Reliability of a Multisegment Foot Model in Shod Running

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RELIABILITY OF A MULTISEGMENT FOOT MODEL IN SHOD RUNNING

By

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Bachelor of Science in Exercise and Sports Science
Oregon State University
2012

A thesis submitted in partial fulfillment of the requirements for the

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**Department of Kinesiology and Nutritional Sciences**

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ABSTRACT

Reliability of a multisegment foot model in shod running

By

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The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear. Eleven participants, five males (25.6±5 yrs, 73±15.8 kg, 1.75±0.05m) and six females (22.5±2.9 yrs, 66.6±7.2 kg, 1.71±0.05 m) granted institutionally approved written consent to participate. Three-dimensional motion capture (10 Vicon T40-S cameras) was used to capture kinematic data at 200Hz. Kinetic data was captured with an in-ground force platform (Kistler Instruments AG, Switzerland Model 9281B 60x40cm, 2000Hz). Participants were instructed to run at 3.5m/s ±5%. Velocity was monitored with the use of two photoelectric timing gates on either side of the force platform along the running pathway. The running pathway was 15m long, with the force platform placed midway through the path. Acceptable trials occurred when the subject’s foot made contact only with the platform and not with the ground adjacent and velocity was 3.5m/s ±5%. Twenty-four 14mm markers were placed over specific anatomical landmarks of the right lower leg and foot/shoe following the guidelines of the Leardini multisegment foot model. Subjects
completed 10 trials while wearing the experimental shoes (New Balance M680 – men’s, and W680 – women’s) as well as 10 trials while barefoot. Participants completed two separate days of testing with identical testing procedures; testing days were separated by at least one day. Conditions were counterbalanced between testing days. Data analysis included the stance phase kinematics reliability testing (ICC $2,1 > 0.7$) and marker placement reliability (marker placement difference $< 10$mm, and ICC $2,1 > 0.7$). Kinematic range of motion at each foot segment (rearfoot, midfoot, and forefoot) across the stance phase were normalized to 101 data points and used for reliability testing. Intersegment ICC values for leg-rearfoot, rearfoot-midfoot, and midfoot-forefoot in three planes were reported. Barefoot and shod reliability values were analyzed and compared separately. Marker placement repeatability, determined as Euclidian distance of markers from rearfoot segment joint center, and standard error of measurement (SEM) were also reported (Bishop, Thewlis, Uden, Ogilvie, & Paul, 2011). Discrete-event kinematic variables were included in analysis: angle at heel-contact, toe-off, maximum value, and total range of motion for all segments in three planes (Deschamps et al., 2011). ICC values for both conditions and all segments and rotations were deemed reliable except for shod, forefoot transverse plane. All markers were placed with excellent repeatability save for shod medial malleolus. The combination of reliable ICC values at all but one segment and plane, coupled with good marker placement repeatability, suggests that the Leardini multisegment foot model can be applied reliably during shod running without alteration of footwear.
ACKNOWLEDGEMENTS

I would like to first thank my colleagues and fellow graduate students for their support and encouragement over the past two years. Graduate school has been an incredible, and at times, perplexing experience and being able to go through this struggle with them has created bonds that will last a lifetime. I would also like to thank my family who have been there from the start and supported me every step of the way. The encouragement they have shown has been inspiring and has allowed me to grow in incredible ways. I would like to specifically thank my mother who has pushed me as a writer and intellectual throughout my entire academic career. I know that any future success I have will greatly benefit from this guidance, no matter how frustrating it might have been at the time of the lesson.

I must also thank my committee members who have helped me throughout this entire process and have pushed me in the right direction and made sure that I put forth the best work that I possibly can. In particular I want to thank Dr. Silvernail who was unfortunate enough to have her office right next door to mine, allowing me to constantly bombard her with questions. I appreciate her patience and willingness to help me through a variety of problems over the last year. Finally, I want to extend a special thank you to Dr. Dufek who has guided me from the beginning of this journey and helped me become the person I am today. She taught me to think in new and unusual ways and has pushed me to become a better researcher than I ever thought possible. Working with her has made the past two years the most beneficial learning experience it could ever be and I truly appreciate all of her hard work.
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CHAPTER 1

Introduction

With the increase in popularity of running for both recreational and competitive populations, and the resulting increase in running-related overuse injuries (RRI), improved research techniques are needed to better understand the relationships between runner, shoe, and injury occurrence (Hreljac, Marshall, & Hume, 1999; Hreljac, 2005; James, Bates, & Osternig, 1979). A better understanding of foot function through improved quantification of the complex interactions of the many bones and joints in the foot may contribute to this improvement (Powell, Williams, & Butler, 2013; Rankine, Long, Canseco, & Harris, 2008). Many footwear experiments involve an over-simplification of the foot as a single rigid segment, often modeled as one degree of freedom (Areblad, Nigg, Ekstrand, O, & Ekstrom, 1987; A Stacoff, Reinschmidt, & Stüssi, 1992). This has been done partially to simplify the complex nature of the foot as well as the foot-shoe relationship, but also due to the inherent difficulty in tracking foot kinematics based on anatomical landmarks with external markers. In their comprehensive review, Rankine et al. found numerous multisegment foot models have been created that utilized larger marker sets with external markers to track foot kinematics during walking and running tasks (Rankine et al., 2008). Several of these models have been used in clinical settings or have only used subjects in barefoot and/or walking conditions (Giacomozzi, Benedetti, Leardini, Macellari, & Giannini, 2006; Pohl, Messenger, & Buckley, 2007). The few experiments that have used multisegment foot models in shod conditions have used sandals or modified footwear with windows cut into the shoe upper or heel counter. While several papers have shown non-significant changes in kinematics
due to these footwear alterations, cutting windows for markers is an extreme method of measuring foot kinematics in clinical and/or research settings when using the subject’s personal footwear or in situations where laboratory-altered footwear are not available (Arnold, Mackintosh, Jones, & Thewlis, 2013; Eslami, Begon, Farahpour, & Allard, 2007; Giacomozzi et al., 2006; Leardini, Benedetti, Catani, Simoncini, & Giannini, 1999; Rebecca Shultz, Birmingham, & Jenkyn, 2007a).

**Purpose**

The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear.

**Research Questions**

1. Is the LMFM a reliable model for tracking foot motion during barefoot running?
2. Is the LMFM a reliable model for tracking foot motion during shod running without alteration of footwear?

**Significance**

There are numerous methods of kinematic running analysis, but analyzing results between and among researchers remains difficult due to differences in segment definitions and data collection procedures. In particular, the difficulty in analyzing foot-
shoe interactions during running is paramount. By establishing the LMFM as a reliable and accurate form of shod running analysis, researchers will be able to more effectively analyze kinematics of both the foot and the shoe during running. The significance of this is that researchers will be able to more easily compare results between experiments, as well as more accurately conjecture on how the foot and shoe relate to running-related injury risk.

**Hypotheses**

1. The LMFM can be applied reliably (ICC $2,1 > 0.7$) onto anatomical landmarks of the foot during barefoot running
   a. Inter-session reliability (Day 1 and Day 2) will be determined for barefoot running

2. The LMFM can be applied reliably (ICC $2,1 > 0.7$) onto anatomical landmarks of the foot during shod running without alteration of footwear
   a. Inter-session reliability (Day 1 and Day 2) will be determined for shod running

3. The LMFM can be applied with good repeatability (inter-session marker accuracy $<10\text{mm}, ICC > 0.7$) in barefoot running

4. The LMFM can be applied with good repeatability (inter-session marker accuracy $<10\text{mm}, ICC > 0.7$) in shod running
Limitations

- The LMFM was the only model used and represents only one of many multisegment foot models that have been used in research and clinical settings.

- A single shoe model was selected for this experiment: New Balance M680 (men’s) W680 (women’s); reliability and accuracy might change with different shoe models.

- Subjects were experienced runners and may not adequately represent non-running populations.

- Subjects were only included if they had no obvious anatomical mal-alignment of the feet. The LMFM requires accurate placement of external markers over relevant skeletal anatomical landmarks; therefore, abnormalities of the feet could influence reliability, accuracy, and kinematic data.

- A specific form of reliability testing (ICC 2,1) was utilized for this study and has particular advantages and limitations. Alternative forms of reliability testing, including other ICC calculations, might generate different results.

- Determination and interpretation of reliability and repeatability values (ICC > 0.7 and <10mm, respectively) are arbitrarily defined. While centered on values previously tested in the literature, successful statistical results do not necessarily represent a true indication of reliability or repeatability.

- Only a single rater was used.

- Data collection procedures included running overground at 3.5m/s±5%, which may be outside of participants’ normal or preferred running pace and could alter kinematics.
- Only healthy and active heelstrike runners were examined in order to better compare between-subject foot kinematics as differences have been observed between foot-strike patterns
- Only the stance phase of running was examined as there is substantial variability in kinematics during the swing phase of walking and running

**Definitions of Terms**

**Angular Kinematics of the Leardini Multisegment Foot Model**

- Leg-rearfoot plantar/dorsi flexion: sagittal plane motion of the rearfoot with respect to the tibia
- Leg-rearfoot pronation/supination: frontal plane motion of the rearfoot with respect to the tibia
- Leg-rearfoot eversion/inversion: transverse plane motion of the rearfoot with respect to the tibia
- Rearfoot-midfoot plantar/dorsi flexion: sagittal plane motion of the midfoot segment with respect to the rearfoot
- Rearfoot-midfoot pronation/supination: frontal plane motion of the midfoot segment with respect to the rearfoot
- Rearfoot-midfoot eversion/inversion: transverse plane motion of the midfoot segment with respect to the rearfoot
- Midfoot-forefoot plantar/dorsi flexion: sagittal plane motion of the forefoot segment with respect to the midfoot segment
- Midfoot-forefoot pronation/supination: frontal plane motion of the forefoot segment with respect to the midfoot segment
- Midfoot-forefoot eversion/inversion: transverse plane motion of the forefoot segment with respect to the midfoot segment

**Stance Phase Variables**

- Initial contact: first contact of the foot/shoe with the force platform. This was determined to be when vertical ground reaction force was greater than 20N
- Toe-off: end of the stance phase, point where foot/shoe is no longer in contact with the ground. This was determined to be when vertical ground reaction force was less than 20N
- Maximum value: the maximum angle reached by the distal segment relative to the proximal segment during the stance phase (reported in degrees)
- ROM: range of motion of the distal segment relative to the proximal segment during the stance phase (reported in degrees)

**Marker Placement Repeatability Variables** (Leardini et al., 2007a)

- 1MB: base of the first metatarsal; dorso-medial aspect of the first metatarso-cuneiform joint
- 1MH: head of the first metatarsal; dorso-medial aspect of the first metatarso-phalangeal joint
- 2MB: base of the second metatarsal; dorso-medial aspect of the second metatarso-cuneiform joint
- 2MH: head of the second metatarsal; dorso-medial aspect of the second metatarso-phalangeal joint
- 5MB: base of the fifth metatarsal; dorso-lateral aspect of the fifth metatarso-cuboid joint
- 5MH: head of the fifth metatarsal; dorso-lateral aspect of the fifth metatarso-phalangeal joint
- Hal: most distal and dorsal point of the head of the proximal phalanx of the hallux
- LatMal: distal apex of the lateral malleolus
- MedMal: distal apex of the medial malleolus
- Nav: most medial apex of the navicular tuberosity
CHAPTER 2

Literature Review

Running-Related Injuries

Over the past several decades, running has become an increasingly popular activity for both competitive athletes and those looking to improve and/or maintain their health and wellness. The New York City Marathon, currently the largest marathon in the world by participation numbers, began in 1970 with 127 participants, while the 2014 iteration of the race featured 50,564 (Marathon, 2014). The data-tracking website Statista (Statista, 2013) reported a record 61.87 million Americans went jogging for recreational purposes in 2013 compared to 45.67 million in 2008. RunnersWorld reported similar numbers for recreational runners, with 40 million Americans running at least six times in 2012, and 29.4 million running at least 50 times during the same year (Douglas, 2013).

Running-related overuse injuries (RRI) continue to be a major focus of running research. In a review of running injuries and their mechanisms, Hreljac (2005) found that between 27% and 70% of recreational and competitive runners can expect a RRI within any one year period of running (Hreljac, 2005). These injury rates represent chronic or repetitive stress injuries that come about as a result of running and do not include acute running injuries such as ankle sprains or fractures that occur due to an isolated injury event. One reason for this large discrepancy in injury rate is the ambiguity behind the definition of RRI. A common definition of RRI is, “any musculoskeletal ailment of the lower extremity that is attributed to running and results in a reduction or stoppage in running mileage for at least one day” (Gallant & Pierrynowski, 2014). However, this
definition is vague at best, as there are differences between authors as to what constitutes a “runner” as well as an “injury.” For example, Hreljac found that several authors defined a RRI as a, “restriction of running speed, distance, duration, or frequency for at least 1 week” (Hreljac, 2005).

Common overuse RRI include: stress fracture, medial tibial stress (shin splints), patellar tendinitis, plantar fasciitis, Achilles tendinitis and chondromalacia (Hreljac et al., 1999; Hreljac, 2005; Shorten, 2000). The exact cause of these injuries remains unknown and theories vary between individual researchers and clinicians. However, many authors agree that chronic RRI are multifactorial and the result of a combination of training methodology, anatomical characteristics, and biomechanical factors (Hintermann & Nigg, 1998; Hreljac et al., 1999; Hreljac, 2005; James et al., 1979; Shorten, 2000). These factors combine to produce specific running mechanics that might expose a runner to increased chance of suffering from some sort of RRI. In the case of training methodology, rapid increases in mileage, duration of runs, frequency of runs, and intensity of runs have all been implicated as possible predisposing factors for RRI(Hreljac et al., 1999; Hreljac, 2005).

Data regarding anatomical and biomechanical factors are mixed and often conflicting. There are some consistencies among authors regarding risk factors which include: medial-longitudinal arch height (pes cavus or pes planus), leg length discrepancies, genu valgum/varum, patella alta, and improper rearfoot kinematics (Hintermann & Nigg, 1998; Hreljac, 2005; Pohl & Buckley, 2008). Kinetic variables that have been speculated to be a cause of overuse running injuries are: the magnitude of impact forces, the rate of impact loading, the magnitude of active (propulsive) forces, and
the magnitude of knee joint forces and moments (Cook, Brinker, & Poche, 1990; Hintermann & Nigg, 1998; Hreljac et al., 1999).

**Running Kinematics**

Gait during running is a complex and multifaceted movement that allows for fast and efficient bipedal ambulation. A complete gait cycle consists of one stride, starting with initial contact by one foot and terminating at next initial contact of the same foot. Running consists of three phases: stance, swing, and float (Dugan & Bhat, 2005; Novacheck, 1998). Swing phase is present in both walking and running gait and is the time in which one foot is in contact with the ground while the other is progressing to the next step. Flight phase is unique to running gait as this is the time in which neither foot is in contact with the ground; this occurs after toe-off of one foot and before initial contact of the opposite foot. During each gait cycle there are two instances of flight phase: one at the beginning and one at the end (Dugan & Bhat, 2005). Novacheck (1998) found that runners spend about 39% of gait in the stance phase, meaning that approximately 61% of gait was spent in either swing or float. However, these percentages vary based on running velocity, with higher running velocity contributing to reduced time spent in stance.

