Effects of Arch Height and Stiffness on Knee and Ankle Stiffness During Landing

Rachael Allison Arnwine

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EFFECTS OF ARCH HEIGHT AND STIFFNESS ON KNEE AND ANKLE STIFFNESS
DURING LANDING
by
Rachael A. Arnwine

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Abstract

Landing is associated with high external forces applied to the skeleton over a short time. A measure reflecting the musculoskeletal system’s acute response is stiffness. Greater lower extremity joint stiffness may predispose individuals to traumatic lower extremity injury. If arch height index (AHI) and stiffness (ASI) are associated with the acute leg-and-joint stiffness response to loading, they may also reflect injury susceptibility during landing. 

Purpose: To evaluate the association between AHI, ASI, and leg and joint stiffness. 

Methods: 55 recreational athletes performed 5 step-off landings from 40 centimeters. AHI and ASI were measured. Three-dimensional kinematics and GRF were collected. Ankle and knee joint angles and moments were calculated. Custom software was used to calculate ankle, knee, and leg stiffness. Correlation analysis was used to determine the association between measures of foot structure and stiffness variables. Independent t-tests were used to compare independent variables in high- and low-arched recreational athletes. 

Results: AHI (p = 0.001) and ASI (p = 0.014) between HA and LA individuals, and a weak but significant association was observed between AHI and leg stiffness (r = 0.272, p = 0.022). AHI was greater in HA individuals, while ASI was greater in LA individuals. Furthermore, ASI was marginally associated with leg stiffness (r = -0.024, p = 0.433). 

Conclusion: Since AHI accounts for only 7% of the variability in ankle, knee, and leg joint stiffness during landing, much remains to be determined.
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<td>Arch Height Index</td>
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<tr>
<td>AHIMS</td>
<td>Arch Height Index Measurement System</td>
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<tr>
<td>ASI</td>
<td>Arch Stiffness Index</td>
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<tr>
<td>DH</td>
<td>Dorsum Height</td>
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<td>HA</td>
<td>High-arch</td>
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<td>FL</td>
<td>Foot Length</td>
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<td>GRF</td>
<td>Ground Reaction Force</td>
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CHAPTER I:

Introduction
Jumping is commonly performed during many sports and physical activities such as volleyball, basketball and soccer. However, the subsequent landing rather than the take-off places the greatest amount of stress on the musculoskeletal system (5, 16,17). Landing is associated with external forces applied to the skeleton over a short period of time. These loading characteristics may contribute to musculoskeletal injuries such as tendinitis, ligament rupture and/or bone injury (10, 25). A measure that captures both load magnitude and the musculoskeletal system’s response to loading is stiffness (4). There are many types of stiffness, including joint stiffness, vertical stiffness, and leg stiffness. Joint (torsional) stiffness is described as the active resistance to change in joint angular displacement with consideration of joint moments (4). Vertical stiffness can be conceptualized as the sum of resistance of the human body to vertical displacement or prevention of limb collapse in response to vertical ground reaction forces (4). Leg stiffness is characterized as the resistance to change in leg length as the result of internal or external forces (4). It is suggested that as greater external forces are applied to the body, greater resistance is required to perform controlled movements (3). Greater leg stiffness values are associated with greater load magnitudes and smaller compliance in response to load (27). Greater joint stiffness is inversely related to leg and vertical stiffness and indicate the production of greater joint moments and smaller joint excursions (26). Arch stiffness and foot structure are important to consider when assessing the function of the foot (8, 20, 22, 31).

Lower extremity stiffness is considered an important factor in musculoskeletal performance. Increased stiffness is associated with increased velocity, jump height, and running economy (metabolic) and efficiency (mechanical) (4). Though necessary for performance, too little or too much stiffness is suggested to increase the risk of musculoskeletal injury (4).
Foot structure has been identified as an anatomical factor associated with altered loading patterns in the lower extremity. The foot is a complex structure composed of 26 bones, 33 ligaments and over 100 joints (23). Further, the foot is the point of contact with the ground and the beginning of the kinetic chain for external loads applied to the skeleton during athletic movements. As the foot contacts with the ground, force propagates through the lower extremity in an ascending pattern (ankle, knee then hip joints). Several methods of assessing foot structure and function exist including arch index (Cavanaugh 1987), arch height index (29), arch stiffness (31), relative arch deformity (29), and first ray angle (21, 29, 31). Foot structure has been suggested to play a prominent role in lower limb biomechanics and may contribute to the incidence of musculoskeletal injury (10, 17, 18, 25, 27, 28, 29). Abnormal foot structure is associated with an increased risk of injury in athletes (10, 26). Arch height index (AHI) has been used to categorize foot structure and is calculated as a ratio of the height of the dorsum to the truncated foot length (29). Individuals with high AHI values (high-arched feet) are more prone to lateral foot and lower extremity injuries, bony injuries, and injuries to the foot and ankle (10, 26). Individuals with low AHI values (low-arched feet) are more likely to sustain medial foot and lower extremity injury, soft tissue injuries, and injury to the knee joint (26).

An association between AHI and leg stiffness has been reported (18, 19), with high-arched individuals having greater leg stiffness when compared to low-arched individuals during landing and running tasks (18, 19, 27). High-arched individuals often have significantly higher knee stiffness during running, when compared to low-arched individuals (27).

Arch height and arch stiffness appear to be related (3), although females tend to have less arch stiffness than males (31). It has been postulated that arch height index and arch stiffness may be associated with lower extremity joint stiffness as well. High-arched individuals have
significantly higher knee stiffness during running, when compared to low-arched individuals (19, 27). If the association between arch height index and arch stiffness with lower limb joint stiffness can be assessed, a deeper understanding of the mechanics of landing may emerge. It is important to understand these associations as both stiffness and foot structure are linked with injury mechanisms and patterns. This leads to the research question: do arch height index and arch stiffness have a strong association with ankle, knee, and leg stiffness during a landing task? The primary purpose of this study was to investigate differences in ankle stiffness, knee joint stiffness, leg stiffness, and arch stiffness between individuals with low and high AHI during a step-off landing task. The secondary purpose of this study was to assess the association between AHI and lower extremity stiffness measures.

