano & Kram

2011). As step width increased, most subjects became unable to reach the target step width during running (Arellano & Kram 2011). The largest step width achieved was 16.74% of leg length ±1.05 SD, during the 25% of leg length condition (Arellano & Kram 2011). Subjects were slightly closer to achieving the target step width during the 20% and the 15% conditions, averaging 14.31% of leg length ±1.08 SD, and 11.78% of leg length ±0.91 SD respectively (Arellano & Kram 2011). A reason for the inability to run at target step widths could be associated with the experimental set-up. Subjects may have felt that it was dangerous to increase step width on a treadmill during running. Step width increases may have been limited in an attempt to stay clear of the edge of the treadmill belt.

Summary

Studies that altered step width during running are limited, and fewer studies have reported running step width (Arellano & Kram 2011; Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). Increased or decreased step width during running might result in different hip, knee, and rearfoot biomechanics. Varying step width during running significantly changes rearfoot kinematics (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991), but changes at the hip and knee joints are still unknown. Changes in lower extremity biomechanics caused by increasing and decreasing preferred step width during running may reflect those seen in runners with knee pain.

Knee Injuries in Runners

The number of adults treated for running related injuries in America has risen from an estimated 8,000 in 1991 to over 30,000 in 1998 (NEISS 2000). The most frequently reported site of running injuries is at the knee joint (van Gent, et al. 2007). ITBS and PFP are two of the most common running-related injuries, and they occur at the knee (Taunton, et al. 2002). Women are about two times more likely to experience ITBS or PFP at the knee compared to men (Taunton, et al. 2002). One reason women are more prone to running related knee injuries than men may be due to anatomical differences (Taunton, et al. 2002). On average, hip width to femur length ratio in women is larger compared to men (Horton & Hall 1989). Hip width is the distance between greater trochanters, and femur length is measured from the greater trochanter to the lateral knee joint space (Horton & Hall 1989). This larger hip width to femur length ratio seen in women could lead to increasing susceptibility to injury around the knee (Horton & Hall 1989). Accordingly, most of the current ITBS and PFP biomechanics research focuses on women (Ferber, et al. 2010; Noehren, et al. 2007; Souza & Powers 2009; Willson & Davis 2008). Biomechanical research has sought to uncover the kinematic and kinetic reasons why some runners develop knee injuries while others do not. Studies that address this issue have compared hip, knee and rearfoot kinematics between runners with PFP or ITBS to healthy runners.

Frontal Plane Hip Biomechanics

Differences exist between runners with PFP or a history of ITBS and healthy runners in frontal plane hip kinematics (Ferber, et al. 2010; Noehren, et al. 2007; Souza & Powers

2009; Willson & Davis 2008). Results from studies comparing hip frontal plane angles in healthy runners to runners with PFP are conflicting (Dierks, et al. 2011; Willson & Davis 2008). Willson et al. (2008) observed larger hip adduction angles (~3°) in women with PFP compared to healthy female runners, at maximum knee extension moment. Kinematic data was reported at peak knee extension moment due to its proposed effect on retro-patellar contact forces (Willson & Davis 2008). Dierks et al. (2011) reported smaller (~3.1°) peak hip adduction angles during stance in runners with PFP compared to healthy runners. In a prospective study, female runners with ITBS had greater (~3.5°) peak hip adduction angles compared to the control group (Noehren, et al., 2007). Similarly, female runners with previous ITBS displayed greater (~2.5°) peak hip adduction angles compared to healthy female runners in a retrospective study (Ferber, et al. 2010). It is currently unknown if any interaction effects exist between male and female runners with and without PFP or previous ITBS. Results differed among studies that compared all runners and studies that only compared female runners with and without PFP. Among runners with knee pain, the biomechanical differences between men and women are still unknown.

Transverse Plane Hip Biomechanics

Runners with PFP have shown differences in hip rotation angles compared to healthy runners (Souza & Powers 2009; Willson & Davis 2008). Souza et al. (Souza & Powers 2009) reported higher (~8°) average hip internal rotation angles in female runners with PFP compared to healthy runners. Willson et al. (Willson & Davis 2008) observed female runners with PFP exhibit significantly smaller (~3°) hip internal rotation angles

when compared to a female control group. A separate study comparing runners with PFP to healthy runners reported similar peak hip internal rotation angles (Dierks, et al. 2011). Evidence in the literature is conflicting for an association between PFP and hip internal rotation during running. Currently, there is no research that reports hip internal rotation in runners with ITBS.

Sagittal Plane Hip Biomechanics

To date, no research has compared sagittal plane hip kinematics in either runners with PFP or previous ITBS to healthy runners.

Hip Biomechanics Summary

Women with PFP have run with higher hip adduction angles at peak knee extensor moment compared to healthy women runners at the time of testing (Willson & Davis 2008). Studies that compare hip internal rotation angles in women with PFP to healthy women show conflicting results (Dierks, et al. 2011; Souza & Powers 2009; Willson & Davis 2008). When runners with PFP are compared to healthy runners, studies have reported a larger, smaller, and similar peak hip internal rotation angle in the PFP group (Dierks, et al. 2011; Souza & Powers 2009; Willson & Davis 2008). Runners with PFP have shown lower peak hip adduction angles compared to healthy runners (Dierks, et al. 2011). Female runners with previous ITBS elicit higher peak hip adduction angles than healthy female runners (Ferber, et al. 2010; Noehren, et al. 2007).

Frontal Plane Knee Biomechanics

Research has reported similar frontal plane knee kinematics in runners with PFP and healthy runners (Dierks, et al. 2011). However, runners with PFP have shown higher (~4.5 Nms) knee abduction impulses than healthy runners (Stefanyshyn, et al. 2006). Research comparing runners with previous ITBS to healthy runners has not reported frontal plane knee angles.

Transverse Plane Knee Biomechanics

In the knee joint, runners with PFP and previous ITBS have different running biomechanics when compared with healthy runners (Dierks, et al. 2011; Ferber, et al. 2010; Noehren, et al. 2007; Willson & Davis 2008). The only two studies that have compared transverse plane knee kinematics in runners with PFP to healthy runners report different variables. One study reported similar peak knee internal rotation angles between healthy runners and those with PFP (Dierks, et al. 2011). Another study reported greater (~4.3°) knee external rotation in female runners with PFP compared to the control group at maximum knee extension moment (Willson & Davis 2008). Due to incomparable results between studies, it is currently unclear how knee rotation is linked to PFP in runners. In a prospective study, female runners with ITBS had a larger (~3.9°) peak knee internal rotation angle than healthy female runners (Noehren, et al. 2007). A retrospective study also reported a higher (~2.9°) peak knee internal rotation angle in female runners with a history of ITBS compared to healthy female runners (Ferber, et al. 2010). Multiple studies have shown similar results in transverse plane knee kinematics of female runners with ITBS (Ferber, et al. 2010; Noehren, et al. 2007).

Sagittal Plane Knee Biomechanics

Few biomechanical differences have been reported in the frontal plane knee between runners with PFP or previous ITBS and healthy runners (Dierks, et al. 2011; Ferber, et al. 2010; Noehren, et al. 2007; Willson & Davis 2008). In the sagittal plane, runners with PFP had lower (~3.6°) knee flexion angles than the control group (Dierks, et al. 2011). The lower knee flexion angles were hypothesized to reduce patellofemoral compressive forces and pain (Dierks, et al. 2011). Willson et al. (Willson & Davis 2008) reported that healthy female runners and female runners with PFP have similar knee flexion angles at the time of maximum knee extensor moment (Willson & Davis 2008). More research is needed to reach a consensus on sagittal plane knee kinematics in runners with PFP as a limited number of studies report conflicting results. Sagittal plane knee kinematics are thought to play a part in the etiology of ITBS (Whiting & Zernicke 2008). Ferber et al. (Ferber, et al. 2010) found that female runners with a history of ITBS had similar peak knee flexion angles compared to healthy runners. Knee flexion at heel strike was noted by Noehren et al. (Noehren, et al. 2007) as being similar between female runners with ITBS and healthy runners.

Knee Biomechanics Summary

Conflicting transverse plane knee results exist in studies that compare healthy runners to runners with PFP (Dierks, et al. 2011; Willson & Davis 2008). Runners with PFP have a smaller peak knee flexion angle than healthy runners during the stance phase of running (Dierks, et al. 2008). Runners with PFP have shown similar frontal plane

kinematics as healthy runners (Dierks, et al. 2011). Runners with PFP have larger peak knee abduction impulses than healthy runners (Stefanyshyn, et al. 2006). Female runners with previous ITBS exhibit a higher peak knee internal rotation angle than healthy female runners (Ferber, et al. 2010; Noehren, et al. 2007). Female runners with ITBS have similar peak knee flexion angles during the stance phase of running as healthy female runners (Ferber, et al. 2010; Noehren, et al. 2007).

Frontal Plane Rearfoot Biomechanics

Knee pain has long been thought to originate from the ground up, starting with the position of the foot on impact with the ground. For this reason, many papers have compared the rearfoot eversion angle in runners with knee pain to healthy runners (Dierks, et al. 2011; Duffey, et al. 2000; Ferber, et al. 2010; Messier, et al. 1995; Noehren, et al. 2007). Healthy runners and runners with PFP have similar peak rearfoot eversion angles (Dierks, et al. 2011; Duffey, et al. 2000). Duffey et al. (Duffey, et al. 2000) noted that runners with PFP had lower (~1.3°) pronation change compared with healthy runners during the first 10% of stance. In the same study, healthy runners and runners with PFP had similar calcaneus-tibia touchdown angles (Duffey, et al. 2000). Peak rearfoot eversion angles in females with ITBS are similar to healthy females during the stance phase of running (Ferber, et al. 2010; Messier, et al. 1995; Noehren, et al. 2007). Ferber et al. (Ferber, et al. 2010) reported higher (~0.05 Nm/kg) peak rearfoot inversion moments in female runners with previous ITBS compared with healthy female runners. These results were hypothesized to show a compensatory method to control rearfoot eversion angle (Ferber, et al. 2010). Peak rearfoot inversion

moment was similar between runners with ITBS and healthy runners in another study (Noehren, et al. 2007). Messier et al. (Messier, et al. 1995) reported that the calcaneus-vertical angle during touchdown in runners with previous ITBS was smaller (~3.3°) than the control group. In the same study, the calcaneus-tibia angle during touchdown was similar between healthy runners and runners with previous ITBS (Messier, et al. 1995). Smaller eversion angles at heel strike are hypothesized to decrease force absorption at the subtalar joint, in effect increasing the force at proximal joints (Messier, et al. 1995).

Rearfoot Biomechanics Summary

Runners with either PFP or ITBS have similar peak rearfoot eversion angles as healthy runners (Dierks, et al. 2011; Duffey, et al. 2000; Ferber, et al. 2003; Messier, et al. 1995; Noehren, et al. 2007). Studies comparing healthy runners to runners with PFP and previous ITBS have reported smaller eversion in initial contact angles, and excursion during first 10% of stance (Duffey, et al. 2000; Messier, et al. 1995). This may indicate that healthy runners and runners with knee pain have different rearfoot angles at initial contact with the ground. Currently previous studies disagree if female runners with ITBS display a different peak rearfoot inversion moment than healthy runners (Ferber, et al. 2010; Noehren, et al. 2007).

