The Influence of Arch Height on Propulsion and Landing Mechanics during Jumping and Hopping Tasks

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
December 16, 2017

Keywords: arch height, propulsion, ground reaction force, kinematics, hopping, electromyography

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Abstract

Arch height has served as a major indicator of foot function during locomotive tasks. Previous studies have identified that structural alterations in arch height, specifically low arch heights, can produce maladaptive kinematic, kinetic and electromyography patterns during the landing and propulsion phases of gait. However anecdotally, the structural differences of low arch height have been suggested to produce movement patterns that are beneficial in lateral directions. Therefore, the purpose of this study was to examine the influence of arch height has on lower extremity kinematics, kinetics, and muscular activity during ballistic jumping and hopping tasks. The results have indicated that the normal arch height produced different sagittal plane kinematics during the landing and propulsion phase of ballistic tasks jumping and hopping tasks. Further, low arch height produced difference mediolateral during the propulsion phases of the ballistic jumping and hopping tasks. Overall, the results of the study suggest that different arch height produced foot mechanics that may be beneficial for directionally specific locomotive tasks.

Acknowledgments

The author would like to first express his deepest gratitude to God for providing guidance, mercy, love thus far. Without your eternal presence, the author feels that this process would have been unachievable. The power behind Your name makes all things possible!

To the dissertation committee, Dr. Wendi Weimar, Dr. Nels Madsen, Dr. Gretchen Oliver, Dr. Keith Lohse, and Dr. Michael Goodlett, your guidance has given the author constant food of intellectual awakening. Your patience and efforts has also given the author the ability to complete a task that was once thought to be impossible.

The author would like to extend additional gratitude to Dr. Wendi Weimar. Doc, you allowed the author to grow and develop into the scientist he has always dreamed of becoming. The constant motivation, support, encouragement, has allowed the author to grow both intellectually in the field of biomechanics and as an individual that will inspire many future scientists. In learning the author has been taught that he was truly bigger than what he imagined and that this process would have been unmanageable without your mentorship. The world will one day understand that the foot is wicked cool!

To the predecessors of the Auburn University Sport Biomechanics Laboratory, Dr. Lloyd “Chip” Wade, Dr. Brian Campbell, Dr. John “Jay” Garner, Dr. Thomas “Craig” Angle, Dr. Adam Knight, Dr. Justin Shroyer, Dr. Joanna Shroyer, Dr. Andrea Sumner, Dr. Jaynesh “Jay” Patel, Dr. Braden Romer, Dr. John Fox, Dr. Jared Rehm, Dr. Adam Jagodinsky, the author would like to thank you for contributing the foundational and fundamental components of the current program. Without your success and dedication, the current opportunity of the author and future graduates of the biomechanics programs would be nonexistent.

To research team, future Dr. Lorraine Smallwood, future Dr. Brandi Decoux, future Dr.

Portia Williams, future Dr. Lauren Brewer, future Dr. Nicholas Moore, future engineer Randall "Randy!" Fawcett, the author would like to thank you for patience and countless support. The constant support allowed the author to remain focused and complete the overall objections.

Additional special thanks would like to be provided to future Drs. Brandi Decoux, Portia Williams, and future engineer Randy Fawcett. Future Dr. Brandi Decoux, you countlessly reminded the author to entrust in his beliefs to complete this process. Your encouragement continuously informed the author that should never ask why but, trust the process, as this is the only way! Future Dr. Portia Williams, the author would like to thank you for the daily support and being a source of inspiration. You have enlightened the author of true future he may obtain, as long as he continues to stay humble and grow. To future engineer Randy Fawcett, the author would like to thank you for the incalculable time and assistance on this research project.

To the family, Mom, Dad, Shakeia, and Alaina, the author would like to thank you for the continuously support you have provided since his first breath. From the constant early morning interactions to the sacrifices, you have provided the author with a foundation of unbreakable love. I love you and the achievement of this degree is for you. To the aunts, uncles, and Godfather, Con-Con, Netta, Marcia, CJ, Aunt Mae, Uncle Dave, and Dr. James Ramseur, the author would like to thank you for installing qualities, such as selflessness, into the author. You have honestly provided the author with daily reminders of the pursuit of this degree was so essential. To Anthony, Joseph, Briana, Frank, Maiya, Kiana, Kiara, Khandice, AJ, Jordan Jerimone, Beatrice, Jason, Rob, Bethany and other cousins in the Cousins, Bisserup, Thomas, and Wood Families, the author would like to thank you continuously pushing him through his academic experience. You all saw the unique quality and never let the author forget it. To my nieces and nephews, Justin, Lynne' Jai, Joe, Ashawn, and LJ, thank you for allowing the author to become an inspiration to you, that will provide you with future opportunities. To my extended parents and brother, Loretta, Joe, and Justin, thank you for lifting me up and supporting the overall goals of my career.

To the alumni of the Auburn University Black Graduate and Professional Student Association, Tim, Dom, Kam, Valecia, Saufeeyah, Shanel, Marvin, Brandon, Karena, Chris, Brittany, Bri, Jason, Rajon, Schavion, Dennis, OJ, Ameenah, Daniel, Tamar, Johnny, Jacoby, future Drs. Shandrea Stallworth, Christien Russell, Brigitte Burpo, Aleah Horton, Johannah Hamilton, and Drs. Derrick Robinson, Leonard Towns-Newby, Alana Dillette, Alexis Davis, Desmond Delk, India Napier, Jessica Copper, April Scott Rashida Askia, in conjunction with the current members of the local and national chapter, future Drs. Andre Westbrook, Ashely Brown, Chassidy Cook, Brianna, Robertson Bassy, Chris Hambie, Joshua Posey Claudia Calder, Jalia Taylor, Churmell Mitchell, Erika Hanely, Jermey Kirk, Kayla Phillips, Jessica Norton, Jessica Bailey Kiona Rodgers, LaVarius Harris, Nathan Roberts, Olivia Cook, Dominque Townsend, Phoenix Ro , Shaina Craige, Shaniqua Williams, Shaniel Bernard, Taylor Johnson and Taylor Langley, thank you for becoming my family and embracing this journey. You all have made an immutable impact on the author’s life and the author shall remain forever grateful.

To the friends of the author, Nealie, Al, Louis, Christian, Justin, Amber, Raechelle, Kerrick, Colter, Kasey, Kat, Maurice, Troy, Ciara, Crystal, Moni, Zaria, and additional extension in the Maryland area, your sense of humor and confidence has allowed the author accomplished one of his greatest feats. To future Drs. Korey Boyd, Jerraco Johnson, and Cory Dixon, you are next! Keep pushing!

To Nana, Grandma, Mom, Loretta, Godmother, Aunt Penny, Mrs. Bea Weimar and Chanel, thank you for acting as the author’s direct inspiration of hope. Your ability to overcome intolerable events has given the author immediate and true insight of overcoming any situation presented, even if it is deemed impossible. An additional thanks is directed toward Nana, as you showed to author to make the most appropriate use of time. You completed an impossible task of reverting weeks into months and were a direct source of motivation to the author.

Finally, the author would like express deep gratitude to his best friend, hero, supporter and better half. Future doctor Jasmine, you have given the author unconditional love and support throughout the process. You have consistently reminded the author to remain strong and look in the mirror, as the strength of a being looks directly back at them. I fought for the now. Always and Forever.

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Chapter I. Introduction

The medial longitudinal arch (MLA) is the foundational source of foot function in locomotion. Particularly, due to the functional role as an anatomical link between the forefoot, midfoot, and rearfoot, the MLA serves as a mediator that enables the foot to configure into specified structural arrangements (i.e. closed-pack and loose-pack) necessary for adequate foot mechanics (Kirby 2017; Abboud et al 2002; Langdon et al 1991). These structural configurations, such as the closed packed or loosed pack alignments, then act as a catalyst to achieve the appropriate foot functions of weight bearing, shock absorption and propulsion (Brockett & Chapman 2016; Stearne et al 2016; Fessel et al 2014; Kelly et al 2014; Francis et al 2013; Devine et al 2012; Tosovic et al 2012; Lynn et al 2012; Hagemann et al 2011; Bosch & Rosenbaum 2010; Bosch et al 2010; Hallemans et al 2005; Lees et al 2005; Bolga & Malone 2004; Abboud et al 2002; Saltzman et al 1995; Langdon et al 1991; Cavanagh & Rodgers 1987; Lewis 1980; Bojsen-Moller 1979). In order to achieve such structural configurations, the MLA relies heavily on its elevated and adaptive properties. Specifically, arch height is a measure that provides an indication of the structural alignments of the different components of the MLA and defines the capability of performing the aforementioned functions efficiently and effectively (Ezema et al 2014; Nilsson et al 2012; Twomey et al 2012; Wilken et al 2011; Cunningham et al 2010; Perry & Burnfield 2010; Twomey et al 2010; Bosch et al 2009; Morton 1952). Any alterations in arch height can induce structural abnormalities and ultimately promote an alternative use of the MLA (Ezema et al 2014; Twomey et al 2012; Levine et al 2012; Wilken et al 2011; Perry & Burnfeild 2010; Twomey et al 2010; Bosch et al 2009). Therefore, it is important to develop a greater understanding of the overall influence of arch height on foot mechanics.

Propulsion Mechanics

A fundamental component of foot mechanics during locomotive tasks consists of generating functional movement patterns that propel the body in a specified direction, while maintaining stability and control. This is primarily achieved by the MLA, with contributing efforts of surrounding passive structures, (i.e. bones, ligaments, fascia) (Francis et al 2013; Honeine et al 2013; Knarr et al 2013; Devine et al 2012; Hamner et al 2010; van Soest et al 1993; Pandy & Zajac 1991; Simon et al 1978, Hicks 1954, 1953). Specifically, the involvement of the first metatarsophalangeal joint, to elevate the MLA and improve the elastic properties of surrounding passive structures, has been suggested to enhance the ability of the foot to absorb shock and contribute to propulsive mechanisms (Bolga & Malone 2004; Lombardi et al 2002; Fuller 2000; Kwong et al 1988; Hicks 1954, 1953). Furthermore, previous literature has suggested that the first metatarsophalangeal and interphalangeal joints improve the mechanical advantage of surrounding musculature, thus influencing the medial transmission of propulsive forces during jumping and locomotive tasks (Glasoe et al 1999; Morton 1964; 1928).

Another major component of propulsion mechanics is the muscle-tendinous interaction of the triceps surae and Achilles Tendon. The plantarflexors utilize the Achilles Tendon to provide motion to the calcaneus so that it may complete its role as a propulsive lever (Honeine et al 2013; Devine et al 2012). Specifically, the calcaneus is the funnel through which the plantarflexors affect the foot components. The capability of the foot to be able to use those forces for propulsion is dependent upon the structural arrangement of the foot and in particular, the MLA (Ayra & Kulig 2010; Kongsgaard et al 2011, 2005; Orendurff et al 2005).

Quantifying Arch Height

The establishment of an arch height classification was a crucial precursor to the generalizability of locomotion research. Prior to the development of a reliable methodological approach to measuring arch heights, evaluating arch height was influenced by the opinion of the researcher or clinician (Goonetilleke 2012; Cavanagh & Rodgers 1987). The lack of a consistent method led to misconceptions about the dynamic changes of the active (i.e. intrinsic and extrinsic musculature) and passive (i.e. bones, ligaments, fascia) components of the MLA (Goonetilleke 2012; Chu et al 1995; Cavanagh & Rodgers 1987; Cobey & Sella 1981; Cureton 1935; Clarke 1933) as well as the influence of such structures on locomotion. However, a study conducted by Williams and McClay (2000) established a universal mathematical criterion, derived from personal anthropometrics, that objectively described the differences in dynamic characteristics of the MLA in various arch types. Specifically, a measurement describing the relationship of foot length, with the relative distance from the ground to the highest point of the dorsum, provided a more precise scale that defined differences in structural alignments and abnormalities of the MLA. Normal arch height (NAH) categorized the healthy structural alignments of the MLA while, low arch height (LAH) defined the changes in positioning of the MLA and surrounding structures (i.e. calcaneus, hallux), which contribute to locomotion (Buldt et al 2015, 2013; Powell et al 2011; Wilken et al 2011; Cobb et al 2009; Houck et al 2008; Hunt & Smith 2004). The development of the arch height measurement provided a way for outcomes of different studies to be combined for a richer understanding of the influence of foot component arrangements on locomotive tasks (Goonetilleke 2012)..

Kinematics, Kinetics and Electromyography Patterns Associated with Arch Height

Research investigating arch heights during locomotive tasks have observed notable differences between NAH and LAH. Specifically, alterations in the structural alignment of the MLA, accompanied by changes in resting calcaneal positioning, can produce dysfunctional and accessory motions throughout the different phases of locomotion. The laterally displaced calcaneus observed in LAH has been suggested to induce prolonged and abnormal rearfoot eversion during the propulsion and landing phases of walking and running gait (Buldt et al 2015; 2013; Powell et al 2011; Wilken et al 2011; Cobb et al 2009; Houck et al 2008; Hunt et al 2004). Similarly, altered kinematic patterns found in rearfoot eversion, during the landing and propulsion phases in LAH, were observed during controlled walking speeds, self-selected running speeds, and controlled running speeds (Prachgosin et al 2015; Powell et al 2011; Williams III et al 2004, 2001; McClay and Manal 1998, 1997). While structural differences in LAH bring about changes in foot mechanics during locomotion, it has also been considered to perpetuate kinematic alterations along the kinetic chain (Khamis & Yizhar 2007). Researchers have revealed increases in tibial internal rotation, femoral internal rotation, knee flexion, knee adduction, and anterior pelvic tilt in individuals with LAH, when compared to NAH (Prachgosin et al 2015; Twomey et al 2012; Wilken et al 2011; Williams III 2004; Williams III et al 2001; McClay & Manal 1998, 1997; Nawoczenski et al 1998; Nigg et al 1993; Kernozek & Ricard 1990; Tiberio et al 1987).

Along with the observed difference in kinematics between arch heights, LAH have displayed injurious kinetic features associated with locomotion. Particularly, when compared to NAH, LAH displayed larger inversion (at heel contact) and peak dorsiflexion (at toe-off) moments, during self-selected walking tasks (Hunt et al 2004). Additionally, LAH displayed increased medial loading, maximal mediolateral ground reaction forces, and vertical ground reaction forces (during stance phase) (Prachgosin et al 2015; Butler et al 2006; Williams III

2003). Furthermore, the center of pressure (COP) stability is reduced in those with lower MLAs during balancing tasks and during treadmill running in which the speed is controlled (Aboutorabi et al 2014; Tsai et al 2006; Williams III 2001). While a LAH creates kinematic and kinetic patterns that reflect faulty mechanics, it has been suggested that such patterns may be beneficial in specified directional movement tasks.

Variations in the MLA have also been shown to cause differences in muscular contributions. Particularly, LAH have shown induced fatigue of the intrinsic and extrinsic musculature that assist with proper bony alignments of the MLA (Mulligan and Cook 2013; Kelly et al 2014, 2012; Tosovic et al 2012; Del Rossi et al 2004). This diminished muscular support places an increased demand on the surrounding ligamentous structures, which can produce an increased laxity and diminished functional role of the MLA (Jung et al 2011; Provenzano et al 2001; Liao and Belkoff 1999; Hurschler et al 1997; Woo et al 1993). The physiology of the foot and ankle musculature have also been influenced by these alterations. Studies have indicated that the muscle activation impairment found in LAH induced significantly smaller physiological cross-sectional areas in the flexor hallucis brevis, abductor hallucis (intrinsic musculature), peroneus longus and peroneus brevis (extrinsic musculature) and significantly larger physiological cross-sectional areas of the flexor hallucis longus and flexor digitorium longus (extrinsic musculature) (Angin et al 2014). Despite the changes that occur in the presence of LAH indicated by previous literature, the influence of LAH on directions other than forward propulsion has yet to be thoroughly examined.

Summary

Previous literature has demonstrated the negative influence of LAH on forward propulsion, increased ancillary motion and even physiological changes. However, little research has considered the role of LAH on movement initiation (acceleration) or non-forward propulsion. Specifically, the anatomical characteristics associated with LAH permit individuals to develop ballistic and explosive propulsion mechanics during locomotive tasks. Although research examining the assumptions remain limited, specific anatomical findings presented in literature support this claim. The laterally displaced calcaneus alters the orientation of the foot and allows individuals with LAH to increase medial foot contribution and the use of the first metatarsophalangeal and first phalangeal joints during propulsion. Additionally, the laterally oriented calcaneus associated with LAH, may alter the line of pull of the triceps surae. This altered line of pull causes the triceps surae to produce a moment about the medial-lateral *and* anteroposterior axes. This altered line of pull may produce a plantarflexed and everted propulsion force. Thus, individuals with a LAH may obtain foot mechanics that favor and enhance lateral movement patterns due to the biaxial contribution of forces to the calcaneus.

Purpose

Therefore, the purpose of this project was to examine the influence of LAH on movement patterns. The implications of this proposed study were multifold: 1) to examine the influence of resting calcaneal position on arch height; 2) to examine the influence of arch height on sagittal and frontal plane ankle kinematics during forward hopping, lateral jumping and stationary hopping tasks; 3) to examine the influence of arch height on peak mediolateral, anteroposterior, and vertical ground reactions forces during forward hopping, lateral jumping and stationary hopping tasks; 4) to examine the influence of arch height on the sagittal and frontal plane resultant angles; 5) to examine the influence of arch height on lower extremity stiffness during stationary hopping; and 4) to examine alterations in the average muscle activity of the lower extremity musculature during forward, horizontal and vertical jumping/hopping between individuals that have lower and normal MLA foot types.

Hypotheses

Research hypotheses for this project are as listed:

H_1: There would be significant differences in resting calcaneal position in individuals in the LAH group when compared to NAH group. It is hypothesized that lower MLA types would have a more laterally displaced calcaneus.

$H_{2:}$ There would be a significant difference in sagittal and frontal plane ankle kinematics within the LAH when compared to the NAH group. It is hypothesize that the lower MLA types would produce greater plantarflexion and eversion during the forward hopping, lateral jumping and stationary hopping tasks.

H_3: There would be a significant in peak mediolateral, anterioposterior, and vertical ground reaction forces between the LAH and NAH groups during jumping/hopping tasks. It was hypothesized that the LAH group would display increased mediolateral ground reaction forces during the lateral jumping tasks and increased vertical ground reaction forces in the stationary hopping tasks. The NAH group was hypothesized to produce an increase in the anterioposterior ground reaction forces in the forward hopping tasks.

H_4: There would be a significant difference in the sagittal and frontal plane resultant angles in the LAH group when compared to the NAH group, during the jumping/hopping tasks. It was hypothesized that the LAH group would produce a smaller frontal plane resultant angle in the lateral jumping and stationary hopping tasks. The NAH was hypothesized to display a smaller sagittal plane angle in the forward hopping task.

H_5: There would be a significant difference in lower extremity stiffness between the LAH and NAH groups during the stationary hopping tasks. It was hypothesized that the LAH group would display an increase in lower extremity stiffness when compared to NAH group.

H_6: There would be a significant difference in muscular firing patterns of the lower extremity between individuals with LAH and NAH, during the forward hopping, lateral jumping and stationary hopping tasks. It was hypothesized that LAH group would display a decrease in peak muscular activation of lower extremity muscular during forward hopping, lateral jumping and stationary hopping tasks.

Limitations

Limitations of this project are as listed:

1. Participants recruited for participation in this study were between the ages of 19-35.
2. Participants with allergies to adhesives were excluded from participation in the study.
3. This research study would only analyze one sex (male).

Delimitations

Delimitations of this project are as listed:

1. The participants recruited for participation were male, NCAA Division I collegiate athletes of basketball, football, and track and field teams.

Chapter II. Review of Literature

The contribution of the complex infrastructure of the foot is a vital component of bipedal movement. While the various components of the architectural framework collectively interact to provide adequate functioning, the medial longitudinal arch (MLA) has been suggested to be the major feature of overall foot mechanics. The architectural characteristics of the MLA (height and mobility) serve as significant determinants of movement pattern outcomes. Despite the evidence that suggests low arch heights (LAH) induce pathological, dysfunctional movement, understanding the success of these arch heights in ballistic and agile motions remains unclear. Therefore, this project examined the influence of anatomical foot characteristics on propulsion in hopping and jumping tasks. Specifically, this project examined the influence of arch height on; resting calcaneal position; ankle kinematics in jumping/hopping tasks; peak ground reaction forces; lower extremity stiffness during hopping tasks; and alterations in the average muscle activity of the lower extremity musculature, during forward, horizontal and vertical jumping tasks. The purpose of this chapter is to present the relevant literature that pertains to the role of the foot in ballistic tasks. The chapter will progress through previous literature in the following order: 1) functional anatomy of the foot; 2) influence of foot mechanics on propulsion; 3) jumping/hopping tasks; and 4) summary.

Functional Anatomy of the Foot

The foot is considered to be a notable structure that influences movement patterns. Composed of over one eighth of the bones in the body, the foot is a terrestrial organ of dynamic and adaptive mechanisms in weight bearing, shock absorption, and propulsion (Morton 1964, 1924b). Due to the complexity associated with the composition of the architectural framework, the collective contribution of each multi-segmented structure is often disregarded and the foot is considered one, rigid link. Therefore, this section will independently present the functional anatomic contributions of the forefoot, rearfoot, and midfoot on foot function. Though it may seem odd not to follow the traditional order of forefoot, midfoot and rearfoot for presentation order, the purpose of this project relies heavily on the MLA, therefore this section will be presented last. Further, the forefoot and rearfoot will only receive cursory attention.