**The aims of this study are to:**

**Aim 1:** To compare ankle and knee joint stiffness, and leg stiffness in individuals with high and low AHI values during a landing task.

**Hypothesis 1:** We hypothesized that individuals with high AHI values will have smaller ankle and knee joint stiffness values and higher leg stiffness values than individuals with low AHI values.

**Aim 2:** To evaluate the association between AHI and ASI on ankle and knee joint stiffness as well as leg stiffness during a landing task.
**Hypothesis 2a:** We hypothesized that AHI would have a moderate-to-strong association with ankle and knee joint stiffness, and the ASI would have a weak positive association with ankle and knee joint stiffness during a landing task.

**Hypothesis 2b:** We hypothesized that AHI would have a moderate-to-strong positive association with leg stiffness, and that ASI would have a weak positive association with leg stiffness during a landing task.

**Literature Review**

The purpose of this literature review is to summarize and discuss current literature of arch height index and arch stiffness. In addition, this literature review summarizes current literature of joint and leg stiffness as well as landing biomechanics.

**Kinetic Chain**

A kinetic chain involves a coordinated sequence of joint musculoskeletal segment actions. The term “chain” suggests that when one joint or segment is in motion, it will cause transfer of kinetics to adjacent joints or segments. The foot is the point of the kinetic chain that interacts with the ground. The foot must have a balance of rigidity and flexibility, as it must be able to support forces much larger than body weight yet also allow for distribution of forces during tasks. When the foot touches the ground, forces are transmitted through the foot to the lower extremity. The kinetic chain suggests that the load at the foot and ankle passes through the lower limb to more proximal joints and segments, if the foot or ankle stiffens (14). If this is the
case, the more proximal joints of the lower extremities could become more at risk for injury, due to increased load.

Foot Structure

With the foot being the point of interaction with the ground in the kinetic chain, it is important to understand the structure of the foot. The human foot is quite complex, containing 28 bones and 33 joints (24). Though the foot is often modeled as a rigid segment that articulates with the lower leg, the foot can be divided into segments such as hindfoot, midfoot, and forefoot, as it does not act as a rigid segment. Previously, it was believed that foot structure is determined by arch height, but the foot is not only characterized by arch height (high, normal, low), but also by function and flexibility (26). It is understood that foot structure and type may affect lower extremity biomechanics and gait and the possible development of musculoskeletal pathology (20). It has been suggested that abnormal foot structure (i.e. high or low-arch) is a modifier of lower extremity biomechanics, possibly associated with higher risk for lower extremity injuries (14, 16, 17). While foot structure is considered to be one of the most important factors, foot flexibility and function are also contributing factors to assessing foot type and risk for pathology (22). Understanding foot structure as one of the possible contributors to lower extremity musculoskeletal injury could lead to possible intervention to prevent or treat said injuries.

Arch Height Index

Arch Height Index is one way to quantify foot and arch structure. AHI can be measured using several different tools or technologies that give us insight to a person’s foot structure (30). For example, AHI can be found via Arch Height Index Measurement System, footprint analysis,
carbon footprint paper, and photographs taken with a mirrored glass box (16, 29). These measures have been compared to radiography, in order to compare reliability and validity (29). Arch Height Index can be found by assessment of dorsum height, by measuring foot length and truncated foot length. The dorsum height specifically is used in order to increase reliability in a loaded and unloaded condition (13). The Arch Height Index Measurement System is used to take these measurements, allowing the foot to be classified into an arch height category: high, normal, and low. Arch Height categories are determined as follows: high: AHI > 0.377, normal: AHI between 0.290-0.377, low: AHI < 0.290 (13). Standardized foot-type classifications allow for subdivisions that may expand our understanding of different foot characteristics or treatment effects among high-arched, normal, and low-arched foot types in research and clinical practice (30).

Studies have used Arch-Height Index as a tool to investigate the association between foot structure and injury patterns, and kinematic and kinetic differences in athletes (13). For example, low-arch foot structure has shown to be linked to the development of osteoarthritis (OA) in the 1st metatarsophalangeal joint (20). Kaufman, et al found that people with high and low-arched feet are almost twice as likely to sustain a stress fracture (10).

Arch height has been found to affect joint moments, leg stiffness, and load attenuation, specifically during landing (19). Powell et al found that high-arched individuals produce significantly smaller total lower extremity work than low-arched athletes (18). The same study also found that high-arched athletes show greater vertical stiffness than low-arched athletes, as well as greater joint stiffness (18). High-arched individuals are considered more ankle driven, while low-arched individuals are knee and hip driven, specifically during landing (18).
**Figure 1:** *Williams et al (29):* Anatomical landmarks used to find measurements of the foot.

FL = foot length, TFL = truncated foot length, DORS = dorsum height, NAV = navicular height.

**Figure 2:** *Zifchock et al (31):* The Arch Height Index Measurement System (AHIMS) Platforms are placed behind the heel and in front of the metatarsal heads of each foot. The posterior heel should be flush with the heel cup (A), the short sliding bar is positioned against the first metatarsal joint (B), the sliding toe bar rests gently against the longest toe (C), and the drop bar rests against the dorsal surface at half the total foot length (D).
**Arch Stiffness**

The arch of the foot has a unique alignment which allows for functional adaptability (31). The arch is an important factor to consider when examining foot structure, as it plays a major role during push-off and early and mid-stance (31). Previous literature has shown that arch structure can vary widely and that different foot types may predispose individuals to certain injuries. Some of the injury patterns may be related to the flexibility of the arch, as different foot structures (i.e. high or low-arch) exhibit differences in flexibility of the foot (31).

Research has shown that there are differences in arch stiffness between males and females, with females exhibiting less arch stiffness than males (31). In addition, studies have often shown a significant association between arch height and arch stiffness. Although this association has been suggested, there are likely other factors to consider. It is important to understand the role of arch stiffness and its association to arch height, as these factors could contribute to musculoskeletal injury.