Summary

Differences in hip, knee, and rearfoot biomechanics during running exist between runners with PFP or ITBS and healthy runners (Dierks, et al. 2011; Ferber, et al. 2010; Messier, et al. 1995; Noehren, et al. 2007; Souza & Powers 2009; Willson & Davis

2008). Studies that compare healthy runners to runners with PFP have conflicting results (Dierks, et al. 2011; Souza & Powers 2009; Willson & Davis 2008). Studies have consistently reported that female runners with ITBS have higher peak knee internal rotation and peak hip adduction angles than healthy female runners (Ferber, et al. 2010; Noehren, et al. 2007). Conflicting peak rearfoot inversion moment results in runners with and without ITBS have been reported (Ferber, et al. 2010; Noehren, et al. 2007). Variables that may be related to knee injury in runners are: peak hip adduction and internal rotation, knee internal rotation, and rearfoot eversion angles, knee abduction impulse, and peak rearfoot inversion moment. Furthermore, men and women might have different responses to increasing or decreasing step width during running. The potential influence of gender on response to step width should be considered since men and women run differently (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001).

Gender Differences in Running Kinematics

Kinematic differences between healthy males and females have been observed at the hip, and knee joint during running (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001). Therefore, different responses in lower extremity biomechanics could occur between men and women when step widths are altered during running. Thus, the potential influence of gender on the response to different step width conditions should be considered to reveal any potential interactions. Currently, no studies consider the influence that gender has on the response to changing step width during running. The

studies that report biomechanical differences between healthy male and female runners are discussed in this section.

Gender Differences in Hip Kinematics

Two studies have compared hip biomechanics in men and women during running (Chumanov, et al. 2008; Ferber, et al. 2003). In the frontal plane, studies have reported that women run with about 3.25° greater peak hip adduction angle than men (Chumanov, et al. 2008; Ferber, et al. 2003). Also, Chumanov et al. (Chumanov, et al. 2008) reported higher hip adduction excursion during running for women compared to men. Men and women have similar kinematics in the sagittal plane (Ferber, et al. 2003). In the transverse plane, women run with about 4° greater peak hip internal rotation angles than men (Chumanov, et al. 2008; Ferber, et al. 2003). Throughout the stance phase of running, women were reported as having larger hip external rotation excursion than men (Ferber, et al. 2003). As the hip and the knee joints are connected by the femur, movement in the hip joint may affect knee joint movement.

Gender Differences in Knee Kinematics

One reason women have a higher risk of incurring knee injuries than men may be due to differences in knee kinematics while running. In the frontal plane, women have shown greater peak knee abduction angles during running compared to men (Ferber, et al. 2003; Malinzak, et al. 2001). Magnitude of reported peak knee abduction angle in women varies from ~4° higher, to ~11° higher compared to men (Ferber, et al. 2003; Malinzak, et al. 2001). Larger peak knee abduction angles seen in women while

running may be due in part to the higher hip adduction angles. Hip adduction is inversely related with knee abduction through the movement of the femur. As the proximal femur is involved in hip adduction, the distal femur moves to abduct the knee, and vice versa. All of the studies that compared running biomechanics in men and women reported on sagittal plane knee kinematics (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001). Most studies have reported similarities in sagittal plane peak knee angles between men and women (Chumanov, et al. 2008; Ferber, et al. 2003). However, Malinzak et al. (Malinzak, et al. 2001) observed that knee flexion was about 8° less in women than in men while running. Knee rotation in women compared to men while running is similar (Ferber, et al. 2003).

Gender Differences in Rearfoot Kinematics

Currently, comparisons of running kinematics have not been made between men and women at the rearfoot. The reported differences in knee and hip biomechanics between men and women while running may suggest that differences in rearfoot biomechanics are also likely.

Summary

Several studies have reported gender differences in running kinematics (Chumanov, et al. 2008; Ferber, et al. 2003; Malinzak, et al. 2001). In response to these findings, differences between healthy men and women should be considered in running studies. In the current study, the influence of gender on the response to altered running step width will be observed.

Overall Summary

Studies agree that increasing and decreasing preferred step width during running significantly changes rearfoot kinematics (Kersting & Neumann 1999; Pohl, et al. 2006; Williams & Ziff 1991). Hip and knee joint biomechanics during running in the experimental step width conditions were not reported. Runners with a history of running related knee injuries, like PFP or ITBS, run differently when compared to healthy runners (Dierks, et al. 2011; Duffey, et al. 2000; Ferber, et al. 2003; Messier, et al. 1995; Noehren, et al. 2007; Souza & Powers 2009; Willson & Davis 2008). Altering preferred step width during running in healthy individuals may result in changes in biomechanical variables that are important in relation to knee injuries. Further, men and women run differently (Chumanov, et al. 2008; Ferber, et al. 2010; Malinzak, et al. 2001). Thus, gender influences should be considered to determine the effects of altered step width during running on lower extremity biomechanics.

CHAPTER III

MATERIALS AND METHODS

Participants

Thirty healthy adults, half of them men, were recruited for this study. Recruitment strategies used were: advertising at running events, word of mouth, and posting flyers (Appendix A) around the University of Tennessee Knoxville's campus and the surrounding area. Individuals who participated in this study were all recreational runners, 18 to 35 years old. A recreational runner was defined as an individual who had been running at least 15 miles a week for one year or more. The exclusion criteria was current lower extremity pain, a history of severe lower extremity injuries, current use of orthotics, and any 'yes' answers to questions on the Physical Activity Readiness-Questionnaire.

Power Analysis

Regression equations for a mixed model analysis of variance (ANOVA) were used in a power analysis to determine the sample size (Park & Shutz 1999). Previous studies comparing key variables: peak hip adduction angle (Ferber, et al. 2010), peak hip internal rotation angle (Souza & Powers 2009), peak knee internal rotation angle (Noehren, et al. 2007), peak knee abduction impulse (Stefanyshyn, et al. 2006), and peak rearfoot inversion moment (Ferber, et al. 2010) between healthy runners and

runners with PFP or previous ITBS provided the data used in the power analysis. The mean and standard deviation for each key variable of the control group and the injured group were used to calculate the effect size. Same-day intra-class correlation coefficient values for each of the key variables were entered into the regression equation (Ferber, et al. 2002). Sample size for this study was determined based on an alpha of 0.05 and a beta of 0.8. The power analysis indicated a sample size of 13 study participants per group was necessary.

Procedures

Upon arrival at the laboratory, written informed consent was provided by all participants (Appendix B). Next, participants completed a Physical Activity Readiness Questionnaire (PAR-Q) along with a custom running health history questionnaire (Appendix C). Only those participants who answered 'no' to all of the questions on the PAR-Q were allowed to continue with the study. The participants then had their weight, height, and leg length measured while barefoot. Leg length was defined as the distance from the anterior superior iliac spine to the distal aspect of lateral malleolus (Magee 1997). The participants then changed into athletic shorts, socks, and laboratory footwear (BITE Footwear, Redmond WA) in preparation for data collection. Participants stood on a template while retro-reflective markers were positioned bilaterally on the lower extremity joints (McIlroy & Maki 1997). Anatomical markers were placed on the iliac crests, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and first and fifth metatarsals. Four retro-

reflective markers in a non-collinear arrangement on molded thermoplastic shells were used as tracking markers for the pelvis, thighs, and shanks (Cappozzo, et al. 1997). The shells were attached bilaterally to the participants' proximal thighs and distal shanks (Manal, et al. 2000), as well as the posterior pelvis. Three non-collinear tracking markers on each heel were used to capture rearfoot movement. One of each heels' three tracking markers were positioned in the midline, on the calcaneal tendon right above its attachment to the calcaneus (Williams & Ziff 1991). Markers placed on the midline of the participants' right and left heel were used to calculate step width.

A nine camera motion capture system (Vicon, Oxford, UK) collected kinematic data at 120 Hz. Kinetic data were collected using a force plate (Advanced Mechanical Technology, Inc., Watertown, MA) synchronized with the motion capture system at 1200 Hz. A standing trial was recorded prior to movement trials.

Control Condition

After the static trial was recorded, the participant practiced running down the 10 meter runway and striking the force plate with the right foot. Five successful trials were recorded for the right limb during the preferred step width condition. A trial was successful when every marker was visible, the foot landed entirely on the force plate, and running speed was within 3.5m/s ±5%.

Experimental Conditions

The experimental conditions, wide step width and narrow step width, were recorded following the preferred step width condition in randomized order. Masking tape was a visual aid used to help participants increase and decrease their preferred step width. Participants were instructed to first practice running while watching each foot land on the line(s) of masking tape. Once participants were able to run with the selected step width, they practiced the task without looking down at the tape. When participants were familiar with the running task, data collection could begin. Five successful trials were collected in the selected step width condition. A trial was successful when all markers were visible, the foot landed entirely on the force plate, and the running speed was within 3.5m/s ±5%.

Narrow Step Width Condition

During the narrow step width condition, a line of tape was laid down on the runway and over the center of the force plate. Narrow step width was defined as 0% of the participants' leg length (Arellano & Kram 2011).

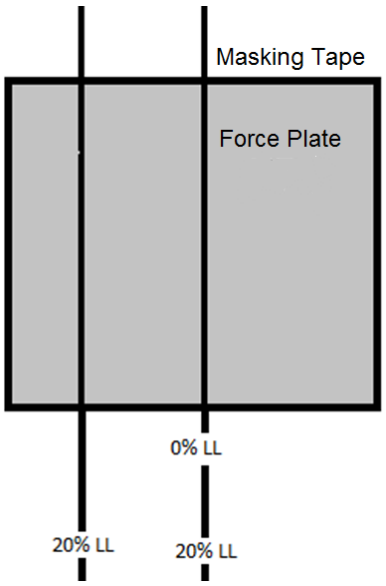

Figure 1: Lab set up during experimental step width condition**.**

Wide Step Width Condition

During the wide step width condition two lines of masking tape were placed parallel to each other down the runway. The right line was centered on the force plate, so the participant could strike the force plate with their right foot while running. Wide step width was defined as 20% of the participants' leg length (Arellano & Kram 2011), and the strips of tape were distanced apart accordingly.