Anatomy and Function of the Forefoot

The forefoot is the most distal division of the foot and has the essential role of terminating the foot-environment interface during locomotion. The anatomy of the forefoot consists of several articulations between the metatarsals and phalanges (Figure 1). The metatarsophalangeal joints are articulations of the proximal phalanges and distal metatarsal heads and are supported by a fibrous capsule and sequence of ligaments (medial collateral, lateral collateral, plantar ligaments) (Griffin & Richmond 2005). The interphalangeal joints are junctions amongst the proximal, intermediate, and distal phalanges that are also strengthened by a fibrous capsule, plantar, medial collateral ligaments, and lateral collateral ligaments (Hamilton 2011). These structural components improve the bony alignments of the forefoot to transmit propulsive forces at terminal foot contact and assist with distributing excessive loads in walking and running gait (Samojla 1994; Hughes et al 1990; Elftman & Manter 1935; Elftman 1934).

Major contributors of the propulsive and load distributive properties of the forefoot during locomotive tasks are the first metatarsophalangeal and interphalangeal joints. The difference in bony dimensions and structural features, when compared to the second, third, fourth, and fifth metatarsophalangeal and interphalangeal joints, optimize the functional contributions of the forefoot. The shorter and wider interphalangeal joints of the hallux have been reported to distribute more than 60% of forefoot loading during the stance phase of walking and running gait (Goonetilleke 2012; Hughes et al 1990; Hutton & Dhanendran 1979). Additionally, the location and function of the sesamoid bones under the great toe have been suggested to aid propulsive mechanics by improving the mechanical advantage of the extrinsic musculature (Wearing et al 2006; Bolgla and Malone 2004; Elftman 1969; Jones 1929; Wood-Jones 1929).

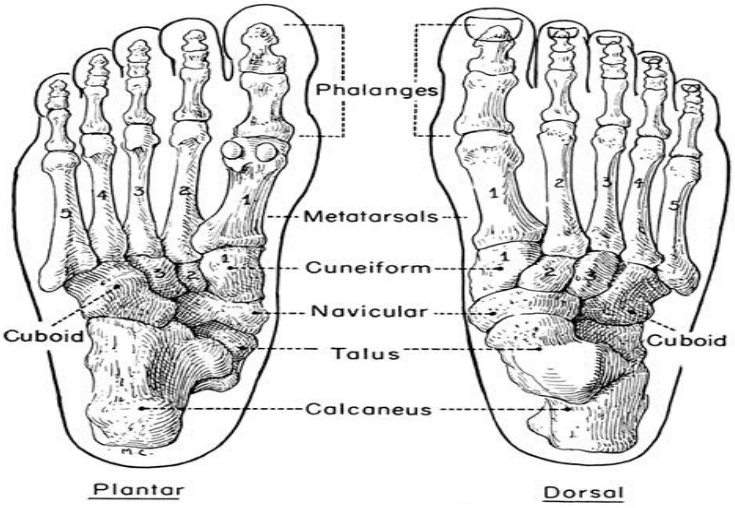


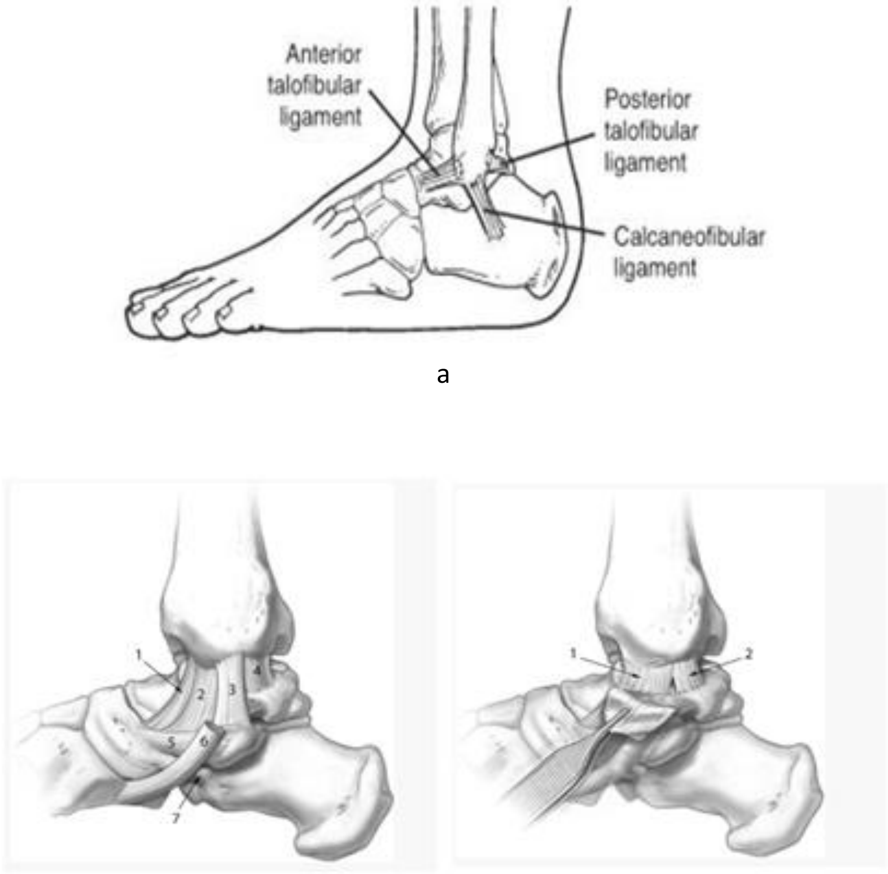
Figure 1. The Structural Anatomy of the Foot, derived from Hamilton 2011.

Anatomy and Function of the Rearfoot

The rearfoot of the foot consists of the least amount of articulations in the foot. However, it is vital in generating propulsive forces for locomotion and interacting with the proximal portions of the lower extremity. Referred to as the foot-ankle complex, the rearfoot is composed of two main articulations, the talocrural and subtalar joints (Hamilton 2011). The talocrural joint is the most proximal articulation of the rearfoot and consists of the talus encased in a secure mortise, formed by the tibia and fibula. This arrangement ensures the stability needed for the kinetic chain to be effectively engaged during weight-bearing tasks (Brockett & Chapman 2016). The additional support from the tibiofibular syndesmosis enforces integrity of the talocrural joint and limits overall joint motion to dorsiflexion and plantarflexion (Hermans & Ranade 2010; Taylor et al 1992).

The subtalar joint is comprised of the junction between the talus and calcaneus. This articulation is a substantial element of the primary shock absorptive and propulsive capabilities of the foot (Brockett and Chapman 2016; Kelikian & Serrafian 2011; Kidd 1999; Barnett and Napier 1952). Collectively, both the subtalar and talocrural joints utilize various bundles of ligaments for rearfoot function. The lateral bundle is composed of three ligaments, the anterior talofibular, posterior talofibular, and calcaneofibular, which assist with optimizing talocrural stability and reducing the lateral motions of the foot-ankle complex (Figure 2). Specifically, the anterior and posterior talofibular ligament improves the stability of the talocrural joint by reducing the amount of anterior and posterior translation of the talus within the mortise (Brockett & Chapman 2016; Kelikian & Serrafian 2011; Golano et al 2010; van den Bekrom et al 2008; Milner & Soames 1997). While increasing the structural integrity of the talocrural joint by anchoring the inferior talus to the calcaneus, the calcaneofibular ligament can be considered to be the most important lateral ligament of the foot-ankle complex. Notably, Trouilloud and colleagues (1988) described the variations in the attachment of the calcaneofibular ligament according to the interaction with the lateral talocalcaneal ligament. While in some cases the lateral talocalcaneal ligament integrates with the calcaneofibular ligament, producing an orientation that can induce proximal or lateral reinforcement between the calcaneus and fibula. In many individuals the lateral talocalcaneal ligament is oriented anteriorly or independent of the calcaneofibular ligament altogether (Golano et al 2010; Trouilloud et al 1988; Figure 3). These alterations in ligamentous attachments can ultimately alter function as well as the calcaneus and fibular articulation itself. Conversely, the medial bundle is composed of a series of superficial ligaments that include the tibionavicular, talocalcaneal (tibiospring), spring ligament (superior and calcaneonavicular ligaments), and deep, anterior and posterior tibiotalar ligaments. These components stabilize the foot-ankle complex by reducing anterior translation, lateral translation, and valgus tilt of the talus (Panchani et al 2014; Boss & Hintermann 2002; Harper 1987; Rasmussen 1985; Figure 2 b & c). The tibionavicular and tibiocalcaneal ligaments, specifically, have been considered to be the strongest ligaments due to their orientation and length (Leardini et al 2000). However, due to the arrangements of the medial ligamentous support of the foot-ankle complex, the functional anatomy in its entirety remains unknown (Savage-Elliot et al 2013; Golano et al 2010; Leardini et al 2000; Figure 3).

The evolutionary adaptation of the calcaneus is often identified as a vital element of rearfoot function. Morton (1964) identified the unique architecture and bony protrusion at the most posterior aspect of the calcaneus (resting calcaneal tuberosity), and accredited it with improving overall stability and propulsion for bipedalism. With regards to stability, the resting calcaneal tuberosity alters the positioning of the center of mass (COM) more anteriorly when compared to our bipedal counterparts, such as the chimpanzees, gorillas, and other apes (Keith 1923). Thus, the foot optimizes the contributions of the tonic posterior muscles for stability during weight bearing tasks by eliminating co-contractions of both the anterior and posterior musculature. Co-contraction of these muscles would result in chronic fatigue to the anterior musculature as these muscles are more phasic in nature and as such are more susceptible to fatigue (Elftman & Manter 1935, 1934; Elftman 1934; Morton 1924). Evolutionary alterations are also responsible for increased resting calcaneal contact with the environment and have induced structural modifications. Researchers have found that this new position of the calcaneus lengthens the Achilles Tendon and has increased the plantarflexion moment and therefore, the generation of propulsive forces (Baxter and Piazza 2014; Morton 1924; 1922). In addition to the influence of the boney arrangement on propulsion, the muscular contributions of the triceps surae has also been suggested to be increased by utilizing the sesamoid fibrocartilage. Specifically, as the Achilles Tendon attaches to the calcaneus, a sesamoid bone acts as a pulley to increase the mechanical advantage of the Achilles Tendon at the calcaneus (Doral et al 2010; Shaw et al 2008).



a

b

c

Figure 2(a). Lateral Ligaments of the Foot-Ankle Complex, derived from Houghton 2011. (*b*) Superficial Medial Ligaments of the Foot-Ankle Complex: 1) Tibionavicular Ligament, 2) Talocalcaneal (Tibiospring) Ligament, 3) Tibiocalcaneal Ligament, 4) (Deep layer) Posterior Tibiotalar Ligament, 5) Superior Calcaneonavicular Ligament 6) (Tendon) Tibialis Posterior, and 7) Plantar Calcaneonavicular Ligament. *(c)* 1) Anterior Tibiotalar Ligament and 2) Posterior Tibiotalar Ligament. Derived from Savage-Elliott et al 2013.

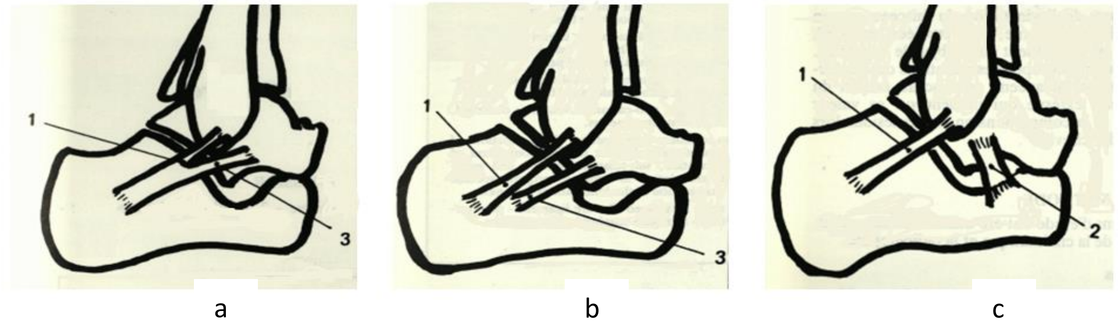


Figure 3 Variations of Calcaneofibular Ligament and Lateral Talocalcaneal Ligament. Derived from Trouilloud et al 1988. (*a*) The integration of the calcaneofibular ligament (1) and lateral talocalcaneal ligament (3) improving subtalar stability and the prohibition of inversion. (*b*) The lateral talocalcaneal ligament is located slightly anterior to the calcaneofibular ligament, minimizing some joint stability and increasing the occurrence of inversion. (*c*) The absence of the lateral talocalcaneal ligament, the calcaneofibular ligament (1) relies on the anterior calcaneal ligament (3) to optimize subtalar stability and the prohibition of inversion.

Anatomy and Function of the Midfoot

The midfoot is comprised of five irregularly shaped tarsals; a cuboid, navicular, and the three cuneiforms (medial, lateral, and intermediate). These structures work in unison, as the interactive moderator of the forefoot and rearfoot (Sayeed & Turner 2008). The role and function of the tarsals has changed as we have evolved from tree dwellers to land dwellers. Specifically, the arboreal life promoted architectural alterations in the foot that allowed the orientations of the tarsals to improve gripping abilities (Morton 1924a, 1922). These architectural alterations were then found to improve the efficiency of terrestrial bipedalism by generating a rigid or compliant structure that transmits and/or stores large forces from the kinetic chain and environment for propulsion (Huson 1991; Morton 1924a, 1922).

The Arches of the Foot

Each division of the foot collectively works together through the creation of a functional half-dome of bony formations of the foot known as arches (O'McKeon et al 2015). These arches, transverse, lateral longitudinal, and medial longitudinal (MLA), are oriented to optimize foot function. The transverse arch is considered to be the most important structure for the midfoot-forefoot interface (Elftman 1934). Formulated by articulations amongst the cuboid, medial, lateral, and intermediate cuneiforms as well as the distal heads of the metatarsals, the transverse arch directs the propulsive forces generated by the rearfoot and ankle (Lewis 1980; Elftman & Manter 1935). Furthermore, the transverse arch has been suggested to contribute to the architectural integrity of the medial and lateral longitudinal arches (Elftman 1934). The functional contribution of the transverse arch can be influenced or constrained by the orientation of the first metatarsophalangeal and interphalangeal joints. Particularly, torsion, hypermobility or a longitudinally shorter first metatarsal can decrease the contribution of the weight distribution and propulsion from the first interphalangeal joints (Elftman 1934; 1928). This can alter the locomotive mechanics of the foot by increasing the demands on the second, third, and fourth interphalangeal joints, making these segments the primary elements of propulsion, in a manner that is similarly observed in gorillas (Lewis 1980; Elftman 1934). Observed alterations of the first metatarsophalangeal and interphalangeal joint orientations have been suggested to produce bony misalignments that influence lateral forefoot loading. These alterations are responsible for the increased appearances of calluses and induced irritation of the nerves around the second, third, and fourth metatarsophalangeal joints (Plank 1995; Soames 1985; Morton 1928).

The lateral longitudinal arch is a transitional structure that is comprised of articulations of the forefoot, midfoot, and rearfoot. This arch contains articulations amongst the calcaneus, cuboid, third cuneiform and third metatarsal. Although this arch has been suggested to assist with shock attenuation and increasing the rigidity of the foot for propulsion, its overall contribution remains unstated (Nillsson et al 2012; Kudou et al 2012; Hallemans et al 2006; Elftman 1934).

Prior to the terrestrial bipedal adaptation, the lateral longitudinal arch acted as the primary structure of propulsive leverage due to a collapse MLA and increased demand of the hallux for gripping (Elftman 1934; Morton 1924, 1922). Thus, the increase in architectural characteristics, such as overall height of the MLA, diminished the contribution of the lateral longitudinal arch.

The MLA is suggested to be the most important arch and structure of the whole foot (Saltzman and Nawoczenski 1995; Rodgers 1988). The MLA includes articulations between the calcaneus, talus, navicular, medial, lateral, and intermediate cuneiforms, as well as the first, second, and third metatarsals. Combined, these structures enhance all functions of the foot. More specifically, the MLA is considered to be the primary contributor for the shock attenuation, propulsive, and weight bearing properties of the foot (Fessel et al 2014; Kelly et al 2014; Tosovic et al 2012; Devine 2012; Bosch & Rosenbaum 2010; Bosch et al 2010; Hallemans et al 2005; Bolga & Malone 2004; Saltzman & Nawoczenski 1995; Cavanaugh & Rodgers 1987; Lewis 1980). A pivotal component that assists with MLA function is the plantar fascia. During locomotive and balancing tasks, the foot uses the medial longitudinal arch as a truss and the plantar fascia as an elastic band (Hicks 1954, 1953). Upon loading, the foot motion at the forefoot (dorsiflexion) causes the plantar fascia to stiffen, resulting in an elevated MLA (Figure 4b). The elevated MLA increases the rigidity of the foot to act as a stable base of support for weight bearing and transmission of loading vertically up the kinetic chain (Kirby 2017). The energy stored in the plantar fascia during weight bearing, in conjunction with the generated propulsive forces of the rearfoot, allow the MLA to transmit forces both anteriorly and predominantly medially for propulsion (Figure 4c). This is commonly known as the windlass mechanism (Hicks 1954; Lapidus 1943).

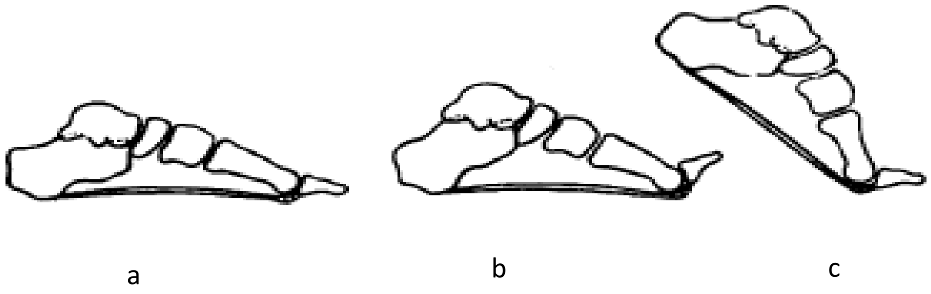


Figure 4. The Windlass Mechanism. (a) Unloaded MLA and complaint plantar fascia. (b) dorsiflexion at the first metatarsophalangeal joint causes tension in the plantar fascia and elevating the MLA. (c) Energy stored in the plantar fascia when loaded is used to propel forward. Derived from Hick 1954.

As the environment in which humans traverse has changed, so has the function and relative importance of each arch. Specifically, the form, structure and function of the MLA is a primary mediation of total foot function and yet is still not well understood. Therefore, it is imperative to continue to investigate the impact alterations in MLA architecture have on foot mechanics. More specifically, an analysis should be conducted examining the influence of architectural modifications in pivotal structures of the foot (i.e. MLA height, MLA stiffness, and resting calcaneal positioning) on foot mechanics (i.e. propulsion and landing and propulsion phases) during locomotive tasks. Although previous research has investigated the influence of architectural modifications of the MLA on landing and propulsion mechanics, during walking and running gait, the effect of such MLA modifications on ballistic motions remains limited (Williams et al 2014,2003, 2001; Butler et al 2007, 2006). Thus, examining the influence of different MLA arch heights in multi-directional jumping tasks will advance our understanding of foot mechanics.

Influence of Foot Mechanics on Propulsion

The foot is an influential source of locomotive mechanisms in bipedalism. Dynamic and adaptive properties of various bony structures, (the arches collectively), are employed to assist different mechanisms of foot function. One of these mechanisms is propulsion. Propulsion can be simply described as one's ability to successfully advance the body forward during locomotive tasks (Perry & Burnfield 2010). For a successful occurrence of propulsion, the foot must develop an interaction with the terrestrial environment and produce forces that allow the body to overcome internal (i.e. inertia) and external (i.e. gravity and friction) forces. The foot must then continue producing propulsion in a cyclic pattern until one reaches a desired location. While these patterns have been investigated during locomotive tasks, such as walking and running, the examination of propulsion mechanisms under more ballistic movement patterns (jumping and hopping) and with alterations in the architectural compositions of the foot, remain limited. Therefore, this chapter will present a theorized application of propulsion under the aforementioned conditions.

Fundamental Elements of Propulsion

The ability of a body to progress forward is heavily dependent upon the creation of propulsive forces. The generation of propulsion forces is reliant upon two main factors, the creation of plantarflexion moments and the position of the center of pressure relative to the center of mass (COM) of the body (Hsaio et al 2015). During locomotion, plantarflexion moments are vital for controlling and progressing the momentum of the body. Specifically, during the initial loading phase of walking gait, a plantarflexion moment is created to improve the involvement of the proximal kinetic chain during the shock absorption and weight bearing periods (Brockett & Chapman 2016; Francis et al 2013). Subsequently, this plantarflexion moment is then used to propel the body forward. While the plantarflexion muscle group assists with generating this plantarflexion moment for locomotive tasks, about 80% has been suggested to be created by the triceps surae (Lardin et al 2015). However, an analysis identifying the greater contribution between the two muscles remains limited and debatable (Wagner et al 2016; Devine et al 2012; Perry & Burnfield 2010; McGowan et al 2009, 2008; Liu et al 2008; Neptune et al 2008, 2001). The two muscles of the triceps surae, the gastrocnemius and soleus affect the function of the plantarflexion moments during stance. Francis and colleagues (2013) identified that early muscular activation of the soleus, in the first 20% of the loading phase of locomotion, could improve stabilization of the body. The researchers also stated that early activation of the gastrocnemius, at approximately 30% of the loading phase of locomotion, caused the onset of the generating propulsive forces during treadmill walking to occur sooner in the gait cycle. Further, due to the proximal articulation at the knee, limb and segmental positioning can modify the contribution of the triceps surae during propulsion. Specifically, researchers have identified that positioning the knee in full extension and the ankle at approximately 15° of dorsiflexion optimizes the mechanical advantage of the triceps surae for plantarflexion moment production (Lardin et al 2015; Li et al 2002).