**Stiffness**

Stiffness is defined as the extent to which an object resists deformation in response to an applied external force. True stiffness is a measure of a material’s response to loading. Stiffness in the musculoskeletal system considers a combination of stiffness values, including muscle, tendon, ligament, cartilage, and bone, with musculotendinous stiffness being considered a modifiable characteristic (3). **Joint or torsional stiffness** is defined as the resistance to change in angular displacement for flexion and rotation after implementation of joint moments (4). It is calculated as the change in joint moment divided by the change in joint angle. **Vertical stiffness** is defined as the sum of resistance of the human body to vertical displacement after utilization of
ground reaction forces (4). One way which vertical stiffness is calculated as the maximum vertical force divided by maximum vertical displacement of the center of mass. **Leg stiffness** is defined as the resistance to change in leg length after utilization of internal or external forces (4). It is calculated as maximum vertical force divided by change in vertical leg length.

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**Formulas for calculating stiffness**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td><strong>VERTICAL STIFFNESS</strong> ( k_{vert} ) ( k_{vert} = \frac{F_{\max}}{\Delta y} )</td>
<td>McMahon and Cheng (1990)</td>
</tr>
<tr>
<td>where ( F_{\max} ) = maximum vertical force; ( \Delta y ) = maximum vertical displacement of the center of mass ( k_{vert} = \frac{m(2\pi/P)^2}{\omega_0^2} )</td>
<td>Cavagna et al. (1988)</td>
</tr>
<tr>
<td>where ( m ) = mass of the body; ( P ) = period of the vertical vibration ( k_{vert} = \frac{m\omega_0^2}{\Delta L} )</td>
<td>McMahon et al. (1987)</td>
</tr>
<tr>
<td>where ( m ) = mass of the body; ( \omega_0 ) = natural frequency of oscillation</td>
<td></td>
</tr>
<tr>
<td><strong>LEG STIFFNESS</strong> ( k_{leg} ) ( k_{leg} = \frac{F_{\max}}{\Delta L} )</td>
<td>McMahon and Cheng (1990)</td>
</tr>
<tr>
<td>where ( F_{\max} ) = maximum vertical force; ( \Delta L ) = change in vertical leg length ( (\Delta L = \Delta y + L_0(1 - \cos \theta) + \sin^{-1}(ut/L_0)); \Delta y = maximum ) displacement of the center of mass; ( L_0 = standing \ leg \ length ) (greater trochanter to floor); ( \theta = half \ angle \ of \ the \ arc \ swept \ by \ the \ leg; ) ( u = horizontal \ velocity; \ t = contact \ time )</td>
<td></td>
</tr>
<tr>
<td><strong>TORSIONAL STIFFNESS</strong> ( k_{joint} ) ( k_{joint} = \frac{\Delta M}{\Delta \theta} )</td>
<td>Farley et al. (1998)</td>
</tr>
<tr>
<td>where ( \Delta M ) = change in joint moment; ( \Delta \theta ) = change in joint angle ( k_{joint} = \frac{2W}{\Delta \theta} )</td>
<td>Arampatzis et al. (1999)</td>
</tr>
<tr>
<td>where ( W ) = negative mechanical work at the joint; ( \Delta \theta ) = change in joint angle</td>
<td></td>
</tr>
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**Figure 3:** Butler et al (4): Formulas for calculating stiffness.

Stiffness is often found by investigating the lower extremity as an ideal spring, moving only in one direction, and having stiffness that is not affected by time, length, or velocity (4). However, it has been suggested that the model should account for all contributors to stiffness, including muscles, tendons, ligaments, and bones (4). The complication of having one model
which assesses all of these variables is evidence for why there are multiple models in which stiffness can be calculated.

**Figure 4: Butler et al** (4): Ideal spring and mass used for calculating vertical stiffness when the leg is oriented vertically.

Vertical stiffness is a measure used when linear movements occur in the vertical direction (i.e. jumping), where there are multiple methods to calculate it (4). Although the three methods to measure vertical stiffness (see Figure 3) are used when the movement occurs in the vertical direction, another method has been developed in order to calculate stiffness when the leg contacts the ground at an angle, therefore the center of mass is not directly over the foot. The method has been termed leg stiffness, which accounts for horizontal velocity, time of contact, peak vertical ground reaction force, and resting leg length, specifically during movements such as running (4). Joint (or torsional) stiffness is used when examining contributions of each joint in lower extremity stiffness, taking into account rotation (4). Though the method of analyzing
stiffness is dependent upon the questions being asked, vertical stiffness is suggested to be used when examining jumping and hopping, while leg stiffness is suggested to be used when analyzing walking and running (4). When focusing on roles of the ankle, knee, or hip joints, torsional (joint) stiffness is suggested (4).

Figure 5: Butler et al (4): Leg stiffness model used for calculating leg stiffness when the leg makes contact with the surface in a non-vertical position.

The more stiffness an object has, the more difficult it is to deform. It is suggested that arch height and arch stiffness can affect each other. For example, there appears to be a somewhat linear association between arch height and arch stiffness. High-arched athletes exhibit greater vertical stiffness during landing (18) and high-arched athletes have also been found to have greater leg and joint stiffness during a running task compared to low-arched athletes (27). In addition, stiffness may be altered by fatigue (15), and that women tend to have less arch stiffness than men (31). There is not a complete understanding on how stiffness affects the lower
extremities, though it is understood that stiffness can be altered and could be dependent upon training and movement in focus.

*Landing Biomechanics*

Landing is a common movement in physical activity and sport. There are many ways to land from a jump, including double-leg and single-leg landings. With landing comes high rates and magnitudes of musculoskeletal loading, which have been suggested to be associated with many different types of musculoskeletal injuries (18). When an athlete lands, a ground reaction force is created and passes through the kinetic chain. High ground reaction forces associated with landing have been suggested to possibly negatively affect the musculoskeletal system, contributing to injury (17). It is understood that stiffness plays a role in these ground reaction forces during landing.