The stance phase serves two purposes: force attenuation and force propagation, and can be further divided into initial contact, midstance, and toe-off (de Asla, Wan, Rubash, & Li, 2006; Dugan & Bhat, 2005). There are three commonly observed foot strike patterns during running: rearfoot, midfoot, and forefoot strike. The rearfoot strike is defined by first foot-ground contact at the lateral heel or posterior portion of the foot,
with midfoot and forefoot strikers making first foot-ground contact with the mid and forefoot, respectively (Rodgers, 1988).

**Foot and Ankle Kinematics**

The talocrural joint, which acts between the talus and tibia is one of the most commonly studied joints of the foot during heelstrike running. The principal rotation at this joint is in the sagittal plane resulting in dorsi/plantarflexion, with minimal motion in the frontal and transverse planes (de Asla et al., 2006; Dugan & Bhat, 2005; Subotnick, 1975). The subtalar joint (STJ), which acts on the inferior portion of the talus and superior portion of the calcaneus, also acts in the sagittal plane with dorsi/plantarflexion between the talus and calcaneus but has greater magnitude of movement in the frontal and transverse planes. These two joints combine to form what is commonly referred to as the ankle joint complex (AJC) or rearfoot (de Asla et al., 2006).

Rearfoot motion is commonly referred to as STJ pronation or supination, with pronation consisting of rearfoot abduction, eversion, and dorsiflexion, while supination consists of rearfoot adduction, inversion, and plantarflexion (Dugan & Bhat, 2005; Hintermann & Nigg, 1998). During the stance phase, movement at the rearfoot follows a supination-pronation-supination pattern from just prior to heel strike to toe-off for each step. Supination creates a close-packed midfoot and shortening of the medial-longitudinal arch and allows for force propagation from midstance to toe-off. Rearfoot pronation creates a loose-packed midfoot and allows for flattening of the medial-longitudinal arch which assists with shock attenuation at the foot during footstrike. Starting in a more supinated position at heelstrike allows for greater rearfoot excursion, increasing the
contact time and total range of motion (ROM) as needed by the body to allow for proper shock attenuation (Dugan & Bhat, 2005; C Reinschmidt & Murphy, 1997; Subotnick, 1975).

While normal pronation allows for shock attenuation during the stance phase, over-pronation has been linked to RRI risk due to possible disruption of normal function (Hintermann & Nigg, 1998). Over-pronation is an ambiguous term that could include one or more of several factors regarding rearfoot kinematics including: pronation excursion (total movement of rearfoot), maximum pronation (maximum pronation value), and pronation velocity (velocity from onset to maximum pronation; Hintermann & Nigg, 1998). Deviations in these characteristics during footstrike, especially when repeated hundreds or thousands of times during a run, are thought to contribute to RRI by producing asymmetric or misappropriated stress on the foot, ankle, and knee (Hintermann & Nigg, 1998; Alex Stacoff et al., 2001). However, specifics of pronation characteristics (including over-pronation) can vary substantially between researchers due to differences in rearfoot motion description and analysis.

Reinschmidt et al. (1997) used intracortical bone pins with markers attached on the calcaneus and tibia in order to track rearfoot motion during shod running and found mean tibiocalcaneal frontal plane ROM of 8.6° (±2.9°). Arndt et al. (2007) also used intracortical bone pins and found frontal plane ROM of 12.2° (±7.1°) at the talocrural joint and 8.9° (±3.2°) at the subtalar joint, which both exceed the total motion at the AJC found by Reinschmidt et al (Arndt et al., 2007; C Reinschmidt & Murphy, 1997). These data show the wide variation in magnitudes of rotation as well as differences in reporting of values as both the talocrural joint and the subtalar joint play important roles in gait.
In their study using a novel radiographic technique, consisting of a combined dual-orthogonal fluoroscopic and magnetic resonance imaging, de Asla et al. (2006) reported motion during two discrete phases of stance: heel strike to midstance, and midstance to toe-off. They reported differences between talocrural and subtalar joints during both phases (Table 1).

**Table 1. Rearfoot kinematics.**

<table>
<thead>
<tr>
<th>Heel strike to Midstance</th>
<th>DF(-)/PF(+)</th>
<th>IV(-)/EV(+)</th>
<th>ER(-)/IR(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Talocrural</strong></td>
<td>9.1°(±5.3°)*</td>
<td>-0.1°(±2.6°)</td>
<td>3.8°(±8.2°)</td>
</tr>
<tr>
<td><strong>Subtalar</strong></td>
<td>0.9°(±1.2°)*</td>
<td>1.7°(±2.7°)</td>
<td>-1.5°(±9.9°)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Midstance to Toe-off</th>
<th>DF(-)/PF(+)</th>
<th>IV(-)/EV(+)</th>
<th>ER(-)/IR(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Talocrural</strong></td>
<td>4.4°(±13.0°)</td>
<td>-1.7°(±2.7°)+</td>
<td>-1.6°(±5.9°)+</td>
</tr>
<tr>
<td><strong>Subtalar</strong></td>
<td>8.5°(±2.9°)</td>
<td>-10.7°(±3.8°)+</td>
<td>12.3°(±8.3°)+</td>
</tr>
</tbody>
</table>

**Adapted from de Asla et al. (2006)**


* Significant difference between Talocrural and Subtalar (heel strike to midstance).

+ Significant different between Talocrural and Subtalar (midstance to toe-off).

These data show the significant variation of motion at the rearfoot between the talocrural and subtalar joints, as well as the differences in types of motion between the two. Specifically, de Asla et al. found that the talocrural joint contributes mostly to sagittal plane motion while the subtalar joint contributes mostly to frontal and transverse plane motion, while Reinschmidt et al. and Arndt et al. found that movement between the two rearfoot joints was similar in magnitude (Arndt et al., 2007; de Asla et al., 2006; C Reinschmidt & Murphy, 1997).
Subotnick (1975) suggested that the minimum necessary movement of the calcaneus during stance begins with 2° of inversion followed by 4° of pronation for a total of 6° of rearfoot motion. He posited that ideal frontal plane rearfoot movement throughout stance is 18° of total motion, with 6° of STJ pronation and 12° of supination, while also suggesting that injury can occur with both hypomobility and hypermobility of the rearfoot beyond those excursions (Subotnick, 1975). In their systematic review of rearfoot motion and running injuries, Hintermann and Nigg (1998) found that individuals with a history of RRI typically show increased pronation of 2-4° during the stance phase. However, they also mention that between 40-50% of runners with excessive pronation do not have a RRI. These data represent examples of both the wide range of magnitudes that have been reported for rearfoot motion (as well as presenting motion at both joints of the rearfoot/AJC) but also the wide range of what might be considered under- or over-pronation. These discrepancies in joint rotation magnitude and data collection techniques make it difficult to determine injury risk during running as normal and over-pronation may be specific to individual runners.

In addition to possible RRI at the foot and ankle, over-pronation has been linked to knee injuries due to the coupling relationship between rearfoot movement and leg transverse plane rotation (Eslami et al., 2007; Pohl & Buckley, 2008; Pohl et al., 2007; C Reinschmidt & Murphy, 1997). When supinating, there is tibial external rotation, while the opposite occurs with STJ pronation, resulting in tibial internal rotation (de Asla et al., 2006; James et al., 1979; C Reinschmidt & Murphy, 1997; Alex Stacoff et al., 2001). Over-pronation has been associated with injury risk due to the opposing transverse torques that develop at the ankle and knee when this mitered hinge-like coupling
mechanism is disturbed by changes in maximum pronation, pronation excursion, time and duration of pronation onset and offset, and/or pronation velocity (Dugan & Bhat, 2005; Kadaba et al., 1989; Pohl et al., 2007; C Reinschmidt & Murphy, 1997; Alex Stacoff, Nigg, Reinschmidt, Van Den Bogert, & Lundberg, 2000).

Similar difficulties arise when assessing RRI risk at the knee as seen at the rearfoot, as magnitudes of rotation and coupling ratio between AJC rearfoot motion and knee transverse motion vary not only between studies but also between individuals. For example, Hintermann and Nigg (1998) found that subjects experienced internal tibial rotation of between 14% and 66% of their total rearfoot eversion motion. They stated that an individual with 20° of rearfoot frontal plane motion would be expected to experience between 3° and 13° of tibial internal rotation at the extremes of this coupling ratio. As it has been suggested that RRI may be caused by changes as modest as 2-4°, and given the wide range of rotations observed, determining RRI risk from rearfoot and tibial kinematics may be specific to individual runners (Hintermann & Nigg, 1998).

These data, and specifically the differences in what is considered normal or abnormal motion, highlight some difficulties associated with determining RRI risk based only on rearfoot motion. Be it from differences in testing procedures, joint/segment definition, or inter subject differences in motion, it’s clear that trying to determine RRI risk using a single segment foot (i.e., rearfoot) is unnecessarily limited in scope and does not adequately address the complex articulations of joints distal to the AJC. Future research should utilize multisegment foot modeling in order to analyze motion of midfoot and forefoot segments and how these segments and articulations might influence RRI occurrence (Bishop, Thewlis, et al., 2011; Pohl & Buckley, 2008).
Midfoot/Forefoot Kinematics

While the AJC/rearfoot has received considerable attention in both healthy and injured populations, recent research has pointed to the importance of motion distal to the rearfoot as a potentially critical factor in both injured and healthy populations (Arndt et al., 2007; Cornwall & McPoil, 2002; Jenkyn, Shultz, Giffin, & Birmingham, 2010; Leardini et al., 2007a, 1999; Levinger et al., 2010; Pohl & Buckley, 2008). Wolf et al. (2008) and Arndt et al. (2007) both used intracortical bone pins during running trials and found similar ROM values at the talonavicular, medial cuneiform-first metatarsal, and the cuboid-fifth metatarsal joints (Arndt et al., 2007; Wolf et al., 2008). Values can be seen in Table 2 below.

Table 2. Midfoot and forefoot kinematics.**

<table>
<thead>
<tr>
<th>Wolf et al.</th>
<th>TN</th>
<th>1Met</th>
<th>5Met</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Sagittal</td>
<td>5.6</td>
<td>2.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Frontal</td>
<td>15.1</td>
<td>2.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Transverse</td>
<td>8.3</td>
<td>2</td>
<td>4.2</td>
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<table>
<thead>
<tr>
<th>Arndt et al.</th>
<th>TN</th>
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<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Sagittal</td>
<td>6.5</td>
<td>2.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Frontal</td>
<td>13.5</td>
<td>4.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Transverse</td>
<td>8.7</td>
<td>1.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>

**Adapted from Arndt et al. (2007) and Wolf et al. (2008)

TN: Talonavicular joint. 1Met: Medial cuneiform-first metatarsal joint. 5Met: cuboid-fifth metatarsal joint.

Values reported in degrees.
While these authors did not directly define foot segments associated with these specific joint rotations, they represent similar interactions of the rearfoot-midfoot and midfoot-forefoot segments of the Leardini multisegment foot model (LMFM; Leardini et al., 2007a). These data show the similarity in the magnitudes of joint rotations present at the rearfoot, midfoot, and forefoot; which further stresses the importance of kinematic analyses of segments distal to the rearfoot during running (Bishop, Paul, Uden, & Thewlis, 2011; Leardini et al., 2007a, 1999; Pohl & Buckley, 2008).

**Kinematic Analyses/Foot Modeling**

Difficulties in tracking and analyzing foot kinematics are related to complications with data collection techniques mostly connected to the complex interactions, and small, difficult to access, bones of the foot. Complications also arise due to differences in joint and segment definitions, especially those distal to the rearfoot. Even when a midfoot segment is included in the model, differences in segment identification can exist. For example, Leardini (2007) and, Jenkyn and Nicol (2007) define the midfoot segment as the navicular, cuneiform, and cuboid bones (Jenkyn & Nicol, 2007; Leardini et al., 2007a) while Bishop et al. combined the midfoot and forefoot segments to include the navicular, cuneiforms, and metatarsals I-V (Bishop, Paul, et al., 2011). Carson et al. (2001) and Powell et al. (2013) did not define a midfoot segment; they only included hindfoot and forefoot segments (Carson, Harrington, Thompson, O’Connor, & Theologis, 2001; Powell et al., 2013).

As there are 26 bones in the foot, there are numerous, complex interactions during gait beyond those discussed previously (Kidder, Abuzzahab, Harris, & Johnson, 1996; C.
J. Nester et al., 2007; Wolf et al., 2008). One of the many problems with assessing RRI is determining principal motions of the foot and how deviations from normal movement patterns might lead to RRI. There is general agreement on overall movement patterns of the foot during running, but specific magnitudes of rotations can vary greatly between both research subjects and studies (Pohl & Buckley, 2008). This has led to a substantial amount of research addressing kinematic analyses of the foot in both barefoot and shod conditions.

Kinematic research focused on the foot consists of a variety of experiments which utilize different forms of measurement. Two such options have been outlined previously (invasive intracortical bone pins and dynamic radiography), and while they provide the most accurate data and are considered the gold standard of kinematic analysis, they are both invasive and expensive and do not represent ideal kinematic analysis for many clinical and research applications. Additional techniques include cadaver models and three-dimensional (3D) motion capture. The most common method, 3D motion capture with the use of external markers, involves placing markers directly onto the skin (barefoot running), on the shoe surface, or with modified shoes (with holes cut into the upper) or sandals (Collins, Ghoussayni, Ewins, & Kent, 2009; C. J. Nester et al., 2007; Wolf et al., 2008).

**Cadaver Models**

Nester et al. (2007) used a dynamic cadaver model to simulate walking across the stance phase with intracortical bone pins attached. This was a unique study that involved complex mechanical loading of cadaver tendons and ligaments to simulate normal
walking gait. The authors acknowledged that there were difficulties and errors assumed during the experiment, notably that there was a severe lack of force contribution from posterior leg muscles resulting in incomplete talocrural and tibial-calcaneal sagittal plane motion. However they did reveal similar motion at the talonavicular (sagittal, frontal, transverse, respectively; reported as mean (standard deviation)): 12.2° (7.1°), 12.4° (5.0°), 16.8° (9.2°), first metatarsal-medial cuneiform 5.6° (2.4°), 6.9° (2.4°), 5.1° (2.1°), and fifth metatarsal-cuboid 12.5° (3.2°), 12.9° (4.4°), 5.1° (1.7°) joints, as seen in previously mentioned intracortical bone pin running studies (Arndt et al., 2007; Wolf et al., 2008).