Forward propulsion of the body can also be influenced by the location of the center of pressure (COP) in regards to the COM of the body. The center of pressure can be defined as a centroid point of all forces acting upon the human body. The progression of the COP has been used to demonstrate foot function and gait efficiency (Becker et al 2014; Lugade & Kaufman 2014; Khoury et al 2013; Chiu et al 2013; Haim et al 2010; De Cock et al 2008). In traditional heel-toe walking gait, the COP trajectory will move from posterior to anterior and may have minor medial-lateral deviations due to the contribution of the inversion muscle group, eversion muscle group, or uneven surfaces (Jamshidi et al 2010; Figure 5). Changes in COP displacement in any direction can decrease the influence of propulsive forces in moving the body forward during locomotion (Hsaio et al 2015). Specifically, changes in COP can induce earlier activations of the triceps surae, and increase or prolong the plantarflexion moment during the initial stance of locomotion, to assist with stabilizing the COM (Lugade et al 2014).

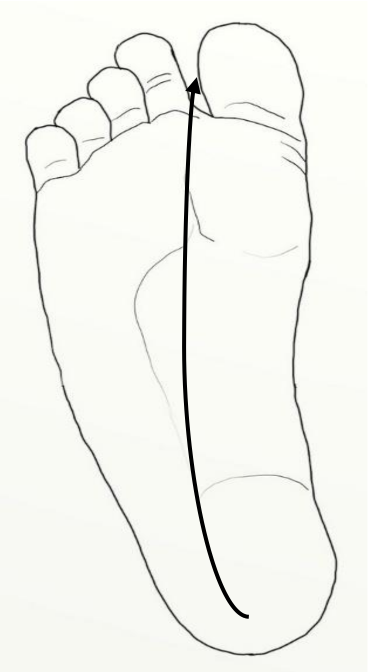


Figure 5. Traditional Progression of the Center of Pressure (Heel-Toe Walking Gait Pattern)

Foot Mechanics

While the human body must actively work to propel the body forward during locomotive tasks, the intricate infrastructure of the foot serves as a foundational element for generating the adequate mechanisms for propulsion. The creation of these mechanisms is stimulated by the interactions of both passive (i.e. bones, ligaments, tendons, and fascia) and active (intrinsic and extrinsic musculature) components of the foot that interface with the terrestrial environment. Specifically, the foot acts as an elastic storage system to transmit energies absorbed while connecting with the ground, to propel the body in a specified direction (Stearne et al 2016; Alexander et al 1987; Hicks 1954). The capability of such function is absent without the contribution and facilitation of the MLA.

To absorb the energies at the initial contact with the ground, the MLA acts as a mediator, reinforcing a loose-packed structural configuration in each division of the foot. This lack of structural integrity is not only beneficial toward conserving and directing the energies at contact for propulsion but, permits an improvement of body position for load distribution in locomotive tasks (Lees et al 2005; Langdon et al 1991). As the body progresses forward, to initiate the propulsive phase of locomotion, the MLA and other passive structures impose a closed-pack configuration of the foot. This structural conversion is commonly observed as the onset of the windlass mechanism. Hicks and colleagues (1954, 1953) suggested that the MLA utilizes surrounding passive structures to initiate the windlass mechanism to increase the overall rigidity of the foot and transmit stored energies for propulsion, which will terminate the foot-environment interface. Abboud and colleagues (2002) further found that the closed-pack configuration in the propulsive phase of locomotion, adjusted by changes in the MLA, increased the stability and load distributive properties of the metatarsals, increased the involvement of the intrinsic musculature to assist with transverse plane stability, and increased the support of the foot intrinsic musculature, which assists with forward propulsion. Researchers have also identified that the windlass mechanism influences the contribution of the triceps surae during the propulsive phases of walking and running gait. Langdon and researchers (1991) stated that the adaptation of loose-pack to close-pack configuration allows for a functional rigid mode, which ultimately improves the ability of the foot to perform as a propulsion device and improves the mechanical advantage of the triceps surae. Caravaggi et al. (2009) further stated that the contraction of the triceps surae elevates the rearfoot thus, locking the midfoot and increasing the overall rigidity of the foot for leverage in walking and running tasks.

While the topic of foot mechanics have been used to identify propulsive profiles of normal foot architecture, research investigating the propulsive mechanics of flawed foot architectures remains limited. When compared to normal foot architecture, lower MLA arch heights exhibit different foot mechanics during locomotive tasks. Specifically, the alteration in MLA height causes lower MLA arch heights to increase the contribution of the medial aspects of the foot during the use of the windlass mechanisms (Bolgla & Malone 2004). Additionally, lower MLA arch heights can exhibit increases in medial loading and peak vertical and mediolateral ground reaction forces (GRF) during walking and running tasks (Prachgosin et al 2015; Butler et al 2006; Williams III 2003). Furthermore, it can be theorized that these loading patterns increase the closed-pack configuration of the bony alignments within the foot, ultimately increasing the overall rigidity of the entire segment.

Although the characteristics associated with lower MLA arch heights could influence variances in movement patterns from normal foot architecture, these structural changes may provide benefits in propulsion mechanics. The orientation of a normal arch height utilizes the vertical and anterior-posterior GRFs experienced during walking and running tasks, in conjunction with the orientation of the rigid foot, to propel the body forward. Nachbauer and Nigg (1992) demonstrated that individuals with lower MLAs exhibited a faster occurrence of peak medial GRF. Although this study did not specifically, analyze the influence of arch height on propulsion, it can be theorized that the early occurrence of a medial GRF during running can induce an altered strategy for propulsion. Further, researchers have identified that the foot may have a tendency to distribute and absorb forces more medially due to the presence of the MLA (Caravaggi et al 2009; Landon et al 1991). The increases of maximum medial loading associated with lower MLA arch heights during walking and running tasks, can be transmitted, via the windlass mechanism, to structures with greater propulsive capabilities in the foot (i.e. first metatarsophalangeal and interphalangeal joints). Furthermore, the laterally displaced calcaneus, amongst those with lower MLA arch heights, can direct and utilize the medial aspect of the foot to enhance lateral propulsive patterns. These findings further suggest that those with lower MLA arch heights may utilize the absorbed energies on the medial side of the foot to generate and produce a more lateral propulsion profile.

Jumping/Hopping Tasks

Jumping is a ballistic motion frequently observed in various athletic settings. Composed of full-body coordinated movement patterns, the performance of jumping tasks are commonly used to assess variables that can influence the outcome of locomotive tasks, such as acceleration, maximal velocity and ability to change direction (Cronin & Hansen 2005; Young 1995). Some prominent elements used to determine jumping performance are evaluated by the interactions of the foot and the environment. Specifically, it has been demonstrated that a major component for optimizing bilateral and unilateral jumping performance is peak vertical ground reaction force. Research has identified the vertical ground reaction force as a primary factor in determining overall height in unilateral and bilateral vertical jumping tasks (Johnston et al 2015; McElveen et al 2010; Corodova & Armstrong 1996; Dowling & Vamos 1993; Robertson & Fleming 1987; Vint & Hinrichs 1996). However, during unilateral horizontal and lateral tasks, there were observed differences in ground reaction force profiles. Meylan and colleagues (2014) suggested increases in anterior-posterior and mediolateral ground reaction forces during horizontal and lateral jumps, when compared to vertical jumping, were a necessary adaptation to improve velocity. It can be theorized that this modification permits individuals to optimize the different propulsive mechanics to meet the demand of the multidirectional tasks. While the findings of these studies demonstrate the result of the foot-environment interface during jumping tasks, an analysis investigating the influence of specific foot mechanics and architecture on such ballistic motions has yet to be undertaken.

Similar to jumping tasks, stationary hopping has been used to assess different propulsive performance measures. For example, in the clinical setting, hopping tasks are used to examine the function and symmetry of a lower limbs upon recovering from severe knee and ankle injuries (Logerstedt et al 2012; Grindem et al 2011; Deneweth et al 2010; Orishimo et al 2010; Sekir et al 2007; Van der Harst et al 2007; Caulfield et al 2002). It has also served as a measurement to determine the amount of lower limb stiffness. Farley and colleagues (1999) found that stationary hopping was an adequate way to assess the rebound of the lower limb while interacting with the ground. Further, in 1998, Farley and colleagues demonstrated that stationary hopping was a reliable measure of how the lower limb made adjustments in stiffness to accommodate different surfaces and these alterations in stiffness were thought to optimize propulsion (Farley, et al

1998). While these results demonstrate the influence of lower extremity stiffness on propulsion mechanics, the influence of arch height was not considered. A study of the influence of foot structure on lower extremity stiffness and loading/propulsive profiles will expand this area of knowledge, which will have implications for propulsive enhancement and an understanding of injury mechanisms.

Summary

The foot is the foundation of locomotion. Supported by intricate ligamentous arrangements, the foot utilizes a series of bony formations to generate the adequate mechanisms for locomotive tasks. Amongst the several articulations of the foot, the MLA is considered the most influential component due to primary functions of shock absorption, propulsion, postural stability, and weight bearing.

The structural characteristics of the MLA are an integral factor in foot function and the outcome of movement patterns. Specifically, the environmental and internal bony interactions of normal MLA arch heights generate mechanisms to optimize the efficiency of locomotion (Perry & Burnfield 2010; Lewis 1980; Morton 1964, 1928, 1924, 1922; Hicks 1954; Elftman and Manter 1935; Elftman 1934). However, any changes in the architectural characteristics of the MLA produce maladaptive movement patterns. Research has demonstrated that individuals with LAH display kinematic changes in tibial internal rotation, femoral internal rotation, knee flexion, knee adduction, and anterior pelvic tilt during locomotive tasks (Prachgosin et al 2015; Twomey et al 2012; Wilken et al 2011; Butler et al 2007; Butler et al 2006; Williams III 2004; Williams III et al 2001; McClay & Manal 1998, 1997; Nawoczenski et al 1998; Nigg et al 1993;

Kernozek & Ricard 1990; Tiberio et al 1987). Additionally, researchers have found that LAHs demonstrate increases in medial loading, maximal medial-lateral ground reaction forces, and vertical ground reaction forces during walking and running tasks (Prachgosin et al 2015; Butler et al 2006; Williams III 2003; Williams III 2001). While these changes in both kinematic and kinetic features found within LAH have been found to increase the risks of foot, knee, and lumbar pain and injuries, these same changes may also serve to improve the performance outcome of ballistic motions. (Ezema et al 2014;Wilken et al 2011; Levinger et al 2010; Twomey et al 2010; Yu et al 2007; Williams Iii et al 2003; Williams Iii et al 2001; Arangio et al 2000; Kaufman et al 1999; Reischl et al 1999; Gould et al 1989; Smikin et al 1989).

LAH display loading profiles and foot mechanics that can be beneficial for the generation of propulsion forces. Propulsion is commonly linked to the windlass mechanism (Hicks 1954; Lapidus 1943). Upon the activation of the windlass mechanism, the foot is arranged into a closed-pack configuration and transmits energies stored by the MLA and plantar fascia, during the weight bearing phase, for propulsion. In NAHs, the loading profiles generate propulsive forces that are directed toward the lateral aspect of the foot and can be viewed to be more advantageous for forward propulsion. Conversely, the increased medial loading of LAH increases the contributive efforts of some of the propulsive structures of the foot, such as the first metatarsophalangeal and interphalangeal joints. Thus, it could be theorized that such foot architecture may produce propulsive mechanics that improve lateral motions. Therefore, the present project examined the influence of arch height (i.e. normal or low) on the propulsive mechanics of various ballistic movement patterns (i.e. jumping/hopping) in multiple directions.

Chapter III. Methods

The purpose of this study was to analyze the influence of foot architecture, specifically normal arch height (NAH) and lower arch height (LAH), on resting calcaneal position, propulsive mechanics, lower extremity stiffness, and muscular activation during jumping/hopping tasks. This project investigated the influence of: 1) resting calcaneal position on arch height; 2) arch height on ankle kinematics during jumping/hopping tasks; 3) arch height on peak mediolateral, anterioposterior, and vertical ground reaction forces during jumping/hopping tasks; 4) of arch height on sagittal and frontal plane resultant angles during jumping/hopping tasks; 5) arch height on lower extremity stiffness during the stationary hopping task and 6) arch height on alterations in the average muscle activity of the lower extremity musculature during forward, horizontal and vertical jumping tasks. The following sections of this chapter provide an outline of the methodology for the overall study: a) participant demographics, b) laboratory setting, c) laboratory instrumentation, d) experimental design and e) experimental analysis.

Participation Demographics

An a priori power analysis (Cohen’s d effect size = 1.00; α = 0.05; & power = 0.80) of F-test were conducted using G*Power v3.1.9.2 for Windows to determine the appropriate sample size needed to reach significance for the current study. The selected effect size was used to estimate main effects of the arch height groups. The results revealed the project would need a total of 40 participants to demonstrated significant difference in the jumping/hopping tasks between the NAH and LAH groups. Therefore, 25 participants with normal arch heights (NAH) and 25 participants with low arch heights (LAH) were going to be recruited to ensure adequate power. However, due to scheduling conflicts, only 22 participants were recruited for this project. The remainder of the participants will be collected and the results published in a peer reviewed journal.

Male, NCAA Division I athletes, between the ages of 19 and 28 were recruited as volunteers for this study. Participants were in good health, without lower extremity musculoskeletal injuries within the last six months, and without an allergy to adhesives. To assure voluntary involvement and health status, participants were required to sign an Institutional Review Board approved Informed Consent document (Appendix A) as well as complete a health screening questionnaire (Appendix B).

Laboratory Setting

Procedures and data collections were conducted in the Sports Biomechanics Laboratory in the School of Kinesiology at Auburn University (Room 020).

Laboratory Instrumentation

Classification of MLA arch height

Foot anthropometric measurements were obtained for arch height classification and arch height stiffness, based upon previous literature (Williams et al 2014, 2003; Butler et al 2008, 2007, 2006). The arch height index (AHI) measurement system (Figure 6) was used to measure the total foot length, the height of the dorsum at half of the total foot length, and truncated foot length of each foot under loaded and unloaded conditions. Total foot length was defined as the distance from the base of the calcaneus to the most distal point of the first or second phalange

(Figure 7). The truncated foot length was defined as the distance from the base of the calcaneus to the centroid of the first metatarsophalangeal joint (Figure 7). The height of the dorsum was defined as the height of the foot dorsum at half of total foot length (Figure 7). Arch height was defined as a ratio between the height of the dorsum at half of the total foot length and truncated foot length (Figure 8). Individuals with an AHI value of 0.31 and below, were placed in the LAH group. Individuals with an AHI value of 0.32 to 0.37 were placed in the NAH group. Prior to data collection, the intraclass correlation coefficients were employed to assess interrater reliability. A minimum intraclass correlation coefficient value of 0.850 was required for the arch height index before data collection was begun. The results of a two-way mixed random absolute agreement revealed an $ICC_{(3,5)}$ = 0.964 (95% CI: 0.866 - 0.994) for arch height index measurements.

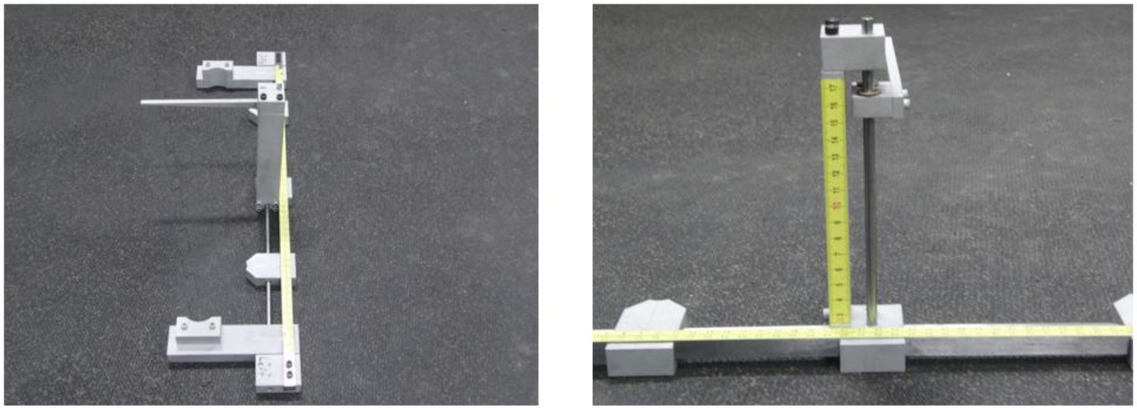


Figure 6. Arch Height Index Measurement Device.

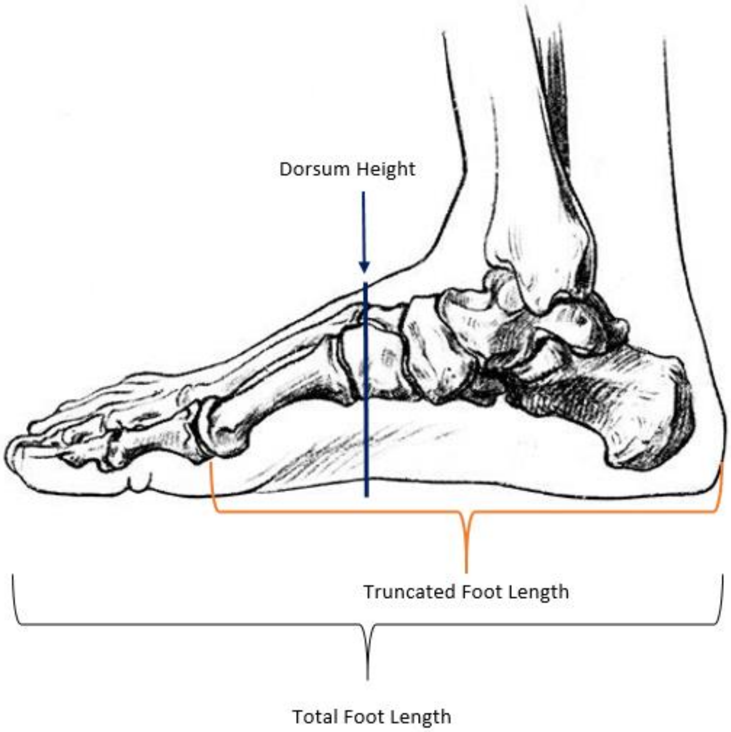


Figure 7. Foot Anthropometrics measured by the Arch Height Index Measurement Device.

$$\text{a. Arch Height Index} = \frac{\text{Height of Foot Dorsum at Half of Total Foot Length}}{\text{Truncated Foot Length}}$$

Figure 8. Computations for MLA Arch Height Classifications.

Kinematics

The analysis of lower limb stiffness and ankle kinematics, of the dominant limb was achieved through the use of a modified marker set and a 10-camera motion capture system

(Vicon®, Los Angeles, CA, USA) collecting at a sample frequency of 100 Hz (Figure 9). Thirteen retroreflective markers were placed on anatomical landmarks of the lower extremity (Table 1), using double-sided tape (Double sided Duck ®, Shur Tech Brands, Avon, OH, USA), to construct a modified three-dimensional model of the lower extremity for analysis (Table 1). Computations of the centroid of the pelvis and ankle kinematics were performed with Visual 3D software (C-Motion Inc., Germantown, MD, USA) to examine pelvic translation, as well as frontal plane and sagittal plane angular positions of the ankle.

The analysis of resting calcaneal angle was measured based upon previous literature (Levinger et al 2004; Razeghi & Batt 2002; Jonson & Gross 1997). Participants were asked to stand on a table with the in a relaxed stance. The calcaneus was then palpated on the medial and lateral borders to determine its center. A longitudinal line was then constructed bisecting calcaneus and the distal one-third of the shank (Razeghi & Batt 2002; Jonson & Gross 1997). A goniometer was placed on the constructed line to measure the appropriate angle. Prior to data collection, the intraclass correlation coefficients were employed to assess interrater reliability. A minimum intraclass correlation coefficient value of 0.850 was required for the resting calcaneal angle before data collection began. The results of a two-way mixed random absolute agreement revealed an $ICC_{(3,5)} = 0.910$ (95% CI: 0.701 - 0.985) in resting calcaneal angle measurements.