Differences in landing patterns do exist as each person is different, such as females demonstrate more errors in characteristics of specific components of landing technique than males (25). In addition, females have a greater prevalence of lower extremity injury than males in landing and cutting tasks (5). With the passing of ground reaction forces through the lower extremity during a landing task exhibiting a proximal to distal progression, it has been suggested that mal-alignment of the foot may result in irregular loading patterns to proximal structures (18). Previous literature has revealed that there is a strong association between foot structure and injury during landing (26). For example, over-pronation of the foot is positively correlated with traumatic knee injury, where low-arched feet are associated with greater pronation than high-arched feet (26). This suggests that foot type may contribute to lower extremity injury during a landing task. It is also understood that landing technique becomes poorer after exercise and
fatigue (25). With differences existing in landing patterns and in foot structure, the association between foot structure and landing is important to assess when looking at injury due to landing.

Stiffness is understood to have an effect on loading and injury risk during landing (4). Studies have also shown that though it may be slight, lower stiffness can create larger forces and moments (4). With this being said, it could be postulated that increasing stiffness at the foot, for example, could progress up the kinetic chain by increasing stiffness in the knee, hip, shank, thigh, etc. It is questioned whether stiffness and arch height of the foot can lead to stiffness in the lower extremity joints during a landing task. If this association exists, it could be a possible contributor to lower extremity injury during landing.

Foot Structure, Stiffness, and Injury

As foot structure varies greatly it is understood that different foot types exhibit different injury patterns (26). It is suggested that abnormal foot structure, such as high or low-arch, could be a factor which increases one’s risk for injury, when compared to a normal arch (26). In addition, landing tasks are associated with high musculoskeletal loads and loading rates, which are understood to influence several types of musculoskeletal injuries (18). Williams et al found that high-arch is associated with more lateral injuries, while low-arch is associated with medial injuries (26). High-arched individuals experiencing more lateral foot injuries than low-arched may be due to the lateral center of pressure in the high-arched foot contributing to lateral loading (26). Medial loading in low-arched individuals may be a contributing factor to higher incidence of medial foot injuries in low-arched individuals than in high-arched individuals (26). Williams et al also found that high-arched individuals display more bony injuries, while low-arched individuals display more soft tissue injuries (26). Ankle and foot injuries are associated with
high-arch, while knee injuries are associated with low-arch (26). Some of the injury patterns related to arch height may also take into account arch flexibility (31). Low-arched feet tend to be more flexible, while high-arched feet tend to be stiffer (31). It has been suggested that low-arches may stretch the soft tissues of the foot, while high-arches may create a less mobile foot, both which can predispose the foot to injury (31).

Stiffness is believed to play a role in lower extremity injury, as it affects the strategy used by the lower limb to attenuate forces (3, 18). It has been postulated that if stiffness increases (decreasing compliance), there may be an increase in the magnitude of forces transmitted to more proximal structures in the kinetic chain (27). In addition, studies have shown that the association between arch height and skeletal contributions to leg stiffness and load attenuation during landing may underlie differences in injury patterns in individuals during different movement tasks (26, 27).

It has also been postulated that there is an optimal amount or ideal range of stiffness needed for performance, but as to not cause injury (4). Too much stiffness is understood to contribute to the reduction in lower limb excursions and increased peak forces, which could lead to increased loading rates, therefore likelihood of bony injury (4). In addition, too little stiffness is thought to put one at risk for soft tissue injury, as it may permit excessive joint motion in the sagittal plane (17, 24). Butler et al suggested in a study comparing injured and uninjured individuals, that the uninjured individuals had reduced peak vertical ground reaction forces, implying that they may have less lower extremity stiffness than those who had been injured, as a result of the injury.

It has been suggested that there may be an association between arch height and stiffness. High-arched individuals have greater leg and knee stiffness when compared to low-arched,
during landing and running tasks (19). High-arched athletes also display more skeletal contribution to leg stiffness during running and landing which could underlie the greater prevalence of bony injury in high-arched individuals (19). In contrast, low-arched athletes perform running and landing tasks with greater muscular contributions to leg stiffness which may contribute to the greater incidence of soft tissue injury in low-arched individuals (19). With consideration of these findings, it is important to understand what may be contributing to these injuries in order to conduct further research, design rehabilitation interventions, and possibly minimize risks of injuries.
CHAPTER II:

Manuscript
Introduction

Jumping is commonly performed during many sports and physical activities; however, the subsequent landing rather than the take-off places the greatest amount of stress on the musculoskeletal system (5, 17, 18). A measure that captures both load magnitude and the musculoskeletal system’s response to loading is stiffness (4). There are many types of stiffness, including joint stiffness, vertical stiffness, and leg stiffness. Joint (torsional) stiffness is described as the active resistance to change in joint angular displacement with consideration of joint moments (4). Leg stiffness is characterized as the resistance to change in leg length as the result of internal and external forces (4). Lower extremity stiffness is considered an important factor in musculoskeletal performance, as increased stiffness is associated with increased velocity, jump height, and running economy (metabolic) and efficiency (mechanical) (4). Though necessary for performance, too little or too much stiffness is suggested to increase the risk of musculoskeletal injury (4).

Foot structure has been identified as an anatomical factor associated with altered loading patterns in the lower extremity, which is important to consider when assessing the function of the foot (8, 21, 22, 31), and the incidence of lower limb musculoskeletal injury (10, 17, 18, 26, 27, 28, 29). Arch height index (AHI) has been used to categorize foot structure (29). Individuals with high AHI values (high-arched feet) are more prone to lateral foot and lower extremity injuries, bony injuries, and injuries to the foot and ankle (10, 26). Individuals with low AHI values (low-arched feet) are more likely to sustain medial foot and lower extremity injury, soft tissue injuries, and injury to the knee joint (26).