Data Processing

Visual 3D (C-Motion, Germantown, MD) was used to process participant data. A descending threshold of -20N from the force plate indicated foot strike and an ascending threshold of -20N indicated toe off. The stance phase was the time between foot strike and toe off during running. Butterworth low-pass filters had a cutoff

frequency of 8Hz for marker trajectories, and 50Hz for ground reaction forces. Regression Equations from de Leva were used to determine body segment parameters for men and women (de Leva 1996). The joint coordinate system and the right hand rule were used to calculate joint angles for the hip, knee, and rearfoot (Grood & Suntay 1983). Inverse dynamics were used to calculate internal knee abduction and rearfoot inversion moments. The knee abduction moment was integrated to find the knee abduction impulse. Step width was defined as the medial-lateral distance from the right to the left foot's mid-heel at initial contact with the ground. The right foot's initial contact with the ground was determined by the ground reaction force signal generated by the force plate. The left foot's initial contact with the ground was indicated as the left mid-heel marker's minimum vertical position. Custom MATLAB software (MathWorks, Natick, MA) was used to extract the dependent variables from the visual 3D output. The dependent variables were analyzed during the stance phase. Peak hip adduction angle was the maximum hip adduction angle during the first half of the stance phase. Peak hip internal rotation angle was the maximum hip internal rotation angle during the first half of the stance phase. Peak knee internal rotation angle was the maximum knee internal rotation angle during the first half of stance phase. Peak knee abduction moment was the maximum knee abduction moment for the first half of stance. Knee abduction angular impulse was the integration of the internal knee abduction moment during the entire stance phase. Peak rearfoot eversion angle was the maximum rearfoot eversion angle for the first half of the stance phase. Peak rearfoot inversion moment was the maximum rearfoot inversion moment for the first half of stance. The

mean of five trials was calculated for every dependent variable in each condition for each participant. Group means were then calculated for each dependent variable.

Statistical Analysis

The dependent variables and step width were analyzed statistically using descriptive statistics, and a 2 x 3 mixed model ANOVA, with gender as a between subjects factor and step width as a repeated measures factor (SPSS Inc, Chicago Ill.). Post hoc least significant difference tests determined where any significant differences existed for step width effects. When a significant interaction occurred, a pairwise sample t-test was used to determine interaction effects. Differences were considered significant if $p < 0.05$.

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PART 2

CHAPTER IV

MANUSCRIPT

Does Changing Step Width Alter Lower Extremity Biomechanics During Running?

Abstract

Purpose: This study sought to determine the biomechanical response of the lower extremity joints in healthy runners to changes in step width during running. **Methods:** Thirty healthy runners, half of them males, participated in this study. A nine camera motion capture system recorded kinematics, and a force plate, synchronized with the motion capture system, recorded ground reaction force data. Participant data were collected in a normal step width running condition, a wide step width running condition, and a narrow step width running condition. Three dimensional gait analyses were done for male and female runners among step width conditions. The dependent variables and step width were each analyzed statistically using a 2 x 3 (gender x condition) mixed model ANOVA. A least significant difference post hoc test determined if interaction effects or differences among conditions existed. Differences were considered significant if $p < 0.05$. **Results:** Step width significantly changed in each condition. Frontal plane biomechanics decreased as step width increased. Peak knee internal rotation angle decreased slightly as step width decreased. Women ran with significantly higher peak hip adduction and knee internal rotation angles compared to men. Women also ran with a significantly lower peak knee abduction moment, and knee abduction angular impulse compared to men. The only interaction effects between step width conditions and gender existed in peak rearfoot inversion moment. **Conclusion:** Step width has an influence over lower extremity biomechanics in healthy runners. When step width increased from narrowest to widest, the frontal plane dependent variables decreased and peak knee internal rotation angle increased. When healthy runners run with a wide step width, their biomechanics are similar to runners with knee injuries.

Key Words: Frontal plane, biomechanics, gender differences

Introduction:

Paragraph Number 1 Running biomechanics are associated with overuse injuries in runners (6, 7, 9, 15, 16, 17, 18, 20, 22, 26). Previous studies have implicated frontal plane variables as associated with overuse knee-injury risk in runners (6, 9, 16, 22, 26). Step width is a frontal plane spatio-temporal variable that may influence biomechanical variables associated with overuse injury. Step width is defined as the medio-lateral distance between each foot's mid-heel at initial contact with the ground. There is a limited amount of research on how altering step width during running changes lower extremity kinematics (11, 19, 25). The effects on rearfoot kinematics from a change in preferred step width during running have been reported. Pohl et al. (19) reported that peak rearfoot eversion angle, and rearfoot eversion excursion increased when preferred step width was decreased during running. When preferred step width was increased, no differences were noted in the rearfoot (19). During this study, the average increase in step width was 6cm and the average decrease in step width was 12cm (19). In another study, the eversion excursion decreased when preferred step width was increased during running and vice versa (11). The change in step width among conditions was not reported in this study (11). Williams et al. (25) reported increases in maximum rearfoot eversion and range of rearfoot eversion when step width was decreased compared to normal step width, and vice versa. Step width was increased by 3cm, and decreased by 2cm among conditions in this study (25). Previous studies have focused solely on changes in rearfoot kinematics after altering a runner's step width, while changes associated with knee and hip biomechanics are unknown.

Paragraph Number 2 The most common overuse injuries associated with running are patello-femoral pain (PFP) and iliotibial band syndrome (ITBS) (23). Approximately 24% of runners have experienced either PFP or ITBS (23). There are differences in lower extremity biomechanical variables in runners with PFP or ITBS compared to healthy runners (6, 7, 9, 15, 16, 21, 22, 26). In the frontal plane, a larger peak hip adduction angle have been reported in runners with PFP at the time of testing (26). Another study reported a smaller peak hip adduction angle in runners with PFP compared to healthy runners (6). In the transverse plane, it is unclear whether runners with PFP have a larger, smaller, or similar peak hip internal rotation angle than healthy runners (6, 21, 26). A previous study noted that female runners who have PFP have a larger peak hip internal rotation angle compared to healthy runners (21). Another study reported a smaller peak hip internal rotation angle in runners with PFP when compared to healthy runners (26). When comparing both male and female runners with PFP to healthy runners, another study found no differences in peak hip internal rotation angle (6). Runners with previous ITBS have a higher peak hip adduction angle compared with healthy runners (9, 16). Previous studies have not reported differences in transverse plane hip mechanics between runners with ITBS and healthy runners (9, 16).

Paragraph Number 3 At the knee, runners with PFP have a similar peak knee internal rotation angle as healthy runners (6). A larger mean internal knee abduction moment, and a larger internal knee abduction angular impulse has been reported in runners with PFP compared to healthy runners (22). Runners with previous ITBS have a higher peak knee internal rotation angle compared to healthy runners (9, 16).

Paragraph Number 4 Previous studies that have altered step width have focused on the response of rearfoot kinematics, noting changes in rearfoot eversion among step width conditions (11, 19, 25). Reports indicate that runners with PFP and healthy runners run with similar peak rearfoot eversion angles (6). Runners with previous ITBS also run with similar peak rearfoot eversion angles as healthy runners (9, 16). Previous studies disagree if runners with previous ITBS have a different peak rearfoot inversion moment than healthy runners (9, 16). A larger peak internal rearfoot inversion moment has been reported in runners with previous ITBS compared to healthy runners (9). A prospective study of runners with future ITBS reported a similar peak internal rearfoot inversion moment compared to healthy runners (16). While studies comparing runners with PFP or previous ITBS to healthy runners have reported conflicting results, clear differences between the two groups exist.

Paragraph Number 5 There are also differences in lower extremity biomechanics between male and female runners (4, 8, 13). Women have a larger peak hip adduction angle and hip adduction excursion during running than men (4, 8). Women also have a larger peak hip internal rotation angle and hip external rotation excursion than men (4, 8). Additionally, women have a larger peak knee adduction angle compared to men during running (8, 13). Most studies report similar sagittal plane angles between male and female runners (4, 8). One study reported a smaller peak knee flexion angle in women compared to men (13). No previous study comparing male and female runners has reported rearfoot biomechanics. Different biomechanics exist between healthy men and women during running, therefore the influence of gender on the response to altered step width during running should be considered.

Paragraph Number 6 The purpose of this study was to determine the biomechanical response of the lower extremity joints to increasing and decreasing step width during running in healthy male and female runners. We hypothesized that peak hip adduction angle, and peak hip internal rotation angle will differ among step width conditions and genders. Also, we hypothesized that peak knee internal rotation angle, peak knee abduction moment, and knee abduction angular impulse will differ among step width conditions and genders. Lastly, we hypothesized that peak rearfoot eversion angle and peak rearfoot inversion moment will differ among step width conditions and genders.

Methods:

Paragraph Number 7 Thirty healthy adults, half of them men, participated in this study (Table 1). All participants were healthy recreational runners, 18 to 35 years of age. A recreational runner was defined as an individual who had been running at least 15 miles a week for one year or more. Individuals were excluded from the study if they reported: current lower extremity pain, a history of severe lower extremity injuries, or current use of orthotics. Participants were also screened for cardiovascular health and were excluded if they answered 'yes' to any question on the Physical Activity Readiness-Questionnaire (24). This study's protocol was approved by the University of Tennessee Institutional Review Board. All participants provided written informed consent before beginning the study.

Paragraph Number 8 After written informed consent was obtained, each participant answered questions to ensure they met the inclusion criteria and had their height and leg length measured. Participants then changed into athletic shorts and laboratory footwear, gait sandals (BITE Footwear, Redmond WA), to prepare for data collection

(2). Running velocity was monitored via two photocells and an electronic timer (Lafayette Instrument Company, Lafayette, IN) distanced three meters apart. A nine camera motion capture system (Vicon, Oxford, UK) collected marker position data at 120 Hz. Ground reaction force data were collected at 1200 Hz using a force plate (Advanced Mechanical Technology, Inc., Watertown, MA) synchronized with the motion capture system.

Paragraph Number 9 Retro-reflective markers were attached bilaterally and directly to the skin on anatomical landmarks. Anatomical landmarks of the lower extremity are the left and right iliac crests, left and right greater trochanters, medial and lateral epicondyles of the femur, medial and lateral malleoli, and first and fifth metatarsals. Four non-collinear markers on molded thermo-plastic shells (3) were placed on the posterior pelvis, proximal thighs, and distal shanks (14). Three tracking markers for the foot were non-collinear on the skin of the heel. Once all of the markers were attached, a standing trial was recorded. All markers except for the tracking markers on the pelvis, thighs, shanks, and feet were removed for the running trials.

Paragraph Number 10 Running data were collected for three step width conditions. In the control condition, participants ran with their preferred step width. In the experimental conditions, participants ran with a narrow step width and a wide step width. The control condition was collected before the experimental conditions, and the order of the experimental conditions was randomized among the participants. The change in step width was determined by each participant's right leg length. Leg length was measured with the participant in the supine position as the distance from the anterior superior iliac spine to the distal aspect of lateral malleolus (12). The narrow

step width condition was 0% of leg length, and the wide step width condition was 20% of leg length (1). During the narrow step width condition, a strip of one inch wide tape was positioned along the length of the runway and centered over the force plate. During the wide step width condition, another strip of tape was placed to the left of the center tape distanced 20% of the participant's leg length away from the first strip. Participants completed approximately five practice trials to adjust to each condition. Participants had adjusted to the condition when they were able to run with each foot hitting the target while looking forward. On average, participants took five to six practice trials before beginning the running trials. Five successful trials were recorded for the right limb during each step width condition. A trial was successful when every marker was visible, the foot landed entirely on the force plate, and running speed was within 3.5m/s ±5%.