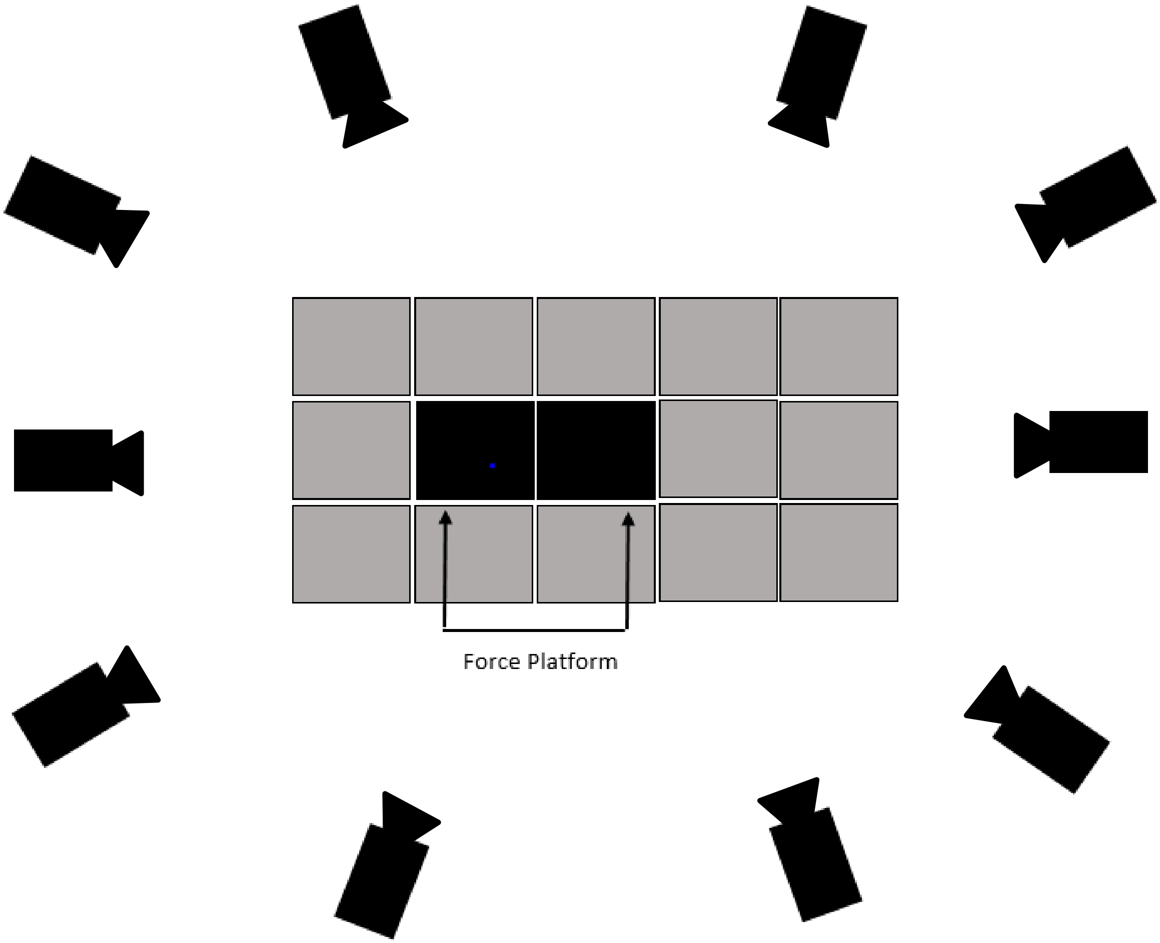


Figure 9. Motion Capture and Force Platform Orientation.

Marker Name	**Anatomical Landmark**	**Segment**
L/R ASIS	Left/Right Anterior Superior Iliac Spine	Pelvis
L/R PSIS	Left/Right Posterior Superior Iliac Spine	Pelvis
SAC	Sacrum	Pelvis
RLKNEE	Right Lateral Tibiofemoral Joint	Shank
R MKNEE	Right Medial Tibiofemoral Joint	Calibration
R THI	Right Shank Marker	Shank
R LANK	Right Lateral Malleolus	Shank
R MANK	Right Medial Malleolus	Calibration
R CAL	Right Base of the Calcaneus	Foot
R FIF	Right 1st Metatarsophalangeal Joint	Foot
R FIR	Right 5th Metatarsophalangeal Joint	Foot

Table 1. Anatomical Landmarks for retro-reflective marker placement.

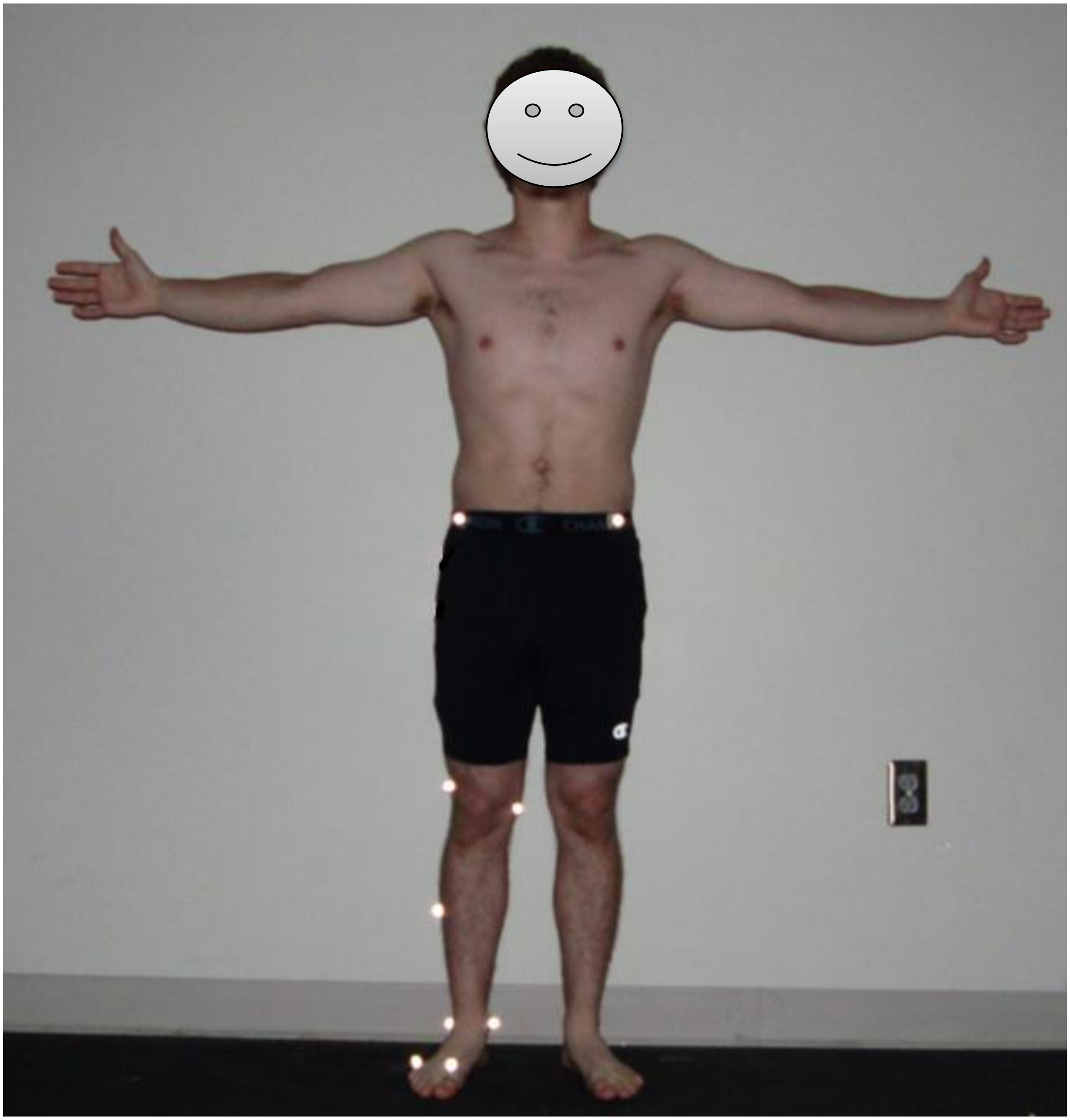


Figure 10a. Anterior Aspect of the Marker Set.

Figure 10 b. Posterior Aspect of the Marker Set.

Kinetics

A force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) with a MiniAmp MSA-6 amplifier (Advanced Mechanical Technology, Inc., Watertown, MA, USA) collected kinetic data at a sampling frequency of 1000 Hz. The force platform was installed such that the top of the platform was even with the floor. Further, the platform was in the center of the laboratory to ensure adequate space for the various jumping/hopping tasks. The peak vertical, mediolateral, and anteroposterior ground reaction forces (GRF) were collected to compare the forces between arch types, during the landing and propulsion phases of each movement type. The landing phase was defined as the time between the moment of initial foot contact to the lowest vertical displacement of the estimated center of mass (COM_e). The propulsion phase was defined as the time from the moment of the lowest vertical displacement of the COM_e to toeoff. In addition, peak vertical forces at maximum loading were used to quantify variations in lower extremity stiffness between each arch height during stationary hopping. Lower extremity stiffness was defined as the maximum peak vertical GRF divided by the change in maximal displacement of the COM_e during the ground contact phase of the hopping trial (Mudie et al 2016; Hobara et al 2015; Figure 11). Resultant force angles in the sagittal and frontal planes were computed from the horizontal (anteroposterior or mediolateral) and vertical force vectors at initial contact (Figure 12a) and toe-off (Figure 23b) during the lateral and forward jumping/hopping tasks. Resultant force angles in the sagittal plane, were computed by combining the vertical and anteroposterior force vectors at initial contact and toe-off. Frontal plan resultant force angles were computed by combining the vertical and mediolateral force vectors at initial contact and toe-off. The analysis of peak GRFs and propulsive force angles was calculated using a specialized program in MATLAB (MATLAB® R2013b, Mathworks, Inc., Natick, MA.).

$$k_{leg} = \frac{F_{zpeak}}{\Delta COM_e}$$

k_{leg} = the stiffness of the leg

F_{zpeak} = peak vertical force

Δ COM_e = difference of COM_e height at initial contact by the maximum vertical displacement

Figure 11. Lower Extremity Stiffness Equation.

Figure 12. (a) Resultant Angle in the Sagittal Plane During Landing Phase. (b) Resultant Angle in the Sagittal Plane During Propulsion Phase.

Surface Electromyography

The examination of the medial gastrocnemius and soleus muscular activity, of the dominant leg, during jumping/hopping tasks was conducted using a pair of bipolar Ag-AgCl surface electrodes (Red Dot, 3M, St. Paul, MN, USA). The surface electrodes were placed with an inter-electrode distance of 2.0 cm over the muscle belly (Kamen & Gabriel 2010). While commonly observed as some of the major contributors for propulsion, some research suggests that the developmental processes of the lower extremity create torsion of the Achilles Tendon causing the fibers of the gastrocnemius to attach to the lateral side of the calcaneus and the fibers of the soleus to attach medially (Francis et al 2013; Honeine et al 2013; Benjamin et al 2007; van Gils et al 1996; White 1943). The electromyographic leads transferred signals to a Noraxon Telemyo 2400T-V2 wireless transmitter (Noraxon® U.S.A. Inc., Scottsdale, AZ, USA) which then relayed the signals to a Noraxon Telemyo 2400R-World Wide Telemetry receiver (Noraxon® U.S.A. Inc., Scottsdale, AZ, USA). Lower extremity muscular activation was collected at a sampling frequency of 1500 Hz and processed using a linear envelope (full-wave rectification, band pass filter with cutoff frequencies of 20 and 400 Hz, a 4th order Butterworth filter, 24dB/octave roll off) (DeLuca, et al 2010). The average peak percentage of the maximal voluntary isometric contractions (MVIC) was used to normalize the peak muscular activation during the landing and propulsion phases of all three jumping/hopping conditions. Prior to data collection, the intraclass correlation coefficients were employed to assess interrater reliability. The minimum intrarater reliability value of 0.850 for the MVIC of the gastrocnemius and soleus were required before data collection began. The results of a series two-way mixed random absolute agreements revealed an $ICC_{(3,5)}$ = .948 (95% CI: 0.462 - 0.993) for MVIC of the medial gastrocnemius and $ICC_{(3,5)}$ = .916 (95% CI: 0.287 - 0.986) for the MVIC of the soleus .

Experimental Procedure

All participants recruited for the study were instructed to report to the Sports Biomechanics Laboratory. Prior to completing any dynamic tasks, participants were asked to read and complete an Auburn University Institutional Review Board approved Informed Consent document (Appendix A) and health-screening questionnaire (Appendix B). The completion of informed consent and health-screening questionnaire was used to assure voluntary consent, eliminate any participants that have sustained a lower extremity injury that may alter their usual jumping/hopping mechanics, and exclude individuals with allergies to adhesives.

Unilateral foot anthropometrics of the dominant limb were taken to classify low arch height (LAH) and normal arch height (NAH). The arch height index measurement device measured the total foot length, truncated foot length, and height of the foot dorsum. These measurements were then used to quantify the arch height. Additionally, limb dominance was determined by asking participants the preferred leg with which they would kick a ball (Mudie et al 2017; Hobara et al 2013; Padua et al 2006). The leg chosen by the participants was identified as the dominant leg. Participants were then asked to stand barefoot, on a table in a relaxed position to record the resting calcaneal angle of the dominant foot. The calcaneus was palpated on the medial and lateral borders to determine its center. Then a longitudinal line was constructed bisecting calcaneus and the distal one-third of the shank (Razeghi & Batt 2002; Jonson & Gross 1997).

Following the determination of the resting calcaneal angle, the skin above the muscle belly of the medial gastrocnemius and soleus was prepared for electrode placement, following the standards of electromyography (Merletti & Torino, 1999). Electromyographic electrodes were placed approximately 2 cm apart on the muscle belly of each muscle (Kamen & Gabriel

2010). Upon electrode placement, MVICs were performed for five seconds in accordance with previous literature (Kamen and Gabriel 2010). The participant was seated with the knee fully flexed, while a strap provided resistance during a toe raise, while the MVIC of the medial gastrocnemius was recorded. The participant was then asked to extend the knee, and plantarflex against resistant while the MVIC of the soleus was recorded. The MVIC's of the aforementioned muscles were used to normalize muscle activity during the dynamic jumping/hopping tasks.

Both LAH and NAH were required to complete the unilateral (forward) horizontal hopping, lateral jumping and unilateral stationary hopping conditions, at a self-selected speed, in a randomized order. The unilateral horizontal hopping condition consisted of three trials of three consecutive hops forward on the dominant leg. The second hop, in which the foot made contact with the force platform, was used for analysis. In the lateral jumping condition, participants began with their dominant foot on the force platform. Participants were then instructed to complete three trials of jumping in the following rhythmic sequence: from the dominant leg to the non-dominant leg, to the dominant leg and back to the non-dominant leg. During this jumping sequence, the participants were instructed to strike the force platform when jumping from the non-dominant leg to dominant leg. An analysis of the foot strike of the dominant leg, back on the force platform was chosen to minimize the influence of initiation and cessation on the data. In the unilateral stationary hopping condition, participants were required to perform nine continuous hops on the dominant leg. To minimize the influence of initiation and cessation, the middle three repetitions were analyzed. The analyses of the non-beginning nor ending hop/jump were chosen as the acceleration patterns of starting and stopping may have influenced the findings. Additionally, to minimize the influence of arm swing on the hopping task, participants were asked to perform all tasks with arms crossed above the waist on the anterior aspect of the body.

Experimental Analysis

All the statistical analyses were performed using SPSS software (version 23.0, SPSS Inc, Chicago, IL, USA) with an a priori alpha level of statistical significance set at $p < 0.05$. To examine statistical differences in frontal and sagittal plane ankle kinematics, two separate 2 (low arch height (LAH) and normal arch height (NAH) x 3 (forward hopping, lateral jumping and stationary hopping) mixed-factorial ANOVAs were employed. These analyses were conducted for both the landing and propulsion phases. Arch height served as the between group factor and the jumping/hopping tasks served as a repeated measure. To investigate the differences in three peak GRF variables, three (vertical, anteroposterior, and mediolateral) separate 2 (LAH and NAH) x 3 (forward hopping, lateral jumping, and stationary hopping) mixed-factorial ANOVAs were employed. These analyses were conducting for both the landing and propulsion phases, while arch height served as the between group factor and jumping/hopping tasks as a repeated measure. To examine the differences the resultant angles in the frontal and sagittal planes, 2 separate, 2 (LAH and NAH) x 3 (forward hopping, lateral jumping, and stationary hopping) mixed-factorial ANOVAs were employed. These analyses were conducted for both the landing and propulsion phases, while arch height served as the between group factor and jumping/hopping tasks as a repeated measure. To examine differences in the peak medial gastrocnemius activity and the soleus variables, 2 separate (gastrocnemius and soleus), 2 (LAH and NAH) x 3 (forward hopping, lateral jumping, stationary hopping) mixed- factorial ANOVAs were employed. For both landing and propulsion phases, arch height group served as the between group factor and movement type as a repeated measure. Mauchly's test was employed to indicate assumptions in sphericity. Any violations in sphericity will be corrected with the Greenhouse-Geisser, resulting in an output of corrected degrees of freedom. Further, follow-up pairwise comparisons were considered only for significant main effects of jumping/hopping tasks, and significant interactions between arch height and the jumping/hopping tasks.

The examination of differences in resting calcaneal angle were assessed with an independent t-test. Lower body stiffness was calculated from the data collected during the stationary hopping tasks. For the lower body stiffness variable, a between subjects design, independent t-test was employed to determine if arch height influences lower body stiffness. The examination of differences in forward and lateral propulsive angles were conducted with a mixed-factorial ANOVA comparing LAH to NAH individuals. For both landing and propulsion phases and arch height group served as the between group factor.

Chapter IV. Results

The purpose of the current study was to investigate the effect of arch height on propulsion and landing mechanics during various jumping tasks. Particularly, the study examined the influence of low and normal arch heights on lower extremity kinematics, kinetics, and electromyography during the propulsive and landing phases of stationary and forward hopping and lateral jumping. The following chapter will present the results of the methodological procedures presented in the previous chapter. This chapter will discuss the results in the following order: 1) Subject demographics; 2) Lower extremity kinematics; 3) Lower extremity kinetics; 4) Lower extremity stiffness; and 5) Electromyography of the lower extremity.

Participant Demographics

Twenty-two, NCAA Division I male athletes volunteered to participate in this study. The normal (n=11) and low arch (n=11) groups consisted of an equal number of participants that met the criterion of the protocol (Table 2). Foot anthropometric measurements were taken to determine the resting calcaneal angle. An independent samples t-test was conducted to determine differences in resting calcaneal angle between arch height groups. The results of this test displayed significant differences between the normal arch height (NAH) group and low arch height group (LAH) ($t(20) = -5.524$, $p < 0.001$; Table 2). Specifically, the results of this statistical analysis demonstrated that LAH had a more laterally displayed calcaneus when compared to NAH. Intratester reliability of arch height classifications and resting calcaneal angle were assessed with intraclass correlation coefficients (ICC) (Table 3).

Arch Height Classification	**n**	**AHI**	**Weight (kg)**	Height **(m)**	**Resting Calcaneal Angle** (°)
Normal	11	0.344 ± 0.018	86.636 ± 13.646	1.83 ± 0.052	4.482 ± 3.60*
Low	11	0.300 ± 0.0147	92.739± 8.261	1.863 ± 0.070	10.636 ± 1.433*

Note. *Denotes statistical significance at $p < 0.05$.

Table 2. Summary of Participant Demographics.

Measurement	**Within-Investigator Reliability**
Arch Height Index	0.964
Resting Calcaneal Angle	0.910

Table 3. Summary of ICC for Foot Anthropometrics.

Ankle Kinematics

To develop a greater understanding of the influence of arch height on foot mechanics during jumping and hopping tasks, ankle kinematics in the sagittal (dorsiflexion/plantarflexion) and frontal (inversion/eversion) planes were analyzed, on the dominant leg only. These data were evaluated using a series of 2 (group) x 3 (jumping/hopping tasks) mixed-factorial ANOVAs. The variables of concern included: peak plantarflexion, dorsiflexion, as well as maximum and minimum eversion ankle angles during the landing and propulsion phases of the forward hopping, lateral jumping and stationary hopping tasks. Significance level was set a priori at $p < 0.05$.

Sagittal Plane Ankle Kinematics: Landing

There was a significant main effect of plantarflexion ankle angles across jumping/hopping tasks ($F_{(2, 40)} = 4.930$, p = 0.012, partial η^2 =0 .198; Table 4). A follow-up pairwise comparison demonstrated that the forward hopping task yielded significantly less plantarflexion when compared to the lateral jumping (p = 0.024) and stationary hopping (p = 0.010) tasks. There was also a significant difference in plantar flexion angles between arch height ($F_{(1, 20)} = 4.420$, p = 0.048; partial $\eta^2 = 0.181$; Table 5). Specifically, NAH produced significantly greater plantarflexion when compared to the LAH. However, there was no significant interaction between arch height and jumping/hopping tasks ($F_{(2, 40)} = 0.470$, p = 0.628; Table 6).

There was a significant main effect of dorsiflexion ankle angles across jumping/hopping tasks ($F_{(2, 40)} = 15.729$, $p < 0.001$, partial $\eta^2 = 0.440$; Table 4). Follow-up pairwise comparisons indicated that the lateral jumping task yielded significantly less dorsiflexion when compared to forward hopping (p = 0.001) and stationary hopping ($p < 0.001$) tasks. However, no significant difference in dorsiflexion angles between arch height ($F_{(1, 20)} = 3.668$, p = 0.070; Table 5) and no significant interaction between arch height and jumping/hopping tasks ($F_{(2, 40)} = 0.451$, p = 0.640; Table 6) was found.