An association between AHI and leg stiffness has been reported (18, 19), with high-arched individuals having greater leg stiffness when compared to low-arched individuals during
landing and running tasks (18, 19, 27). High-arched individuals often have significantly higher knee stiffness during running, when compared to low-arched individuals (27).

Arch height and arch stiffness appear to be related (3), and it has been postulated that arch height index and arch stiffness may be associated with lower extremity joint stiffness as well. If the association between arch height index and arch stiffness with lower limb joint stiffness can be assessed, a deeper understanding of the mechanics of jump landing may emerge. It is important to understand these associations as both stiffness and foot structure are linked with injury mechanisms and patterns. This leads to the research question: do arch height index and arch stiffness have a strong association with ankle, knee, and leg stiffness during a landing task? The primary purpose of this study was to investigate differences in ankle stiffness, knee joint stiffness, leg stiffness, and arch stiffness between individuals with low and high AHI during a step-off landing task. The secondary purpose of this study was to assess the association between AHI and lower extremity stiffness measures. It was expected that AHI would have a moderate-to-strong association and that arch stiffness would have a weak association with ankle, knee, and leg stiffness during a landing task.

Methods

Participants

Fifty-five recreational athletes (25 Male, 30 Female), 18-35 years of age, participated in this study. Participants were screened for inclusion using the Physical Activity Readiness Questionnaire (PAR-Q) and given informed consent prior to participating in the study. All participants were uninjured at the time of testing and for the previous six months. A recreational athlete was defined as an individual that exercises at least three times per week, for a minimum
of 30 minutes per session. Anthropometric data were obtained including height, body mass, total foot length, truncated foot length, and dorsum height. These measurements were taken in seated (unloaded) and bilateral standing (loaded) positions. Arch Height Index (AHI) was calculated using foot measurements from the AHI Measurement System™ as the quotient of the dorsum height divided by the truncated foot length (29). Participants were categorized into high, normal, and low-arched based on arch height index. The high-arched individuals were the 10 subjects with the highest AHI, the 10 subjects with the lowest arch were considered low-arched, and the remaining subjects were considered normal-arched. Arch stiffness was calculated as 0.4 multiplied by the subject mass, divided by AHI seated minus AHI standing (31).

Experimental Protocol

Participants wore activewear during data collection and standardized cushioned running shoes (1080, New Balance). Following informed consent and anthropometric measurements, participants completed a five-minute warmup on a stationary bicycle at a moderate, self-selected pace. Retroreflective markers were used to define and track the pelvis, thigh, and shank. To define the pelvis, anatomical markers were placed on the right and left anterior superior iliac spines, iliac crests, and greater trochanters. Anatomical markers were also placed bilaterally on the medial and lateral femoral epicondyles, medial and lateral malleoli, and 1st and 5th metatarsal heads to define the right and left thighs, shanks and feet. Retroreflective marker clusters were placed on the posterior pelvis, lateral thighs, lateral shanks, and heel of each foot. A static calibration trial was captured to define the centers of joint rotation and establish the association between the joint centers and tracking markers. Following the static calibration trial, anatomical markers were removed for dynamic testing.
Each participant then performed five successful step-off landing trials from a box with a height of 40 cm. The step-off landing task was characterized by the participant stepping off of a box and landing bilaterally with each foot on a force platform. A successful trial was achieved if the participant landed bilaterally and adopted a stable bilateral posture upon landing. Three-dimensional kinematics and ground reaction forces (GRFs) were collected simultaneously, using an 8-camera motion capture system (240 Hz, Qualisys Inc.®, Sweden) and two force platforms (1200 Hz, AMTI, Watertown, MA, USA), respectively. Of the 55 subjects collected, 20 were used for tests of difference. The 10 subjects with the highest AHI were described as having a high-arch and the 10 subjects with the lowest AHI were described as having a low-arch

_data analyses_

The landing task was examined between initial contact and peak knee flexion, using ground reaction forces. Initial contact was defined as the time at which the feet hit the force platform. Peak knee flexion was defined as the time which the subject reached maximum knee flexion following initial contact, prior to the participant beginning to return to erect posture. These events represent the beginning and end of load attenuation during landing. Visual 3D (C-Motion, Germantown, MD, USA) was used to process three-dimensional kinematic and kinetic data. Three-dimensional kinematic data were low-pass filtered using a 4th-order, zero-lag Butterworth filter a 10 Hz cutoff frequency, and GRF data were low-pass filtered using a 4th-order, zero-lag Butterworth filter with a 50Hz cutoff frequency. Sagittal plane ankle and knee joint angles and moments as well as 3D GRFs. A right-hand rule was used to define joint rotation polarity, and a Cardan rotational sequence was used for 3D angular computations, where x represents the mediolateral axis, y represents the anteroposterior axis, and z represents the
longitudinal axis. Ankle, knee, and hip joint angular kinetic variables were expressed in the shank, thigh, and pelvis coordinate systems. Newtonian inverse dynamics were used to compute joint moments. When calculating pelvis displacement, a single pelvis tracking marker was used. Stiffness variables were calculated using custom software (MATLAB, MathWorks Inc., Natick, MA). Ankle and knee joint stiffness were calculated as the change in joint moment divided by the change in joint angle, normalized to body mass, between initial contact and peak vertical ground reaction force as shown in **Equation 1** (6), represented as kN•m/kg:

**Equation 1**

\[
K_{Joint} = \frac{\Delta M}{\Delta \theta}
\]

where \(\Delta M\) is the change in joint moment, and \(\Delta \theta\) is the change in joint angle (6).

Leg stiffness was calculated between the events of initial contact and peak vertical ground reaction force shown in **Equation 2** (6), represented as kN•m:

**Equation 2**

\[
K_{Leg} = \frac{F_{max}}{\Delta L}
\]

Where \(F_{max}\) is maximum GRF vector magnitude, \(\Delta L\) is change in total limb length. Total limb length was calculated as the change in resultant length of the limb between initial contact and peak GRF magnitude. Subject means were calculated as the average value of the five landing trials for each variable of interest.