Magnitudes of rotation were greater across all joints during walking compared with running, but this result is consistent with those found by others (Lundgren et al., 2008; Wolf et al., 2008). Cadaver model joint rotations are similar in magnitude as those done in vivo with intracortical bone pins and dynamic radiography which suggests strong validity of the model for analyzing joint kinematics of the foot (C. Nester et al., 2007). However, errors remain present in the model; specifically the sagittal plane joint motion at the AJC, and the validity of dynamic use of the model. Only walking simulation studies have been performed with cadaver models making the results difficult to apply to studies regarding running kinematics. In addition to these errors, difficulty in completing experiments of this type (quality of cadaver specimens, whether dead tissue replicates in vivo movement, proper manipulation of movement and application of assistive walking gait forces) make cadaver research difficult for most research applications.
Early work examining foot and shoe kinematics consisted of single segment foot models where both two dimensional and three dimensional kinematic analyses consisted of markers placed on the leg and heel (Areblad et al., 1987; A Stacoff et al., 1992). These studies aimed to examine changes in rearfoot frontal plane motion (pronation/supination) as it might relate to RRI risk. Both of these experiments used posteriorly positioned cameras to record rearfoot motion during shod running. Areblad et al. (1987) used a three-dimensional system in order to identify potential errors involved with camera placement during two-dimensional analyses. While these studies do provide some information about movement between the foot and leg in the frontal plane, they assume a single segment rigid foot and ignore any contribution of movement distal to the ankle.

Stacoff et al. (1992), attempted to further investigate shod running by comparing barefoot, shod, and shod with windows cut into the heel counter and compared kinematics to determine the validity of using windows for placing markers directly onto the skin while shod. The authors reported similar results across conditions: Achilles tendon frontal plane angle 14.9° (4.2°) for shod no windows, and 14.1° (3.8°) shod with medium-sized windows. They also acknowledged that larger windows could compromise heel counter rigidity while small windows would negate the window effect due to difficulties with marker tracking. The authors concluded that heel counter windows of appropriate size give a more accurate recording of foot movement compared with shoe movement, as shoe markers consistently overestimated movement by 2-3° (A Stacoff et
al., 1992). However, it should be noted that there were only two windows cut into the heel counter and that this study also assumed a single segment, rigid foot. It has been shown that foot kinematics are far more complex and require assessment of joints and segments distal to the rearfoot (Arndt et al., 2007; Leardini et al., 2007a; Wolf et al., 2008). In order to apply this data collection technique to a multisegment model, multiple windows would need to be cut into the shoe which could further compromise its integrity (Shultz & Jenkyn, 2012).

Shultz and Jenkyn (2012) determined a maximum diameter of hole that could be cut into the shoe upper and heel counter without compromising the structural integrity of the shoe or significantly altering foot kinematics during level walking. However, the authors acknowledge that there were limitations to this study including use of only a single healthy subject, use of a single brand and model of shoe for each of the different shoe types (motion control, cushion, and stability), and that foot motions may differ between movements (i.e., walking compared to running) (Rebecca Shultz & Jenkyn, 2012).

Bishop et al. (2011a) also found that their method of in-shoe kinematic analysis (with markers placed on the skin of the foot through windows cut into the shoe upper) did not significantly alter foot kinematics, but again analyzed only walking gait. These authors also acknowledged that running gait would require separate reliability testing on both kinematics and material testing of the shoe upper and heel counter to determine if marker windows had compromised the shoes (Bishop, Paul, et al., 2011a). Furthermore, in a follow-up study combining both multisegment foot modeling and dynamic x-ray, Bishop et al. (2011b) were able to determine that markers on the shoe upper could be reliably
placed over the skeletal anatomical landmarks that they were representing (Bishop, Thewlis, et al., 2011b).

**Multisegment Modeling**

It has been shown that multisegment foot modeling, utilizing external markers on either the foot or shoe, has become a more common method in both clinical and research settings due to a more accurate representation of foot motion (compared to single segment), and non-invasive data collection techniques (Leardini et al., 2007a; Powell et al., 2013; Seo et al., 2014). In their comprehensive review of the literature, Deschamps et al. (2011) found 15 distinct multisegment models consisting of between four and nine segments (Deschamps et al., 2011), while Rankine et al. (2008) found 27 models (including modifications on previous models) between two and nine segments (Rankine et al., 2008).

Powell et al. (2013) compared two multisegment foot models (LMFM and Oxford) that differed in their definitions of foot segments with the LFM identifying four segments (leg, rearfoot, midfoot, and forefoot), while the Oxford defined three segments (leg, rearfoot, and forefoot) (Powell et al., 2013). The experiment included both barefoot walking and barefoot running and examined high- and low-arched athletes. In the LFM group, they reported rearfoot-midfoot frontal plane motion of 4.3° (1.5°), and midfoot-forefoot motion of 8.1° (2.3°) in high-arched athletes. Low-arched athletes showed rearfoot-midfoot motion of 5.9° (0.9°) and 13.5° (4.5°) in the midfoot-forefoot. For the Oxford model, they found midfoot motion (i.e., motion between the rearfoot and forefoot segments of the model) of 9.2° (3.4°) in high-arched, and 13.0° (4.2°) in low-arched
These values are similar to other studies using external marker based-multiprojection foot models (Leardini et al., 2007a, 1999) as well as the previously mentioned studies using intracortical bone pins (Arndt et al., 2007; Wolf et al., 2008). However, they do differ in joint and segment definitions. These differences in joint and segment definitions make it difficult to draw conclusions on what constitutes healthy or normal movement, making it difficult to speculate on RRI risk.

While substantial improvements have been made and multiprojection models have been used more frequently in recent years, difficulties still remain as implementation and analysis of different models can vary significantly. Differences between and among studies can include the number of segments modeled, location of markers, use of marker arrays, method of 3D orientation description, reference positions, and validity and repeatability analyses. Both Rankine et al. (2008) and Deschamps et al. (2011) argue that terminology, data collection techniques, and analysis must become more consistent in order to improve multiprojection modeling techniques and practices (Deschamps et al., 2011; Rankine et al., 2008).

**Footwear**

Since the introduction of running-specific footwear, substantial research has been done to determine the influence of footwear on running performance and RRI (Bates, Osternig, Sawhill, & James, 1983; Cook et al., 1990; Nigg & Bahlsen, 1988; Christoph Reinschmidt, Stacoff, & Stussi, 1992; Rebecca Shultz & Jenkyn, 2012; TenBroek, Rodrigues, Frederick, & Hamill, 2014). And while it is clear that running shoes can alter both running kinetics and kinematics, footwear research protocols are often done using
single segment foot modeling, with a focus on rearfoot frontal plane motion (C. Reinschmidt, Van Den Bogert, Murphy, Lundberg, & Nigg, 1997; A Stacoff et al., 1992). Others have made alterations to the test shoes (Rebecca Shultz & Jenkyn, 2012), or used sandals (Eslami et al., 2007; Morio, Lake, Gueguen, Rao, & Baly, 2009). Although these studies can provide some information regarding the foot-shoe interaction, they can also mask or ignore subtle changes that occur with shoe alterations that might influence RRI risk. With two-dimensional or single segment models, foot movement distal to the rearfoot is ignored. And while sandals or laboratory-altered shoes may reduce errors associated with externally based marker placement, they do not represent a true running shoe and therefore results must be regarded tentatively (Rebecca Shultz & Jenkyn, 2012). Establishing consistent multisegment modeling test methods would allow both clinicians and researchers to analyze walking and running gait in shod conditions using the subjects’ own footwear, without the additional cost or potential influence of shoe alterations.

**Leardini Multisegment Foot Model**

Given all of the differences observed with the various models and forms of kinematic analysis, it is clear that any estimation of RRI risk due to changes in foot segment rotations are precarious due to the lack of consistency of what constitutes normal and abnormal movement patterns. This is especially true when there is a lack of agreement on what signifies a functional unit of the human foot (Cornwall & McPoil, 2002; Wolf et al., 2008). Indeed, if non-functional joints or segments are being observed and conclusions on proper kinematics are based off of these data, then recommendations regarding avoidance or treatment of RRI become even more tenuous. Because of this, multisegment
modeling as well as generalizable joint and segment definitions, become even more important methods for kinematic analysis.

In light of the previous success in dealing with multiple populations (clinical and healthy, pediatric and adult subjects) as well as both walking and running activities, the Leardini multisegment foot model (LMFM) is a sound and practical choice for establishing generalized kinematics during both barefoot and shod running (Deschamps et al., 2012; Leardini et al., 2007a, 1999; Levinger et al., 2010; Powell et al., 2013). Establishing this model as a reliable source of kinematic data during shod running allows for better opportunities for footwear researchers and clinicians to explore how footwear influences whole-foot kinematics.

**Summary**

While difficulties still persist, external marker-based multisegment foot modeling remains the most viable method of determining foot and leg kinematics when compared with the alternatives. While intracortical bone pins and radiographical techniques both represent more accurate descriptions of foot kinematics, they are invasive measurement techniques that are not appropriate for many academic or clinical examinations (Bishop, Thewlis, et al., 2011; Deschamps et al., 2011; Lundgren et al., 2008; R. Shultz, E., & Jenkyn, 2011; Wolf et al., 2008). Other options include single segment modeling, sandals, or shoes with marker windows cut into the shoe upper; with all of these methods presenting important drawbacks for use in shod running analysis.

The LMFM has been established in previous research for use in both barefoot walking and running protocols (Arnold et al., 2013; Caravaggi, Benedetti, Berti, &
Leardini, 2011; Powell et al., 2013) but to our knowledge, it has not been used in a shod running study without alteration of footwear. Establishing this model as reliable will allow researchers to compare data regarding foot-shoe interactions as well as allowing running shoe researchers and developers to explore the effects of footwear on segments distal to the rearfoot.

In conclusion, the advancement of research regarding both healthy and injured runners, and their relationship to footwear, requires the formation of standard practices for collecting and reporting kinematic data during shod running studies. Instituting consistent reporting on complex foot kinematics will help to eliminate conflicting reports especially as they relate to RRI and associated risk factors. By testing the reliability of the LMMF, this study aims to establish a consistent method of collecting kinematic data during shod running, as well as present a method of uniform reporting of foot kinematics.
CHAPTER 3

Methodology

The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear. This was accomplished with a test-retest reliability assessment including both barefoot and shod running on two separate test days. Barefoot running was included in this study to establish tester reliability as this model has previously been applied during a barefoot running task (Powell et al., 2013). Intraclass correlation coefficient (ICC 2,1) was used to measure the test-retest reliability. In addition, standard error of measurement (SEM), marker placement repeatability measurements, and discrete gait event kinematics were reported as suggested supplemental reliability and validity measures (Bishop, Paul, et al., 2011; Deschamps et al., 2011; Leardini et al., 2007a; Weir, 2005).

Subject Characteristics

Eleven participants, five males (25.6±5 yrs, 73±15.8 kg, 1.75±0.05m) and six females (22.5±2.9 yrs, 66.6±7.2 kg, 1.71±0.05 m), were recruited from the greater Las Vegas area by word of mouth. Inclusion criteria consisted of healthy adults, aged 18-55 years old, active runners (ran at least two days a week, and/or ran at least eight miles a week; USA, 2013). In addition, participants were free from any lower extremity injury within the last six months, had no history of lower extremity amputation or joint replacement, no obvious anatomical mal-alignment of the foot, and no current use of orthotics. Participants granted institutionally approved written consent prior to volunteering for the study (Appendix I).
**Instrumentation**

**Footwear**

All participants wore laboratory shoes for this study: the New Balance M680 (men’s) or W680 (women’s, Figure 1). The shoe was classified as a cushion trainer type shoe with a 12mm heel-toe drop and was marketed to both beginner and experienced runners. It had a semi-curve last with a dual density outsole, as well as a rigid heel counter. It was a shoe that represents a standard for runners across age and experience groups. There were no anticipated difficulties for participants to run in this shoe during testing.

*Figure 1.* New Balance 680 (Women’s W680 – top, Men’s M680– bottom).
**Three-Dimensional Motion Capture**

Ten Vicon T40-S infrared cameras (Vicon Motion Systems Ltd., Oxford, UK) were used to track kinematic data sampling at 200Hz. Prior to data collection, the system was calibrated using a standard Vicon 5-marker T-frame reference tool. The calibrated volume was approximately 5.0m x 1.0m x 1.5m. Residual norms (< 2.0mm) were deemed acceptable. Data were collected and labeled in Vicon Nexus and imported to Visual 3D (C-Motion Inc. Rockville, MD) as C3D files for further processing.

**Force Platform**

A Kistler in-ground force platform (Kistler Instruments AG, Switzerland Model 9281B 60x40cm) sampling at 2000Hz was used to collect kinetic data in three dimensions. Analog voltages were converted to digital data by way of an A/D converter box (16 bit).

**Timing Gate**

Two photoelectric timing gates synchronized with a multifunction timer were used to monitor running speed which was set at 3.5m/s. Trials were considered successful when speed was within ±5% of 3.5m/s. Timing gaits were placed perpendicular to the running path, at approximately hip height. Timing gates were placed approximately 2 meters in front of and 2 meters behind the force platform.
Marker Setup

Reflective markers (fourteen mm diameter) were placed over skeletal anatomical landmarks of the leg, foot, and shoe. Specific marker placement is illustrated in Figure 2.

Figure 2. Leardini Multisegment Foot Model.

Procedure

Participants arrived at the UNLV biomechanics laboratory and were given an institutionally approved informed consent form to read, any questions were answered, procedures were explained, and informed consent signed. Participant gender, age, mass, height, and shoe size were measured and recorded and the participant was then fitted with a correct size test shoe. Participants were instructed to complete a self-directed five minute warm-up which included walking, running, and stretching. Following the warm-
up, retro-reflective markers (14mm diameter) were placed onto the right foot and lower leg with double sided tape following the LFM (Leardini et al., 2007a) seen in Figure 2. Participants started with either shod or barefoot running, with the order counter-balanced between test days. Once the markers were placed on either the shoe or foot, the participants were allowed to familiarize themselves with the data collection procedures. They were instructed to run along the defined 15m pathway within the biomechanics laboratory while making right foot contact with an in-ground force platform. A successful trial was one in which they contacted the force platform only (i.e., no contact with the area surrounding the force platform) without targeting the force platform. They were also instructed to maintain a velocity of 3.5m/s ±5% during all running trials. Trials were repeated if there was poor contact with the force platform or if velocity was outside of the required range. Prior to beginning the dynamic data collection trials, a calibration trial was recorded. Participants assumed a neutral standing posture with both feet placed comfortably in double support (Leardini et al., 2007a). A total of 10 acceptable trials were collected during both shod and barefoot running followed by 10 trials completed in the alternate condition. Markers were completely removed following the first condition and reattached for the second condition. Data collection procedures were identical between shod and barefoot conditions. All participants were heel-strike runners and were instructed to assume the same running pattern in the barefoot condition (Kinoshita, Bates, & DeVita, 1985; Pohl & Buckley, 2008). Participants were allowed ample rest time between trials and conditions as needed. In the event that marker(s) fell off during data collection, they were replaced by the examiner and a new static trial was collected before resuming dynamic trials. Following the collection of 20 trials (both barefoot and shod
conditions) the markers were removed and participants were allowed a cool-down phase (walking, running, stretching, etc.) if needed.