Sagittal Plane Ankle Kinematics: Propulsion

There was no significant main effect of plantarflexion ankle angles across jumping/hopping tasks ($F_{(2, 40)} = 1.211$, p = 0.309; Table 4) and no significant interaction between arch height and jumping/hopping tasks ($F_{(2, 40)} = 0.504$, $p = 0.608$; Table 6) were found. However, there was a significant difference in plantarflexion ankle angle between arch heights ($F_{(1, 20)} = 6.981$, $p = 0.016$, partial $\eta^2 = 0.259$; Table 5). More specifically, the NAH group produced greater plantarflexion when compared to the LAH, however the lack of a significant interaction between arch height and the jumping/hopping tasks indicates that this was a global finding and not identifiable within a specific task.

Further, there was a significant main effect of peak dorsiflexion angles across the jumping/hopping tasks ($F_{(2, 40)} = 24.112$, $p < 0.001$ partial $\eta^2 = 0.547$; Figure 15). Follow-up pairwise comparisons demonstrated that the lateral jumping task produced less dorsiflexion when compared to the forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. No significant difference between arch heights ($F_{(1, 20)} = 3.936$, $p = 0.061$; Table 4) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2, 40)} = 1.063$, $p = 0.355$) were found.

	Forward Hopping		Lateral Jumping		Stationary Hopping					
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing										
Plantarflexion (°)	63.032	(8.273)*$^{a, b}$	58.358	(7.372)*^{a}	56.761	(7.381)*^{b}	2	40	4.930	0.012*
Dorsiflexion (°)	94.897	(5.003)^{*c}	90.513	(3.214)*$^{c, d}$	95.679	(5.327)*^{d}	2	40	15.729	< 0.001*
Propulsion										
Plantarflexion (°)	44.112	(8.692)	43.837	(6.275)	45.976	(5.165)	2	40	1.211	0.309
Dorsiflexion (°)	96.069	(5.096)*^{e}	89.644	(3.546)*$^{e, f}$	95.654	(5.381)*^{f}	2	40	24.112	< 0.001*

Table 4. Main Effects of Peak Sagittal Plane Ankle Angles during the Landing and Propulsive Phases for the Jumping/Hopping Tasks.

	Normal Arch Height		Low Arch Height					
	M	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing								
Plantarflexion (°)	57.173	(5.063)*	61.595	(5.631)*	1	20	4.420	0.048*
Dorsiflexion (°)	92.427	(4.648)	95.146	(5.152)	1	20	3.668	0.070
Propulsion								
Plantarflexion (°)	41.866	(6.622)*	47.417	(5.919)*	1	20	6.981	0.016*
Dorsiflexion (°)	92.276	(5.063)	95.303	(5.631)	1	20	3.936	0.061

Note. Angles smaller than 90° indicate plantarflexion and angles greater than 90° indicate dorsiflexion.
* Denotes statistical significance at $p < 0.05$.

Table 5. Main Effects of Peak Sagittal Plane Ankle Angles Between Arch Height During the Landing and Propulsive Phases.

	Normal Arch Height			Low Arch Height						
	Forward Hopping	Lateral Jumping	Stationary Hopping	Forward Hopping	Lateral Jumping	Stationary Hopping				
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*df*	df_{error}	*F*	*p*
Landing										
Plantarflexion (°)	60.413 (9.082)	55.409 (6.819)	55.697 (6.219)	65.652 (6.793)	61.307 (6.964)	57.826 (8.559)	2	40	0.470	0.628
Dorsiflexion (°)	93.115 (5.187)	89.603 (3.081)	94.023 (4.554)	96.679 (4.320)	91.423 (3.221)	97.336 (5.728)	2	40	0.451	0.640
Propulsion										
Plantarflexion (°)	40.478 (8.748)	41.393 (5.307)	43.728 (5.426)	47.747 (7.282)	46.282 (6.433)	48.223 (3.931)	2	40	0.504	0.608
Dorsiflexion (°)	93.766 (5.594)	88.846 (3.373)	94.211 (4.457)	98.371 (3.403)	90.441 (3.693)	97.097 (6.029)	2	40	1.063	0.355

Note. Angles smaller than 90° indicate plantarflexion and angles greater than 90° indicate dorsiflexion.
* Denotes statistical significance at $p < 0.05$.

Table 6. Interaction of the Jumping/Hopping Tasks and Arch Height for Peak Sagittal Plane Ankle Angles during the Landing and Propulsion Phases for the Jumping/Hopping Tasks

Frontal Plane Ankle Kinematics: Landing

A series of 2 (group) x 3 (jumping/hopping tasks) mixed-factorial ANOVAs were performed to investigate the influence of arch height on peak inversion and eversion ankle kinematics. The results yielded that there was significant main effect for the eversion angles, during the landing phase, within the jumping/hopping tasks ($F_{(1.350, 27.002)} = 44.557$, $p < 0.001$, partial $\eta^2 = 0.690$; Table 7). A follow-up pairwise comparison demonstrated that the lateral jumping task yielded significantly larger, minimum eversion angles when compared to forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. The results of this analysis failed to find significant differences between arch heights ($F_{(1, 20)} = 1.921$, $p = 0.181$; Table 8) and no significant interaction between arch heights and jumping/hopping tasks ($F_{(1.350, 27.002)} = 0.470$, $p = 0.628$; Table 9) was found.

In addition, significant main effects for inversion angles during the landing phase, across the jumping/hopping tasks was found ($F_{(1.160, 23.194)} = 108.690$, $p < 0.001$, partial $\eta^2 = 0.845$; Table 7).. A follow-up pairwise comparison demonstrated that the lateral jumping task yielded significantly less inversion when compared to forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. The results also demonstrated that there was no significant difference between arch heights ($F_{(1, 20)} = 0.337$, $p = 0.546$; Table 8) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(1.160, 23.194)} = 3.272$, $p = 0.078$; Table 9).

Frontal Plane Ankle Kinematics: Propulsion

For eversion angles during the propulsion phase, there was a significant main effect across jumping/hopping tasks ($F_{(1.503, 30.054)} = 25.653$, $p < 0.001$, partial $\eta^2 = 0.562$; Table 7). Specifically, lateral jumping produced significantly greater eversion when compared to forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. Additionally, forward hopping produced significantly greater eversion when compared to the stationary hopping tasks ($p = 0.001$). The results also displayed that there was no significant difference between arch heights ($F_{(1, 20)} = 4.332$, $p = 0.050$; Table 8) and no significant interaction between arch heights and the jumping/hopping tasks ($F_{(1.503, 30.054)} = 0.753$, $p = 0.451$; Table 9) were found.

Further, there was a significant main effect for peak inversion angles during the propulsion phase, across jumping/hopping tasks ($F_{(2, 40)} = 89.369$, $p < 0.001$, partial $\eta^2 = 0.817$; Table 7). A follow-up pairwise comparison demonstrated that lateral jumping yielded significantly less inversion when compared to forward hopping ($p< 0.001$) and stationary hopping ($p < 0.001$) tasks. Additionally, forward hopping produced significantly less inversion when compared to the stationary hopping task ($p = 0.003$). The results of this analysis also displayed no significant differences between arch heights ($F_{(1, 20)} = 0.005$, $p =0.945$; Table 8) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2,40)} = 2.136$, $p = 0.131$;Table 9) was found.

	Forward Hopping		Lateral Jumping		Stationary Hopping					
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing										
Eversion (°)	-14.281	(11.977)*[a]	-33.315	(9.808)*[a, b]	-10.985	(9.583)*[b]	1.350	27.002	44.557	< 0.001*
Inversion (°)	-7.449	(6.989)*[c]	-30.046	(8.112)*[c, d]	-7.385	(5.101)*[d]	1.160	23.194	108.690	< 0.001*
Propulsion										
Eversion (°)	-18.636	(11.246) *[e, f]	-32.002	(16.308) *[e, g]	-10.983	(6.467) *[f, g]	1.503	30.054	25.653	< 0.001*
Inversion (°)	-10.564	(6.264) *[h, i]	-26.412	(7.657) *[h, j]	-6.056	(6.662) *[i, j]	2	40	89.396	< 0.001*

Note. Angles smaller than -10 degrees indicate eversion and angles greater than -10 degrees indicate inversion.
* Denotes statistical significance at the 0.05. [a-j] Probability values of significant pairwise comparisons: [a] $p < 0.001$; [b] $p < 0.001$; [c] $p < 0.001$; [d] $p < 0.001$; [e] $p = 0.001$; [f] $p = 0.001$; [g] $p < 0.001$; [h] $p < 0.001$; [i] $p = 0.003$; [j] $p < 0.001$.

Table 7. Main Effects of Peak Frontal Plane Ankle Angles during the Landing and Propulsive Phases for the Jumping/Hopping Tasks.

	Normal Arch Height		Low Arch Height					
	M	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing								
Eversion (°)	-21.789	(14.793)	-17.265	(13.709)	1	20	1.921	0.181
Inversion (°)	-15.498	(12.577)	-14.957	(13.140)	1	20	0.377	0.546
Propulsion								
Eversion (°)	-24.248	(12.819)	-16.833	(15.745)	1	20	4.332	0.050
Inversion (°)	-14.424	(9.859)	-14.263	(12.382)	1	20	0.005	0.945

Note. Angles smaller than -10 degrees indicate eversion and angles greater than -10 degrees indicate inversion.
* Denotes statistical significance at $p < 0.05$.

Table 8. Main Effects of Peak Frontal Plane Ankle Angles Between Arch Heights during the Landing and Propulsive Phases of the Jumping/Hopping Tasks.

	Normal Arch Height			Low Arch Height						
	Forward Hopping	Lateral Jumping	Stationary Hopping	Forward Hopping	Lateral Jumping	Stationary Hopping				
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*df*	df_{error}	*F*	*p*
Landing										
Eversion (°)	-18.654 (14.073)	-33.077 (12.287)	-13.636 (11.276)	-9.908 (7.819)	-33.553 (7.134)	-8.334 (7.089)	1.350	27.002	0.470	0.628
Inversion (°)	-10.451 (6.816)	-28.537 (9.721)	-7.735 (5.219)	-4.447 (6.023)	-31.554 (6.219)	-7.035 (5.210)	1.160	23.194	3.272	0.078
Propulsion										
Eversion (°)	-24.415 (11.332)	-34.518 (10.978)	-13.810 (6.404)	-12.858 (7.982)	-29.485 (20.593)	-8.156 (5.408)	1.503	30.054	0.735	0.451
Inversion (°)	-11.963 (5.329)	-24.638 (8.603)	-6.672 (4.597)	-9.165 (7.050)	-28.190 (6.497)	-5.439 (8.439)	2	40	2.136	0.131

Note. Angles smaller than -10 degrees indicate eversion and angles greater than -10 degrees indicate inversion
* Denotes statistical significance at $p < 0.05$.

Table 9. Interaction of the Jumping/Hopping Tasks and Arch Height for Peak Frontal Plane Ankle Angles During the Landing And Propulsion Phases for the Jumping/Hopping Tasks.

Lower Extremity Kinetics

To determine the effect of arch height on landing and propulsion, peak ground reaction forces (GRF) were investigated in forward and stationary hopping as well as lateral jumping, on the dominant limb only. Peak maximum and minimum GRFs were extracted using Visual 3D (C-Motion, Germantown, MD) and normalized to body weight for statistical analysis. It was hypothesized that the low arch height (LAH) group would develop medial/lateral and vertical GRFs that would provide an advantage for lateral movements while the normal arch height (NAH) group would generate anteroposterior and vertical forces that would be beneficial for forward motions. Comparisons for the landing phase will be presented first, followed by the comparisons for the propulsive phase.

Landing Phase Ground Reaction Forces

In the medial/lateral direction, there was a significant main effect across the jumping/hopping tasks ($F_{(1.295, 25.890)} = 72.135$, $p = < 0.001$, $\eta^2 = 0.783$; Table 10). Follow-up pairwise comparisons indicated that lateral jumping yielded significantly greater force in the medial direction when compared to forward hopping ($p< 0.001$) and stationary hopping ($p< 0.001$). Additionally, results from the follow-up pairwise comparison demonstrated that forward hopping yielded greater force, in the medial direction, when compared to stationary hopping ($p< 0.001$). The results of this analysis also displayed that there was no significant difference between arch height ($F_{(1, 20) =}$ 0.001, $p= 0.974$; Table 11) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(1.295, 25.980)} = 0.269$, $p = 0.669$; Table 12).

In the anteroposterior direction, there was a significant main effect across the jumping/hopping tasks ($F_{(2, 40)} = 51.883$, $p = < 0.001$, $\eta^2 = 0.722$; Table 10). Follow-up pairwise comparisons indicated that the stationary hopping task yielded significantly less force in the anterior direction when compared to forward hopping ($p < 0.001$) and lateral jumping ($p < 0.001$) tasks. The results of this analysis also displayed no significant difference between arch height ($F_{(1,20)} =$ 0.355, p= 0.558; Table 11) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2, 40)}$ = 2.609, p = 0.086; Table 12) was noted.

In the vertical direction, there was a significant main effect across the jumping/hopping tasks ($F_{(1.536, 30.723)}$ = 8.308, p = 0.003, η^2 = 0.293; Table 10). Follow-up pairwise comparisons indicated that the forward hopping task yielded significantly less force in the vertical direction, when compared to lateral jumping ($p < 0.001$) and stationary hopping (p = 0.008) tasks. Specifically, the foot strikes the ground hardest during the forward hopping condition, followed by the stationary hopping, and then the lateral jumping condition. The results of this analysis displayed that there was no significant difference between arch height ($F_{(1, 20)} =$ 0.419, p= 0.525; Table 11) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(1.536, 30.723)}$ = 0.672, p = 0.480; Table 12) was noted.

Propulsive Phase Ground Reaction Forces

In the mediolateral direction, there was a significant main effect across jumping/hopping tasks ($F_{(1.258, 25.154)}$ = 11.526, $p < 0.001$, η^2 = 0.366; Table 10). Follow-up pairwise comparisons indicated that the lateral jumping task yielded significantly greater force, in the lateral direction, when compared to the forward hopping task (p= 0.011) and stationary hopping task (p = 0.001). Specifically, during lateral jumping the foot pushes into the ground, in the lateral direction (the foot receives a medially directed force), with more force then during the forward hopping and stationary hopping tasks. In addition, there was a significant difference between arch height ($F_{(1, 20)}$ = 4.502, p = 0.047, η^2 = 0.184; Table 11). The results indicated that individuals with LAH produced larger lateral forces when compared to the NAH individuals. Further, there was no significant interaction between arch height and the jumping/hopping tasks ($F_{(1.258, 25.154)} = 1.756$, $p = 0.198$; Table 12).

In the anteroposterior direction, there was a significant main effect across jumping/hopping tasks ($F_{(1.055, 21.103)} = 15.350$, $p = < .001$, $\eta^2 = 0.434$; Table 10). Follow-up pairwise comparisons indicated that the forward hopping task yielded significantly greater force, in the posterior direction, when compared to lateral jumping ($p < 0. 001$) and stationary hopping ($p= 0. 002$) tasks. The results of this analysis displayed that there was no significant difference between arch height ($F_{(1, 20)} = 1.374$, $p =0.255$; Table 11) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(1.055, 21.103)} = 0.147$, $p = 0.719$; Table 12) was noted.

In the vertical direction, there was a significant main effect across jumping/hopping tasks ($F_{(2, 40\ )} = 43.993$, $p < 0.001$, $\eta^2 = 0.687$; Table 10). Follow-up pairwise comparisons indicated that the forward hopping task yielded greater force, in the vertical direction, when compared to the lateral jumping task ($p< 0.001$) and stationary hopping tasks ($p = 0.001$). Additionally, results of the follow-up pairwise comparison demonstrated that the stationary hopping task yielded greater force, in the vertical direction, when compared to the lateral jumping task ($p < 0.001$). The results also displayed that there was no significant difference between arch height ($F_{(1,20)} = 0.115$, $p =0.738$; Table 11) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2,40)} = 1.060$, $p = 0.356$; Table 12) was noted.

	Forward Hopping		Lateral Jumping		Stationary Hopping					
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing										
Mediolateral (N/BW)	-21.633	(17.750)*[a, b]	-81.767	(32.184)*[a, c]	-7.740	(2.929)*[b, c]	1.295	25.890	72.135	< 0.001*
Anteroposterior (N/BW)	-34.828	(15.861)*[d]	-38.218	(17.145)*[e]	-6.772	(8.241)*[d, e]	2	40	51.883	< 0.001*
Vertical (N/BW)	70.995	(31.174)*[f, g]	27.709	(17.453)*[f]	35.906	(57.455)*[g]	1.536	30.723	8.308	0.003*
Propulsion										
Mediolateral (N/BW)	1.0104	(9.636)*[h]	-12.393	(17.772)*[h, i]	4.442	(2.582)*[i]	1.258	25.154	11.526	0.001*
Anteroposterior (N/BW)	33.785	(14.915)*[j, k]	4.337	(25.041)*[j]	6.161	(2.385)*[k]	1.055	21.103	15.350	0.001*
Vertical (N/BW)	348.726	(66.433)*[l, m]	207.694	(32.826)*[l, n]	281.475	(47.060)*[m, n]	2	40	43.993	< 0.001*

Note. Ground reaction forces were normalized by body weight and thus are expressed in units of Newtons per body weight (N/BW).
* Denotes statistical significance at the 0.05. [a-n] Probability values of significant pairwise comparisons: [a] $p < 0.001$; [b] $p = 0.001$; [c] $p < 0.001$; [d] $p < 0.001$; [e] $p < 0.001$; [f] $p < 0.001$; [g] $p = 0.008$; [h] $p = 0.011$; [i] $p < 0.001$; [j] $p = 0.002$; [k] $p < 0.001$; [l] $p < 0.001$; [m] $p < 0.001$; [n] $p < 0.001$.

Table 10. Main Effects of Peak Ground Reaction Forces during the Landing and Propulsive Phases for the Jumping/Hopping Tasks.

	Normal Arch Height		Low Arch Height					
	M	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing								
Mediolateral (N/BW)	-39.959	(36.344)	-37.133	(41.230)	1	20	0.001	0.974
Anteroposterior (N/BW)	-27.983	(19.407)	-25.229	(20.775)	1	20	0.355	0.558
Vertical (N/BW)	41.420	(28.179)	48.320	(53.966)	1	20	0.419	0.525
Propulsion								
Mediolateral (N/BW)	0.1329	(6.334)*	-4.760	(18.136)*	1	20	4.502	0.047*
Anteroposterior (N/BW)	13.285	(17.453)	16.237	(25.030)	1	20	1.374	0.255
Vertical (N/BW)	281.521	(78.609)	277.075	(75.559)	1	20	0.115	0.738

Note. Ground reaction forces were normalized by body weight and thus are expressed in units of Newtons per body weight (N/BW).
* Denotes statistical significance at $p < 0.05$.

Table 11. *Main Effects of Peak Ground Reaction Forces Between Arch Heights During the Landing and Propulsive Phases of the Jumping/Hopping Tasks.*

	Normal Arch Height			Low Arch Height						
	Forward Hopping	Lateral Jumping	Stationary Hopping	Forward Hopping	Lateral Jumping	Stationary Hopping				
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*df*	df_{error}	*F*	*p*
Landing										
Mediolateral (N/BW)	-23.425 (21.439)	-78.975 (26.846)	-8.478 (3.302)	-19.840 (13.963)	-84.558 (37.912)	-7.002 (2.432)	1.295	25.980	0.269	0.669
Anteroposterior (N/BW)	-31.911 (14.801)	-42.816 (15.466)	-9.221 (10.041)	-37.745 (17.044)	-33.620 (18.209)	-4.323 (5.347)	2	40	2.609	0.086
Vertical (N/BW)	66.370 (31.429)	31.305 (19.960)	26.586 (10.741)	75.619 (31.716)	24.113 (14.590)	45.226 (81.399)	1.160	23.194	3.272	0.078
Propulsion										
Mediolateral (N/BW)	2.185 (6.186)	-6.018 (4.209)	4.231 (2.768)	-0.164 (12.397)	-18.768 (23.582)	4.653 (2.498)	1.258	25.154	1.756	0.198
Anteroposterior (N/BW)	32.161 (14.416)	1.326 (12.595)	6.368 (2.534)	35.409 (15.923)	7.348 (33.738)	5.954 (2.330)	1.055	21.103	0.147	0.719
Vertical (N/BW)	339.060 (83.622)	212.140 (41.274)	293.364 (44.573)	358.391 (45.494)	203.249 (22.712)	269.586 (48.509)	2	40	1.060	0.356

Note. Ground reaction forces were normalized by body weight and thus are expressed in units of Newtons per body weight (N/BW).
* Denotes statistical significance at $p < 0.05$.

Table 12. Interaction of the Jumping/Hopping Tasks and Arch Height for Peak Ground Reaction Forces During the Landing And Propulsion Phases for the Jumping/Hopping Tasks.

Resultant Ground Reaction Force Angle

The relationship amongst the generated GRFs during the landing and propulsion phases of the jumping/hopping tasks were also analyzed. The resultant force vector was computed in the frontal (angle between the medial/lateral and vertical GRFs) and sagittal plane (angle between the anterior/posterior and vertical GRFs). A series of 2 (foot type) X 3 (jumping/hopping tasks) mixed model ANOVAs, with a p value set at $p < 0.05$, were performed to analyze the maximum resultant angle of resultant vectors during the landing and propulsive phases of each hop/jump condition. Significant main effects were noted between the jumping/hopping tasks, but no significant differences were found between arch heights nor were significant interactions between arch height and the jumping/hopping tasks determined. The results that failed to demonstrate significance will be presented in Tables 14 and 15.