**Statistical Analysis**

Due to sample size, a normal distribution of current data was assumed (11). Three independent samples t-tests were used to compare mean leg stiffness, ankle and knee joint
stiffness values between high- and low-arched recreationally active individuals. Bivariate correlations were used to evaluate the association of AHI and arch stiffness (independent variables) with leg stiffness as well as ankle and knee joint stiffness values. Significance was set at $p < 0.05$.

**Results**

AHI values were greater in high compared to low-arched individuals ($p = 0.001, d = 5.38$). ASI values were lower in high compared to low-arched individuals ($p = 0.014, d = -1.22$) (Table 1). No differences were observed in ankle stiffness between high- and low-arched individuals ($p = 0.276, d = -0.78$) during the landing task. Further, no differences were observed in knee stiffness between high- and low-arched individuals ($p = 0.149, d = -0.62$). Finally, there were no differences in leg stiffness between high- and low-arched individuals ($p = 0.146, d = 0.44$) during the landing task (Table 2).

A weak, significant association was observed between AHI and leg stiffness ($r = 0.272, p = 0.022$). Negligible associations were found between AHI and ankle stiffness ($r = 0.008, p = 0.475$) and knee stiffness ($r = -0.127, p = 0.178$). Negligible associations were also observed between ASI and ankle stiffness ($r = 0.065, p = 0.323$), knee stiffness ($r = -0.063, p = 0.327$), and leg stiffness ($r = -0.024, p = 0.433$).

**Discussion**

The primary purpose of this study was to investigate differences in ankle stiffness, knee joint stiffness, leg stiffness, and arch stiffness between individuals with low and high AHI during a step-off landing task. The secondary purpose of this study was to assess the association between AHI and lower extremity stiffness measures. There were minimal associations between
AHI, ASI, and ankle and knee stiffness. In addition, there was a significant but weak association between AHI and leg stiffness.

The differences in foot structure and function are important to consider when investigating lower extremity stiffness. The significant differences in AHI and ASI between high- and low-arched individuals is consistent with previous literature (19, 27, 31), as shown with independent samples t-tests. Subjects with a high-arch had less arch stiffness, and those with a low-arch exhibited more arch stiffness. These findings contrast with previously published literature (19, 27, 31). Low-arched feet have been described as more flexible and compliant, while high-arched feet are described as more rigid and less compliant (31). The significant difference in ASI between high-arched and low-arched individuals coincided with previous literature, where a significant relationship between AHI and ASI has been reported (31). Previous literature has found that a high-arch is likely to be stiffer than a low-arch upon weight-bearing, which lends understanding to the relationship between AHI and ASI. Though this has been found, it has been reported that other factors are likely involved as only 9% of the variance in AHI has been explained by arch stiffness (31).

Individuals with abnormal foot structure have been suggested to have significant differences in ankle and knee joint stiffness. The non-significant differences found in ankle or knee stiffness between high- and low-arched individuals contrasted with previous literature (27), which has shown high-arched individuals to have significantly greater knee stiffness when compared to low-arched individuals in running. Smaller knee flexion excursions in high-arched individuals were reported one mechanism underlying greater knee stiffness values (27). Though our results contrast with previous research, the previous study investigated a running task, not a landing task (27). The difference in the dynamic tasks between the two studies could contribute
to the contrasting findings, as there are differences in landing patterns between a bilateral step-off landing and running. In addition, the subjects included in our investigation were recreationally active, exercising at least 3 times per week for 30 minutes per session. The type of activity they were involved in varied among the subject population. The differences in population, physical activity or training, and dynamic task completed could contribute to the contrasting results.

Our hypothesis that AHI would have a strong association and ASI would have a weak association with ankle and knee stiffness was rejected, as there were minimal associations between measures of foot structure (AHI and ASI) and ankle or knee joint stiffness. The hypothesis that AHI would have a strong association with leg stiffness was also rejected, although a weak but significant association was present. ASI showed a minimal association with leg stiffness, rejecting this hypothesis.

The current findings suggest that foot structure and leg stiffness may not be strongly associated with one another. Though the hypothesis of a moderate-to-strong association between AHI and leg stiffness was rejected, a weak but significant association was present. Previous research has found an association between leg stiffness and AHI, with high-arched individuals having greater leg stiffness during running and landing tasks (19, 27). Though this was consistent with our findings and this study used a similar landing protocol, the population included only female athletes involved in university club sports, which was different than our recreationally active population. A second study has shown high-arched individuals to have significantly greater leg stiffness when compared to low-arched individuals (27). High-arched individuals in this study exhibited smaller center of mass displacements when compared to the low-arched individuals, which is suggested to underlie greater leg stiffness in the high-arched individuals.
Though our results were consistent with the results in this study, the subjects were completing a running task, while our subjects completed a landing task.

Limitations to this investigation are important to consider. The population of the investigation included recreationally active individuals, therefore not a highly-trained or elite population. With the consideration of the definition of “recreationally active” comes the wide variety of physical activity or training in which the subjects take part in. With this variability of physical activity, the comparison of these individuals may not be as reliable as a comparison of individuals with similar or the same exercise or training schedule. The standardized footwear worn by the subjects could also be a limitation to this investigation. With the subjects having different AHI but wearing the same shoe, it is possible that some natural movement of the foot was masked by wearing the standardized shoe. Another limitation includes the possibility of inaccuracies in the measurements of AHI and ASI. In addition, AHI and ASI were measured in a static nature whereas different results are possible if measured when completing a functional movement, which could be measured using a different arch assessment method.

The findings from the current study suggest that foot structure and function may be contributing, not driving, factors when investigating ankle, knee, and leg stiffness during landing. The minimal association found between AHI and ankle or knee joint stiffness, and the weak but significant association between AHI and leg stiffness during a step-off landing contrasted with the hypothesis. In addition, the minimal association between ASI and ankle, knee, or leg stiffness during a step-off landing also contrasted the hypothesis. These findings suggest that there may be more factors to consider when investigating lower extremity stiffness during landing. With the consideration of the findings in this study contrasting with much of
previous literature, future research is necessary to further understand the contributions to joint and leg stiffness during landing.