The second data collection period (Day2) was scheduled at least one day later. Informed consent form was again read with any questions answered and then signed again for re-consent. The same procedures as Day 1 were followed with the subjects allowed a five minute self-directed warm-up followed by marker placement. Conditions were counterbalanced between days. A new static calibration was collected at the beginning of Day 2 and the same procedures were followed in the event that marker(s) fell off. Following the data collection period, any questions from the participants were answered and they were then thanked for volunteering.

**Data Reduction**

Data were collected and labeled using a custom model within Vicon Nexus software and saved as .C3D files and transferred to Visual 3D for processing. Kinematic data were filtered using a zero-lag, 4th order Butterworth filter with a cutoff frequency of 12Hz, while kinetic data were filtered with a cutoff frequency of 50Hz (Shultz & Jenkyn, 2012). Filtering and data processing were done with custom pipelines written in Visual 3D (Appendix II). Kinematic data from static trials were subtracted from the corresponding values over the stance phase in order to calculate offset values for all joint rotations (Leardini et al., 2007a; Leardini et al., 2007b). Relative joint rotation angles were defined as the distal segment relative to the proximal segment, based on the local coordinate systems of both segments (Bishop, Paul, et al., 2011; Deschamps et al., 2011; Kidder et al., 1996; Leardini et al., 2007a). Kinematic data were analyzed across the
stance phase starting with heel contact and ending at toe-off. The stance phase kinematics were normalized to 101 data points beginning with heel contact and ending at toe-off. Kinetic data were used to determine heel contact and toe-off, with stance beginning when vertical ground reaction force was greater than 20N and ending when vertical ground reaction force was less than 20N.

**Data Analysis**

Intraclass correlation coefficients (ICC $2,1$) were calculated separately for the stance phase of barefoot and shod conditions between tests to reveal test-retest reliability (i.e., Day 1 and Day 2 values for each condition computed separately). ICC values greater than 0.7 (Bishop, Thewlis, et al., 2011; Leardini et al., 1999; Lundgren et al., 2008) were deemed acceptable and the model considered reliable. Values were calculated and reported in the sagittal, frontal, and transverse planes of motion for each segment of the LMFM which included the rearfoot, midfoot, and forefoot. These values were calculated and reported for each condition resulting in nine ICC values for each of the barefoot and shod conditions. ICC $2,1$ was chosen as this form of the calculation represents a two-way mixed model which attempts to account for error variance in the form of both systematic error (i.e., rater error) as well as random error (Shrout & Fleiss, 1979; Weir, 2005). In addition, standard error of measurements (SEM) values were calculated in order to provide an absolute index of reliability. This statistic attempts to measure the typical error of the specific measurement being examined and is measured in the units of interest (in this situation SEM was measured in degrees; Weir, 2005). SEM values were compared to results from other studies when available.
Marker placement repeatability values were also reported to describe marker position placement for barefoot and shod conditions between test days. A local coordinate system (LCS) was defined by using three fixed markers on the posterior portion of the right shoe or foot (depending on condition). The Euclidian distance of each marker from the origin of this LCS was calculated as the marker placement repeatability of markers between test days. Repeatability values were acceptable if they differed by less than 10 mm between test days. ICC values were also calculated with measurements deemed reliable when ICC > 0.7 (Bishop, Paul, et al., 2011).

In addition, several discrete kinematic variables were computed and included angles at initial contact, toe-off, maximum value, and the magnitude of total ROM throughout the stance defined as the difference between the maximum and minimum angles recorded (Bishop, Paul, et al., 2011). Values were reported for each plane of motion, segment, and condition as they occurred during the stance phase. Values were reported as the mean difference (MD) between test days, and also included ICC and SEM calculations (Bishop, Paul, et al., 2011; Deschamps et al., 2012).
CHAPTER 4

Results

4.1 Stance Phase ICC values

The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear. By establishing the LMFM as a reliable and accurate form of shod running analysis, researchers will be able to more effectively analyze kinematics of both the foot and the shoe during running. This in turn will allow researchers to more easily compare results between experiments, as well as more accurately conjecture on how the foot and shoe relate to running-related injury risk.

Tables 3 and 4 present the stance phase ICC values for shod and barefoot conditions. Values above 0.7 were considered reliable. Values were calculated for each segment of the LMFM (rearfoot, midfoot, and forefoot) as well as for each plane of motion (sagittal, frontal, and transverse). Mean data represents the reliability score of that segment and plane for all subjects.
| Subject | Rearfoot | | | | Midfoot | | | | | | Forefoot | | | |
|---------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|         | Sagittal | Frontal | Transverse | Sagittal | Frontal | Transverse | Sagittal | Frontal | Transverse | Sagittal | Frontal | Transverse |
| 1       | 0.960    | 0.924    | 0.936      | 0.870    | 0.820    | 0.907      | 0.924    | 0.914    | 0.658     |
| 2       | 0.962    | 0.975    | 0.959      | 0.903    | 0.893    | 0.954      | 0.909    | 0.782    | 0.518     |
| 3       | 0.983    | 0.887    | 0.954      | 0.675    | 0.679    | 0.789      | 0.717    | 0.908    | 0.106     |
| 4       | 0.986    | 0.985    | 0.966      | 0.971    | 0.943    | 0.979      | 0.991    | 0.949    | 0.954     |
| 5       | 0.971    | 0.914    | 0.905      | 0.807    | 0.834    | 0.919      | 0.659    | 0.951    | 0.896     |
| 6       | 0.989    | 0.963    | 0.924      | 0.869    | 0.352    | 0.953      | 0.981    | 0.020    | 0.850     |
| 7       | 0.978    | 0.870    | 0.699      | 0.961    | 0.884    | 0.968      | 0.492    | 0.895    | 0.761     |
| 8       | 0.883    | 0.895    | 0.868      | 0.914    | 0.659    | 0.899      | 0.207    | 0.831    | 0.076     |
| 9       | 0.967    | 0.867    | 0.862      | 0.860    | 0.708    | 0.717      | 0.837    | 0.496    | 0.845     |
| 10      | 0.975    | 0.926    | 0.773      | 0.986    | 0.457    | 0.98       | 0.843    | 0.947    | 0.426     |
| 11      | 0.978    | 0.711    | 0.871      | 0.374    | 0.538    | 0.776      | 0.905    | 0.143    | 0.010     |
| Mean    | 0.969    | 0.934    | 0.935      | 0.863    | 0.855    | 0.935      | 0.832    | 0.839    | 0.596     |

Notes: ICC values reported for each plane of motion and segment.

Unreliable values (<0.7) highlighted in yellow.

Mean data represents reliability of all trials for all subjects.
Table 4. Barefoot Stance Phase ICC values.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Rearfoot</th>
<th>Midfoot</th>
<th>Forefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Frontal</td>
<td>Transverse</td>
</tr>
<tr>
<td>1</td>
<td>0.981</td>
<td>0.959</td>
<td>0.931</td>
</tr>
<tr>
<td>2</td>
<td>0.99</td>
<td>0.947</td>
<td>0.976</td>
</tr>
<tr>
<td>3</td>
<td>0.987</td>
<td>0.821</td>
<td>0.941</td>
</tr>
<tr>
<td>4</td>
<td>0.972</td>
<td>0.954</td>
<td>0.968</td>
</tr>
<tr>
<td>5</td>
<td>0.939</td>
<td>0.831</td>
<td>0.579</td>
</tr>
<tr>
<td>6</td>
<td>0.993</td>
<td>0.947</td>
<td>0.932</td>
</tr>
<tr>
<td>7</td>
<td>0.964</td>
<td>0.901</td>
<td>0.425</td>
</tr>
<tr>
<td>8</td>
<td>0.972</td>
<td>0.909</td>
<td>0.792</td>
</tr>
<tr>
<td>9</td>
<td>0.974</td>
<td>0.925</td>
<td>0.940</td>
</tr>
<tr>
<td>10</td>
<td>0.988</td>
<td>0.976</td>
<td>0.869</td>
</tr>
<tr>
<td>11</td>
<td>0.995</td>
<td>0.929</td>
<td>0.913</td>
</tr>
<tr>
<td>Mean</td>
<td>0.979</td>
<td>0.94</td>
<td>0.926</td>
</tr>
</tbody>
</table>

Notes: ICC values reported for each plane of motion and segment.

Unreliable values (<0.7) highlighted in yellow

Mean data represents reliability of all trials for all subjects

Subject-specific reliability was good (ICC > 0.7) for shod rearfoot segment rotations. All sagittal, frontal, and transverse plane rotation values demonstrated good reliability. Shod midfoot segment reliability was good in the sagittal and transverse
planes, although not as strong in the frontal plane as four subjects showed unreliable motion (range 0.352-0.659). Two subjects had unreliable values in midfoot sagittal plane (range 0.374-0.675). Forefoot segment motion was the least reliable joint rotation with all but two subjects demonstrating at least one unreliable motion during stance (range 0.01-0.658). The sagittal plane was again the most reliable, followed by frontal and transverse, respectively. Overall, shod individual ICC values were reliable in 82 of the total of 99 (82.8%) segment planar motions. Group mean values for the stance phase showed good reliability for all segments and planes except for forefoot transverse plane (0.596).

Barefoot stance phase ICC values are presented in Table 4 and also show good reliability overall (89 out of 99; 89.9%). Two subjects showed poor reliability for rearfoot transverse plane motion (range 0.425-0.0579) with good reliability for both sagittal and frontal plane motion. Midfoot motion reliability was similar to the shod condition in that four subjects also showed poor reliability for midfoot frontal plane motion (range 0.394-0.572). Forefoot sagittal plane motion was reliable for all subjects while forefoot frontal and transverse showed poor reliability for two subjects each (range 0.376-0.695). Group barefoot reliability was good for all segments and planes.

4.2 Stance Phase ROM

Shod (Figures 4-6) and barefoot (Figures 7-9) stance phase range of motion (ROM) values are presented below. Values represent population data across stance, beginning with heel contact (when vertical ground reaction force > 20N) and ending at toe-off (when vertical ground reaction force < 20N). Data were normalized to 101 data points.
Figure 3. Shod rearfoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
Figure 4. Shod midfoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
Shod Forefoot ROM

Figure 5. Shod forefoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
Barefoot Rearfoot ROM

Figure 6. Barefoot rearfoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
Figure 7. Barefoot midfoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
Figure 8. Barefoot forefoot segment ROM across the stance phase. The data presented are the mean data of the study population.

Joint kinematics are presented by axis of rotation (A- sagittal, B- frontal, C- transverse).
4.3 Discrete Gait Event Kinematics

In their systematic review of multisegment foot models, Deschamps et al (2011) recommended reporting absolute kinematic data along with reliability statistics as there is a risk of models being described as reliable while reporting inconsistent absolute values (Deschamps et al., 2011). One of the goals of reliability testing using multisegment foot models is to gain a better understanding of whole-foot kinematics and function as it relates to injury risk. There is a wide range of magnitudes reported for rotation at joints of the foot making it difficult to establish parameters of what is considered healthy or risky movement, especially as it relates to running related injuries (Arndt et al., 2007; de Asla et al., 2006; Wolf et al., 2008). Tables 5 and 6 show population data for all segments and planes of motion for heel contact, toe-off, maximum value during stance, and the stance phase ROM for the shod and barefoot conditions, respectively.
Table 5. Shod Stance Phase Kinematics at Discrete Gait Events.

<table>
<thead>
<tr>
<th>Gait Event</th>
<th>Joint Rotation</th>
<th>Segment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rearfoot</td>
<td>Midfoot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Heel Contact</td>
<td>Sagittal Day1</td>
<td>-6.914</td>
<td>4.180</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>-6.600</td>
<td>4.755</td>
</tr>
<tr>
<td></td>
<td>Frontal Day1</td>
<td>-2.599</td>
<td>3.903</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>-2.182</td>
<td>4.217</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>2.554</td>
<td>4.393</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>2.225</td>
<td>4.124</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>20.613</td>
<td>4.507</td>
</tr>
<tr>
<td></td>
<td>Frontal Day1</td>
<td>-4.124</td>
<td>3.269</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>-3.153</td>
<td>4.745</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>-2.211</td>
<td>3.098</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>-0.780</td>
<td>3.227</td>
</tr>
<tr>
<td>Maximum</td>
<td>Sagittal Day1</td>
<td>21.830</td>
<td>4.774</td>
</tr>
<tr>
<td></td>
<td>Frontal Day1</td>
<td>7.766</td>
<td>3.178</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>8.727</td>
<td>3.209</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>9.673</td>
<td>4.518</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>10.125</td>
<td>4.240</td>
</tr>
<tr>
<td>ROM</td>
<td>Sagittal Day1</td>
<td>41.713</td>
<td>3.429</td>
</tr>
<tr>
<td></td>
<td>Frontal Day1</td>
<td>12.990</td>
<td>2.235</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>13.835</td>
<td>3.791</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>12.328</td>
<td>3.683</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>12.176</td>
<td>4.790</td>
</tr>
</tbody>
</table>

MD: mean difference, SD: standard deviation between Day1 and Day2 test sessions, values presented in degrees
Table 6. Barefoot Stance Phase Kinematics at Discrete Gait Events.