Resultant Angles in the Sagittal and Frontal Planes: Landing

The resultant angle in the sagittal plane (constructed by the peak anteroposterior forces and vertical GRF, measured counter clockwise from the horizontal axis) was considered. There was a significant main effect for the resultant angle in the sagittal plane across jumping/hopping tasks ($F_{(1.315,\ 26.307)} = 13.890$, $p < 0.001$, $\eta^2 = 0.410$; Table 13). Pair wise comparisons indicated that stationary hopping yielded a significantly smaller sagittal plane resultant angle than forward hopping ($p < 0.001$) and lateral jumping ($p < 0.001$) tasks. This finding indicates that the resultant angle of the force applied to the ground by the foot (and thereby, on the foot by the ground) during the stationary hopping, was significantly smaller (more anteroposterior), then during either forward hopping and stationary hopping.

There was a significant main effect for the resultant angle in the frontal plane (constructed by the peak medial/lateral and vertical GRF, measured counter clockwise from the vertical axis), for the jumping/hopping tasks ($F_{(1.295, 25.910)} = 25.195$, $p < .0\ 001$ $\eta^2 = 0.557$; Table 13). A follow-up pair wise comparison indicated that the lateral jumping task yielded a significantly larger frontal plane resultant angle when compared to the forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. This finding indicates that the resultant angle of the force applied to the ground by the foot (and thereby, on the foot by the ground) during lateral jumping, was significantly smaller (more medial/lateral), then during either the forward hopping or stationary hopping tasks.

Resultant Angles in the Sagittal and Frontal Planes: Propulsion

The resultant angle in the sagittal plane (constructed by the peak anteroposterior forces and vertical GRF, measured counter clockwise from the horizontal axis) was also considered. There was a significant main effect across the jumping/hopping tasks ($F_{(1.152\ ,\ 23.033)} = 15.783$, $p < 0.\ 001$; Table 14). Follow-up pairwise comparisons indicated that all angles of the jumping/hopping tasks were significantly different from each other (Table 15). This finding indicates that the resultant angle of the force applied to the ground by the foot (and thereby, on the foot by the ground) during the forward hopping task, was significantly smaller (more posterior), then during either the lateral jumping ($p < 0.001$) or stationary hopping ($p < 0.001$) tasks. Further, stationary hopping produced a significantly smaller horizontal resultant angle than the forward hopping task ($p < 0.001$), but a greater horizontal resultant angle then the lateral jumping task ($p = 0.041$). Moreover, the lateral jumping tasks yielded a significantly smaller horizontal resultant angle than the forward hopping ($p < 0.001$) or stationary hopping ($p = 0.041$) tasks.

There was a significant main effect in the resultant angle in the frontal plane (constructed by the peak medial/lateral and vertical GRF, measured counter clockwise from the vertical axis), across the jumping/hopping tasks ($F_{(1.183,\ 23.656)} = 29.233$, $p < 0.001$; Table 13). Pair wise comparisons indicated that the lateral jumping task yielded a significantly larger frontal plane resultant angle when compared to forward hopping ($p < 0.001$) and stationary hopping ($p < 0.001$) tasks. This finding indicates that the resultant angle of the force applied to the ground by the foot (and thereby, on the foot by the ground) during lateral jumping, was significantly smaller (more medial), then either forward hopping or stationary hopping.

	Forward Hopping		Lateral Jumping		Stationary Hopping					
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing										
Sagittal (°)	89.154	(4.984)*^{a}	91.911	(9.218)*^{b}	84.568	(4.093)*$^{a, b}$	1.315	26.307	13.890	< 0.001*
Frontal (°)	87.083	(4.905)*^{c}	99.211	(10.367)*$^{c, d}$	88.368	(1.602)*^{d}	1.295	25.910	25.195	< 0.001*
Propulsion										
Sagittal (°)	79.444	(4.733) *$^{e, f}$	92.370	(11.902) *$^{e, g}$	87.015	(1.508) *$^{f, g}$	1.152	23.033	15.783	< 0.001*
Frontal (°)	88.499	(6.959) *^{h}	108.171	(14.348) *$^{h, i}$	87.917	(1.337) *^{i}	1.183	23.656	29.233	< 0.001*

Note. *Denotes statistical significance at the 0.05. $^{a\text{-}i}$ Probability values of significant pairwise comparisons: $^{a}p < 0.001$; $^{b}p < 0.001$; $^{c}p < 0.001$; $^{d}p < 0.001$; $^{e}p < 0.001$; $^{f}p < 0.001$; $^{g}p = 0.041$; $^{h}p < 0.001$; $^{i}p < 0.001$.

Table 13. Main Effects of Resultant Sagittal and Frontal Plane GRF Angles during the Landing and Propulsive Phases for the Jumping/Hopping Tasks

		Normal Arch Height						
M *(SD)*	*M* *(SD)*		df_{error}	*F*			*p*	
Landing								
Sagittal (°)	89.244	(5.884)	87.845	(8.145)	1	20	0.373	0.548
Frontal (°)	91.585	(7.931)	91.522	(9.280)	1	20	0.001	0.974
Propulsion								
Sagittal (°)	86.687	(9.298)	85.866	(8.963)	1	20	0.198	0.661
Frontal (°)	95.170	(11.897)	94.554	(14.460)	1	20	0.094	0.762

Table 14 Main Effects of Peak Ground Reaction Forces Between Arch Heights During the Landing and Propulsive Phases of the Jumping/Hopping Tasks

	Normal Arch Height			Low Arch Height						
	Forward Hopping	**Lateral Jumping**	**Stationary Hopping**	**Forward Hopping**	**Lateral Jumping**	**Stationary Hopping**				
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*df*	df_{error}	*F*	*p*
Landing										
Sagittal (°)	90.150 (4.334)	93.096 (5.501)	84.487 (4.430)	88.160 (5.586)	90.726 (12.045)	84.649 (3.943)	1.315	26.307	0.471	0.550
Frontal (°)	88.506 (5.130)	97.755 (10.461)	88.494 (1.651)	85.659 (4.443)	100.666 (10.564)	88.242 (1.621)	1.295	25.910	1.180	0.303
Propulsion										
Sagittal (°)	79.902 (4.887)	93.114 (12.430)	87.046 (1.432)	78.987 (4.764)	91.627 (11.905)	86.984 (1.649)	1.152	23.033	0.048	0.861
Frontal (°)	89.740 (9.355)	107.469 (10.637)	88.302 (1.219)	87.258 (3.288)	108.872 (17.834)	87.532 (1.394)	1.183	23.656	0.208	0.693

Note. *Denotes statistical significance at $p < 0.05$.

Table 15. Interaction of the Jumping/Hopping Tasks and Arch Height for Resultant Sagittal and Frontal Plane GRF Angles During the Landing And Propulsion Phases for the Jumping/Hopping Tasks.

Lower Extremity Stiffness

The analysis of the lower extremity stiffness variable was employed to examine the influence of arch height on how the body utilized the structures of the lower extremity to resist deformation, during the stationary hopping task. An independent samples t-test was conducted to determine statistical differences in lower extremity stiffness between NAH and LAH groups. The results of the independent samples t-test failed to demonstrate statistical significance ($t_{(20)} = 1.678$, $p = 0.109$; Table 16).

	Normal Arch Height		**Low Arch Height**				
	M	*(SD)*	*M*	*(SD)*	*t*	*df*	*p*
Lower Extremity Stiffness	20.997	(5.682)	17.414	(4.225)	1.678	20	0.109

Note. * Level of significance set a priori at *p* < 0.05.

Table 16. Influence of Arch Height on Lower Extremity Stiffness in Stationary Hopping Task.

Surface Electromyography

To develop a greater understanding of the effect of arch height on the mechanics of jumping/hopping tasks, average electromyography (EMG) data were extracted for analysis. Average EMG data were reported, normalized to maximal voluntary isometric contractions. It was hypothesized that LAH group would display a decrease in peak muscular activation of the lower extremity during forward hopping, lateral, jumping and stationary hopping tasks in comparison to NAH. Intratester reliability of MVIC's of the soleus and medial gastrocnemius were assessed with intraclass correlation coefficients (ICC) (Table 17).

Muscle	Within-Investigator Reliability
Soleus	0.9.16
Medial Gastrocnemius	0.946

Table 17. Summary of ICC for MVICs of the Soleus and Medial Gastrocnemius.

Average Amplitude of the Soleus and Medial Gastrocnemius during the Landing Phase

A 2 (group) x 3 (jumping/hopping tasks) mixed-factorial ANOVA was performed to investigate the influence of arch height on average EMG activity of the soleus during the landing phase of the jumping/hopping tasks. The results demonstrated that there was a significant main effect across the jumping/hopping tasks ($F_{(2, 40)}$ = 4.294, p = 0.020, η^2 = 0.177; Table 18). Follow-up pairwise comparisons indicated that the lateral jumping task yielded a significantly lower average amplitude when compared to forward hopping (p = 0.019) and stationary hopping (p= 0.017) tasks. Additionally, the results also yielded that there was no significant difference between arch height ($F_{(1, 20)}$ = 1.512, p = 0.233; Table 19) nor a significant interaction between arch height and the jumping/hopping tasks ($F_{(2, 40)}$ = 0.814, p = 0.450; Table 20).

A 2 (foot type) X 3 (jumping/hopping tasks) mixed-factorial ANOVA was performed to also investigate the influence of arch height on average EMG activity of the medial head of the gastrocnemius during the landing phase of the jumping/hopping tasks. The results demonstrated that there was a significant main effect within the jumping/hopping tasks ($F_{(2, 40)}$ = 3.934, p = 0.028, η^2 = 0.164; Table 18). Follow-up pairwise comparisons displayed that lateral jumping task yielded a significantly lower average amplitude when compared to the forward hopping task (p = 0.025). The results from this statistical analysis also yielded that there was no significant difference between arch height ($F_{(1, 20)} = 0.238$, p = 0.631; Table 19) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2, 40)} = 0.631$, p = 0.537; Table 20) was noted.

Average Amplitude of the Soleus and Medial Gastrocnemius during the Propulsion Phase

A 2 (group) x 3 (jumping/hopping tasks) mixed-factorial ANOVA was performed to investigate the influence of arch height on average EMG activity of the soleus during the propulsion phase of the jumping/hopping tasks. The results demonstrated that there was a significant main effect across the jumping/hopping tasks ($F_{(2, 40)} = 3.475$, p = 0.041, $\eta^2 = 0.148$; Table 18). Follow-up pairwise comparisons displayed that the lateral jumping task yielded a significantly higher average amplitude when compared to the stationary hopping (p= 0.034) task. Results from this statistical analysis yielded that there was no significant difference between arch type ($F_{(1, 20) =}$ 2.079, p = 0.165; Table 19) nor was a significant interaction between arch height and the jumping/hopping tasks found ($F_{(2, 40)} = 0.013$, p = 0.910; Table 20).

A 2 (foot type) X 3 (jumping/hopping tasks) mixed-factorial ANOVA was performed to investigate the influence of arch height on average EMG activity of the medial head of the gastrocnemius during the propulsion phase of the jumping/hopping tasks. There was a significant main effect across the jumping/hopping tasks ($F_{(2, 40)} = 3.335$, p = 0.045, $\eta^2 = 0.144$ Table 18). A follow-up pairwise comparison determined that lateral jumping yielded a significantly lower average amplitude when compared to forward hopping (p = 0.020). Additionally, the results from this statistical analysis yielded that there was no significant difference between arch height ($F_{(1, 20)}= 0.013$, p =0.910; Table 19) and no significant interaction between arch height and the jumping/hopping tasks ($F_{(2, 40)} = 0.679$, p = 0.513; Table 20) was found.

	Forward Hopping		Lateral Jumping		Stationary Hopping					
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing										
Soleus (%MVIC)	53.794	(34.792)*^{a}	29.331	(30.973)*$^{a, b}$	53.513	(33.947)*^{b}	2	40	4.294	0.020*
Gastrocnemius (%MVIC)	85.572	(65.590)*^{c}	42.741	(42.339)*^{c}	65.159	(35.940)	2	40	3.934	0.028*
Propulsion										
Soleus (%MVIC)	22.762	(21.572)	31.227	(23.429)*^{d}	16.187	(15.519)*^{d}	2	40	3.475	0.041*
Gastrocnemius (%MVIC)	41.736	(32.225)*^{e}	57.725	(35.297)*^{e}	45.859	(28.232)	2	40	3.355	0.045*

*Note.**Denotes statistical significance at the 0.05. $^{a-e}$ Probability values of significant pairwise comparisons: $^{a}p = 0.019$; $^{b}p = 0.017$; $^{c}p = 0.025$; $^{d}p = 0.034$; $^{e}p = 0.020$.

Table 18. Main Effects of Average EMG Activity of the Soleus and Gastrocnemius during the Landing and Propulsive Phases for the Jumping/Hopping Tasks.

	Normal Arch Height		Low Arch Height					
	M	*(SD)*	*M*	*(SD)*	*df*	df_{error}	*F*	*p*
Landing								
Soleus (%MVIC)	50.978	(33.943)	40.114	(35.192)	1	20	1.512	0.233
Gastrocnemius (%MVIC)	61.530	(41.707)	67.451	(60.999)	1	20	0.238	0.631
Propulsion								
Soleus (%MVIC)	27.521	(24.586)	19.263	(16.193)	1	20	2.079	0.165
Gastrocnemius (%MVIC)	49.115	(32.495)	47.765	(32.558)	1	20	0.013	0.910

Note. * Denotes statistical significance at $p < 0.05$.

Table 19. Main Effects of Between for Arch Height for Average EMG Activity of the Soleus and Gastrocnemius during the Landing and Propulsive Phases

	Normal Arch Height			Low Arch Height						
	Forward Hopping	Lateral Jumping	Stationary Hopping	Forward Hopping	Lateral Jumping	Stationary Hopping				
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*df*	df_{error}	*F*	*p*
Landing										
Soleus (%MVIC)	62.241	38.784	51.910	45.348	19.877	55.116	2	40	0.814	0.450
	(33.359)	(35.422)	(31.860)	(35.669)	(23.734)	(37.408)				
Gastrocnemius	76.939	49.654	57.998	94.204	35.827	72.321	2	40	0.631	0.537
(%MVIC)	(26.558)	(54.211)	(38.629)	(90.361)	(26.843)	(33.279)				
Propulsion										
Soleus (%MVIC)	26.602	35.894	20.066	18.921	26.560	12.309	2	40	0.013	0.987
	(24.582)	(28.840)	(18.949)	(18.452)	(16.526)	(10.658)				
Gastrocnemius	40.607	55.909	50.828	42.864	59.541	40.889	2	40	0.679	0.513
(%MVIC)	(34.036)	(36.632)	(27.294)	(31.928)	(35.598)	(29.573)				

Table 20. Interaction of the Jumping/Hopping Tasks and Arch Height for Average EMG Activity of the Soleus and Gastrocnemius during the Landing and Propulsive Phases for the Jumping/Hopping Tasks

Chapter V. Discussion

The purpose of this project was to investigate the influence of anatomical alterations of the medial longitudinal arch (MLA) on the development of kinematic, kinetic, and electromyographic measures during ballistic movements. Specifically, this project examined the effect normal (NAH) and low arch heights (LAH) have on: 1) sagittal and frontal plane ankle kinematics, 2) normalized peak ground reaction force production, 3) normalized mean electromyography (EMG), and 4) lower extremity stiffness during the landing and propulsion phases of during forward hopping, lateral jumping, and stationary hopping. The following chapter will discuss the results of the present study. The outline of the following chapter has been broken down into the following sections: 1) the influence of arch height on sagittal and frontal plane ankle kinematics; 2) the influence of arch height on normalized peak force production; 3) the influence of arch height on lower extremity stiffness; 4) the influence of arch height on normalized average EMG activity of the soleus and medial head of the gastrocnemius; 5) synthesis of related data and 6) limitations and future studies.

Influence of Arch Height on Sagittal and Frontal Plane Ankle Kinematics

The ankle is the immediate connection amongst the foot and proximal kinetic chain that has an essential role in contributing to the adequate kinematics for propulsion and shock absorption (Nyska & Mann 2002). However due to the major influence arch height has on both locomotive and foot mechanics, the functional role of the ankle can be altered. Particularly the alterations in arch height commonly observed in low arch height (LAH), when compared to normal arch height (NAH), can produce notable differences in ankle kinematics within the frontal and sagittal planes that can induce increased calcaneus eversion, increase internal tibial rotation, and increased internal femoral rotation and modify propulsive mechanics during gait

(Buldt et al 2015, 2013; Prachgosin et al 2015; Chang et al 2012; Powell et al 2011; Wilken et al 2011; Levinger et al 2010; Mosca 2010; Cobb et al 2009; Houck et al 2008; Tweed et al 2008; Butler et al 2007,2006; Hunt et al 2004; Bolgla and Malone 2004; Bordelon 1983). While these findings provide valuable insight into ankle kinematics during walking and running tasks, studies examining the role of arch height on producing similar kinematic patterns during more ballistic motions, such as jumping and hopping, remain scarce. Therefore, an aim of this study was to investigate the influence of arch height on ankle kinematics, during different locomotive phases of jumping and hopping tasks.

Sagittal Plane Ankle Kinematics Between Arch Height

The results of the present project suggest that there are differences in sagittal plane ankle kinematics, specifically greater plantarflexion produced by the NAH group, during the landing and propulsion phases of the jumping/hopping tasks (Table 5). To the author's knowledge, this study presents novel findings to the literature surrounding the influence of arch height on ankle kinematics in ballistic tasks. Previous studies examining the influence of arch height on walking and running gait found that both arch types produced similar angles of dorsiflexion during walking and running (Jankowicz-Szymanska et al 2017; Twoney et al 2012, 2010; Powell et al 2011; Cobb et al 2009). It was further demonstrated that NAH and LAH presented differences of only 2˚ in total sagittal plane motion (Hunt and Smith 2004). Conversely, the present study indicated NAH produced greater plantarflexion angles when compared to LAH. While previous research demonstrated no changes in plantarflexion angles during gait, it is possible that the difference in arch height, in conjunction with the nature of the jumping tasks, are responsible for the alterations in plantarflexion found (Twoney et 2012; Cobb et al 2009). Specifically, increased contact of the talar dome with the distal head of the tibia, typically observed in LAH, may restrict the plantarflexion range of motion when compared to NAH (Brockett & Chapman 2016; Djun & Tan 2015; Wilken et al 2011; Ledoux et al 2006; Bolgla & Malone 2004; Donatelli 1987; Olsen & Seidel 1983; Root et al 1977). Further, it is also possible that subject population contributed to the unique findings of the current project, as previous literature considered a non-athletic population. While the lack of published literature regarding the influence of arch height on jumping tasks prevents further comparison, the findings of this preliminary investigation encourage more research on this variable.

Sagittal Plane Ankle Kinematics in the Jumping/Hopping Tasks during the Landing Phase

The results of the present study demonstrated that the forward hopping tasks displayed less plantarflexion during landing, without regards to arch height, when compared to lateral jumping and stationary hopping (Table 4). Previous research has shown that decreases in plantarflexion, with regard to jumping mechanics similar to the forward hopping task, permits the leg to pass over the foot for propulsion (Mason-McKay et al 2017; Manutel et al 2013; Perry & Burnfield 2010; Tweed et al 2008; Piva et al 2005). Further, decreases in plantarflexion has also been suggested to increase the contribution of the proximal kinetic chain for adequate landing mechanics (Fong et al 2011). While an analysis of the kinematics associated with the more proximal chain was not conducted for this study, it may be a contributor of the differences found between the jumping tasks. Specifically the decrease in plantarflexion observed in the forward hopping task could suggest the involvement of the lower extremity in jumping and landing mechanics that are needed to stabilize the center of mass prior propelling the body forward (Mason-McKay et al 2017; Macrum et al 2012).

The results of the current project identified less dorsiflexion in the lateral jumping task during landing, without regards to arch height, when compared to forward hopping and stationary hopping (Table 4). While literature examining ankle kinematics during jumping/hopping tasks remains limited, the results in the current study do enhance previous findings of similar tasks. Studies examining the differences of forward and lateral jumping tasks identified greater dorsiflexion during the landing phase of a lateral jump, when compared to the unilateral forward jumping (Sinsurin et al 2013; Monteleone et al 2012). It is possible that the differences in dorsiflexion observed in the present study, during landing, could be influenced by the objective of the overall task. The previous studies examined dorsiflexion during the landing phase upon jumping over an obstacle and from a box (Sinsurin et al 2013; Monteleone et al 2012). However, the analysis of the dorsiflexion in the current study was conducted in tasks that required the propulsion in a specific direction. These differences suggest that a different kinematic pattern is employed when negotiating obstacles and when landing from a height than when performing cyclical jumping/hopping motions.

Sagittal Plane Ankle Kinematics in the Jumping/Hopping Tasks during the Propulsion Phase

The results of the present study demonstrated that no differences in plantarflexion in jumping/hopping tasks during the propulsion phase were noted (Table 4). However, this is not surprising as literature has presented similar findings in various jumping tasks. Previous studies have reported differences of 3 – 6 ˚ in plantarflexion at take-off during drop jumping and long jumping with and without counter-movements (Shu et al 2016; Papaiakovou 2013; Smith 1983). While these studies did not examine differences amongst the jumping types, the findings of this study conclude jumping/hopping tasks may exhibit similar propulsion mechanics.