References


7. Harry, J. R., James, C. R., & Dufek, J. S. (2019). Weighted vest effects on impact forces and


Table 1: Anthropometric measurements of HA and LA recreationally active participants used in comparison analysis, including height, mass, arch height index, and arch stiffness index.

<table>
<thead>
<tr>
<th></th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>AHI</th>
<th>ASI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall (N=55)</strong></td>
<td>169.4 ± 13.2</td>
<td>69.9 ± 12.7</td>
<td>0.354 ± 0.034</td>
<td>1629.8 ± 2226.6</td>
</tr>
<tr>
<td>HA (N=10)</td>
<td>164.7 ± 2.59</td>
<td>57.8 ± 3.3</td>
<td>0.402 ± 0.025</td>
<td>960.8 ± 318.8</td>
</tr>
<tr>
<td>LA (N=10)</td>
<td>168.8 ± 5.24</td>
<td>66.5 ± 12.1</td>
<td>0.297 ± 0.012</td>
<td>2227.2 ± 1435.5</td>
</tr>
<tr>
<td>(p)-value</td>
<td></td>
<td></td>
<td>&lt; 0.001</td>
<td>0.014</td>
</tr>
<tr>
<td>Cohen’s (d)</td>
<td></td>
<td></td>
<td>5.38</td>
<td>-1.22</td>
</tr>
</tbody>
</table>
Table 2: Comparison of ankle, knee, and leg stiffness between HA and LA recreationally active participants.

<table>
<thead>
<tr>
<th></th>
<th>kAnkle (kN•m/kg)</th>
<th>kKnee (kN•m/kg)</th>
<th>kLeg (kN•m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>0.16 ± 0.01</td>
<td>0.48 ± 0.20</td>
<td>11635.8 ± 14395.7</td>
</tr>
<tr>
<td>LA</td>
<td>0.14 ± 0.04</td>
<td>0.62 ± 0.23</td>
<td>6970.9 ± 4103.5</td>
</tr>
<tr>
<td>p-value</td>
<td>0.276</td>
<td>0.149</td>
<td>0.146</td>
</tr>
<tr>
<td>Cohen’s d</td>
<td>-0.78</td>
<td>-0.62</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Figure 6: Scatter plot of association between AHI and ankle stiffness.

\[ y = 0.0173x - 0.1585 \]

\[ R^2 = 7\times10^{-5} \]
Figure 7: Scatter plot of association between ASI and ankle stiffness.
Figure 8: Scatter plot of association between AHI and knee stiffness.

$y = -0.9246x + 0.9605$

$R^2 = 0.016$
Figure 9: Scatter plot of association between ASI and knee stiffness.

\[ y = -7 \times 10^{-6}x + 0.643 \]

\[ R^2 = 0.004 \]
Figure 10: Scatter plot of association between AHI and leg stiffness.
Figure 11: Scatter plot of association between ASI and leg stiffness.
Recruitment Flyer

Recreational Athletes Needed for a Research Study!

You may be able to participate if you:
- Are 18 - 35 years
- Are currently not injured
- Participate in organized recreational athletics:
  - At least 3 times per week
  - At least 30 minutes per session

School of Health Studies is studying common interventions to change biomechanics during sport movements

2 sessions of 60-90 minutes at UM Fieldhouse (By the track)

The University of Memphis is committed to education of a non-discriminatory student body.
Consent to Participate in a Research Study

Foot Structure and Clinical Interventions Alter
Lower Extremity Biomechanics during Dynamic Movements

WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study in which we are examining the relationship between foot structure and lower body performance during a number of movement tasks when wearing different clinical interventions including different shoe types, an ankle brace and an insole. Movement tasks will include walking, running, jumping and landing. This invitation is being extended to you because you have indicated to the investigator on the Training Activity form that you have been physically training more than three times per week for at least 30 minutes per session at a moderate or vigorous intensity, and that you are both familiar with and confident in safely performing walking, running, jumping and landing tasks. If you volunteer to take part in this study, you will be one of about 82 people to do so at the University of Memphis.

WHO IS DOING THE STUDY?

The person directly in charge of this study is Douglas Powell, PhD of the School of Health Studies at The University of Memphis. There may be other people on the research team assisting at different times during the study.

WHAT IS THE PURPOSE OF THIS STUDY?

The overall purpose of this study is to identify the effect of foot structure and clinical interventions on lower extremity movement characteristics. The outcome may better inform medical professionals regarding the use of these interventions in specific populations based on foot structure. Also, these findings may help strength and conditioning professionals and athletic trainers prevent injury by determining the effects of these clinical interventions on movement patterns.

ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

Prior to inclusion in the study, you will complete the Physical Activity Readiness Questionnaire (PAR-Q). If you report any condition that would predispose you to injury you will be excluded from participating in the study, unless medical clearance is first obtained. Lastly, if you are under 18 or over 35 years of age, you will be ineligible to participate.

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research procedures will be conducted at the University of Memphis in the Musculoskeletal Analysis Laboratory located in FH171 of the Elma Neal Roane Fieldhouse. Once preliminary paperwork and screening have been completed, you will be asked to come to the Musculoskeletal Analysis Laboratory two times for testing purposes. Each of those visits will take approximately 60 to 90 minutes. The total amount of time you will be asked to volunteer for this study is approximately 2 to 3 hours over a 14-day period.

WHAT WILL YOU BE ASKED TO DO?

A total of two testing sessions lasting up to 90 minutes each are required. Testing during both sessions will occur in the following order: (1) measurement of anthropometric variables, (2) warm-up exercises, (3) placement of measurement sensors, and (4) completion of dynamic testing including two of the following dynamic movements during each session: walking, running, jumping and landing tasks. You will need to dress in a manner that will enable us to identify various anatomic landmarks so that measurements can be taken and so that you may perform the dynamic tasks. You will be given the opportunity to familiarize yourself with the specific movement tasks. The second testing session will take place within a two-week period following the first data collection session. You will be asked to refrain from additional strenuous exercise for 48 hours prior to testing sessions.