<table>
<thead>
<tr>
<th>Gait Event</th>
<th>Joint Rotation</th>
<th>Segment</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal Day1</td>
<td>Rearfoot</td>
<td>1.419</td>
<td>3.117</td>
<td>0.417</td>
<td>3.412</td>
<td>-3.810</td>
<td>4.845</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Rearfoot</td>
<td>1.479</td>
<td>2.441</td>
<td>0.722</td>
<td>3.117</td>
<td>-4.495</td>
<td>5.663</td>
</tr>
<tr>
<td>Heel</td>
<td>Frontal Day1</td>
<td>Midfoot</td>
<td>-2.391</td>
<td>2.902</td>
<td>-0.267</td>
<td>1.653</td>
<td>-0.044</td>
<td>2.674</td>
</tr>
<tr>
<td>Contact</td>
<td>Day2</td>
<td>Midfoot</td>
<td>-2.514</td>
<td>2.841</td>
<td>-1.061</td>
<td>1.526</td>
<td>0.082</td>
<td>2.694</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>Forefoot</td>
<td>-0.126</td>
<td>3.825</td>
<td>2.538</td>
<td>4.042</td>
<td>-2.198</td>
<td>2.644</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Forefoot</td>
<td>0.505</td>
<td>3.745</td>
<td>1.526</td>
<td>4.108</td>
<td>-2.539</td>
<td>2.768</td>
</tr>
<tr>
<td></td>
<td>Sagittal Day1</td>
<td>Frontal</td>
<td>17.586</td>
<td>3.739</td>
<td>9.286</td>
<td>3.234</td>
<td>-10.790</td>
<td>4.005</td>
</tr>
<tr>
<td>Toe-Off</td>
<td>Frontal Day1</td>
<td>Transverse</td>
<td>-5.009</td>
<td>3.173</td>
<td>0.920</td>
<td>1.990</td>
<td>-5.289</td>
<td>2.771</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Transverse</td>
<td>-5.011</td>
<td>3.649</td>
<td>-0.111</td>
<td>1.639</td>
<td>-4.066</td>
<td>2.495</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>Sagittal</td>
<td>-3.656</td>
<td>2.716</td>
<td>9.194</td>
<td>4.263</td>
<td>-4.554</td>
<td>2.851</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Sagittal</td>
<td>-2.290</td>
<td>3.184</td>
<td>8.041</td>
<td>3.408</td>
<td>-5.192</td>
<td>3.372</td>
</tr>
<tr>
<td>Maximum</td>
<td>Frontal Day1</td>
<td>Transverse</td>
<td>4.827</td>
<td>2.291</td>
<td>0.994</td>
<td>1.960</td>
<td>1.861</td>
<td>1.566</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Transverse</td>
<td>4.302</td>
<td>1.512</td>
<td>0.456</td>
<td>1.111</td>
<td>1.929</td>
<td>1.350</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>Sagittal</td>
<td>5.461</td>
<td>2.770</td>
<td>9.259</td>
<td>4.158</td>
<td>1.676</td>
<td>1.137</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>Sagittal</td>
<td>6.389</td>
<td>2.702</td>
<td>8.117</td>
<td>3.358</td>
<td>1.773</td>
<td>1.598</td>
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<tr>
<td>ROM</td>
<td>Frontal Day1</td>
<td>Frontal</td>
<td>10.131</td>
<td>1.566</td>
<td>4.353</td>
<td>2.272</td>
<td>7.763</td>
<td>2.179</td>
</tr>
<tr>
<td></td>
<td>Transverse Day1</td>
<td>Sagittal</td>
<td>9.653</td>
<td>3.071</td>
<td>19.813</td>
<td>4.148</td>
<td>7.102</td>
<td>2.240</td>
</tr>
</tbody>
</table>

Notes: MD: mean difference, SD: standard deviation between Day1 and Day2 test sessions, values presented in degrees
Table 7. Shod Discrete Gait Event ICC Values.

<table>
<thead>
<tr>
<th>Gait Event</th>
<th>Joint Rotation</th>
<th>Rearfoot</th>
<th>Midfoot</th>
<th>Forefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ICC</td>
<td>SEM</td>
<td>ICC</td>
</tr>
<tr>
<td>Heel Contact</td>
<td>Sagittal</td>
<td>0.706</td>
<td>2.422</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.922</td>
<td>1.134</td>
<td>0.731</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.919</td>
<td>1.212</td>
<td>0.828</td>
</tr>
<tr>
<td>Toe-Off</td>
<td>Sagittal</td>
<td>0.844</td>
<td>1.817</td>
<td>0.342</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.706</td>
<td>2.173</td>
<td>0.836</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.655</td>
<td>1.858</td>
<td>0.784</td>
</tr>
<tr>
<td>Maximum</td>
<td>Sagittal</td>
<td>0.835</td>
<td>1.885</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.83</td>
<td>1.317</td>
<td>0.871</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.897</td>
<td>1.405</td>
<td>0.78</td>
</tr>
<tr>
<td>ROM</td>
<td>Sagittal</td>
<td>0.771</td>
<td>1.728</td>
<td>0.701</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.687</td>
<td>1.688</td>
<td>0.794</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.902</td>
<td>1.326</td>
<td>0.727</td>
</tr>
</tbody>
</table>

Notes: SEM: standard error of measurement, values presented in degrees
Values falling below reliable range (ICC < 0.7) highlighted in yellow
Table 8. Barefoot Discrete Gait Event ICC Values.

<table>
<thead>
<tr>
<th>Gait Event</th>
<th>Joint Rotation</th>
<th>Rearfoot</th>
<th>Midfoot</th>
<th>Forefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>SEM</td>
<td>ICC</td>
<td>SEM</td>
</tr>
<tr>
<td>Heel Contact</td>
<td>Sagittal</td>
<td>0.770</td>
<td>1.333</td>
<td>0.854</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.905</td>
<td>0.885</td>
<td>0.758</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.939</td>
<td>0.935</td>
<td>0.914</td>
</tr>
<tr>
<td>Toe-Off</td>
<td>Sagittal</td>
<td>0.794</td>
<td>1.907</td>
<td>0.718</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>0.918</td>
<td>0.977</td>
<td><strong>0.627</strong></td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>0.815</td>
<td>1.269</td>
<td>0.831</td>
</tr>
<tr>
<td>Maximum</td>
<td>Sagittal</td>
<td>0.794</td>
<td>1.907</td>
<td>0.725</td>
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<tr>
<td></td>
<td>Frontal</td>
<td>0.817</td>
<td>0.813</td>
<td><strong>0.530</strong></td>
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<tr>
<td></td>
<td>Transverse</td>
<td>0.826</td>
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</tr>
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<td>ROM</td>
<td>Sagittal</td>
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<td>1.915</td>
<td><strong>0.451</strong></td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
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<td>1.324</td>
<td>0.735</td>
</tr>
<tr>
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<td>Transverse</td>
<td>0.923</td>
<td>0.862</td>
<td>0.770</td>
</tr>
</tbody>
</table>

Notes: SEM: standard error of measurement, values presented in degrees
Values falling below reliable range (ICC < 0.7) highlighted in yellow

Discrete gait event reliability followed a similar pattern as the stance phase and marker placement repeatability with barefoot producing more reliable values overall. Shod forefoot events were least reliable with six unreliable values (range 0.188-0.677), followed by midfoot (three values; range 0-0.459) and rearfoot (two values; range 0.655-0.687). Toe-off was the least reliable gait event across all segments and axes with six of nine unreliable, followed by heel contact with three, while maximum angle had two and ROM one. SEM calculations are also given in Tables 7 and 8 with values measured in degrees. SEM values represent the difference in absolute measurement between test days.
Barefoot values showed greater reliability compared with shod with seven unreliable segments/planes compared to 11 for the shod condition. Rearfoot was most reliable with only frontal plane ROM falling below 0.7. Midfoot and forefoot both showed three unreliable values (range 0.451-0.627, and 0.63-0.694, respectively). Heel contact was reliable across all segments and planes with toe-off and maximum angle both showing two unreliable values and ROM showing three.

4.4 Marker Placement Repeatability

Marker placement repeatability was excellent across all subjects, with only five of 110 measurements falling outside of the acceptable range (> 10mm) for both shod and barefoot conditions. In addition, no individual subject had more than two markers fall out of the acceptable range in either condition. Individual subject values can be seen in Tables 10 and 11. Rearfoot markers were least repeatable for the shod condition as only lateral and medial malleoli as well as one navicular marker fell outside the acceptable repeatability range. Forefoot marker placement was less repeatable for the barefoot condition, especially the first metatarsal as three of the five unacceptable measures were on the first metatarsal base or head, followed by one each on second metatarsal base and one at the medial malleolus. Subject-specific marker placement repeatability values are presented in Tables 10 and 11 for the shod and barefoot conditions, respectively. Group means for marker placement repeatability for both the shod and barefoot conditions are given in Table 12.
Table 9. Marker Label Definitions.

<table>
<thead>
<tr>
<th>Marker Label</th>
<th>Anatomical Landmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1MB</td>
<td>1st Metatarsal Base</td>
</tr>
<tr>
<td>1MH</td>
<td>1st Metatarsal Head</td>
</tr>
<tr>
<td>2MB</td>
<td>2nd Metatarsal Base</td>
</tr>
<tr>
<td>2MH</td>
<td>2nd Metatarsal Head</td>
</tr>
<tr>
<td>5MB</td>
<td>5th Metatarsal Base</td>
</tr>
<tr>
<td>5MH</td>
<td>5th Metatarsal Head</td>
</tr>
<tr>
<td>Hal</td>
<td>Proximal Hallux</td>
</tr>
<tr>
<td>LatMal</td>
<td>Lateral Malleolus</td>
</tr>
<tr>
<td>MedMal</td>
<td>Medial Malleolus</td>
</tr>
<tr>
<td>Nav</td>
<td>Navicular Tuberosity</td>
</tr>
</tbody>
</table>

Table 10. Shod Marker Placement Repeatability.

<table>
<thead>
<tr>
<th></th>
<th>1MB</th>
<th>1MH</th>
<th>2MB</th>
<th>2MH</th>
<th>5MB</th>
<th>5MH</th>
<th>Hal</th>
<th>LatMal</th>
<th>MedMal</th>
<th>Nav</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 2</td>
<td>6.160</td>
<td>2.930</td>
<td>3.910</td>
<td>1.280</td>
<td>0.130</td>
<td>1.610</td>
<td>2.530</td>
<td>2.520</td>
<td>4.150</td>
<td>6.790</td>
</tr>
<tr>
<td>Subject 3</td>
<td>6.440</td>
<td>2.740</td>
<td>2.390</td>
<td>2.420</td>
<td>7.950</td>
<td>2.800</td>
<td>0.030</td>
<td>1.540</td>
<td>0.070</td>
<td>0.100</td>
</tr>
<tr>
<td>Subject 4</td>
<td>1.480</td>
<td>0.680</td>
<td>0.120</td>
<td>0.680</td>
<td>0.120</td>
<td>0.680</td>
<td>0.120</td>
<td>0.680</td>
<td>0.120</td>
<td>0.680</td>
</tr>
<tr>
<td>Subject 5</td>
<td>7.450</td>
<td>2.610</td>
<td>7.020</td>
<td>1.660</td>
<td>1.250</td>
<td>2.210</td>
<td>1.350</td>
<td>4.680</td>
<td>3.860</td>
<td>5.630</td>
</tr>
<tr>
<td>Subject 7</td>
<td>0.060</td>
<td>2.900</td>
<td>0.790</td>
<td>3.720</td>
<td>0.780</td>
<td>3.310</td>
<td>0.370</td>
<td>0.570</td>
<td>6.900</td>
<td>4.800</td>
</tr>
<tr>
<td>Subject 8</td>
<td>2.220</td>
<td>4.500</td>
<td>0.990</td>
<td>2.410</td>
<td>4.400</td>
<td>8.750</td>
<td>0.090</td>
<td>9.660</td>
<td>11.580</td>
<td>1.860</td>
</tr>
<tr>
<td>Subject 9</td>
<td>1.170</td>
<td>0.840</td>
<td>2.680</td>
<td>1.930</td>
<td>7.490</td>
<td>2.050</td>
<td>4.960</td>
<td>9.600</td>
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<tr>
<td>Subject 10</td>
<td>4.010</td>
<td>0.380</td>
<td>0.180</td>
<td>0.550</td>
<td>5.540</td>
<td>2.330</td>
<td>5.720</td>
<td>1.170</td>
<td>1.640</td>
<td>1.840</td>
</tr>
<tr>
<td>Subject 11</td>
<td>2.540</td>
<td>0.910</td>
<td>1.270</td>
<td>1.730</td>
<td>3.480</td>
<td>2.230</td>
<td>1.650</td>
<td>1.120</td>
<td>2.970</td>
<td>1.120</td>
</tr>
</tbody>
</table>

Notes: Values exceeding repeatability standards (mean difference > 10mm) highlighted in yellow
Measure as Euclidian distance (mm)
Table 11. Barefoot marker placement repeatability.

<table>
<thead>
<tr>
<th>Marker</th>
<th>1MB</th>
<th>1MH</th>
<th>2MB</th>
<th>2MH</th>
<th>5MB</th>
<th>5MH</th>
<th>Hal</th>
<th>LatMal</th>
<th>MedMal</th>
<th>Nav</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Metatarsal Base</td>
<td>0.510</td>
<td>0.100</td>
<td>0.270</td>
<td>0.300</td>
<td>5.080</td>
<td>0.130</td>
<td>4.150</td>
<td>0.200</td>
<td>0.370</td>
<td>1.080</td>
</tr>
<tr>
<td>2nd Metatarsal Base</td>
<td>0.250</td>
<td>0.840</td>
<td>6.890</td>
<td>1.250</td>
<td>7.560</td>
<td>0.650</td>
<td>0.500</td>
<td>0.920</td>
<td>3.790</td>
<td>1.630</td>
</tr>
<tr>
<td>2nd Metatarsal Head</td>
<td>2.280</td>
<td>2.970</td>
<td>2.340</td>
<td>0.990</td>
<td>3.840</td>
<td>1.070</td>
<td>0.190</td>
<td>3.110</td>
<td>3.110</td>
<td>2.700</td>
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<tr>
<td>5th Metatarsal Base</td>
<td>12.300</td>
<td>9.690</td>
<td>10.890</td>
<td>5.980</td>
<td>5.670</td>
<td>6.800</td>
<td>6.120</td>
<td>0.110</td>
<td>8.530</td>
<td>8.110</td>
</tr>
<tr>
<td>5th Metatarsal Head</td>
<td>9.370</td>
<td>5.960</td>
<td>6.030</td>
<td>0.230</td>
<td>3.720</td>
<td>0.650</td>
<td>0.500</td>
<td>0.920</td>
<td>3.790</td>
<td>1.630</td>
</tr>
<tr>
<td>Proximal Hallux</td>
<td>1.090</td>
<td>11.780</td>
<td>3.560</td>
<td>4.600</td>
<td>5.670</td>
<td>7.860</td>
<td>7.750</td>
<td>0.680</td>
<td>12.970</td>
<td>3.850</td>
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<tr>
<td>Lateral Malleolus</td>
<td>8.940</td>
<td>1.360</td>
<td>7.480</td>
<td>3.640</td>
<td>6.050</td>
<td>6.350</td>
<td>1.790</td>
<td>0.130</td>
<td>0.010</td>
<td>7.310</td>
</tr>
<tr>
<td>Medial Malleolus</td>
<td>0.600</td>
<td>1.330</td>
<td>1.510</td>
<td>2.600</td>
<td>0.440</td>
<td>1.860</td>
<td>1.420</td>
<td>1.390</td>
<td>9.910</td>
<td>0.340</td>
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<tr>
<td>Navicular Tuberosity</td>
<td>1.960</td>
<td>0.090</td>
<td>0.850</td>
<td>2.380</td>
<td>8.390</td>
<td>3.310</td>
<td>0.830</td>
<td>4.710</td>
<td>2.970</td>
<td>0.530</td>
</tr>
<tr>
<td>1st Metatarsal Base</td>
<td>3.420</td>
<td>0.830</td>
<td>5.120</td>
<td>5.400</td>
<td>1.140</td>
<td>2.440</td>
<td>5.840</td>
<td>0.030</td>
<td>0.090</td>
<td>2.140</td>
</tr>
</tbody>
</table>

Notes: Values exceeding repeatability standards (mean difference > 10mm) highlighted in yellow
Measure as Euclidian distance (mm)

Table 12. Marker Placement Repeatability Reliability.