Paragraph Number 11 Visual 3D (C-Motion, Germantown, MD) was used to process participant 3D kinematic and kinetic data. Regression equations from de Leva were used to determine body segment parameters for men and women (5). Moment of inertia values for each axis of rotation were calculated using adjusted segmental mass, center of mass, and radii of gyration parameters for males and females (5). Marker trajectories and ground reaction force data were filtered using a Butterworth low-pass filter with cutoff frequencies of 8Hz for marker trajectories and 50Hz for ground reaction forces. The joint coordinate system were used to calculate joint angles for the hip, knee, and rearfoot (10). The dependent variables were peak values during the loading phase of running, the first 50% of the stance phase, in each condition. An increasing ground reaction force threshold of 20N indicated foot strike in each trial. A decreasing

ground reaction force threshold of 20N indicated toe off in each trial. The stance phase was between foot strike and toe off. Inverse dynamics were used to calculate internal knee abduction and rearfoot inversion moments. The negative internal knee abduction moment across the stance phase was integrated to find the knee abduction angular impulse. Peak internal knee abduction moment, internal knee abduction angular impulse, and peak internal rearfoot inversion moment were normalized by participant height and body weight. Step width was defined as the medio-lateral distance between the mid-heel markers at foot strike. Right foot strike was determined by the force plate. Left foot strike was determined as the left foot mid-heel marker's minimum vertical position. Step width was calculated by finding the difference of the right and left mid-heel markers frontal plane positions. Custom MATLAB software (MathWorks, Natick, MA) was used to extract the peak value of each dependent variable from the Visual 3D output. The mean of five trials was calculated for every dependent variable in each condition for each participant. Group means and standard deviations were then calculated for each dependent variable.

Paragraph Number 12 The dependent variables and step width were each analyzed statistically using a 2 x 3 (gender x step width condition) mixed model ANOVA, with gender as a between subjects factor and step width as a repeated measures factor (SPSS Inc, Chicago Ill.). Post hoc comparisons using a least significant difference test determined where any significant differences existed for step width effect. When a significant interaction occurred, a pairwise sample t-test was used in post hoc comparisons. Differences were considered significant if $p < 0.05$.

Results:

Paragraph Number 13 Results of dependent variables and step width among each condition are listed in Table 2. Absolute and normalized step width was significantly different among each condition. Men and women ran with similar step widths between all three conditions, with no interaction effect. Step width was greater in the narrow condition compared to the preferred ($p < 0.001$) and wide conditions ($p < 0.001$). Step width was also greater in the preferred condition compared to the wide condition ($p < 0.001$). Peak hip adduction angle increased as step width decreased from widest to narrowest, and was larger in women compared to men with no interaction effect. Peak hip adduction angle was greater in the narrow condition compared to the preferred ($p < 0.001$) and wide conditions ($p < 0.001$). Peak hip adduction angle was also greater in the preferred condition compared to the wide condition ($p < 0.001$). Peak hip internal rotation angle was similar between conditions and genders, with no interaction effect. Peak knee internal rotation angle decreased as step width decreased from widest to narrowest and was larger in women, but had no interaction effect. Peak knee internal rotation angle was greater in the narrow condition compared to the wide condition ($p = 0.002$). Peak knee abduction moment increased as step width decreased from widest to narrowest, and was larger in men with no interaction effect. Peak knee abduction moment was greater in the narrow condition compared to the preferred ($p = 0.048$) and wide conditions ($p < 0.001$). Peak knee abduction moment was also greater in the preferred condition compared to the wide condition ($p < 0.001$). Knee abduction angular impulse increased as step width decreased from widest to narrowest, and was larger in men with no interaction effect. Knee abduction angular impulse was greater in the

narrow condition compared to preferred ($p = 0.005$) and wide conditions ($p < 0.001$). Knee abduction angular impulse was also greater in the preferred condition compared to the wide condition ($p < 0.001$). Peak rearfoot eversion angle increased as step width decreased from widest to narrowest and was larger in women with no interaction effect. Peak rearfoot eversion angle was greater in the narrow condition compared to preferred ($p = 0.003$) and wide conditions ($p < 0.001$). Peak rearfoot eversion angle was also greater in the preferred condition compared to the wide condition ($p < 0.001$). Peak rearfoot inversion moment had a significant interaction effect. Peak rearfoot inversion moment increased as step width decreased from widest to narrowest in men more so than women. In men, peak rearfoot inversion moment was greater in the narrow condition compared to the wide condition ($p < 0.001$), and in the preferred condition compared to the wide condition ($p < 0.001$). In women, peak rearfoot inversion moment was greater in the narrow condition compared to the wide condition ($p < 0.001$), and in the preferred condition compared to the wide condition ($p = 0.007$)

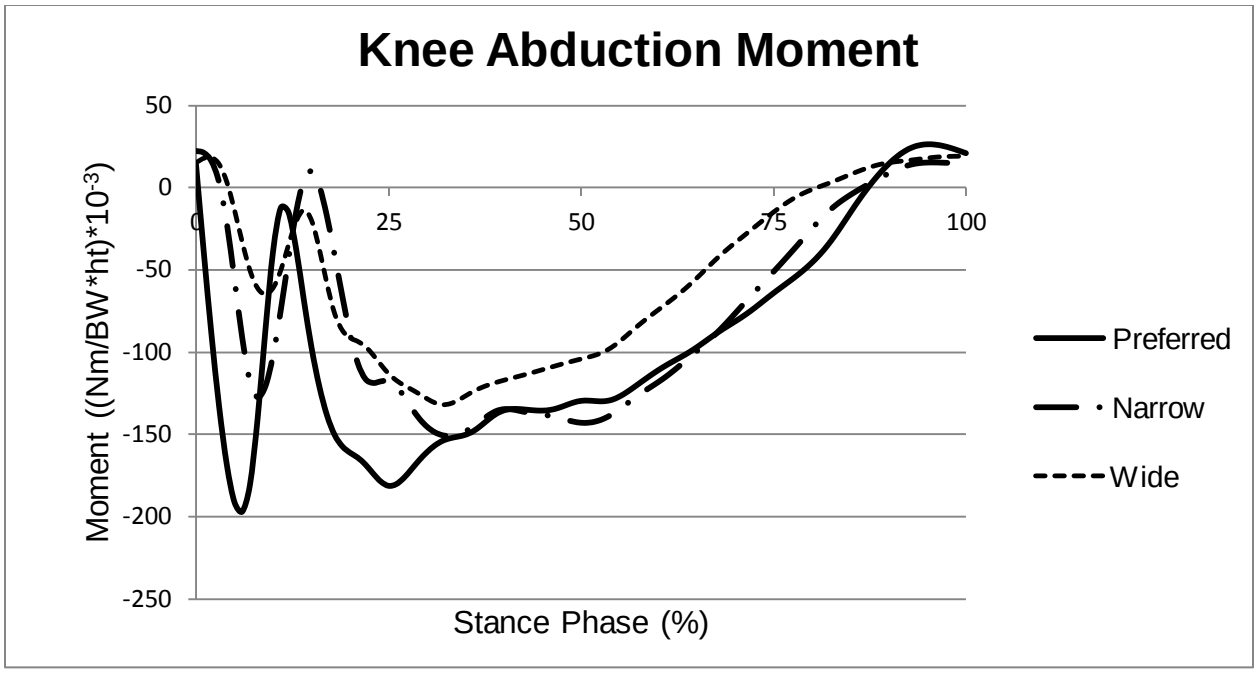

Figure 2: Representative data of knee abduction moment during the stance phase of running among step width conditions.

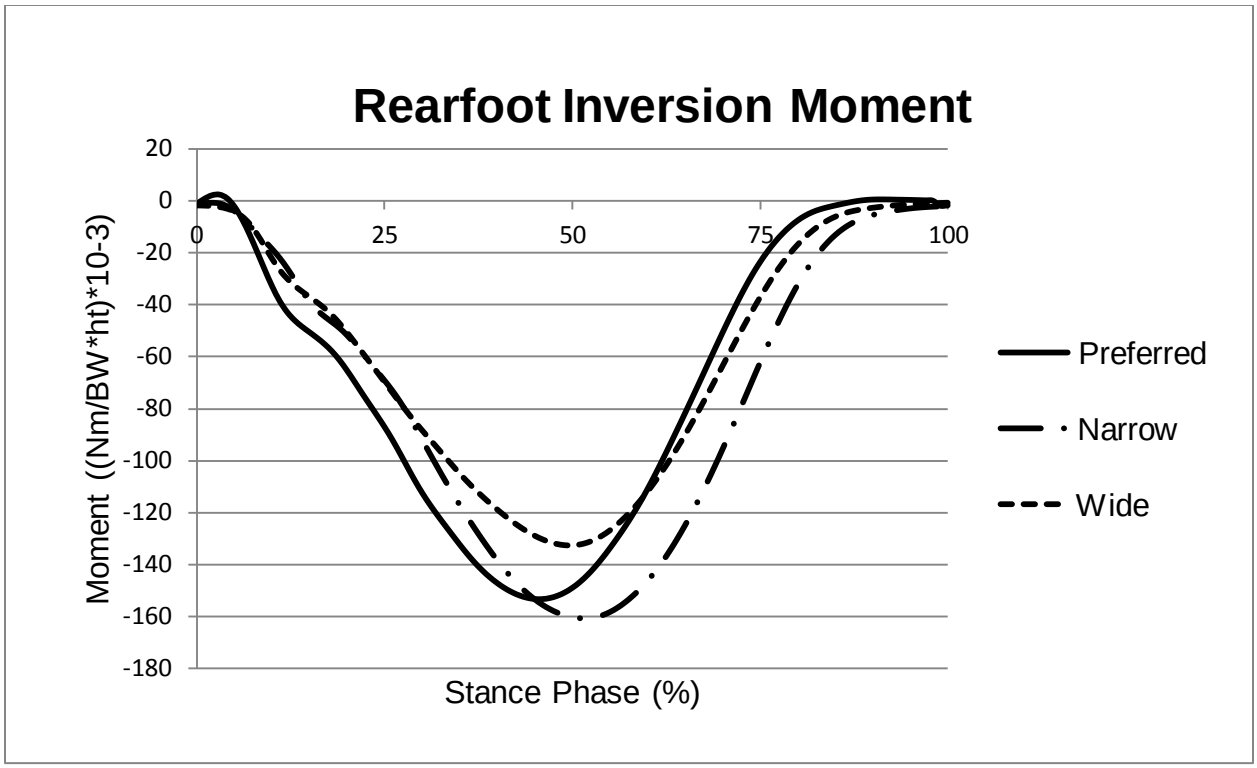

Figure 3: Representative data of rearfoot inversion moment during the stance phase of running among step width conditions.

Discussion:

Paragraph Number 14 The aim of this study was to determine the biomechanical response of the lower extremity joints to changes in step width during running in healthy runners. Changes in step width had a significant inverse relationship with frontal plane biomechanics. When step width increased from narrowest to widest, peak hip adduction angle, peak knee abduction moment, knee abduction angular impulse, and peak rearfoot eversion angle decreased. Only peak rearfoot inversion moment had an interaction effect, indicating male and female runners had different responses to changes in step width for this variable.

