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The effect of arch height on variances in gait phases: A kinematic analysis

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THE EFFECT OF ARCH HEIGHT ON VARIANCES IN GAIT PHASES: A KINEMATIC ANALYSIS

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Abstract

Millions of individuals suffer from pain or injury as a result of structural abnormalities of the medial longitudinal arch of the foot and/or improper footwear. A majority of the research on abnormalities of the medial longitudinal arch is focused on how the arch alters foot kinematics during gait but does not ask how abnormalities may contribute to deviations in knee kinematics as well. The purpose of this study was to determine the effect of foot arch types on deviations in healthy biomechanical gait in addition to the implications of orthotics in order to ultimately aid in the decrease of arch-attributed pain. Nine college-age students at the University of Northern Iowa underwent foot arch screening procedures and completed a walking trial on video. The video was kinematically analyzed to determine relationships between arch height and variances in gait variables. The data showed that individuals with abnormal arches (high or low-arch groups) had altered ankle and knee joint angles at both heel strike and toe off, had diminished stance phase duration, had altered ankle and knee joint angular velocities during stance phase, and lengthened stride velocities and frequencies. This study revealed that in addition to altered foot kinematics during gait, knee joint kinematics are also altered during gait. Understanding variations in ankle and knee joint kinematics due to abnormalities of the medial longitudinal arch will help health care professionals better diagnose and treat patients.

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CHAPTER I: INTRODUCTION

Statement of Problem

Structural abnormalities of the medial longitudinal arch of the foot have commonly thought to be a predisposing factor to pain and injury. These abnormalities can contribute to pain and/or injury in the foot, ankle, knee, hip, and low back. However, there is a gap in the research on the connection between an individual's arch type and biomechanical deviances in gait. The way in which an individual walks could potentially be a result of the structure of the medial longitudinal arch of the foot. As an individual likely takes thousands of steps in a day, the structural abnormalities of the arch may impact quite specifically the way in which the individual walks. The purpose of this study was to determine the effect of foot arch types on deviations in healthy biomechanical gait in addition to the implications of orthotics in order to ultimately aid in the decrease of arch-attributed pain.

Research Questions

1. What is the effect of arch type (normal/planus/cavus foot) on ankle and knee angle at both heel strike and toe off?
2. What is the effect of arch type (normal/planus/cavus foot) on duration of stance phase and angular velocity of the ankle and knee during this phase?
3. What is the effect of arch type (normal/planus/cavus foot) on stride length, velocity, and frequency?

Significance

Millions of individuals suffer from pain or injury as a result of structural abnormalities of the medial longitudinal arch of the foot and/or improper footwear. A majority of the research on abnormalities of the medial longitudinal arch is focused on how the arch alters foot kinematics during gait, but does not ask how abnormalities may contribute to deviations in knee kinematics as well. When an individual is walking, all moving parts of the body must be taken into account, rather than just the foot. Abnormal arch heights are thought to be contributing factors to conditions other than foot pain, including conditions such as patellofemoral pain syndrome (knee pain) and low back pain. It is important to examine the connections between varying arch height on variances in gait phases at the ankle, knee, and hip joints. Understanding how variations in the way an individual walks due to arch abnormalities will help health care professionals better diagnose and treat patients.

CHAPTER II: REVIEW OF RELATED LITERATURE

Arch Height

The shape and constitution of the bones and other anatomical structures keep the medial longitudinal arch of the foot in its form. Ligaments of this arch include the spring, deltoid, interosseous, long plantar, and short plantar ligaments, and the plantar aponeurosis. Muscles include the tibialis anterior, tibialis posterior, flexor hallucis longus, and flexor digitorum longus. The combination of these structures working in accordance with the bones of the foot ensure that an individual can adequately support the weight of the body in erect posture. Additionally, having a healthy arch helps distribute pressure across the feet and keep the body aligned, stable, and balanced (Neely, 1998). Williams and McClay (2000) conducted a study that found around 60% of the adult U.S. population has a normal arch, 20% has a high arch, and 20% has a low arch. With just under half of the population experiencing abnormal arches, it is important to understand how abnormalities of the medial longitudinal arch can lead to pain and injury with exercise.