<table>
<thead>
<tr>
<th>Marker</th>
<th>Shod</th>
<th>Barefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD</td>
<td>SD</td>
</tr>
<tr>
<td>1st Metatarsal Base</td>
<td>4.075</td>
<td>2.937</td>
</tr>
<tr>
<td>1st Metatarsal Head</td>
<td>2.321</td>
<td>2.061</td>
</tr>
<tr>
<td>2nd Metatarsal Base</td>
<td>2.561</td>
<td>2.237</td>
</tr>
<tr>
<td>2nd Metatarsal Head</td>
<td>2.423</td>
<td>1.609</td>
</tr>
<tr>
<td>5th Metatarsal Base</td>
<td>3.592</td>
<td>2.784</td>
</tr>
<tr>
<td>5th Metatarsal Head</td>
<td>3.297</td>
<td>2.580</td>
</tr>
<tr>
<td>Proximal Hallux</td>
<td>2.952</td>
<td>3.127</td>
</tr>
<tr>
<td>Lateral Malleolus</td>
<td>4.435</td>
<td>4.423</td>
</tr>
<tr>
<td>Medial Malleolus</td>
<td>5.585</td>
<td>4.959</td>
</tr>
<tr>
<td>Navicular Tuberosity</td>
<td>3.696</td>
<td>4.187</td>
</tr>
</tbody>
</table>

Notes: Mean difference (MD) and standard deviation (SD) of group data measured as Euclidian distance (mm)
Values falling below reliability standards (ICC < 0.7) highlighted in yellow
Mean difference values for marker placement repeatability all fell within the acceptable range for both shod and barefoot conditions with the exception of the shod medial malleolus. This marker seemed to have lower repeatability overall as it was also responsible for four out of the ten subject specific markers to lie outside of the acceptable range (given in Tables 10 and 11).

4.5 Summary

In summary, individual subject ICCs showed 171 of a possible 198 segments and planes had good reliability (ICC > 0.7) across both the barefoot and shod conditions. Group ICC values showed 17 of a possible 18 segments and planes were reliable (ICC > 0.7). 210 of the possible 220 subject-specific markers showed good repeatability, only the 1st metatarsal base (two) and medial malleolus (four) had unacceptable repeatability values for multiple subjects across both conditions. Group marker placement repeatability values were reliable at 19 of the 20 markers across both shod and barefoot conditions. Discrete gait event kinematic values were overall less reliable with 18 of 72 values across all segments, planes, and conditions showing unreliable values. SEM values fell below the standard deviation for all segments, planes, conditions, and discrete events.
CHAPTER 5

Discussion

5.1 Stance Phase ICC

The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear. This model had been previously established as a reliable measurement technique during barefoot walking and running (Caravaggi et al., 2011; Leardini et al., 2007a, 1999; Levinger et al., 2010; Powell et al., 2013) but has not been used with footwear. The potential impact of establishing this model as a reliable source of measuring kinematic data during shod running is wide-ranging, as it would allow researchers and clinicians an opportunity to examine whole-foot kinematics with footwear so that the shoe-user interaction can be further studied. The barefoot running condition was included in this study to provide a basis for comparison of reliability measurements. Marker placement repeatability, standard error of measurement (SEM), and discrete gait event kinematics were also included as these parameters have been better established in the literature previously (Arndt et al., 2007; Bishop, Paul, et al., 2011; Bishop, Thewlis, et al., 2011; Leardini et al., 2007a, 1999; Pohl et al., 2007; Wolf et al., 2008).

It is important to note that interpretation of reliability measures, including ICC, is based on arbitrarily determined parameters. For the purposes of this study, an ICC greater than 0.7 was determined to be reliable (Leardini et al., 1999). Furthermore, ICC values
can be calculated in a variety of ways. For this study, ICC $2,1$ was chosen based on previous work as this model attempts to account for both systematic (rater) and random error (Bishop, Paul, et al., 2011; Shrout & Fleiss, 1979; Weir, 2005). It is possible that alternate interpretations of these data could result in different results as they relate to the reliability of the LMFM. It is also possible that ICC values were influenced either by low levels of between-subjects variability and/or high intra-subject variability, both of which could result in a lower ICC value (Weir, 2005). SEM values were included with the reliability measurements for discrete gait event kinematics in order to, “provide an absolute index of reliability” (Weir, 2005).

In their systematic review, McGinley et al. (2009) found a general trend of gait kinematic values being considered reliable whether using ICC or correlation of multiple coefficients (CMC, used as a measure of consistency across the stance phase), based on planar motion. They found that sagittal plane motion was most reliable with values above 0.8, with frontal plane above 0.7, and transverse plane below 0.7 (McGinley, Baker, Wolfe, & Morris, 2009). However, there is still a lack of a standardized interpretation of ICC values, leading some investigators to opt instead for ranges of reliability scores. Wright et al. (2011) classified ICC values less than 0.4 as having poor repeatability, between 0.4 and 0.75 represented fair to good repeatability, while greater than 0.75 represented excellent repeatability (Wright, Arnold, Coffey, & Pidcoe, 2011). Seo et al. (2014) meanwhile, interpreted ICC values less than 0.5 as poor, between 0.5 and 0.75 as fair to good, and greater than 0.75 as excellent (Seo et al., 2014).

In the present study, the stance phase kinematics were used to calculate ICC with values greater than 0.7 being considered reliable (Leardini et al., 1999). Barefoot ICC
values were overall more reliable than shod with seven of the eleven participants showing at least one unreliable segment/plane compared with nine for the shod condition. In all, 89 of 99 ICC values were reliable for barefoot with shod showing 82 of 99 values across all subjects. In addition to showing greater overall reliability, the lowest ICC in the barefoot condition was 0.376 (subject 2, forefoot transverse plane) while the lowest ICC in the shod condition was 0.01 (subject 11, forefoot transverse plane). For group results, all segments and axes were reliable in the barefoot condition while the forefoot transverse plane in the shod condition was considered unreliable with an ICC of 0.596.

These trends were consistent with previous work outlined above, as transverse plane motion was the only unreliable planar motion observed (shod, forefoot). In addition, transverse plane motion showed the lowest mean ICC value across both conditions and all segments (sagittal: 0.926, frontal: 0.885, transverse: 0.875) and was also responsible for the lowest ICC score observed in both conditions (shod: subject 11 forefoot 0.01; barefoot: subject 2: forefoot 0.376).

Although there are limitations with reliability measures such as ICC, the high rate of success found for group ICC statistics in this study suggest that the LMFM can be applied reliably in both barefoot and shod running. All inter-subject ICC values were found to be reliable based on the pre-determined standard save for shod forefoot, transverse plane motion. The next lowest ICC value was 0.832 for shod forefoot, sagittal plane motion. Based on previously reported interpretations of ICC, all values would be considered to have excellent reliability, while the shod forefoot transverse plane, deemed unreliable for this study, might be considered fair to good by others (Leardini et al., 1999; McGinley et al., 2009; Seo et al., 2014; Wright et al., 2011).
5.2 Stance Phase Reliability Comparisons

As previously mentioned, there is a dearth of information regarding reliability data during shod running tasks. Therefore, results of the present study were compared to studies done using other multisegment food models as well as studies that analyzed walking gait. For example, in their work comparing reliability of their novel multisegment model with the LMFM, Leo et al. (2014) reported barefoot walking ICC values of 0.837, 0.697, and 0.728 for sagittal, frontal, and transverse planes, respectively for the rearfoot segment. These values were compared with their own findings using the LMFM, for which they reported 0.933, 0.899, and 0.854, which match closely with the results of the present study (0.979, 0.94, and 0.926; Seo et al., 2014). For the forefoot segment they reported 0.84, 0.687, and 0.813 for their novel model, and 0.741, 0.801, and 0.761 for the LMFM (Seo et al., 2014). These values are again similar to the present study which reported forefoot ICC values of 0.952, 0.866, and 0.89.

Other studies have used similar analysis techniques, but instead used CMC for their reliability measurement. In another barefoot walking study utilizing their own model, Pohl et al. (2007) found rearfoot CMC values of 0.964, 0.972, and 0.962 and forefoot CMC values of 0.881, 0.847, and 0.989 (Pohl et al., 2007). These values represent similarly high levels of reliability compared with what was observed during barefoot running trials in the present study.

Leardini et al. (1999) also analyzed barefoot walking trials and reported fair to excellent intra-subject values (rearfoot: range 0.76-0.91, midfoot: range 0.64-0.75, forefoot: range 0.75-0.78). However, they reported poor to fair values when analyzing
inter-subject CMCs (range for all segments/planes: 0.03-0.61; Leardini et al. 1999). Lundgren et al. (2008) used intracortical bone pins during barefoot walking and reported similar results for intra-subject CMC values with 96% of rearfoot values above 0.7, 100% of midfoot values above 0.7, and 78% of forefoot above 0.7. However, they observed only one inter-subject CMC of 0.7 (rearfoot sagittal plane), with the remaining segments and planes falling below 0.7 (Lundgren et al., 2008).

These data help to explain the difficulty in assessing multisegment reliability using only a reliability statistic (either ICC or CMC) and reinforce the need to also include additional measures such as absolute kinematic values and SEM (Bishop, Paul, et al., 2011; Deschamps et al., 2011; Weir, 2005). As previously discussed, high levels of intra-subject variability and/or low inter-subject variability can both contribute to deflated ICC values. This might explain the reversal of results in the Leardini (1999) and Lundgren (2008) papers when compared to the present study, where inter-subject ICC values were excellent, especially when compared to intra-subject values.

5.3 Gait ROM Comparisons

There is a paucity of literature of shod running kinematic data using multisegment foot models, however multiple studies have analyzed barefoot running. Arndt et al. (2007), Powell et al. (2013), and Barnes et al. (2011) used multisegment models in either barefoot or shod running. In the present study, segment angles at heel contact, toe-off, maximum value, and ROM during stance were calculated, and mean and standard deviation values reported, as well as SEM and ICC values (Tables 5-8). The stance phase ROM values were compared with other running studies where data were available (Table
This comparison showed the similarities in magnitudes of rotation during the stance phase which, while not a direct measure of reliability, shows that similar values can be obtained using the LMFM in both barefoot and shod running.

**Table 13. Running Foot Segment ROM Values.**

| Author             | Plane | Rearfoot |  | Rearfoot |  | Rearfoot |  |
|--------------------|-------|----------|  |----------|  |----------|  |
| Arndt et al. (2007)| Sagittal   | 24.7  | 3.9 | 6.5  | 2.9 | 11.4  | 1.6 |
|                    | Frontal    | 12.2  | 7.1 | 13.5 | 4.1 | 5.1   | 0.6 |
|                    | Transverse | 8.7   | 3.9 | 8.7  | 1.4 | 9.6   | 1.4 |
| Powell et al. (2013)| Sagittal     | *    | *  | *    | *  | *    | *  |
|                    | Frontal     | *    | *  | 3.7  | 3.2 | 6.5   | 3.1 |
|                    | Transverse  | *    | *  | *    | *  | *    | *  |
| Barnes (2011)      | Sagittal   | *    | *  | *    | *  | *    | *  |
|                    | Frontal    | 13.2  | 3.3 | *    | *  | 3.5   | 2.2 |
|                    | Transverse | *    | *  | *    | *  | 4.7   | 1.3 |
| Present Study Barefoot | Sagittal  | 29.91 | 4.35 | 20.84 | 3.29 | 18.46 | 4.05 |
|                     | Frontal    | 9.95  | 1.87 | 4.24  | 1.87 | 7.27  | 2.18 |
|                     | Transverse | 9.50  | 3.11 | 19.55 | 3.72 | 7.27  | 2.93 |
| Present Study Shod | Sagittal   | 41.33 | 3.61 | 9.68  | 2.34 | 11.49 | 3.45 |
|                     | Frontal    | 13.41 | 3.02 | 3.35  | 1.03 | 3.71  | 1.42 |
|                     | Transverse | 13.08 | 3.74 | 6.03  | 1.23 | 4.27  | 1.46 |

All values presented in degrees. * represents non-reported value.

In their study using intracortical bone pins during barefoot running, Arndt et al. (2007) reported rearfoot ROM of 24.7° (±3.9°), 12.2° (±7.1°), and 8.7° (±3.9°) in the sagittal, frontal, and transverse planes, respectively (Arndt et al., 2007). These values compare favorably with the current results for barefoot running: 29.9° (±4.4°), 9.9°
(±1.9°), and 9.5° (±3.1°) as well as shod running: 41.3° (±3.6°), 13.4° (±3°), and 13.1° (±3.7°). Shod running values were greater than barefoot running in both studies, specifically in the sagittal plane, which is consistent with the literature (Bishop, Paul, et al., 2011; C. Reinschmidt et al., 1997; A Stacoff et al., 1992; TenBroek et al., 2014). These comparisons are particularly important as intracortical bone pin studies are often considered the gold standard and most valid method for multisegment kinematic analysis (Deschamps et al., 2011; Nester, 2009). Magnitudes of rotation are similar but there are differences, particularly in the midfoot frontal plane. Discrepancies might be attributed to the fact that Arndt et al (2007) did not identify foot segments and instead reported rotation of individual bones of the foot (Arndt et al., 2007). The midfoot ROM values given in Table 13 represent motion at the talonavicular joint which is similar, but not identical to the midfoot segment of the LMFM (Leardini et al., 2007a).

Barnes et al. (2011) used gait sandals employing a three segment model (leg, rearfoot, and forefoot) during running and reported ROM of 13.2° (±3.3°) and 3.5° (±2.2°) for rearfoot and forefoot frontal plane motion, respectively (Barnes, Wheat, & Milner, 2011). These values also compared well with the current results: 9.9° (±1.9°), and 7.3° (±2.2°) for barefoot, 13.4° (±3°), and 3.7° (±1.4°) for shod running.

While these values are not directly indicative of reliability for the LMFM for shod running, they show that similar results can be obtained using the methods incorporated in the present study. As suggested by Deschamps et al. (2011), establishing consistent kinematic absolute values in addition to reliability measures is important in advancing multisegment modeling research. It is also important to note that these studies utilized different data collection procedures including the footwear worn, the
multisegment model used, and running velocity, all of which might impact kinematic data (Ferber, McClay Davis, Williams, & Laughton, 2002; Rankine et al., 2008; TenBroek et al., 2014). Acknowledging these limitations, it is still encouraging to see similar results found with the present study as these data do provide additional support for reliability (Bishop, Paul, et al., 2011).

5.4 SEM Comparisons

Several authors have described the importance of SEM for interpreting foot segment kinematics for both researchers and clinicians, as opposed to isolated ICC values (Ferber et al., 2002; McGinley et al., 2009; Weir, 2005). Bishop et al. (2011) presented SEM measures compared with mean differences (MD) measured between raters for discrete gait event kinematics. They found that SEM, used as a measure of sensitivity to detect changes, was effective as all reported SEM values were below the MD across all segments and rotations. The authors reported MD ranges of 2.6° and 13° across all segments and planes with SEM values ranging from 0.4° to 3.9° (Bishop, Paul, et al., 2011).