Paragraph Number 15 Step width was significantly different among all conditions, indicating that the method used in this study to change step width during running succeeded. Peak hip adduction angle changed significantly in each condition, getting smaller as step width increased from narrowest to widest. It has been reported that runners with PFP and previous ITBS have ~3° larger peak hip adduction angles compared to healthy runners (9, 16, 26). Running with a wide step width decreased the peak hip adduction angle by ~3° in healthy runners. Increasing step width in runners with high peak hip adduction angles may reduce peak angles to the level of healthy runners. Throughout the conditions, peak hip internal rotation angle was not affected by the change in step width. Previous studies comparing runners with PFP to healthy runners have not reached a consensus on the role that peak hip internal rotation plays in runners with PFP (6, 21, 26). Peak hip internal rotation is not thought to be linked to ITBS, and previous studies comparing runners with ITBS to healthy runners do not report it (9, 16).

Paragraph Number 16 Changing step width during running has little influence on knee internal rotation. As step width increased from narrowest to widest, peak knee internal rotation angle significantly increased by ~1°. The change in internal rotation at the knee was not proximally influenced, since the peak hip internal rotation angle did not change among step width conditions. Foot position in the transverse plane could cause the changes seen in peak knee internal rotation angle among step width conditions. Although the differences in peak knee internal rotation angle among step width conditions were small, future studies should explore the source of the internal rotation. Runners with previous ITBS run with a larger peak knee internal rotation angle (~4°)

than healthy runners (9, 16). Altering step width would not impact runners with high peak knee internal rotation angles. Peak knee abduction moment significantly decreased as step width increased from narrowest to widest. High mean knee abduction moments have been reported in runners with PFP compared to healthy runners (22). Running with a wide step width could help runners with high knee abduction moments to decrease those moments down to healthy levels. Knee abduction angular impulse also significantly decreased as step width increased from narrowest to widest. Greater knee abduction angular impulse has been reported in runners with PFP compared to healthy runners (22). A wide step width could reduce large knee abduction angular impulses during running, found in runners with PFP, in the direction of healthy levels.

Paragraph Number 17 At the rearfoot, peak rearfoot eversion angle decreased (~1°) as step width increased from narrowest to widest. Previous studies have reported decreases in peak rearfoot angles (~2°) as step width increases from narrowest to preferred (19, 25), and preferred to widest (19) during running. In previous studies, step width was decreased until participants ran with a crossover (negative) step width (19, 25). Crossover conditions in previous studies could explain the higher change in peak rearfoot eversion angle compared to the current study. As step width increased from narrowest to widest peak rearfoot inversion moment decreased greater in men than in women. Large peak rearfoot inversion moments have been reported in runners with ITBS when compared to healthy runners (9). Running with a wide step width may decrease the large peak rearfoot inversion moments found in male runners with ITBS. Future studies could examine the change in rearfoot position and moment arm size to

understand the possible relationships between peak rearfoot eversion angle and inversion moment.

Paragraph Number 18 For most variables, men and women reacted similar to changes in step width, indicating they would not need to be considered separately. Since there was an interaction effect for peak rearfoot inversion moment, we recommend considering men and women separately when analyzing this variable. Multiple biomechanical differences exist during running between healthy male and female runners. In this study, women ran with significantly higher (~3.2) peak hip adduction angles than men. Our finding of greater peak hip adduction angles in women compared to men is consistent with previous studies (4, 8). In the transverse plane, previous studies report that women run with a larger peak hip internal rotation angle, and a similar peak knee internal rotation angle compared to men (4, 8). The current study reported a similar peak hip internal rotation angle, and a larger peak knee internal rotation angle in women compared to men. It is not clear why the transverse plane angles in our study did not reflect the findings of previous studies. Comparisons of peak knee abduction moment, knee abduction angular impulse, peak rearfoot eversion angle, and peak rearfoot inversion moment in women to men during running have not previously been reported.

Paragraph Number 19 A limitation to this study was that participants only had a single testing session to practice running with a wide and narrow step width. Experiments that focus on gait retraining take place over several weeks and visits. However, participants in this study were able to increase and decrease their step width significantly between all conditions.

Paragraph Number 20 Until this study, there has been very little research on the effects of step width on running biomechanics. When healthy runners run with narrow step widths, their biomechanics mimic those seen in runners with knee injuries. The biomechanics of healthy runners move in the opposite way when running with a wide step width. Widening the preferred step width during running of runners who display larger than normal biomechanics in the frontal plane may reduce the risk of injury. The two most common overuse running injuries, PFP and ITBS, have associated biomechanics, some of which are in the frontal plane. Future research in this area should focus on the effects that increasing step width has on runners with PFP or ITBS.

Conclusion:

Paragraph Number 21 In conclusion, step width significantly influences lower extremity biomechanics during running in healthy runners. When step width is increased from narrowest to widest peak hip adduction angle, peak knee abduction moment, knee abduction angular impulse, and peak rearfoot eversion angle decreases. When step width is increased from narrowest to widest, male runners have greater decreases in peak rearfoot inversion moment than female runners. When step width is increased from narrowest to widest peak knee internal rotation angle increases. Peak hip internal rotation angle does not change in response to step width changes.

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Table 1: Characteristics of male and female participants, mean (standard deviation)

	Men	Women
Age (year)	25.67 (3.15)	24.67 (4.82)
Height (m)	1.77 (0.05)	1.65 (0.06)
Mass (kg)	73.94 (4.27)	59.03 (6.60)
Leg length (cm)	94.77 (4.61)	87.63 (3.07)
Weekly mileage (mi)	35.33 (17.27)	24.93 (10.40)

Table 2: Dependent variables for men and women in each step width condition, mean (standard deviations)

	Gender	Total	Narrow	Preferred	Wide	Interaction P-Value	Step Width P-Value	Gender P-Value
Step Width (cm)	Total	7.6 (6.8)	1.2 (3.4) [PW]	6.0 (4.1) [W]	15.5 (2.4)	0.943	<0.001	0.532
	Male	7.9 (7.1)	1.4 (3.8)	6.3 (4.5)	15.9 (2.2)			
	Female	7.3 (6.6)	1.1 (3.1)	5.6 (3.7)	15.0 (2.5)			
Step Width (%)	Total	6.9 (6.3)	1.1 (3.1) [PW]	5.4 (3.7) [W]	14.1 (2.4)	0.927	<0.001	0.676
	Male	7.4 (6.7)	1.2 (2.5)	5.7 (3.6)	14.2 (2.2)			
	Female	6.3 (5.9)	0.9 (3.7)	5.1 (3.9)	14.0 (2.6)			
Peak Hip Adduction Angle (˚) ^	Total	12.7 (4.6)	14.8 (4.1) [PW]	13.2 (4.1) [W]	10.0 (4.3)	0.124	<0.001	0.004
	Male	10.6 (4.0)	12.5 (3.3)	11.7 (3.8)	7.7 (3.5)			
	Female	14.7 (4.3)	17.1 (3.6)	14.7 (3.9)	12.2 (4.0)			
Peak Hip Internal Rotation Angle (˚)	Total	9.5 (4.7)	9.5 (4.7)	9.9 (4.7)	9.3 (4.7)	0.063	0.133	0.385
	Male	10.3 (4.9)	10.5 (4.6)	10.7 (5.1)	9.6 (5.3)			
	Female	8.8 (4.3)	8.4 (4.7)	9.1 (4.3)	8.9 (4.1)			

	Gender	Total	Narrow	Preferred	Wide	Interaction P-Value	Step Width P-Value	Gender P-Value
Peak Knee Internal Rotation Angle (˚) ^	Total	4.0 (5.0)	3.6 (4.9) [W]	4.0 (5.3)	4.4 (4.9)	0.701	0.008	0.048
	Male	2.2 (5.5)	1.9 (5.4)	2.2 (5.8)	2.5 (5.5)			
	Female	5.8 (3.8)	5.2 (3.9)	5.8 (4.2)	6.3 (3.5)			
Peak Knee Abduction Moment (Nm/BW*ht)*10^{-3} ^	Total	60.6 (21.5)	66.0 (18.4) [PW]	62.1 (23.9) [W]	53.8 (20.8)	0.514	<0.001	0.012
	Male	69.7 (15.1)	73.9 (12.3)	71.5 (18.7)	63.7 (12.4)			
	Female	51.6 (23.3)	58.1 (20.3)	52.6 (25.4)	44.0 (23.2)			
Knee Abduction Angular Impulse (Nms/BW*ht)*10^{-3} ^	Total	7.1 (2.9)	7.9 (2.5) [PW]	7.2 (3.0) [W]	6.2 (2.9)	0.597	<0.001	0.011
	Male	8.3 (1.9)	9.0 (1.7)	8.5 (2.1)	7.5 (1.7)			
	Female	5.9 (3.1)	6.8 (2.7)	5.9 (3.4)	4.9 (3.3)			
Peak Rearfoot Eversion Angle (˚) ^	Total	6.0 (4.0)	7.3 (3.9) [PW]	6.2 (3.6) [W]	4.7 (4.2)	0.070	<0.001	0.048
	Male	4.7 (3.6)	5.7 (3.5)	5.2 (3.3)	3.1 (3.7)			
	Female	7.4 (4.0)	8.9 (3.7)	7.1 (3.7)	6.2 (4.2)			

	Gender	Total	Narrow	Preferred	Wide	Interaction P-Value	Step Width P-Value	Gender P-Value
Peak Rearfoot Inversion Moment (Nm/BW*ht)*10^{-3} #	Total	42.0 (16.6)	44.2 (16.7)	43.5 (17.2)	38.4 (15.8)	0.035	<0.001	0.432
	Male	44.4 (20.0)	46.6 (21.2) W	47.1 (20.6) W	39.5 (18.7)			
	Female	39.6 (12.0)	41.8 (10.8) W	39.9 (12.5) W	37.2 (12.8)			

Symbols indicate: # - significant interaction effect among gender and condition, ^ - significant differences between genders, N - significantly different from narrow step width condition, P - significantly different from preferred step width condition, W - significantly different from wide step width condition.

CONCLUSION

Increasing step width from narrowest to widest during running decreased peak hip adduction angle, peak knee abduction moment, knee abduction impulse, and peak rearfoot eversion angle. An interaction effect existed for peak rearfoot inversion moment between genders and step width conditions. Increasing step width from narrowest to widest during running decreased peak rearfoot inversion moment greater in men than in women. When step width increased from narrowest to widest, peak knee internal rotation angle increased. No difference was observed in peak hip internal rotation angle among step width conditions. In conclusion, step width significantly influences biomechanics during running in healthy runners.