Findings of the present project indicate that there is significantly less dorsiflexion during the propulsion phase of lateral jumping tasks, regardless of arch height, when compared to lateral hopping and stationary hopping tasks (Table 4). A possible explanation for this finding may be found in the multi-planar landing mechanics associated with this task. Landing in both the frontal and sagittal planes limits the ability of the ankle to enter into a more close-pack position (Arnsdoff et al 2011; Norkus & Floyd 2001; Sarrafian 1993). In addition, the minimization of dorsiflexion increases the ability to propel in the lateral direction in a rhythmic sequence without the restriction contributed by the interaction of the talus and tibia.

Frontal Plane Ankle Kinematics Between Arch Height

The results of current project demonstrated that arch height had no effect on frontal plane motion during the propulsion and landing phases of the jumping/hopping tasks (Table 8). This is somewhat surprising as literature presented different findings in running and walking tasks. Previous studies demonstrated that LAH displayed more inversion during the landing and propulsive phases (Cobb et al 2009; Houck et al 2008). Conversely, research has also demonstrated that LAH produced more eversion which supports the notion that rearfoot position influences frontal plane motion (Levinger et al 2010; Powell et al 2010; Wilken et al 2010; Chuter et al 2009; Krugh & Keysor 1996; Kernozek et al 1990). Hunt and Smith (2004) presented that the nonsignificant findings in frontal plane motion between LAH and NAH during walking may be attributed by the differences of 1° in total frontal plane range of motion during walking gait. While the results of the present study support this concept, due to the lack of literature investigating the jumping/hopping tasks, it is difficult to definitely concur with the findings of Hunt and Smith (2004). Further research is needed to examine differences that may be detectable with a larger participant population.

Frontal Plane Ankle Kinematics in the Jumping/Hopping Tasks during the Landing Phase

Findings of statistical analyses of this study demonstrated that the lateral jumping tasks displayed less inversion during the landing phase, without regards to arch height (Table 7). These findings have been supported by previous literature despite, the limited research investigating differences between the jumping/hopping tasks performed in this current study. Previous research has shown that jumping tasks in the lateral direction have exhibited 3 -14˚ inversion when compared to forward hopping tasks (Donovan & Feger 2017; Ridder et al 2015; Earl et al 2007; Delahunt et al 2007, 2006). An explanation of these findings can suggest that the foot is placed in a more everted position throughout the lateral jumping task when compared to the forward and stationary hopping tasks, ultimately implying differences in landing mechanics that can be influential for propulsion.

Frontal Plane Ankle Kinematics in the Jumping/Hopping Tasks during the Propulsion Phase

The results of the current project suggest that during the propulsion phases of the jumping tasks, lateral jumping tasks produced less inversion and greater eversion (Table 7). These findings are supported by previous literature that has indicated that lateral jumping places the foot in a more everted position during the landing phase, which aids in preparing the foot for propulsion (Donovan & Feger 2017; Ridder et al 2015; Earl et al 2007; Delahunt et al 2007; Delahunt et al 2006). Secondly, during more forward motions, previous literature has suggested that the foot utilizes the outside border for lateral and vertical propulsion (Bolgla & Malone 2004; Hessert et al 2004 Elftman & Manter 1935; Elftman 1934). Therefore, in the forward and stationary hopping tasks the foot must be positioned in a more inverted position to produced more adequate propulsion mechanics, thus allowing the lateral jumping task to demonstrate less inversion.

Summary of Frontal and Sagittal Plane Kinematics

The sagittal and frontal plane ankle kinematic data from the current study presented both expected and unforeseen results. With respect to arch height, differences were only observed in the sagittal plane, as the NAH produced greater plantarflexion during the landing and propulsion phases when compared to LAH. This finding was not expected because it was believed that the structural alterations associated with the LAH, which increases the interaction between the talus and tibia, would yield greater plantarflexion and diminish any restrictions of the close-packed system (Brockett & Chapman 2016; Djun & Tan 2015; Ledoux et al 2006; Norkus et al 2001; Sarrafian 1993; Donatelli 1987; Olson & Seidel 1983; Root et al 1977). Furthermore, the lack of like findings between the present project and walking/running research suggests that the propulsion and landing mechanics in the sagittal plane differ in more ballistic tasks (Jankowicz-Szymanska et al 2017; Shihetal et al 2012; Twoney et al 2012, 2010; Powell et al 2010; Cobb et al 2009; Hunt & Smith 2004).

Frontal plane kinematics presented similarities amongst arch heights during the propulsion and landing phased of the jumping/hopping tasks. This finding was unexpected as it was hypothesized that the LAH would produce greater eversion, as the alteration in the rearfoot positioning has been found to produce kinematic changes (Levinger et al 2010; Powell et al 2010; Wilken et al 2010; Chuter et al 2009; Krugh & Keuser 1996; Kernozek et al 1990). However, a study conducted by Hunt and Smith (2004) suggested that LAH and NAH produce similar ranges of motion, which would diminish any presentable differences. Therefore future research should consider any changes as a percentage of total active range of motion of these joints.

Although the overall aim was to investigate the influence of arch height on ankle kinematics in the sagittal and frontal planes during the landing and propulsion phases of forward hopping, lateral jumping, and stationary hopping tasks, the present study also presented novel findings in the analyses of the ankle kinematics of different jumping/hopping tasks. Overall, the current study observed that individuals presented: (a) less dorsiflexion during the landing and propulsion phases of the lateral jumping task; presented less plantarflexion during the landing phase of the forward hopping tasks; and no differences in dorsiflexion during the landing phase of the jumping/hopping tasks; less inversion during the landing and propulsion phases of the lateral jumping task; and greater eversion during the landing and propulsion phases of the lateral jumping tasks. The frontal plane kinematics findings were consistent with the findings of previous studies. These findings further our understanding of the ankle kinematics during ballistic tasks, as no project has considered sequential, ballistic tasks of this nature. In addition, the differences noted between the findings of the current project and previous work on running and single jumps suggest that there is a difference in kinematic patterns between unilateral and contralateral tasks. Yet, as this project did not identify differences between arch type during specific tasks, completing this project with the required number of participants to detect a significant finding is required before conclusions can be made.

	Landing				**Propulsion**			
	Sagittal Plane		**Frontal Plane**		**Sagittal Plane**		Frontal Plane	
	Plantarflexion	Dorsiflexion	Inversion	Eversion	Plantarflexion	Dorsiflexion	Inversion	Eversion
Tasks								
Forward Hopping	>	>	<	<	=	>	<	<
Lateral Jumping	<	<	>	>	=	<	>	>
Stationary Hopping	>	>	<	<	=	>	<	<
Classification								
Normal Arch Height	>	=	=	=	>	=	=	=
Low Arch Height	<	=	=	=	>	=	=	=

Note. Greater than and less than signs indicate significance. Equal signs indicate non-significance.

Table 21. Summary of the Ankle Kinematics Findings during Landing and Propulsion Phases of the Jumping/Hopping Tasks.

Influence of Arch Height on Normalized Peak Ground Reaction Force

Ground reaction forces (GRFs) are an interactive measurement used in research to identify force production magnitudes throughout different phases of locomotion. During such tasks, the force components can indicate specific loading and propulsion patterns that enhance or hinder movement (Nilsson & Thorstensson, 1989). Specifically, force patterns generated in the desired direction with minimal deviations permit individuals to move in an efficient manner (Neptune et al 2004; Hudson 1991). However, differences in arch heights can produce motions that deviate from traditional force patterns and can induce mechanical abnormalities associated with pathological arch heights (Williams III et al 2001). Conversely, the development of these unique force patterns in LHA may have beneficial applications to movements in the medial and lateral directions. Therefore, an aim of the current study was to investigate the influence of arch height on peak force production during the landing and propulsion phases of jumping/hopping tasks in the medial/lateral, anterior/posterior and vertical directions.

Peak Ground Reaction Force Between Arch Heights

The results of the present study only revealed greater peak ground reaction forces, particularly in the LAH group, in the mediolateral direction, during the propulsion phase (Table 11). These results are supported by a previous study that observed an increase in medial loading in the LAH, when compared to NAH during running (Nachbauer & Nigg 1992). Additionally, literature has demonstrated that the bony arrangement of the LAH predisposes the foot to a medial shift of the center of pressure. This center of pressure not only identifies how the ground if acting on the foot, but how the foot is acting on the ground. Therefore, the medial shift of the center of pressure supposes that the LAH foot produce forces through a location closer to the medial border of the foot than the NAH foot (De cock et al 2008; Fuller 1999). Thus, the increased peak ground reaction force observed during the propulsion phase may be a result of the anatomical positioning of LAH.

The lack of differences observed during the landing phase and in the anteriorposterior and vertical directions in the propulsion phase fail to support previous findings in literature (Table 10). Studies have indicated that interaction and production of peak ground reaction forces in specified directions assist with propelling the body forward and slowing the body down (Stearne et al 2016; Hsaio et al 2015, Nilsson & Thorstensson 1989; Alexander et al 1987; Hicks 1954). Therefore, it would be expected that the NAH would produce greater forces in the anterioposterior direction during the landing and propulsion phases, as literature has suggested it more advantageous toward generating forces in this direction, and that LAH would present the similar findings in the mediolateral direction (Bolgla & Malone 2004; Hessert et al 2004; Elftman & Manter 1935; Elftman 1934). It is possible that the lack of significant findings is the result of participants creating greater peak vertical ground reaction forces, which allowed a greater achievement of height while diminishing directionally specific ground reaction forces (Ortega et al 2010).

The lack of significant differences in vertical ground reaction forces in the current study supports previous literature, which also found no differences in vertical ground reaction forces between NAH and LAH (Shojaedin & Akbari 2013; Table 10). In addition, previous studies have demonstrated that collegiate athletes and more experienced movers can exert greater peak vertical ground reaction forces, when compared to recreational athletes (Saunders et al 2014; Lipsker 2013; Chang et al 2012; Seegmiller & McCaw 2003; Decker et al 2003; McClay et al 1994). The generation of higher vertical ground reaction forces, in conjunction with the minimal differences of less than 2% of normalized vertical ground reaction forces produced by NAH and LAH, can diminish differences amongst the arch heights (Shojaedin & Akbari 2013).

Peak Ground Reaction Force in the Jumping/Hopping Tasks during the Landing Phase

Findings of the current study revealed that the lateral jumping tasks produced greater mediolateral ground reaction forces when compared to the stationary and forward hopping tasks, regardless of arch height (Table 10). While these findings were expected, Meylan and colleagues (2010) presented no differences in mediolateral peak ground reaction forces between forward and lateral jumping tasks similar to the present project. Conflicting the Meylan finding, previous work examining the kinetics of triple jumping and lateral jumping tasks indicated that the lateral jump displayed twice as much ground reaction force in the mediolateral direction (Perttunen et al 2000; Ramey & Williams 1985). An explanation that may address the differences between findings in literature and the present study stems from the overall objective of the tasks. Meylan and colleagues (2010) required the participants to complete only three, independent, lateral jumps while landing on both feet. The current study required the participants to perform a series of unilateral jumps in a rhythmic sequence while landing on the non-dominant leg at the completion of the task. Further research is required before specific conclusions can be made, however, the finding of larger mediolateral forces during lateral jumping tasks, regardless of arch type, are aligned with mechanical principles. During lateral motion, the ground must provide a medial force to stop the foot from moving laterally, while in the forward motion hops, the ground must exert a force in the posterior direction to stop the foot from moving forward so that the body can pass over the foot.

The findings also revealed that stationary hopping tasks displayed decreases in peak ground reaction force in the anteroposterior direction when compared to the lateral jumping and forward hopping tasks, without regards to arch height (Table 10). This result is supported by principles in mechanics. Because there should be little translation of the body, there is no need for the ground to produce a force to stop translation of the body, through the foot. Furthermore, the results are supported by findings in literature that suggest that the demand of the stationary hopping tasks typically only require ground reaction forces in the vertical direction to propel the body upward (Nilsson & Thorstensson 1989; Ker et al 1987). The rhythmic sequence associated with the execution of the stationary hopping and the minimal translation of the body diminish the production of anteroposterior ground reaction forces. Research has further suggested that jumping tasks similar to stationary hopping produce smaller vertical ground reaction forces when compared to jumping tasks in the forward and lateral directions (Perttunen et al 2000; McNair & Prapavessis 1999; Aura & Viitasalo 1989; Ramey & Williams 1985). Therefore, it can be concluded that the nature of the stationary hopping task did not require large forces in the anteroposterior direction during landing.

Results of the current project found that the forward hopping task produced greater peak vertical ground reaction forces, without regards to arch height (Table 10). Although stationary hopping was expected to produce greatest amount of vertical ground reaction forces, as seen in the study conducted by Meylan and colleagues (2010), previous studies noted similar findings of the present study (Perttunen et al 2000; Ramey & Williams 1985). Literature suggests that ballistic tasks in the forward direction requires the production of larger vertical ground reaction forces to achieve the greater height, commonly observed in bounding (Perttunen et al 2000;

Vitasalo 1989; Ramey & Williams 1985). Thus, achieving a greater height would equate to a fall from a higher height, requiring a larger force to slow and eventually stop the downward velocity.

Peak Ground Reaction Force in the Jumping/Hopping Tasks during the Propulsion Phase

The results of the present study revealed that lateral jumping tasks displayed larger peak ground reaction forces in the mediolateral direction when compared to the stationary and forward hopping tasks, without regards to arch height (Table 10). Literature has suggested that the generation of forces in a specific direction can influence the outcome of a jump (Meylan et al 2010). Furthermore, several studies have found that there is an increase in mediolateral ground reaction forces during lateral jumping tasks, when compared to vertical and forward hopping tasks, during the propulsion phase (Hewit et al 2012; Meylan et al 2010; Ramey & Williams 1985). It is reasonable to conclude that the difference noted in the lateral jumping task is associated with the nature of the task and the everted posture of the foot, presented during the landing phase, which has been found to provide an advantage for propulsion in the lateral direction (Donovan & Feger 2017; Ridder et al 2015; Meylan et al 2010; Earl et al 2007; Delahunt et al 2007; Delahunt et al 2000; Bolgla & Malone 2004; Hessert et al 2004).

The findings of the present study also revealed that forward hopping generated greater peak anteroposterior ground reaction forces when compared to the lateral jumping and stationary hopping tasks, without regards to arch height (Table 10). Based upon this finding, it is suggested that larger posterior force was need to propel the person in the forward direction, as previously mentioned in literature (Bolgla & Malone 2004). This concept has also been supported by previous research that demonstrated greater anteroposterior ground reaction force during the propulsion phase of a forward hopping task when compared to vertical and lateral jumping tasks (Hewit et al 2012; McClay et al 1999; Mero & Komi 1994; Aura & Viitasalo 1989).

Furthermore, the current project revealed that the forces in the vertical direction differed amongst all the jumping/hopping tasks (Table 10). Specifically, the forward hopping task generated greater peak vertical ground reaction forces in comparison to the stationary hopping and lateral jumping tasks. The findings also suggested that the stationary hopping tasks produced greater peak vertical ground reaction forces when compared to the lateral jumping task. It is reasonable to conclude that the difference in the vertical ground reaction forces reflect the objective of the jumping/hopping tasks. While the lateral jumping and stationary hopping tasks required a more rhythmic sequence of motions, the forward hopping tasks required an increase in maximum vertical force to increase flight time (Perttunen et al 2000; Viitasalo 1989; Ramey & Williams 1985). It is also possible that the increase in vertical ground reaction force in the stationary hopping, when compared to the lateral jumping tasks, can be attributed to the difference in the direction the foot utilizes for propulsion (Meylan et al 2010). However, research identifying the findings of the current study are limited and should be further examined.

Summary of Peak Ground Reaction Forces

The results of the present study revealed a difference in peak ground reaction force production across arch height only in the mediolateral direction. More specifically, the LAH produced greater peak mediolateral ground reaction forces when compared to the NAH. This finding was expected because, (1) of the nature of the task and (2) the everted foot posture, associated with the LAH, influenced the ability to generate propulsion force off the medial aspect of the foot and in the medial direction (Meylan et al 2010; Bolgla & Malone 2004; Hessert et al 2004; Nachbauer & Nigg 1992). Further, no differences in the vertical direction were anticipated as literature has indicated that vertical ground reaction forces differ minimally amongst arch types during locomotive tasks (Saunders et al 2014; Shojaedin & Akbari 2013).

However, the lack of a significant finding in the anteroposterior direction between arch heights was not anticipated. Literature has suggested that NAH utilizes the lateral portion of the foot, to make the foot a more rigid lever and therefore generate the anteroposterior ground reaction forces to move in the forward direction more efficiently (Bolgla & Malone 2004; Hessert et al 2004). The lack of differences presented during the landing phase was also not anticipated due to the different foot postures associated with the two arch types. While more data is needed to fully understand these findings, it is reasonable to suggest that the ballistic nature of the task is so demanding that it requires specific landing and propulsion strategies regardless of foot posture.

While an aim of the present study was to examine the influence of arch height on peak ground reaction forces during jumping/hopping tasks, the analysis within the jumping/hopping tasks provided findings that can enhance the literature. The findings of this study revealed that jumping/hopping tasks generate greater ground reaction forces that are directionally specific to the overall objective of the motion in accordance with previous findings (Stearne et al 2016; Hsaio et al 2015; Nilsson & Thorstensson 1989; Ker et al 1987; Hicks 1954). Further data is required to definitively determine the influence of arch height on ground reaction forces during landing and propulsion.

	Landing			**Propulsion**		
Peak GRF:	*Mediolateral*	*Anteroposterior*	*Vertical*	*Mediolateral*	*Anteroposterior*	*Vertical*
Tasks						
Forward Hopping	<	>	>	<	>	>
Lateral Jumping	>	>	<	>	<	<
Stationary Hopping	<	<	<	<	<	<
Classification	=	=	=	>	=	=
Normal Arch Height	=	=	=	<	=	=
Low Arch Height						

Note. Greater than and less than signs indicate significance. Equal signs indicate non-significance.

Table 22. Summary of Peak Ground Reaction Force Findings during Landing and Propulsion Phases of the Jumping/Hopping Tasks.

Influence of Arch Height on Resultant Ground Reaction Force Angle

Ground reaction force resultant angles are a variable used to determine ways of reducing braking and increasing propulsive components of an object (Hunter 2005). This has served as a valuable tool in locomotive research providing the ability to enhance the acceleration quantities of an individual in a specific direction (Hewit et al 2012; Mann & Sprague 1983, Wood 1987). While literature has identified some of the skeletal and muscular modifications needed to achieve the adequate propulsion, the influence of architectural changes of vital propulsive structures in the body are commonly unconsidered. Therefore, an aim in the present study was to examine the influence of arch height on resultant ground reaction force angles in jumping/hopping tasks.

Resultant Ground Reaction Force Angle Between Arch Heights

The findings of the present study revealed no differences in frontal or sagittal plane resultant ground reaction force angles between arch heights (Table 14). To the author's knowledge this study presents novel findings to the literature regarding the influence of arch height on resultant ground reaction force angles during jumping/hopping tasks. However, this variable has been applied to other locomotion tasks. Specifically, literature has demonstrated that higher ground reaction forces, particularly in the vertical direction, minimize forward propulsion due to the large contribution of the vertical force provided to the resultant vectors (Morin et al 2011; Kugler & Janshen 2010; Hunter et al 2005; Roberts & Scales 2002). Therefore, the results of the present study, while investigating more ballistic motions, resulted in the same findings, thus expanding the application and understanding of direction of force development. Furthermore, the use of this variable, particularly in ballistic motions that require large vertical forces, appears to be inappropriate.

Resultant Ground Reaction Force Angles in the Jumping/Hopping Tasks during the Landing Phase

Findings of the present study revealed the stationary hopping task, yielded the least vertical resultant ground reaction force angle in the sagittal plane (Table 13). More specifically, this finding indicates that during landing phase of the stationary hopping task, the ground reaction forces acting in the sagittal plane (anteroposterior and vertical ground reaction force vector) form a resultant angle that deviates from the vertical direction. As presented in literature, the resultant angle developed be attributed by the positioning of the center of mass, rather than the overall objective of the jumping/hopping tasks (Hof et al 2005; Caulfield & Garrett 2004). Therefore, the center of mass would have to be adjusted to counteract the tendency of the body to move forward.

The findings in this study also, revealed that the lateral jump motion produced the least vertical resultant ground reaction force angle, in the frontal plane (anteroposterior and vertical ground reaction force vector; Table 13). This findings indicates that during landing of the lateral jumping task, the ground reaction forces acting in the frontal plane form a resultant angle that deviates from the vertical direction. As presented in literature, higher ground reaction forces, particularly in the vertical direction, produce directional changes to minimize movement of objects (Morin et al 2011; Kugler & Janshen 2010; Hunter et al 2005; Roberts & Scales 2002). Therefore, the findings support this idea and suggest that the lateral jumping condition will require a larger force in order to stop the foot from moving in the lateral direction.