Ferber et al. (2002) reported SEM and MD numbers at the ankle joint center (AJC), with SEM values of 0.81°, 0.49°, and 0.32°, and MD values of 0.44°, 0.18°, and 0.89° in the sagittal, frontal, and transverse planes, respectively (Ferber et al., 2002). While these values differ from the results of the current study, similarly small magnitudes were observed in the present study with SEM and MD values of 1.7°, 1.7°, and 1.3° and 0.7°, 0.8°, and 0.2°, respectively. It is important to note that Bishop et al. (2011) analyzed MD values between two rates and reported higher inter-subject ICC values, which
directly influences SEM values (Bishop, Paul, et al., 2011; Weir, 2005). Ferber et al. (2002) used a single segment foot during shod running and values may differ as a result, although the results of Ferber et al. (2002) are closer to the results of the present study. Although there are differences in these values, it is still encouraging to see similar magnitudes of results for both absolute values of gait kinematics as well as supplemental reliability measures such as MD and SEM.

SEM in particular, allows for a more universal interpretation of results as it represents an absolute measure of consistency of a rating. “The SEM is largely independent of the population from which it was determined, i.e., the SEM ‘is considered to be a fixed characteristic of any measure, regardless of the sample of subjects under investigation’” (Weir, 2005). All ICC and SEM measures for discrete gait event kinematics are given in Tables 7 and 8. For the shod condition, SEM values across all segments and planes were between 0.453° and 2.923°, while the barefoot condition scores were between 0.725° and 2.435° which is consistent with previously reported values (Bishop, Paul, et al., 2011; Ferber et al., 2002).

5.5 Marker Placement Repeatability

The final piece of supplemental reliability as suggested by Bishop et al. (2011) was marker placement repeatability between days and raters (Bishop, Paul, et al., 2011). It has been established that one of the biggest obstacles facing multisegment kinematic analyses is the repeatable and accurate application of markers to the anatomical landmarks they are supposed to represent, as incorrect placement of markers can have a considerable impact on gait kinematic data regardless of testing procedures (Ferber et al.,
The method for determining marker placement repeatability employed by Bishop et al. (2011) involved comparing the mean difference of individual marker distances from a local coordinate system origin. In their study, nine foot marker distances were determined between raters with the MD and ICC values reported. They found a MD range of between 2.1mm and 13.1mm between raters with ICC ranges between 0.75 and 0.98. The authors determined that a difference greater than 10mm represented an inaccurate marker placement. They reported a MD range between 2.1mm and 13.1mm and ICC values between 0.75 and 0.98 (Bishop, Paul, et al., 2011).

In the present study, MD fell between 2.32mm and 5.58mm with ICC values between 0.658 and 0.985 in the shod condition, with only the medial malleolus measured as unreliable (0.658). In the barefoot condition, MD fell between 2.2mm and 4.98mm with an ICC range of 0.701 and 0.981.

While the similar values observed between the present study and those found by Bishop et al (2011) suggests that markers can be placed with good repeatability in shod kinematic analyses, it is important to note that the results reported here are relative to a single researcher, and not a team of individuals. In addition, validity testing, using either intracortical bone pins or dynamic radiography, is recommended to determine the true accuracy of markers in relation to anatomical landmarks in shod kinematic analyses.

Values from the present study do not necessarily represent the accuracy of marker placement in relation to the anatomical landmarks that they are supposed to represent, but they are a good indication of the repeatability of placing markers on shoes. And, when combined with the additional measurements of the present study, these data represent an excellent source of support for shod multisegment testing.
**Conclusion**

The purpose of this study was to determine kinematic and marker placement reliability of the Leardini multisegment foot model (LMFM) for tracking foot kinematics during barefoot and shod running without alteration of footwear. This was done in order to provide a method for a more in-depth analysis of foot-shoe interactions, specifically aimed at examining running footwear. Given that only a single segment and plane showed an unreliable ICC value for the stance phase kinematics, in addition to the satisfactory supplemental reliability measures, it is reasonable to suggest that the LMFM can reliably measure foot kinematics in shod running without alteration of footwear.
**Recommendations**

There are several ways in which to continue and improve upon the current research. First is to establish validity testing of multisegment models specifically working with shod conditions. This study found good reliability and anatomical relevance could be measured, however limitations remain until these values can be compared to validated results. Intracortical bone pins and dynamic radiography represent the best options for establishing shod multisegment validity.

While many models exist and differ in their number and definition of segments, continued use of these models allows researchers to expand upon current knowledge of foot and leg kinematics. The model used here incorporated midfoot and forefoot segments distal to the rearfoot which represented the typical ankle joint complex often employed in kinematic analyses. Future research should replicate the present study with different models being used that also include midfoot and forefoot segments but differ in segment classification. Other future research should expand upon the present study by using different footwear conditions (athletic and casual, and also include orthotics), different subject populations (healthy and clinical), and different movements (walking, running, jumping, etc.).

In addition, reliability and repeatability measures are key to expanding multisegment modeling research and therefore future research should also focus on standardized practices for various study protocols. Intra- and inter-trial, intra- and inter-session, as well inter-rater reliability and repeatability should be also further explored.
APPENDIX A

Informed consent document

TITLE OF STUDY: Reliability of a multisegment foot model in shod running

INVESTIGATORS: J.S. Dufek, Ph.D., J. Silvernail, Ph.D., A.G. Coupe, K. Bartel

CONTACT PHONE NUMBER: A.G. Coupe, 503.201.5815 J.S. Dufek, Ph.D., 702.895.0702

Purpose of the Study
You are invited to participate in a research study. The purpose of this study is to assess the reliability of the Leardini multisegment foot model (which is a method of placing reflective markers on the leg and foot/shoe so we can measure foot movement) during running with unaltered running shoes. You will run with shoes and also barefoot while using this model of reflective markers during both conditions.

Participants
You are being asked to participate in the study because you are a healthy individual between the ages of 18-55 years. You are also an experienced runner, currently participating in at least 2 hours of running per week (able to run 3.5m/s across our 15m runway in the laboratory). In addition, you do not have a current or recent history (within last 6 months) of lower extremity injury, you have no obvious anatomical mal-alignment of your feet, nor do you have a history of lower extremity joint replacement (e.g., knee or
hip replacement). You also do not use an orthotic device for everyday activities or for running/exercising.

**Procedures**
If you volunteer to participate in this study, you will be asked to do the following:

1) Have your height, weight, gender, shoe size, and age recorded. You will then be provided with laboratory shoes which you will use for the experiment (New Balance V680, below);

![New Balance V680](image)

2) Next, you will complete a warm up, which may include stretching, walking or running for five minutes;
3) There will be two data collection periods (Day 1 and Day 2) which will be separated by at least 1 day. Data collection periods will be identical and will include placing reflective markers on your lower leg and foot or shoe (Figures 1, 2) after which time you will run over a force platform embedded in the ground along a 15m runway within the biomechanics laboratory at a pace of 3.5m/s. Trials will need to be repeated if this pace is not maintained or if there is poor contact with the force platform. A total of 30 trials for each condition will be allowed to collect 10 good trials (total of 60 attempts per day);
4) You will complete 10 trials in each of two conditions: shod (with shoes) and barefoot, for a total of 20 trials on Day 1 and again on Day 2. After completing one condition (either shod or barefoot), the markers will be completely removed and reattached for the second condition;
5) You will be allowed as much rest as needed during each trial and condition. Following each data collection you will also be allowed a cool-down phase where you can walk, run, and/or stretch as you see fit;
6) After completing both conditions on Day 1, you will be asked to return for the second data collection (Day 2), where the exact same procedures will be completed;

![Vicon reflective marker](image)

**Figure 1.** Vicon reflective marker.
Benefits of Participation
There may be no direct benefits to you as a participant in this study. You may however, learn about running kinematics and kinetics as well as the effects that footwear might have on your running mechanics. You may also gain an increased understanding of running footwear design.

Risks of Participation
There are risks involved in all research studies. It is possible that muscle soreness will occur during the experimental protocol. However, the demands of the task are minimal in comparison to those in common practice during a typical running/training protocol. It is unlikely that injury will occur as the physical task of running is occurring in a controlled environment and you will be asked to complete a warm-up before testing as well as an optional cool-down phase following testing.

Cost /Compensation
There will be no financial cost to you to participate in this study. The study will take between 60-90 minutes (for each data collection period) of your time including preparation, verbal instructions, and running trials. You will not be compensated for your time.
Contact Information
If you have any questions or concerns about the study, you may contact Austin Coupe at 503.201.5815, couple@unlv.nevada.edu or Dr. Janet Dufek at 702.895.0702. For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact the UNLV Office of Research Integrity – Human Subjects at 702-895-2794 or toll free at 877-895-2794 or via email at IRB@unlv.edu.

Voluntary Participation
Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with the university. You are encouraged to ask questions about this study at the beginning or any time during the study.

Confidentiality
All information gathered in this study will be kept completely confidential. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be destroyed.

Participant Consent:
I have read the above information and agree to participate in this study. I am at least 18 years of age. A copy of this form has been given to me.

_________________________  __________
Signature of Participant       Date

_________________________
Participant Name (Please Print)

Video Taping
This study involves videotaping. It is my understanding that I will appear within the field of view of the camera.

_________________________  __________
Signature of Participant       Date

_________________________
Participant Name (Please Print)
Re-Consent: Please sign below to affirm your voluntary participation in the research study at the time of the Day 2 data collection
I have read the above information and agree to participate in this study. I am at least 18 years of age. A copy of this form has been given to me.

_________________________________________  __________________________
Signature of Participant                      Date

_________________________________________
Participant Name (Please Print)

Video Taping
This study involves videotaping. It is my understanding that I will appear within the field of view of the camera.

_________________________________________  __________________________
Signature of Participant                      Date

_________________________________________
Participant Name (Please Print)
APPENDIX B

Visual3D Pipeline

File_New

; Create_Hybrid_Model
/CALIBRATION_FILE=
!/SUFFIX=
!/RANGE=ALL_FRAMES
;
Apply_Model_Template
/MODEL_TEMPLATE=
/CALIBRATION_FILE=::CALIBRATION_FILE
;
Open_File
! Ask for the Movement data files.
! Multiple files can be selected in the dialog file listing using CTRL-Click
/FILE_NAME=::FOLDER
;
Assign_Model_File
! Assigning the Movement files to the model
! Just bring up the dialog box...
/CALIBRATION_FILE=::CALIBRATION_FILE
/MOTION_FILE_NAMES=*.c3d
;
Switch_to_Model_Builder_Mode

;
Set_Subject_Height
!/CALIBRATION_FILE=
!/HEIGHT=
;
Set_Subject_Weight
!/CALIBRATION_FILE=
!/WEIGHT=
;
Interpolate
/SIGNAL_TYPES=TARGET
!/SIGNAL_FOLDER=ORIGINAL
!/SIGNAL_NAMES=
!/RESULT_FOLDER=PROCESSED
!/RESULT_SUFFIX=
!/MAXIMUM_GAP=10
!/NUM_FIT=3
!/POLYNOMIAL_ORDER=3
;
Lowpass_Filter
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
!/SIGNAL_NAMES=
!/RESULT_FOLDER=PROCESSED
!/RESULT_SUFFIX=
!/FILTER_CLASS=BUTTERWORTH
/FREQUENCY_CUTOFF=12
/NUM_REFLECTED=20
! /NUM_EXTRAPOLATED=0
/TOTAL_BUFFER_SIZE=30
/NUM_BIDIRECTIONAL_PASSES=2
;
Lowpass_Filter
/SIGNAL_TYPES=FORCE
! /SIGNAL_FOLDER=ORIGINAL
/SIGNAL_NAMES=FP1
! /RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
! /FILTER_CLASS=BUTTERWORTH
/FREQUENCY_CUTOFF=50
/NUM_REFLECTED=20
! /NUM_EXTRAPOLATED=0
/TOTAL_BUFFER_SIZE=30
/NUM_BIDIRECTIONAL_PASSES=2
;
Set_Use_Processed_Analog
/USE_PROCESSED=TRUE
;
Set_Use_Processed_Targets
/USE_PROCESSED=TRUE
;
Event_Threshold
/SIGNAL_TYPES=FORCE
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=FP1
/RESULT_EVENT_NAME=HS
/SIGNAL_COMPONENTS=Z
! /FRAME_OFFSET=0
! /TIME_OFFSET=
! /EVENT_SEQUENCE=
! /EXCLUDE_EVENTS=
! /EVENT_SEQUENCE_INSTANCE=0
! /EVENT_SUBSEQUENCE=
! /SUBSEQUENCE_EXCLUDE_EVENTS=
! /EVENT_SUBSEQUENCE_INSTANCE=0
/EVENT_INSTANCE=1
/THRESHOLD=20
/ON_ASCENT=TRUE
/ON_DESCENT=FALSE
! /FRAME_WINDOW=8
! /ENSURE_FRAMES_BEFORE=FALSE
! /ENSURE_FRAMES_AFTER=FALSE
;
Event_Threshold
/SIGNAL_TYPES=FORCE
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=FP1
/RESULT_EVENT_NAME=TO
/SIGNAL_COMPONENTS=Z
! /FRAME_OFFSET=0
! /TIME_OFFSET=
! /EVENT_SEQUENCE= 
!/EXCLUDE_EVENTS=
!/EVENT_SEQUENCE_INSTANCE=0
!/EVENT_SUBSEQUENCE=
!/SUBSEQUENCE_EXCLUDE_EVENTS=
!/EVENT_SUBSEQUENCE_INSTANCE=0
/EVENT_INSTANCE=1
/START_AT_EVENT=HS
/THRESHOLD=20
/ON_ASCENT=FALSE
/ON_DESCENT=TRUE
!/FRAME_WINDOW=8
!/ENSURE_FRAMES_BEFORE=FALSE
!/ENSURE_FRAMES_AFTER=FALSE
;
Open_Report_Template
/REPORT_TEMPLATE=
;
File_Save_As
!/FILE_NAME=
;
Export_Data_To_Ascii_File
/SIGNAL_TYPES=LINK_MODEL_BASED
!/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_NAMES=Shank_RF+RF_MF+MF_FF
!/FILE_NAME=
!/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/SIGNAL_PRECISION=5
!/START_LABEL=
!/END_LABEL=
/EVENT_SEQUENCE=HS+TO
!/EXCLUDE_EVENTS=
!/USE_POINT_RATE=FALSE
/NORMALIZE_DATA=TRUE
!/NORMALIZE_POINTS=101
/EXPORT_MEAN_AND_STD_DEV=TRUE
!/USE_P2D_FORMAT=FALSE
!/USE_XML_FORMAT=FALSE
!/USE_SHORT_FILENAME=FALSE
!/EXPORT_EMPTY_SIGNALS=FALSE
!/EXPORT_WITHOUT_HEADER=FALSE
!/EXPORT_NAN=FALSE
;
Static Calibration

Set_Use_Processed_Analog
/USE_PROCESSED=TRUE
;
Set_Use_Processed_Targets
/USE_PROCESSED=TRUE
;
Event_Explicit
/EVENT_NAME=Start
/FRAME=1
! /TIME=
;
Event_Explicit
/EVENT_NAME=End
/FRAME=21
! /TIME=
;
Open_Report_Template
/REPORT_TEMPLATE=
;
File_Save_As
!/FILE_NAME=
;
Export_Data_To_Ascii_File
/SIGNAL_TYPES=LINK_MODEL_BASED
! /SIGNAL_FOLDER=ORIGINAL
/SIGNAL_NAMES=Shank_RF+RF_MF+MF_FF
!/FILE_NAME=
!/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/SIGNAL_PRECISION=5
!/START_LABEL=
!/END_LABEL=
/EVENT_SEQUENCE=Start+End
!/EXCLUDE_EVENTS=
!/USE_POINT_RATE=FALSE
/NORMALIZE_DATA=TRUE
!/NORMALIZE_POINTS=101
/EXPORT_MEAN_AND_STD_DEV=TRUE
!/USE_P2D_FORMAT=FALSE
!/USE_XML_FORMAT=FALSE
!/USE_SHORT_FILENAME=FALSE
!/EXPORT_EMPTY_SIGNALS=FALSE
!/EXPORT_WITHOUT_HEADER=FALSE
!/EXPORT_NAN=FALSE
;

Marker Placement Repeatability

File_New

;
Create_Hybrid_Model
/CALIBRATION_FILE=
!/SUFFIX=
!/RANGE=ALL_FRAMES
;
Apply_Model_Template
/MODEL_TEMPLATE=
/CALIBRATION_FILE=::CALIBRATION_FILE
;
Open_File
! Ask for the Movement data files.
Multiple files can be selected in the dialog file listing using CTRL-Click

/FILE_NAME=:::FOLDER

Assign_Model_File

Assign the Movement files to the model

/FILE_NAME=:::FOLDER

Assign_Model_File

Just bring up the dialog box...