APPENDICES

Appendix A

Flyer

THE UNIVERSITY of TENNESSEE

Runners Needed for A Research Study



- **If you meet these criteria, you may qualify to participate:**
- Currently running at least 15 miles per week
- Currently healthy and free from injury
- Male or Female, Age 18 - 35

Please contact Trey Brindle for further details:
Call 865-974-2091or e-mail Trey at rbrindl1@utk.edu

Trey Brindle
865-974-2091
rbrindl1@utk.edu

Appendix B

Informed Consent

INFORMED CONSENT FORM

Does changing step width alter lower extremity kinematics during running?

Principal Investigator: Richard A. Brindle III
Address: Dept of Kinesiology, Recreation, and Sport Studies
University of Tennessee
1914 Andy Holt Avenue, HPER 136
Knoxville, TN 37966
Phone: (865) 974-2091

Purpose
You are invited to take part in a research study entitled "Does changing step width alter lower extremity kinematics during running?" This study aims to find out if differences exist in running biomechanics when the preferred step width is altered during running. This study involves one visit to our laboratory for approximately 90 minutes.

You have been invited to take part in this study because you are a healthy adult who has been running at least 15 miles a week for a year or longer. To take part in the study, you should not have any current injuries or any previous major injuries or surgeries that might affect the way you run. You will be allowed to rest in between running trials if needed.

If you meet these criteria and agree to participate, you will be asked to complete a health questionnaire so that we can determine that you do not have health risks that would prohibit you from participating. If you do not meet all of these criteria or choose not to participate in the study, your visit will end.

Laboratory Visit
If you meet the inclusion criteria, then you will stay at the lab for the data collection. First, you will take an online survey. After the survey, your height, weight, and length of your leg will be measured. Then, you will change into your own running shorts. If you do not have your own running shorts we will provide shorts for you to wear. We will provide you with a pair of laboratory shoes and socks to wear. You will then have small silver balls attached to your waist, hips, leg, and foot using medical tape and plastic shells with neoprene wraps. These will not interfere with your ability to move. The motion capture cameras in our lab record the position of these balls as you move within the lab space. They will not record an image of you.

Next, you will run across a 17 meter walkway, at a typical running speed of 8.3 miles per hour (7:13 mile pace). You will be able to practice the running speed and running in the laboratory. You will be able to rest as often as you need. After you have completed five acceptable trials at your preferred step width, you will run with altered step widths. Strip(s) of masking tape will be laid down over the runway and will be used as targets to

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help you increase and decrease your step width during running. You will have as much time needed to practice hitting the strip(s) of masking tape with a target on the lab shoes. Once you feel comfortable running at the desired step width and speed, five acceptable running trials for each of two new step widths will be recorded.

Potential Risks
The potential risks associated with this study include falls as you run. We will do our best to minimize these risks by explaining what will happen in the session and letting you practice. If you become injured during the data collection, standard first aid procedures would be carried out as needed. The University of Tennessee does not 'automatically' reimburse participants for medical claims of other compensation. If physical injury is suffered in the course of research, or for more information, please notify the investigator in charge (Richard A Brindle III, (865) 974-2091).

Benefits of Participation
While participation in this study may not benefit you at the time of data collection, its purpose is to provide information on how healthy runners react to altered step width during running. This may lead to the development of rehabilitation techniques for runners who experience knee pain.

Confidentiality
Your identity will be kept confidential by using code numbers to identify your information. These numbers will be used during all processing and analysis of the data and reports of the study and its results.

Contact Information
If you have any questions at any time about the study, you can contact Richard Brindle. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Questions and/ or Withdrawal
Your participation in this study is voluntary; you may decline to participate without penalty. You may ask questions and/ or withdraw your consent at any time and discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be destroyed.

Consent
I have read the above information. I have received a copy of this form. I agree to participate in this study.

Participant's Signature	**Date**	**Participant #**
Investigator's Signature	**Date**	

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Appendix C

Physical Activity Readiness Questionnaire and Running Healthy History Questionnaire

Physical Activity Readiness Questionnaire

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor? Yes or No
2. Do you feel pain in your chest when you do physical activity? Yes or No
3. In the past month, have you had chest pain when you were not doing physical activity? Yes or No
4. Do you lose your balance because of dizziness or do you ever lose consciousness? Yes or No
5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity? Yes or No
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition? Yes or No
7. Do you know of any other reason why you should not do physical activity? Yes or No

Running Health History Questionnaire

1. What is your sex? Male or Female
2. What is your age?
3. What is your height (inches)?
4. What is your weight (pounds)?
5. What leg would you use to kick a ball? Right Left No Preference
6. How many years have you been running?
7. How many miles did you run in the past seven days?
8. Was the last seven days representative of your typical weekly running mileage? Yes or No
9. How many miles do you run in a typical week?
10. Have you ever experienced knee pain due to running that caused you to alter your regular training schedule on at least one occasion? Yes or No
11. Which of your knees have been injured? Right Left
12. Did your knee pain cause you to reduce your weekly mileage total or stop running for a period of time? Yes or No
13. Have you ever been diagnosed by a doctor, athletic trainer, or physical therapist with a knee injury(s)? Yes or No
14. Which of the following knee injuries have you ever been diagnosed by a doctor, athletic trainer, or physical therapist?
    - Anterior Knee Pain (Patellofemoral Pain Syndrome)
    - Runner's Knee (Iliotibial Band Friction Syndrome)
    - Patellar Tendonitis/Tendonosis
    - Quadriceps Tendonitis/Tendonosis

- Patellar Bursitis
- Other Knee Injury

15. If you checked "Other Knee Injury" for the above question, please specify the type of knee injury.
16. Have you experienced knee injury(s) caused by running more than once? Yes or No
17. Are you currently running with knee pain? Yes or No
18. Have you ever experienced any other type of injury, e.g. lower back pain, hip pain, thigh muscle strains, ankle sprains, foot pain, Achilles tendonitis/tendonosis, stress fracture, torn ACL? Yes or No
19. Please specify the type of injury(s) you have experienced.

Thank you for completing the Running History survey.

Appendix D

Results

Participant Information

Participant Information						
Participant	Gender	Age (yr)	Height (m)	Body Mass (kg)	Leg Length (cm)	Weekly Mileage (mi)
1	m	25	1.77	65.9	91.5	27
2	m	27	1.75	75.62	91	60
3	f	31	1.74	75.71	90	35
4	f	25	1.6	51.43	84.5	50
5	m	29	1.68	74.87	93	21
6	f	24	1.69	56.1	90	15
7	f	24	1.57	62.9	86	19
8	m	24	1.8	80.76	85.5	20
9	m	28	1.78	73.12	98.5	25
10	f	19	1.68	56.3	94.5	18
11	f	24	1.71	63.69	90.5	18
12	f	22	1.63	55.33	86.5	18
13	m	28	1.8	72.04	98.5	80
14	m	24	1.78	77.78	97.5	20
15	m	23	1.84	72.81	98.5	35
16	m	21	1.71	67.22	92	40
17	m	33	1.78	77.16	97	36
18	m	27	1.81	71.22	101	23
19	f	27	1.67	53.56	89	15
20	f	24	1.64	59.97	87.5	17
21	m	24	1.74	77.36	91	55
22	m	21	1.77	75.14	96	35
23	m	25	1.74	69.4	89.5	25
24	f	35	1.64	56.33	86	25
25	f	19	1.61	63.4	87	17
26	f	19	1.57	50.48	84.5	30
27	f	24	1.73	67.05	90.5	27
28	m	26	1.85	78.74	101	28
29	f	32	1.68	56.74	85	40
30	f	21	1.58	56.41	83	30
Male Mean		25.67	1.77	73.94	94.77	35.33
Male Standard Deviation		3.15	0.05	4.27	4.61	17.27
Female Mean		24.67	1.65	59.03	87.63	24.93
Female Standard Deviation		4.82	0.06	6.60	3.07	10.40

Step Width (cm)

Step Width (cm)			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	0.07	0.12	0.17
2	0.02	0.06	0.17
3	0.00	0.05	0.17
4	0.04	0.04	0.12
5	0.00	0.08	0.15
6	0.00	0.01	0.14
7	-0.04	0.04	0.15
8	0.01	0.07	0.20
9	0.01	0.07	0.17
10	-0.01	0.05	0.16
11	0.01	0.06	0.14
12	-0.01	0.02	0.12
13	-0.03	0.01	0.11
14	0.08	0.10	0.18
15	0.00	0.08	0.17
16	0.03	0.12	0.14
17	0.01	0.05	0.16
18	-0.04	-0.04	0.18
19	0.02	0.05	0.19
20	-0.03	-0.01	0.16
21	0.06	0.08	0.17
22	0.04	0.01	0.15
23	0.00	0.11	0.13
24	-0.02	0.08	0.15
25	0.00	0.04	0.10
26	0.05	0.12	0.17
27	0.03	0.11	0.19
28	-0.05	0.02	0.13
29	0.05	0.11	0.17
30	0.05	0.07	0.13
Male Mean	0.01	0.06	0.16
Male Standard Deviation	0.04	0.05	0.02
Female Mean	0.01	0.06	0.15
Female Standard Deviation	0.03	0.04	0.02

Step Width (%)

Step Width (%)			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	6.76	10.97	15.92
2	1.40	5.04	15.20
3	0.41	7.63	13.65
4	0.46	6.27	16.74
5	0.60	6.80	16.62
6	-2.86	0.96	11.06
7	8.03	9.53	17.49
8	0.30	8.23	16.32
9	2.49	11.26	13.26
10	0.83	5.03	15.50
11	-4.07	-3.74	18.67
12	5.68	7.24	15.25
13	3.50	1.31	14.85
14	0.06	9.66	11.81
15	-4.66	1.69	13.14
16	0.10	4.30	15.39
17	3.71	3.70	10.51
18	0.01	1.20	12.58
19	-3.30	3.41	12.92
20	-1.22	4.28	13.78
21	1.05	5.01	13.03
22	-0.94	1.37	10.68
23	1.51	4.63	16.56
24	-2.20	-0.55	13.64
25	-1.85	6.57	12.76
26	0.35	3.71	8.68
27	4.95	9.86	14.50
28	2.78	10.28	16.97
29	4.49	9.53	14.83
30	4.09	6.05	11.15
Male Mean	1.26	5.86	15.03
Male Standard Deviation	3.65	4.23	2.11
Female Mean	0.90	4.89	13.20
Female Standard Deviation	2.61	3.17	2.30

Peak Hip Adduction Angle

Peak Hip Adduction Angle			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	11.77	10.06	5.36
2	14.37	12.04	10.00
3	21.30	17.66	17.83
4	13.52	13.44	12.30
5	11.53	9.68	9.18
6	16.12	14.16	9.00
7	20.17	18.63	13.97
8	12.25	12.02	9.33
9	8.66	8.38	4.46
10	16.06	14.99	10.29
11	16.92	14.82	13.49
12	19.31	17.98	12.30
13	15.64	14.66	10.03
14	13.47	13.50	7.12
15	14.64	12.39	8.58
16	13.88	11.95	12.54
17	7.90	6.39	2.31
18	13.80	14.57	4.17
19	20.78	18.62	17.42
20	18.26	19.23	13.79
21	5.15	3.96	0.91
22	13.65	16.24	11.50
23	12.36	10.93	10.96
24	17.00	14.01	9.23
25	8.35	4.95	2.51
26	14.56	10.35	10.41
27	20.06	15.58	14.23
28	18.37	18.76	9.50
29	13.10	9.83	9.36
30	20.44	16.76	16.62
Male Mean	12.50	11.70	7.73
Male Standard Deviation	3.27	3.76	3.51
Female Mean	17.06	14.73	12.18
Female Standard Deviation	3.59	3.93	3.94