Resultant Ground Reaction Force Angles in the Jumping/Hopping Tasks during the Propulsion Phase

Findings in the present study revealed that the forward hop task provided the least vertical resultant ground reaction force angle when compared to the lateral jumping and stationary hopping tasks (Table 13). The findings also revealed that the lateral jumping task produced a larger angle when compared to the station hopping task. Previous research has suggested that the outcomes of jumping tasks are influenced by the mechanics applied to the movement (Hunter 2006). Further research suggests that the vertical component of jumping tasks can be used as a component to enhance stability or propulsion (Hof et al 2005; Caulfield & Garrett 2004). Literature suggests that rapid motions can produce a flatter resultant ground reaction force angle or produce changes within the object to slow the object down for directional changes (Kugler & Janshen 2010; Seyfarth et al 2002). Therefore, the application of a vertical force assists with providing some stability, to the center of mass as it is projected of out the base of support, for propulsion (Hof et al 2005; Caulfield & Garrett 2004). Thus, findings of this study may suggest that the use of the vertical ground reaction force may adapt a directional specific method as a benefit to the objective of the task.

Further findings of this study revealed that lateral jumping task generated the least vertical resultant force angle, when compared to the forward and stationary hopping tasks (Table 13). From the notion that jumping tasks develop beneficial adaptations for jumping tasks, the contribution of the positioning of the foot may have influenced the observance differences in ground reaction forces in the vertical direction. Specifically, the multiplanar positioning of the foot during the landing and propulsion phases may disrupt any the vertical components to the resultant ground reactions force angle (Hunter 2006). Therefore, suggests that directional specific adaptations of the foot during the lateral jumping task may act as a benefit to the object of the task.

Summary of Resultant Ground Reaction Force Angles

The results of the present study revealed that the vast differences in the ground reaction force magnitudes minimized observable differences in the resultant angles in the sagittal and frontal planes. While the hypothesis regarding arch heights was not observed, there were unexpected differences in the jumping/hopping tasks. Specifically, the lateral jumping tasks produced greater resultant ground reaction force angle deviations from vertical in the frontal plane, during both the landing and propulsion phases. Further, the forward hopping condition yielded the greater resultant ground reaction force angle deviations from vertical in the sagittal plane, but only during the propulsion phase. These findings support previous literature that suggested that while performing rapid movements, these resultant ground reaction force angles will become less vertical to slow the body and prepare for propulsion (Kugler & Janshen 2010; Seyfarth et al 2002).

	Landing		**Propulsion**	
GRF Angle:	*Sagittal Plane*	*Frontal Plane*	*Sagittal Plane*	*Frontal Plane*
Tasks				
Forward Hopping	>	<	<	<
Lateral Jumping	>	>	>	>
Stationary Hopping	<	<	<	<
Classification	=	=	=	=
Normal Arch Height	=	=	=	=
Low Arch Height				

Note. Greater than and less than signs indicate significance. Equal signs indicate non-significance.

Table 23. Summary of Ground Reaction Force Angle Findings during Landing and Propulsion Phases of the Jumping/Hopping Tasks.

Influence of Lower Extremity Stiffness

Lower extremity stiffness is a commonly used approach that examines how the body can identify changes in stiffness as a system to utilized energy in the most mechanically efficient method (Butler et al 2003; Farley et al 1998). Typically, lower extremity stiffness is used to translate the mechanics of the system to the performance of locomotive tasks (Viale et al 1998, Blickhan 1989). Due to the dynamic ability of the foot, differences in arch height may produce alternations to the system that may interrupt the sequential processing of energy. While the analysis of arch height on running tasks were presented, the concepts surrounding these findings and the influence of more ballistic tasks on this measure, remain limited. More data is required to fully realize the implications of this variable. Furthermore, this variable should also be expanded to consider the stiffness in the forward and lateral directions as well.

Lower Extremity Stiffness Between Arch Heights

The findings of the present study indicated no differences in lower extremity stiffness between arch heights (Table 16). Previous research has indicated that those classified as having lower arches present with lower extremity stiffness, but greater muscular stiffness during landing tasks than those classified as high arched (Powell, et al. 2017). Powell and colleagues (2017) also suggested that arch height influences how the body attenuates landing forces, with those with high arches utilizing skeletal components to absorb the force and those with low arches employing more muscular components. More data is needed to full appreciate the influence of arch height on lower extremity stiffness.

Summary of Lower Extremity Stiffness

Altogether, the findings of the present study revealed no differences in lower extremity stiffness. While the Powell et al. (2017) project expands our understanding by partitioning the stiffness into bone versus muscle, and indicating that individuals with different arch heights utilize different attenuation strategies, the findings of that study only referred to running tasks. Until the present project can finish data collection on the suggested number of participants, final conclusions must be withheld.

	Lower Extremity Stiffness	
	Normal Arch Height	*Low Arch Height*
Statistical Findings	=	=

Table 24. Summary of Lower Extremity Stiffness Between Normal and Low Arch Height.

Influence of Arch Height on Surface Electromyography of the Soles and Medial Head of the Gastrocnemius

The soleus and gastrocnemius are considered to be a major factor in generating the forces to propel the body forward (Brockett & Chapman 2016; Hsaio et al 2015; Francis et al 2013). The additional role of the soleus as a major stabilizer for the lower extremity for weight bearing suggests the musculature may perform different roles during locomotive tasks (Francis et al 2013). While literature has presented the effects of different arch heights on muscle activitaion during walking and running, the influence of arch height on the average activation of the primary plantarflexors, during ballistic tasks, remain limited.

Surface Electromyography of the Soleus

The findings of analyses demonstrated no differences in average soleus EMG activity between arch heights during the landing or propulsion phases (Table 19). While this was not expected, literature surrounding these findings are limited. While the analysis of the influence arch height has on propulsion mechanics of walking was absence, research has revealed the soleus produce greater peak EMG activity during the propulsion phase to stabilize and prevent misalignment of the rearfoot (Cobb et al 2009; Houck et al 2008; Hunt et al 2004). This misalignment is commonly observed in LAH, with the laterally displace calcaneus (Buldt et al 2015; 2013; Powell et al 2011; Wilken et al 2011; Cobb et al 2009; Houck et al 2008; Hunt et al 2004). With the additional contribution of early onset of fatigue in musculature of the lower extremity of LAH, due to the bony misalignments, it would be expected to see differences in peak and averages EMG activity of the soleus (Mulligan and Cook 2013; Kelly et al 2014, 2012; Tosovic et al 2012; Del Rossi et al 2004). An explanation of these findings is that the total number of participants, surrounding the population of this study, and overall objectives surrounding the ballistic jumping/hopping tasks may have diminished any notable changes. Thus, additional research should be conducted to examine difference upon increasing the number of participants.

The results also demonstrated that the lateral jumping task produced lower average soleus activity during the landing phase when compared to the forward and stationary hopping tasks. Further the results suggest that the lateral jumping task produced an increase in average soleus EMG activity compared to the stationary hopping but, demonstrated no differences with the forward hopping task (Table 18). The findings of this research are similar to what has been observed in walking. Literature has suggested that the soleus assisted with reducing the forward motion of the lower limb to permit adequate weight bearing during walking tasks (Francis et al 2013; Hunt et al 2004). However, since the tasks of the present project are so very different from walking, more data is needed to determine what role the soleus is contributing to this motion. Joint moments in conjunction with kinematic parameters will allow for identification of muscle action.

During the propulsive phase, the soleus produced significantly larger average EMG activity in the lateral jumping condition than during the stationary hopping condition, but not the forward hopping condition (Table 18). These findings suggest that the soleus plays a different role in lateral propulsion, then in landing from a lateral jump. Due to the limited range of motion associated with the lateral jumping tasks, it is reasonable to suggest that the soleus does not utilize the SSC during the contact phase with the force platform. While the goal of the lateral jumping was to move back and forth in a rhythmic sequence and jump as far as possible, the individual must utilize the triceps surae to propel laterally. Therefore, a potential explanation for the diminished average soleus activity during the propulsive phase of lateral jumping, could be attributed to the SSC. If the soleus can be found to not be utilizing the SSC, then the increased average EMG activity of the soleus may be necessary to compensate for the lack of the contribution of the passive structures. However, this is supposition at this point. Further research should be conducted to develop more definitive conclusions of the presented findings.

Surface Electromyography of the Medial Gastrocnemius

The findings of analyses demonstrated no differences in average medial gastrocnemius EMG activity betwen arch heights during the landing or propulsion phases (Table 19). These findings were supported by Murley and colleagues (2009) that revealed no differences in peak medial gastrocnemius EMG activity during walking and running tasks. Conversely, literature revealed differences of both increased and increased peak activation of the medial gastrocnemius in NAH, during landing and propulsive phase respectively, when compared to LAH in walking tasks (Khodaveisi et al 2016; Chang et al 2012). It was further concluded that the increase observed during the landing phase acted as a compensatory mechanisms to adjust for the everted positioning of the foot (Wang & Gutierrez-Farewik 2001). While the analysis displayed no differences between arch height, despite the findings of previous literature, the overall objective of the more ballistic jumping/hopping tasks may have minimized any notable changes. Thus, additional research should be conducted to examine difference upon increasing the number of participants.

The findings revealed that average EMG activity of the medial gastrocnemius was difference across jumping/hopping tasks, during landing (Table 18). Specifically, differences were observed between the lateral jumping and stationary hopping conditions, with the medial gastrocnemius registering less average activity during the lateral jumping condition. It should also be noted that the largest medial gastrocnemius activity was registered during the forward hopping condition, but due to the large standard deviation, it failed to reach significance. It was hypothesized that the medial gastrocnemius would be active during landing to resist dorsiflexion. This resistance of dorsiflexion allows the body to absorb the landing forces over a longer period of time, and stretches the plantarflexors in preparation for the next hop/jump (Lardin et al 2015; Li et al 2002). This stretching of the plantarflexors is the first step of the stretch shortening cycle (SSC) and would be appropriate for the hopping tasks that occur in the sagittal plane (Bolgla & Malone 2004). However, landing during the lateral jumping condition, would require the evertors to resist motion in the frontal plane. Therefore, it is reasonable to suggest that the limited activity of the plantarflexors during the landing of the lateral jumping task, suggests that the performers are utilizing a different muscle or mechanism to slow the foot/body in the lateral direction, than in the forward, or vertical tasks. However, without the joint moments and kinematics of the ankle and knee joint, diminished activity of the medial gastrocnemius is not a fully concluded finding.

The average EMG activity of the medial gastrocnemius was greatest during the propulsion phase of the lateral jumping task, and significantly different from the activity recorded during the forward hopping task. Interestingly, Benjamin and colleagues (2007) suggested that the medial gastrocnemius and soleus blend differently in the Achilles tendon. Specifically, the medial gastrocnemius blends laterally and the soleus blends medially. In conjunction with the findings in the frontal plane, decreased EMG activity of the medial gastrocnemius may be attributed to the positioning of the foot that would place the muscle's line of pull at a disadvantage that would require an a change in the triceps surea EMG activity. The consistent everted position of the foot during the lateral jumping tasks may also induce an anatomical "lock" of the subtalar and talocrual joints and limit the range of motion in the foot-ankle complex (Caravaggi et al. 2009; Bolgla & Malone 2004). More data is needed before specific assumptions are concluded, however the results of the present study do indicate that the soleus and medial gastrocnemius produce different average emg activity magnitudes across different jumping/hopping tasks. Future research will synchronize the EMG activity with the joint kinematics and joint moments to develop a precise explanation of the differing roles of the soleus and medial gastrocnemius during these tasks, and between the two arch types.

Summary

The influence of arch height on locomotive tasks is a popular topic in the field of biomechanics. Many findings affiliated with this topic have identified structural alterations of the MLA that produce excessive motions which can induce an early incidence of chronic maladaptive locomotive movement patterns and pathologies (Ezema et al 2014; Twomey et al 2012; Levine et al 2012;Wilken et al 2011; Perry & Burnfield 2010; Twomey et al 2010; Bosch et al 2009). Recently, anecdotal accounts within the podiatric and athletic communities suggest that such movement patterns, in conjunction with the structural alterations of specific arch heights, provides a beneficial component during ballistic locomotive tasks. Therefore, this present study examined the influence of arch height on mechanics of jumping/hopping tasks.

The findings of this study revealed possible modifications in locomotive mechanics between arch heights. Particularly, this project noted that LAH foot types exhibit an increase eversion. Previous literature has supported this finding by indicating that this eversion posture is due to the collapsed medial longitudinal arch and height of the navicular (Jankowicz-Szymanska et al 2015; Jimenez-Ormeno et al 2013; Wozniacka et al 2013; Villarroya et al 2009; Mauch et al 2008; Mickle et al 2005; Dowling et al 2001, Riddiford-Harland et al 2000). The influence of this everted foot posture has been investigated during locomotive tasks such as running and walking, which have identified increased resting calcaneal and rearfoot eversion during the propulsion and landing phases (Buldt et al 2015, 2013; Powell et al 2011; Wilken et al 2011; Cobb et al 2009; Houck et al 2008; Hunt et al 2004). As a result, it is reasonable to conclude that LAH foot types would produce maximal eversion however, the results from the present study demonstrated a greater observance of maximal eversion in NAH foot types when compared to LAH. While this conclusion finds support within the previous literature, the increase in eversion seems to suggest that the inclusion of a more sensitive arch type measure may be needed. Specifically, considerations should be given to a measure of arch height stiffness as the foot alters considerably under loading and extreme dynamic tasks.

Additionally, the different arch height groups demonstrated differences in force patterns during the jumping/hopping tasks. Specifically, The LAH demonstrated increased medial force during the propulsion phase of the lateral jump, when compared to NAH. This finding suggests that arch height differences can induce directional differences in force production during locomotive tasks. Furthermore, these changes in kinetic patterns may be the cause of or the result of kinematic differences noted across arch types. Further research is needed to determine if the altered kinematic, kinetic and EMG variables are the result of the altered foot posture associated with LAH.

Despite the minimal findings, this study enhanced the previous literature by identifying differences in kinematic, kinetic and EMG variables across arch heights during ballistic, locomotive tasks. While individuals with different arch heights provide different kinematics, kinetics and EMG during locomotive tasks, the patterns generated by a specific arch height may produce traits that are advantageous for specific directional movement patterns. Thus, additional research should be conducted to strengthen the conclusions of the present study and assist with identifying advantageous foot postures for specific movements.

In conclusion, by investigating ballistic motions that mimic portions of acceleration in the forward and lateral directions, the present project has produced results that highlight the complexities of the human body. For example, suggesting that the muscles that cross the ankle may have altered roles during motions that require dramatic plantarflexion. Specifically, that the muscles most responsible for center of mass acceleration are not those that cross the ankle. These results also suggest that the musculature that does cross the ankle may play a larger role in foot posture than in actual force generation.

	Landing		**Propulsion**	
Muscle Activity:	*Soleus*	*Gastrocnemius*	*Soleus*	*Gastrocnemius*
Tasks				
Forward Hopping	>	>	=	>
Lateral Jumping	<	<	>	<
Stationary Hopping	>	=	<	=
Classification	=	=	=	=
Normal Arch Height	=	=	=	=
Low Arch Height				

Note. Greater than and less than signs indicate significance. Equal signs indicate non-significance.

Table 25. Summary of EMG Activity of the Soleus and Gastrocnemius during Landing and Propulsion Phases of the Jumping/Hopping Tasks.

Limitations and Future Research

The present study incurred several limitations that may have affected the findings and outcomes. The largest limitation of the present project was the failure to secure the power analysis recommended number of participants. As this study produced novel findings associated with the examination of arch height on different jumping/hopping tasks, further investigations should be conducted to meet the appropriate power and effects sizes. Additionally, only one gender was considered during this project, male. Future investigation should be conducted to analyze the influence of arch height on jumping/hopping tasks across both genders, as differences in center of mass location may have dramatic influences on the outcome measures. Further, to the author's knowledge this was the first study to examine differences amongst jumping /hopping tasks, with the additional factor of arch height. As a result, many findings presented in this study had to be compared to trends and significant results of other locomotive tasks, such walking, running and landing from a jump. Of particular note were the variables that are beyond the reach of the author at this time, that have the capability of enhancing the findings of the project. For example, at present, no method is available to calculate stiffness during lateral motion (non-gravitational direction). This tool would enhance our understanding of the anisotropic nature of the body. Considered the gold standard for identifying arch type, the present project used an external device to assess arch height. Future research should work to secure radiographic evidence of arch type and consider developing unique anthropometric models of the participants that identifies the typical segmental postures and joint angles, as well as the current methodology of comparing results to purely anatomical neutral. Last, joint angle kinematics should be investigated in light of each joint active range of motion. By presenting the findings as a percentage of total, active range of motion, it is believed that the flexibility between participants will not hamper the applicability of the findings.

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Appendix A

Participant Health Screening Questionnaire

Please read the following questions and provide an honest answer. If you do not understand the question, please ask the investigator for further explanation. Check the appropriate answer.

Participant Number: _________

	YES	**NO**
1. Are you younger than the age of 19 or older than the age of 28?	____	____
2. Have you obtained any lower extremities injuries within the last six months?	____	____
3. Do you have any allergies to adhesives?	____	____
4. Have you had any surgical procedures to the foot and/or ankle?	____	____
5. Do you currently have any injuries that would prevent you from performing a minimum of 12 forward hopping, 9 lateral hopping, and 27 times on your dominant limb at a self-selected pace?	____	____
6. Do you have any illnesses any injuries that would prevent you from performing a minimum of 12 forward hopping, 9 lateral hopping, and 27 times on your dominant limb at a self-selected pace?	____	____
7. Do you have any reason to believe that your health or well-being will be at risk while participating in this study?	____	____

Signature of participant:________________________________ Date:___________

Participants that answer “Yes” to any of the questions above will be omitted from this study.

Appendix B

****DO NOT AGREE TO PARTICIPATE UNLESS AN IRB APPROVAL STAMP HAS BEEN APPLIED TO THIS DOCUMENT****

INFORMED CONSENT
For a Research Study entitled
"Influence of Arch Height on Propulsive and Landing Mechanics During Jumping and Hopping Tasks"

You have been invited to participate in a research study examining the influence of arch height on the propulsive and landing mechanics of jumping and hopping tasks. The study is being conducted by Christopher Wilburn, under the supervision of Dr. Wendi Weimar in the Auburn University School of Kinesiology. Your participation in this study could assist with grasping a greater understanding of how specific arch heights generate different propulsive and landing mechanisms in athletic movements. You have been selected as a potential participant because you are male collegiate athlete, between the ages of 19 and 28, without any injuries to the lower extremity within the last six months, without any surgical procedures to the foot and ankle, and without allergies to adhesives.

What will be involved if you participate? If you agree to participate in this research study, you will be invited to come to the Sports Biomechanics Laboratory for approximately 75 minutes to perform several hopping tasks. Prior to completing these dynamic tasks, you will be given a health screening questionnaire to affirm your ability to physically complete the tasks. Anthropometric measures of your height, weight, arch height and limb lengths will be obtained. Additional foot anthropometric measurements will be taken to classify your arch type and foot position.

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Participant Initials

Data collection and familiarization of the research study will be performed in one 75 minute meeting. The protocol involves performing three trials of each of the three different jumping and hopping tasks, on your dominant leg, at a self-selected pace. The forward hopping tasks will consist of five consecutive hops forward on the dominant leg. The lateral hopping tasks will consist of jumping in the following rhythmic sequence: from the dominant leg to the non-dominant leg, to the dominant leg and back to the non-dominant leg (ice skating motion). The stationary hopping tasks will consist of nine continuous hops, in one spot, on the dominant leg.

After being familiarized with each dynamic task, careful skin preparation (shaving, abrasion, and cleaning with alcohol) will be performed for electrode placement over the muscle belly of the calf (gastrocnemius and soleus) and buttocks (gluteus medius). Electromyography will show the timing and magnitude of muscle activity during the three different jumping tasks. Next, you will perform maximal voluntary contractions of the calf (gastrocnemius and soleus) and buttocks (gluteus medius), where the muscle activity will be recorded. The muscle activity produced during each trial will be used to normalize the muscle activity of your hopping tasks. Prior to the maximal voluntary contractions, you will be allowed to warm up and stretch. Then, experimentation will begin. Three trials of each condition will be performed. After completing all conditions successfully, you will be thanked for your participation.

Are there any risks or discomforts? While participating in this study it is possible that you might incur muscle soreness, a joint sprain or a muscle strain. However, injuries are unlikely due to care taken to warm-up and that you are performing a task that is part of your usual activities. In the event you sustain an injury during participation; there is no current plan to cover the medical cost associated with the injury related to this study.

If you change your mind about participating, you can withdraw at any time during the study. Any data that may have been collected that can be associated with you, will be destroyed immediately and withdrawn from the study. Your decision about whether or not to participate or to stop participating will not jeopardize your relations, both present and future, with the Sport Biomechanics Laboratory, School of Kinesiology, Auburn University Athletic Department, or Auburn University.

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Participant Initials

Confidentiality. Any information obtained in connection with this study that can be identified with you will remain confidential. The information obtained from this project will be used for presentations at scientific conferences and published in scientific journals.

If you have any questions, please ask them now or please feel free to contact Christopher Wilburn (czw0043@auburn.edu), or Dr. Wendi Weimar at (weimawh@auburn.edu).

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by e-mail at IRBadmin@auburn.edu or IRBChair@auburn.edu or phone at (334)- 844 -5966.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's Printed Name	Participant's Signature	Date
Investigator Conducting Consent Printed Name	Investigator's Signature	Date

Appendix C

Coefficent of Variation *((SD/M)* 100)* *Measure:*	*Time 1*	*Time 2*	*Time 3*
Arch Height Index	7.512 %	7.095 %	7.453
Calcaneal Angle	8.332 %	9.365 %	7.375 %
Soleus	1.685 %	1.696%	1.616%
Medial Gastrocnemius	3.230 %	3.190%	3.148 %

Summary of Coefficent of Variation of the ICC