/MOTION_FILE_NAMES=*.c3d

Switch_to_Model_Builder_Mode

Set_Subject_Height

/HEIGHT=

Set_Subject_Weight

/WEIGHT=

Interpolate

/SIGNAL_TYPES=TARGET

/RESULT_SUFFIX=

Lowpass_Filter

/FREQUENCY_CUTOFF=12

NUM_REFLECTED=20

/NUM_EXTRAPOLATED=0

TOTAL_BUFFER_SIZE=30

NUM_BIDIRECTIONAL_PASSES=2

Lowpass_Filter

/SIGNAL_TYPES=FORCE

/RESULT_SUFFIX=

/NUM_EXTRAPOLATED=0

TOTAL_BUFFER_SIZE=30

NUM_BIDIRECTIONAL_PASSES=2
Set_Use_Processed_Analog
/USE_PROCESSED=TRUE
;
Set_Use_Processed_Targets
/USE_PROCESSED=TRUE
;
Event_Threshold
/SIGNAL_TYPES=FORCE
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=FP1
/RESULT_EVENT_NAME=HS
/SIGNAL_COMPONENTS=Z
! /FRAME_OFFSET=0
! /TIME_OFFSET=
! /EVENT_SEQUENCE=
! /EXCLUDE_EVENTS=
! /EVENT_SEQUENCE_INSTANCE=0
! /EVENT_SUBSEQUENCE=
! /SUBSEQUENCE_EXCLUDE_EVENTS=
! /EVENT_SUBSEQUENCE_INSTANCE=0
/EVENT_INSTANCE=1
/THRESHOLD=20
/ON_ASCENT=TRUE
/ON_DESCENT=FALSE
! /FRAME_WINDOW=8
! /ENSURE_FRAMES_BEFORE=FALSE
! /ENSURE_FRAMES_AFTER=FALSE
;
Event_Threshold
/SIGNAL_TYPES=FORCE
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=FP1
/RESULT_EVENT_NAME=TO
/SIGNAL_COMPONENTS=Z
! /FRAME_OFFSET=0
! /TIME_OFFSET=
! /EVENT_SEQUENCE=
! /EXCLUDE_EVENTS=
! /EVENT_SEQUENCE_INSTANCE=0
! /EVENT_SUBSEQUENCE=
! /SUBSEQUENCE_EXCLUDE_EVENTS=
! /EVENT_SUBSEQUENCE_INSTANCE=0
/EVENT_INSTANCE=1
/START_AT_EVENT=HS
/THRESHOLD=20
/ON_ASCENT=FALSE
/ON_DESCENT=TRUE
! /FRAME_WINDOW=8
! /ENSURE_FRAMES_BEFORE=FALSE
! /ENSURE_FRAMES_AFTER=FALSE
;
Open_Report_Template
/REPORT_TEMPLATE=
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=1MB_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=False
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=1MB
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
!/SEQUENCE_PERCENT_START=0
!/SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
!/APPEND_TO_EXISTING_VALUES=FALSE
;

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/RESULT_METRIC_NAME=1MH_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=False
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=1MH
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
!/SEQUENCE_PERCENT_START=0
!/SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
!/APPEND_TO_EXISTING_VALUES=FALSE
;

 Metric_Mean
!/RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=2MH_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=False
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=2MH
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
!/SEQUENCE_PERCENT_START=0
!/SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
!/APPEND_TO_EXISTING_VALUES=FALSE
;

 Metric_Mean
!/RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=5MB_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=False
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=5MB
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=5MH_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALSE
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=5MH
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=Hall_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALSE
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=Hall
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=LatMal_mean
!/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALSE
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=LatMal
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=MedMal_mean
! /APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALSE
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=MedMal
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
! /RESULT_METRIC_FOLDER=PROCESSED
/RESULT_METRIC_NAME=Nav_mean
! /APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALSE
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=Nav
/SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=ALL
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
! /SEQUENCE_PERCENT_START=0
! /SEQUENCE_PERCENT_END=100
/GENERATE_MEAN_AND_STDDEV=FALSE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+1MB_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=1MBAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+1MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=1MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+2MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=2MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+3MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=3MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+4MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=4MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+5MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=5MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+6MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=6MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+7MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=7MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+8MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=8MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+9MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=9MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+10MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=10MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+11MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=11MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+12MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=12MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+13MH_mean
/COMPONENT_SEQ
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+5MB_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=5MAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+5MH_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=5MHAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+Hall_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=HallAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+LatMal_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=LatMalAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+MedMal_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=MedMalAccuracy
;
Subtract_Signals
/SIGNAL_TYPES=KINETIC_KINEMATIC+METRIC
/SIGNAL_FOLDER=Right Rearfoot+PROCESSED
/SIGNAL_NAMES=ProxEndPos+Nav_mean
/COMPONENT_SEQUENCE=ALL
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=NavAccuracy
;
Signal_Magnitude
/SIGNAL_TYPES=DERIVED
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=1MBAccuracy
/RESULT_TYPES=METRIC
! /RESULT_FOLDER=PROCESSED
/RESULT_NAME=1MBacc
! /RESULT_SUFFIX=
;
Signal_Magnitude
/SIGNAL_NAMES=MedMalAccuracy
/RESULT_TYPES=METRIC
! /RESULT_FOLDER=PROCESSED
/RESULT_NAMES=MedMalacc
! /RESULT_SUFFIX=

; Signal_Magnitude
/SIGNAL_TYPES=DERIVED
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=NavAccuracy
/RESULT_TYPES=METRIC
! /RESULT_FOLDER=PROCESSED
/RESULT_NAMES=Navacc
! /RESULT_SUFFIX=

; File_Save_As
! /FILE_NAME=

; Export_Data_To_Ascii_File
/SIGNAL_TYPES=METRIC
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_NAMES=1MBacc+1MHacc+2MBacc+2MHacc+5MBacc+5MHacc+Hallacc+LatMalacc+MedMalacc+Navacc
! /FILE_NAME=
! /SIGNAL_COMPONENTS=
/COMPONENT_SEQUENCE=X
/SIGNAL_PRECISION=5
! /START_LABEL=
! /END_LABEL=
! /EVENT_SEQUENCE=
! /EXCLUDE_EVENTS=
! /USE_POINT_RATE=FALSE
! /NORMALIZE_DATA=FALSE
! /NORMALIZE_POINTS=101
/EXPORT_MEAN_AND_STD_DEV=TRUE
! /USE_P2D_FORMAT=FALSE
! /USE_XML_FORMAT=FALSE
! /USE_SHORT_FILENAME=FALSE
! /EXPORT_EMPTY_SIGNALS=FALSE
! /EXPORT_WITHOUT_HEADER=FALSE
! /EXPORT_NAN=FALSE
;
References


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during the stance phase of walking. *Journal of the American Podiatric Medical Association,*
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Desloover, K. (2012). Repeatability of a 3D multi-segment foot model protocol in presence
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Ferber, R., McClay Davis, I., Williams, D. S., & Laughton, C. (2002). A comparison of within-


analysis with an integrated system for functional assessment of talocalcaneal coalition.


A biomechanical perspective. *Physical Medicine and Rehabilitation Clinics of North America,*


Shultz, R., Birmingham, T., & Jenkyn, T. (2007). Validation of windows for examining kinematics of the foot with respect to the shoe using a multisegmented foot model.


Curriculum Vitae

Austin Coupe CV

- **Contact Information**
  - Austin Coupe
  - 3896 Swenson Street  Las Vegas, Nevada, 89119
  - 503-201-5815  coupe@unlv.nevada.edu

- **Education**
  - Masters of Science (MS) University of Nevada, Las Vegas
    - Kinesiology and biomechanics
    - Expected completion date: May, 2015
  - Bachelors of Science (BS) Oregon State University Graduate June, 2012
    - Exercise and Sports Science
    - Minors in chemistry and psychology

- **Honors and Awards**
  - Graduate assistantship UNLV Department of Kinesiology and Nutrition Sciences. 2013-14
  - Graduate assistantship UNLV Department of Kinesiology and Nutrition Sciences. 2014-15
  - UNLV Graduate and Professional Student Association Research Grant Fall, 2014 - $1,250.00 “Effect of Outsole Degradation on Running Kinetics and Kinematics”
  - Member of Mortar Board National Senior Honor Society, Oregon State University Cap and Gown Chapter 2011-12
  - Recipient of the Ruth E. Warnke Scholarship presented by the College of Health and Human Sciences, Oregon State University 2011-12
  - Nominated to Oregon State University Honor Roll 2011-12
  - Named to the Oregon State University Deans List 2009-11
  - Undergraduate Research Award Program 2011-12 award recipient, work with Dr. Marc Norcross (Oregon State University department of Exercise Physiology)
  - Undergraduate Research Award Program 2010-11 award recipient, work with Dr. Mike Pavol (Oregon State University department of Biomechanics)
  - Recipient of Hank Bauer Leadership Award 2010-11
  - Recipient of Academic Accomplishment Award Kappa Sigma Fraternity, Gamma Sigma Chapter, Oregon State University 2007-08
  - Recipient of Diversity Achievement Award, Oregon State University 2007-11

- **Teaching Experience**
  - Graduate teaching assistant UNLV; laboratory course section of undergraduate biomechanics course (approximately 20 students). Fall 2013; Spring, Summer, Fall 2014; Spring, Summer 2015
  - Responsible for developing, implementing and teaching laboratory lectures and assignments, evaluating and reporting grades
- Research Experience
  o University of Nevada at Las Vegas Biomechanics laboratory 2013-14:

  ▪ Reliability of a Multisegment Foot Model in Shod Running September 2014-present
    • Serves as master’s degree research thesis
    • Aims to test the reliability and accuracy of the Leardini multisegment foot model during shod running in un-altered running shoes
    • Vicon 3D motion capture, Kistler in-ground force platforms

  ▪ Effect of Outsole Degradation on Running Kinetics and Kinematics September 2014-present
    • 2014-15 UNLV GPSA Research Grant funded project
    • Aims to analyze changes in running mechanics as a result of outsole degradation of running shoes through extended (300 miles) outdoor running
    • Vicon 3D motion capture, Kistler in-ground force platforms, ultrasonic thickness gage

  ▪ Kinetic Asymmetry Between New and Worn Running Shoes August 2014-present
    • Examined the kinetic asymmetry between new and worn running shoes where one shoe in a pair of running shoes was mechanically loaded to failure (500 simulated miles)
    • Kistler in-ground force platforms, mechanical impact tester
    • Poster presented at the Southwest chapter of the American College of Sports Medicine conference, October 2014 (first author)

  ▪ Relationship Between Resistance Band Tension and Muscle Activity of a Hip Exercise Device June 2014-October 2014
    • Analyze trunk, hip, and leg muscle activity during exercise with a commercially-available hip exercise device for use in an office environment
    • Noraxon wireless EMG
    • Poster presented at the Southwest chapter of the American College of Sports Medicine conference, October 2014 (second author)

  ▪ Active workstation: Kinematics and Cognition. January 2014-present
    • Examined kinematic variables of individuals while using a treadmill work-station desk
    • Vicon 3D motion capture, Signature workstation treadmill desk

  ▪ Relationship Between Heart Rate Variability and Head Acceleration October 2013 – March 2014
    • Examined the relationship between head acceleration/deceleration during drop landings with heart rate variability
    • Polar heart rate monitor, 2D accelerometer, Kistler in-ground force platforms

  ▪ The Effects of Rearfoot Shoe Construction on Biomechanics of Walking November 2013 – April 2014
- Explored the effects of a commercially available spring-bed rearfoot construction shoe versus other traditionally constructed shoe models on ground reaction forces during walking
- Kistler in-ground force platforms, Basler high-speed camera, MaxTRAQ motion analysis software, footwear impact testing device

**Biomechanics of the Lacrosse** Shot August 2013 – April 2014
- Examined upper extremity muscle activation during a lacrosse shot of players with different ability and experience
- Noraxon EMG, high-speed video, radar speed gun
- Poster presented at the Southwest chapter of the American College of Sports Medicine conference, October 2014 (second author)

- Oregon State University Biomechanics laboratory 2010-12
  - **A Comparison of Neural Profiles and Lower Extremity Energy Absorption in Healthy and ACL-reconstructed Populations** November 2011-June 2012
    - Identify differences in lower extremity kinetics and kinematics in healthy and ACL-reconstructed individuals
    - Kistler in-ground force platforms, Vicon 3D motion capture, Biodex systems III Isokinetic Dynamometer, surface EMG
  - **Identifying Different Types of Fallers Through Gait Analysis** September 2010-June 2011
    - Attempt to identify fall characteristics and types through gait analysis
    - Kistler in-ground force platforms, Vicon 3D motion capture

- **Statistics and Computer experience**
  - Matlab
  - Vicon Nexus
  - Noraxon EMG
  - IBM SPSS
  - Bioware
  - MaxTRAQ
  - Microsoft Office

- **Professional experience**
  - Abstract submitted for poster presentation at the American Society of Biomechanics Annual Meeting “The Relationship Between Head Acceleration and Heart Rate Variability: A Possible Diagnostic Tool For Head Injury Severity” Janet S. Dufek, Nancy A Ryan-Wenger, Aaron Prado, Austin Coupe
  - Thematic poster presentation in Running Footwear 2015 World Congress ACSM “Kinetic Asymmetry Between New and Worn Running Shoes”
  - SW ACSM conference 2014 poster presentation “Kinetic Asymmetry Between New and Worn Running Shoes”
  - SW ACSM conference 2013 presenter “Effect of Simulated Obesity on Double-Support Phase of Gait”