Peak Hip Internal Rotation Angle

Peak Hip Internal Rotation Angle			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	7.73	8.03	5.42
2	9.93	8.54	8.28
3	6.69	5.90	4.66
4	4.93	4.86	6.06
5	7.21	7.62	6.96
6	12.14	11.96	10.91
7	9.19	10.82	10.82
8	19.00	19.79	20.68
9	10.92	10.23	9.52
10	10.92	11.30	11.94
11	8.54	8.37	8.65
12	9.93	10.13	6.26
13	14.95	18.37	15.98
14	6.47	6.13	5.73
15	9.52	12.55	12.04
16	6.53	7.53	1.73
17	14.26	12.25	11.05
18	11.47	11.64	9.99
19	18.28	17.04	17.53
20	12.95	14.11	13.53
21	6.68	5.45	4.20
22	12.44	12.84	12.69
23	2.82	1.84	3.21
24	9.26	11.30	8.94
25	6.11	11.33	10.47
26	-3.05	-0.50	-0.08
27	5.35	6.01	6.54
28	18.16	17.82	16.26
29	9.14	8.01	9.42
30	5.13	5.63	8.39
Male Mean	10.54	10.71	9.58
Male Standard Deviation	4.59	5.08	5.34
Female Mean	8.37	9.09	8.94
Female Standard Deviation	4.74	4.30	4.10

Peak Knee Internal Rotation Angle

Peak Knee Internal Rotation Angle			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	7.73	8.03	5.42
2	9.93	8.54	8.28
3	6.69	5.90	4.66
4	4.93	4.86	6.06
5	7.21	7.62	6.96
6	12.14	11.96	10.91
7	9.19	10.82	10.82
8	19.00	19.79	20.68
9	10.92	10.23	9.52
10	10.92	11.30	11.94
11	8.54	8.37	8.65
12	9.93	10.13	6.26
13	14.95	18.37	15.98
14	6.47	6.13	5.73
15	9.52	12.55	12.04
16	6.53	7.53	1.73
17	14.26	12.25	11.05
18	11.47	11.64	9.99
19	18.28	17.04	17.53
20	12.95	14.11	13.53
21	6.68	5.45	4.20
22	12.44	12.84	12.69
23	2.82	1.84	3.21
24	9.26	11.30	8.94
25	6.11	11.33	10.47
26	-3.05	-0.50	-0.08
27	5.35	6.01	6.54
28	18.16	17.82	16.26
29	9.14	8.01	9.42
30	5.13	5.63	8.39
Male Mean	1.91	2.16	2.54
Male Standard Deviation	5.38	5.84	5.53
Female Mean	5.24	5.83	6.28
Female Standard Deviation	3.92	4.18	3.54

Peak Knee Abduction Moment

Peak Knee Abduction Moment			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	-77.99	-69.52	-76.69
2	-54.08	-41.57	-53.05
3	-50.92	-32.41	-29.43
4	-62.10	-56.55	-54.80
5	-80.51	-78.80	-62.31
6	-37.36	-33.71	-24.60
7	-51.11	-38.86	-26.84
8	-80.65	-83.64	-64.29
9	-85.37	-77.64	-64.63
10	-98.02	-110.29	-84.49
11	-43.48	-32.43	-31.89
12	-83.32	-78.24	-74.89
13	-86.02	-69.79	-74.78
14	-74.11	-60.00	-52.33
15	-55.10	-42.21	-39.31
16	-76.24	-78.67	-69.02
17	-79.79	-75.21	-62.62
18	-87.61	-107.14	-69.08
19	-64.36	-70.94	-67.12
20	-63.20	-52.68	-48.60
21	-74.02	-87.51	-78.65
22	-58.40	-59.00	-60.11
23	-53.57	-48.69	-45.29
24	-27.36	-12.96	-1.14
25	-59.97	-74.67	-59.44
26	-72.74	-53.45	-42.86
27	-79.11	-73.52	-60.00
28	-84.67	-93.26	-82.99
29	-24.76	-25.38	-14.75
30	-53.78	-43.35	-39.24
Male Mean	-73.88	-71.51	-63.68
Male Standard Deviation	12.33	18.66	12.36
Female Mean	-58.11	-52.63	-44.01
Female Standard Deviation	20.34	25.38	23.16

Knee Abduction Angular Impulse

Knee Abduction Impulse			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	-12.07	-10.56	-10.71
2	-5.69	-4.16	-4.77
3	-6.37	-3.60	-3.49
4	-6.89	-6.26	-6.05
5	-9.55	-9.05	-7.38
6	-4.59	-2.99	-1.61
7	-5.69	-3.34	-1.92
8	-10.92	-10.21	-8.71
9	-11.02	-10.30	-7.79
10	-12.13	-13.83	-12.07
11	-5.23	-3.67	-3.28
12	-9.38	-8.90	-8.12
13	-8.61	-7.54	-7.35
14	-10.13	-8.28	-7.37
15	-6.33	-4.51	-3.82
16	-8.66	-9.60	-8.14
17	-8.66	-8.96	-7.28
18	-9.59	-10.96	-7.62
19	-7.12	-8.83	-7.41
20	-7.08	-5.68	-4.81
21	-9.36	-9.46	-9.14
22	-7.49	-7.97	-8.09
23	-7.56	-6.53	-6.31
24	-3.03	-1.19	-0.12
25	-7.81	-8.25	-7.61
26	-9.01	-5.72	-4.58
27	-10.08	-9.17	-7.83
28	-9.24	-9.00	-8.37
29	-2.17	-2.16	-0.93
30	-5.14	-4.91	-4.39
Male Mean	-8.99	-8.47	-7.52
Male Standard Deviation	1.74	2.06	1.66
Female Mean	-6.78	-5.90	-4.95
Female Standard Deviation	2.66	3.37	3.26

Peak Rearfoot Eversion Angle

Peak Rearfoot Eversion Angle			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	-3.63	-1.75	-0.63
2	-7.02	-7.26	-5.51
3	-9.17	-5.51	-4.30
4	-5.52	-4.60	-3.48
5	-6.66	-9.05	-4.33
6	-8.69	-8.55	-5.76
7	-7.48	-7.30	-3.95
8	-6.51	-3.17	-1.85
9	-5.20	-5.48	-1.89
10	-17.41	-13.18	-14.66
11	-3.67	-1.45	-1.07
12	-11.83	-10.72	-10.54
13	-3.29	-3.01	-1.14
14	0.25	0.90	2.88
15	-4.53	-4.14	-3.22
16	-6.04	-6.22	-5.26
17	-15.41	-11.77	-13.49
18	-7.54	-9.50	-3.86
19	-8.12	-9.01	-6.15
20	-6.31	-5.52	-5.06
21	-2.56	-3.72	0.29
22	-2.65	-3.30	-0.79
23	-6.00	-3.63	-3.23
24	-13.42	-10.82	-12.61
25	-11.45	-12.49	-10.32
26	-4.02	-0.81	-1.53
27	-6.16	-5.95	-1.92
28	-8.17	-7.42	-5.14
29	-11.36	-6.26	-8.13
30	-8.29	-3.97	-3.69
Male Mean	-5.67	-5.23	-3.15
Male Standard Deviation	3.52	3.32	3.69
Female Mean	-8.86	-7.08	-6.21
Female Standard Deviation	3.72	3.72	4.16

Peak Rearfoot Inversion Moment

Peak Rearfoot Inversion Moment			
Participant	Narrow Step Width	Preferred Step Width	Wide Step Width
1	-27.43	-24.82	-17.41
2	-51.11	-48.31	-41.69
3	-44.20	-45.79	-41.11
4	-67.88	-71.50	-65.70
5	-44.36	-52.93	-40.29
6	-38.70	-39.34	-35.86
7	-44.52	-49.22	-44.64
8	-32.36	-24.89	-23.86
9	-68.91	-78.94	-63.00
10	-55.78	-44.83	-48.06
11	-36.13	-37.24	-35.40
12	-44.79	-41.72	-38.02
13	-33.97	-40.62	-27.09
14	-16.43	-26.78	-21.79
15	-46.89	-52.31	-46.43
16	-53.03	-49.46	-45.97
17	-85.26	-80.97	-79.72
18	-89.09	-83.00	-68.08
19	-46.99	-42.53	-39.80
20	-42.20	-46.20	-42.96
21	-23.20	-22.71	-21.99
22	-39.05	-38.29	-29.94
23	-34.99	-30.37	-25.43
24	-35.65	-32.34	-31.71
25	-43.46	-41.71	-38.47
26	-25.04	-21.03	-16.25
27	-23.56	-19.47	-10.53
28	-52.56	-51.49	-40.38
29	-40.41	-38.32	-38.81
30	-38.09	-26.83	-30.26
Male Mean	-46.58	-47.06	-39.54
Male Standard Deviation	21.18	20.59	18.67
Female Mean	-41.83	-39.87	-37.17
Female Standard Deviation	10.81	12.56	12.76

Appendix E

Statistical Analysis

Step Width (cm)

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.903	2.746	2	.253	.912	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	.317	2	.158	239.045	.000
	Greenhouse-Geisser	.317	1.824	.174	239.045	.000
	Huynh-Feldt	.317	2.000	.158	239.045	.000
	Lower-bound	.317	1.000	.317	239.045	.000
condition * GENDR	Sphericity Assumed	7.743E-5	2	3.871E-5	.058	.943
	Greenhouse-Geisser	7.743E-5	1.824	4.246E-5	.058	.931
	Huynh-Feldt	7.743E-5	2.000	3.871E-5	.058	.943
	Lower-bound	7.743E-5	1.000	7.743E-5	.058	.811
Error(condition)	Sphericity Assumed	.037	56	.001		
	Greenhouse-Geisser	.037	51.062	.001		
	Huynh-Feldt	.037	56.000	.001		
	Lower-bound	.037	28.000	.001		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.514	1	.514	242.858	.000
GENDR	.001	1	.001	.401	.532
Error	.059	28	.002		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.047*	.006	.000	-.059	-.035
	3	-.143*	.006	.000	-.156	-.129
2	1	.047*	.006	.000	.035	.059
	3	-.095*	.008	.000	-.111	-.080
3	1	.143*	.006	.000	.129	.156
	2	.095*	.008	.000	.080	.111

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Step Width (%)