Initials: ______________________

IRB #: ______________________

Expiration Date: ______________________

Page 1 of 3
WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

Since you already perform training and competition activities and have experience in the experimental tasks, the tasks you will be doing will not expose you to increased risk of injury. In fact, since fatigue will be minimized, the testing is likely to be less risky than some of your typical training and competition activities. However, any exercise that includes dynamic tasks presents some risk of injury during the acceleration and deceleration phases as well as in the unlikely scenario in which a person falls down. The tests in this study may cause delayed muscular soreness (usually 24-48 hrs. post-exercise), muscle strains or tears, and/or joint injury. These risks are similar to your risk as an adult routinely involved in physical activities. Risks will be minimized by thorough instruction and supervised practice following appropriate guidelines as described by the American College of Sports Medicine (ACSM) and the National Strength and Conditioning Association (NSCA). If any abnormal signs or symptoms appear during participation, the exercise will be terminated and you will receive immediate attention.

WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

There is no guarantee that you will get any benefit from taking part in this study. However, some people have experienced improvements in their sport performance when participating in similar research. Your willingness to take part, however, may help society gain a better understanding of this research topic.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering. If you are a student at The University of Memphis, whether or not you decide to take part in this study, your choice will have no adverse effect on your academic status or grade in any class in which you are enrolled.

IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, you do not have to participate. There are no other choices.

WHAT WILL IT COST YOU TO PARTICIPATE?

There are no costs associated with taking part in the study.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will make every effort to keep private all research records that identify you to the extent allowed by law. However, there are some circumstances in which we may have to share your information with other people. We may be required to provide the Physical Activity Readiness Questionnaire (PAR-Q) to medical professionals in the case of a serious injury occurring during the study. Also, we may be required to show information which identifies you to people with research oversight authority from The University of Memphis who need to be sure we have done the research appropriately.

Your study-related information will be combined with information from other people taking part in the investigation. When we share the study design and findings with others in written and/or oral form, we will only report the combined information we have gathered and you will not be personally identified. We will make concerted attempts to publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. All paper records and portable storage devices will be secured in a locked file cabinet that is accessible only to the investigators of the study.

Initials: __________________________

IRB #: __________________________
Expiration Date: __________________________

Page 2 of 3
CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study, you still have the right to decide at any time that you no longer want to continue or have us include your data in any statistical analysis. You will not be treated differently if you decide to stop taking part in the study.

The individuals conducting the study may need to withdraw you from it. This may occur if you are not able to follow the directions they give you or if they find that your being in the study is more risk than benefit to you.

ARE YOU PARTICIPATING OR CAN YOU PARTICIPATE IN ANOTHER RESEARCH STUDY AT THE SAME TIME AS PARTICIPATING IN THIS ONE?

You may take part in this study if you are currently involved in another research study that does not require strenuous physical activity. It is important to let the investigator/your doctor know if you are in another research study. You should also discuss with the investigator before you agree to participate in another research study while you are enrolled in this study.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that may be due to the study, you should contact Douglas Powell, PhD at dwpowell@memphis.edu or (901) 678-5209 immediately. In the case of a life-threatening emergency, you should call 911.

It is important for you to understand that the University of Memphis does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Memphis will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research-related harm cannot be included as regular medical costs. Therefore, the medical costs related to your care and treatment because of research-related harm will be your responsibility. A co-payment/deductible from you may be required by your insurer or Medicare/Medicaid even if your insurer or Medicare/Medicaid has agreed to pay the costs. The amount of this co-payment/deductible may be substantial. You do not give up your legal rights by signing this form.

WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Douglas Powell, PhD, at dwpowell@memphis.edu. If you have any questions about your rights as a volunteer in this research, contact the Institutional Review Board staff at the University of Memphis at (901) 678-2705.

We will give you a signed copy of this consent form to take with you.

WHAT IF NEW INFORMATION IS LEARNED DURING THE STUDY THAT MIGHT AFFECT YOUR DECISION TO PARTICIPATE?

If the researcher learns of new information concerning this study that might change your willingness to continue as a participant, the information will be provided to you. You may be asked to sign a new informed consent form if the information is provided to you after you have joined the study.

__________________________
Signature of person agreeing to take part in the study

__________________________
Name of [authorized] person obtaining informed consent

__________________________
Printed name of person agreeing to take part in the study

__________________________
Date

__________________________
Date

Initials:

IRB #: 
Expiration Date: 

Page 3 of 3
IRB Approval

From: irb@memphis.edu <irb@memphis.edu>
Sent: Friday, March 31, 2017 11:35 AM
To: Douglas Winston Powell (dwpowell) <dwpowell@memphis.edu>
Subject: PRO-FY2017-188 - Initial: Approval - Expedited

Institutional Review Board
Office of Sponsored Programs
University of Memphis
315 Admin Bldg
Memphis, TN 38152-3370

Mar 31, 2017

PI Name: Douglas Powell
Co-Investigators: Maxime Paquette, Ross Smith, Lindsey Allison
Advisor and/or Co-PI:
Submission Type: Initial
Title: Influence of foot structure and clinical interventions on lower extremity biomechanics during dynamic movements
IRB ID: #PRO-FY2017-188

Expedited Approval: Mar 31, 2017
Expiration: Mar 31, 2018

Approval of this project is given with the following obligations:

1. This IRB approval has an expiration date, an approved renewal must be in effect to continue the project prior to that date. If approval is not obtained, the human consent form(s) and recruiting material(s) are no longer valid and any research activities involving human subjects must stop.

2. When the project is finished or terminated, a completion form must be submitted.

3. No change may be made in the approved protocol without prior board approval.

Thank you,
James P. Whelan, Ph.D.
Institutional Review Board Chair
The University of Memphis.