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.859	4.102	2	.129	.876	.964	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	2646.812	2	1323.406	211.450	.000
	Greenhouse-Geisser	2646.812	1.753	1509.958	211.450	.000
	Huynh-Feldt	2646.812	1.927	1373.296	211.450	.000
	Lower-bound	2646.812	1.000	2646.812	211.450	.000
condition * GENDR	Sphericity Assumed	.951	2	.475	.076	.927
	Greenhouse-Geisser	.951	1.753	.542	.076	.906
	Huynh-Feldt	.951	1.927	.493	.076	.921
	Lower-bound	.951	1.000	.951	.076	.785
Error(condition)	Sphericity Assumed	350.488	56	6.259		
	Greenhouse-Geisser	350.488	49.081	7.141		
	Huynh-Feldt	350.488	53.966	6.495		
	Lower-bound	350.488	28.000	12.517		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	4232.344	1	4232.344	242.396	.000
GENDR	3.119	1	3.119	.179	.676
Error	488.892	28	17.460		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-4.292*	.530	.000	-5.376	-3.207
	3	-13.033*	.648	.000	-14.360	-11.706
2	1	4.292*	.530	.000	3.207	5.376
	3	-8.741*	.743	.000	-10.263	-7.220
3	1	13.033*	.648	.000	11.706	14.360
	2	8.741*	.743	.000	7.220	10.263

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Peak Hip Adduction Angle

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.605	13.548	2	.001	.717	.772	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	363.384	2	181.692	77.346	.000
	Greenhouse-Geisser	363.384	1.434	253.379	77.346	.000
	Huynh-Feldt	363.384	1.544	235.313	77.346	.000
	Lower-bound	363.384	1.000	363.384	77.346	.000
condition * GENDR	Sphericity Assumed	10.971	2	5.485	2.335	.106
	Greenhouse-Geisser	10.971	1.434	7.650	2.335	.124
	Huynh-Feldt	10.971	1.544	7.104	2.335	.120
	Lower-bound	10.971	1.000	10.971	2.335	.138
Error(condition)	Sphericity Assumed	131.549	56	2.349		
	Greenhouse-Geisser	131.549	40.156	3.276		
	Huynh-Feldt	131.549	43.239	3.042		
	Lower-bound	131.549	28.000	4.698		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	14404.103	1	14404.103	402.247	.000
GENDR	363.109	1	363.109	10.140	.004
Error	1002.654	28	35.809		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	1.561*	.265	.000	1.019	2.104
	3	4.823*	.399	.000	4.005	5.641
2	1	-1.561*	.265	.000	-2.104	-1.019
	3	3.262*	.490	.000	2.257	4.266
3	1	-4.823*	.399	.000	-5.641	-4.005
	2	-3.262*	.490	.000	-4.266	-2.257

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Peak Hip Internal Rotation Angle

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.904	2.732	2	.255	.912	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	6.436	2	3.218	2.092	.133
	Greenhouse-Geisser	6.436	1.824	3.528	2.092	.138
	Huynh-Feldt	6.436	2.000	3.218	2.092	.133
	Lower-bound	6.436	1.000	6.436	2.092	.159
condition * GENDR	Sphericity Assumed	8.959	2	4.480	2.912	.063
	Greenhouse-Geisser	8.959	1.824	4.911	2.912	.068
	Huynh-Feldt	8.959	2.000	4.480	2.912	.063
	Lower-bound	8.959	1.000	8.959	2.912	.099
Error(condition)	Sphericity Assumed	86.149	56	1.538		
	Greenhouse-Geisser	86.149	51.084	1.686		
	Huynh-Feldt	86.149	56.000	1.538		
	Lower-bound	86.149	28.000	3.077		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	8184.939	1	8184.939	128.942	.000
GENDR	49.346	1	49.346	.777	.385
Error	1777.375	28	63.478		

Peak Knee Internal Rotation Angle

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.925	2.101	2	.350	.930	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	10.468	2	5.234	5.219	.008
	Greenhouse-Geisser	10.468	1.861	5.626	5.219	.010
	Huynh-Feldt	10.468	2.000	5.234	5.219	.008
	Lower-bound	10.468	1.000	10.468	5.219	.030
condition * GENDR	Sphericity Assumed	.716	2	.358	.357	.701
	Greenhouse-Geisser	.716	1.861	.385	.357	.686
	Huynh-Feldt	.716	2.000	.358	.357	.701
	Lower-bound	.716	1.000	.716	.357	.555
Error(condition)	Sphericity Assumed	56.165	56	1.003		
	Greenhouse-Geisser	56.165	52.099	1.078		
	Huynh-Feldt	56.165	56.000	1.003		
	Lower-bound	56.165	28.000	2.006		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1435.976	1	1435.976	21.285	.000
GENDR	288.219	1	288.219	4.272	.048
Error	1889.031	28	67.465		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.418	.292	.163	-1.016	.179
	3	-.835*	.239	.002	-1.324	-.347
2	1	.418	.292	.163	-.179	1.016
	3	-.417	.242	.096	-.912	.079
3	1	.835*	.239	.002	.347	1.324
	2	.417	.242	.096	-.079	.912

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*. The mean difference is significant at the .05 level.

Peak Knee Abduction Moment

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.973	.733	2	.693	.974	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	2306.865	2	1153.432	24.333	.000
	Greenhouse-Geisser	2306.865	1.948	1184.331	24.333	.000
	Huynh-Feldt	2306.865	2.000	1153.432	24.333	.000
	Lower-bound	2306.865	1.000	2306.865	24.333	.000
condition * GENDR	Sphericity Assumed	63.768	2	31.884	.673	.514
	Greenhouse-Geisser	63.768	1.948	32.738	.673	.511
	Huynh-Feldt	63.768	2.000	31.884	.673	.514
	Lower-bound	63.768	1.000	63.768	.673	.419
Error(condition)	Sphericity Assumed	2654.495	56	47.402		
	Greenhouse-Geisser	2654.495	54.539	48.672		
	Huynh-Feldt	2654.495	56.000	47.402		
	Lower-bound	2654.495	28.000	94.803		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	330880.448	1	330880.448	321.675	.000
GENDR	7376.097	1	7376.097	7.171	.012
Error	28801.275	28	1028.617		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-3.921*	1.892	.048	-7.798	-.045
	3	-12.149*	1.640	.000	-15.509	-8.790
2	1	3.921*	1.892	.048	.045	7.798
	3	-8.228*	1.792	.000	-11.898	-4.558
3	1	12.149*	1.640	.000	8.790	15.509
	2	8.228*	1.792	.000	4.558	11.898

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Knee Abduction Angular Impulse

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.802	5.960	2	.051	.835	.913	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	41.199	2	20.600	32.649	.000
	Greenhouse-Geisser	41.199	1.669	24.680	32.649	.000
	Huynh-Feldt	41.199	1.826	22.562	32.649	.000
	Lower-bound	41.199	1.000	41.199	32.649	.000
condition * GENDR	Sphericity Assumed	.657	2	.328	.521	.597
	Greenhouse-Geisser	.657	1.669	.394	.521	.565
	Huynh-Feldt	.657	1.826	.360	.521	.581
	Lower-bound	.657	1.000	.657	.521	.477
Error(condition)	Sphericity Assumed	35.332	56	.631		
	Greenhouse-Geisser	35.332	46.742	.756		
	Huynh-Feldt	35.332	51.129	.691		
	Lower-bound	35.332	28.000	1.262		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	4540.529	1	4540.529	248.486	.000
GENDR	135.378	1	135.378	7.409	.011
Error	511.639	28	18.273		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.701*	.229	.005	-1.170	-.231
	3	-1.651*	.224	.000	-2.110	-1.192
2	1	.701*	.229	.005	.231	1.170
	3	-.950*	.153	.000	-1.264	-.637
3	1	1.651*	.224	.000	1.192	2.110
	2	.950*	.153	.000	.637	1.264

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Peak Rearfoot Eversion Angle

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.721	8.842	2	.012	.782	.849	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	100.870	2	50.435	36.547	.000
	Greenhouse-Geisser	100.870	1.563	64.520	36.547	.000
	Huynh-Feldt	100.870	1.698	59.389	36.547	.000
	Lower-bound	100.870	1.000	100.870	36.547	.000
condition * GENDR	Sphericity Assumed	8.375	2	4.187	3.034	.056
	Greenhouse-Geisser	8.375	1.563	5.357	3.034	.070
	Huynh-Feldt	8.375	1.698	4.931	3.034	.065
	Lower-bound	8.375	1.000	8.375	3.034	.092
Error(condition)	Sphericity Assumed	77.280	56	1.380		
	Greenhouse-Geisser	77.280	43.775	1.765		
	Huynh-Feldt	77.280	47.557	1.625		
	Lower-bound	77.280	28.000	2.760		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	3274.861	1	3274.861	85.660	.000
GENDR	164.134	1	164.134	4.293	.048
Error	1070.469	28	38.231		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-1.108*	.342	.003	-1.809	-.407
	3	-2.584*	.208	.000	-3.011	-2.158
2	1	1.108*	.342	.003	.407	1.809
	3	-1.477*	.340	.000	-2.172	-.781
3	1	2.584*	.208	.000	2.158	3.011
	2	1.477*	.340	.000	.781	2.172

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Peak Rearfoot Inversion Moment

Mauchly's Test of Sphericity[b]

Measure:gender

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.923	2.152	2	.341	.929	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + GENDR

Within Subjects Design: condition

Tests of Within-Subjects Effects

Measure:gender

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	608.360	2	304.180	24.928	.000
	Greenhouse-Geisser	608.360	1.858	327.483	24.928	.000
	Huynh-Feldt	608.360	2.000	304.180	24.928	.000
	Lower-bound	608.360	1.000	608.360	24.928	.000
condition * GENDR	Sphericity Assumed	87.145	2	43.572	3.571	.035
	Greenhouse-Geisser	87.145	1.858	46.910	3.571	.038
	Huynh-Feldt	87.145	2.000	43.572	3.571	.035
	Lower-bound	87.145	1.000	87.145	3.571	.069
Error(condition)	Sphericity Assumed	683.326	56	12.202		
	Greenhouse-Geisser	683.326	52.015	13.137		
	Huynh-Feldt	683.326	56.000	12.202		
	Lower-bound	683.326	28.000	24.405		

Tests of Between-Subjects Effects

Measure:gender

Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	158815.756	1	158815.756	197.335	.000
GENDR	511.423	1	511.423	.635	.432
Error	22534.431	28	804.801		

Pairwise Comparisons

Measure:gender

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.736	.999	.467	-2.783	1.311
	3	-5.846*	.912	.000	-7.715	-3.978
2	1	.736	.999	.467	-1.311	2.783
	3	-5.110*	.781	.000	-6.710	-3.511
3	1	5.846*	.912	.000	3.978	7.715
	2	5.110*	.781	.000	3.511	6.710

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*. The mean difference is significant at the .05 level.

VITA

Richard A. Brindle III ventured one hours driving distance west from his childhood home in Chesterfield, VA, to Longwood University in the fall of 2006. After four memorable years he graduated with a bachelor's degree in kinesiology. Shortly after finishing his undergraduate studies, he continued to travel west to the University of Tennessee. He is currently pursuing a master's degree in exercise science with a concentration in biomechanics. In the future, he plans to continue his studies focusing on the field of biomechanics.