Abnormalities of the lower limbs and specifically of the feet can lead to injury when undertaking exercise, as the lower half of the body bears most of the body’s weight. Neely (1998) suggested that several lower-limb abnormalities have shown to increase risk for injury, including limited ankle dorsiflexion, limited hip eversion, excessive joint laxity, discrepancy of leg lengths, excessively supinated or pronated foot, and excessively high or low arches of the foot. Furthermore, Neely explains high arch feet are inflexible, while flat feet tend to be hypermobile and vulnerable to a high degree of pronation. If an individual with flat arches experiences pronation during the toe off phase of gait, stability is lost and the foot experiences trauma; in a closed kinetic chain like the lower body, this results in force transmission to the knees and hips. The same applies at heel strike, when the foot should be supinated. If the foot is in pronation, it is unable to adequately absorb ground reaction forces and must rely on ligaments and muscles for stabilization. Further research needs to be conducted to fully describe these methods, but this mechanism demonstrates arch height may be a risk factor for exercise-related injury.

With the knowledge that abnormal arches may be a contributor to exercise-related injury, it is of importance to be able to measure and classify what an abnormal arch type is. The same study by Williams and McClay (2000) investigated multiple methods of estimating the height of the medial longitudinal arch. They found the most reliable method of estimating height of the medial longitudinal arch was to have participants in a 10% weight bearing stance and to divide navicular height by foot length. The most reliable and valid method, though, was determined using the dorsum height at 50% foot length divided by truncated foot length. This formula produces a value called the arch height index, which will be used to screen participants in this research project. Furthermore, a study conducted by McCrory, Young, Boulton, and Cavanagh (1997) confirms arch height index provides a quantitative means of describing height of the medial longitudinal arch. This study confirmed so by comparing measured navicular height with navicular height measured from weight bearing radiographs. The correlation coefficient between arch height index and normalized navicular height was found to be $r=0.71$.

Although manual measurements of the medial longitudinal arch have shown to be reliable and valid, technology in recent years has been developed to assess arch height as well. Telfer and Woodburn (2010) conducted a meta-analysis of technologies that involve 3D surface scanning for use of footwear development, custom orthotic design, and other ergonomic implications. PubMed and ScienceDirect databases were used and 38 articles that met the search criteria were included. The latest technologies to produce 3D representations of the foot can be split into two categories: scanners and digitizers. Scanning is a process where images are converted to a digital form using video equipment and digitizing involves the 3D shape having its features traced and stored as codes on a computer. The utility of scanners for both clinical and research purposes has been shown, especially for anthropometric measurements. They allow large numbers of subjects to be scanned quickly and easily. Furthermore, the measurements, in general, are quite comparable to those taken manually and the study showed there were no significant differences between the automatically generated measurements and those taken manually.

The Foot Levelers 3D Body View scanner (Foot Levelers, 3D Body View, Roanoke, Virginia) is one specific piece of technology that assesses arch height and will be used in this research project. This particular scanner identifies asymmetries in the feet with arch height mapping and illustrates how the feet impact the entire lower body kinetic gain. The kiosk is composed of a platform with a scanner and is user-friendly; it has the patient follow three basic steps to obtain necessary measurements, and it completes foot assessments in under 60 seconds. The scanner then generates an image of the arches and provides a score ranging from 0 (optimal) to 125+ (severe). Then, the scanner can even suggest an appropriate Foot Levelers Orthotic (Scanner Technology). Technology such as this makes it quite simple and painless for the general population to self-assess their individual arch-type and seek intervention as needed.

Healthy Biomechanical Gait Patterns

A typical gait cycle can be classified in several different ways. Fundamentally, gait contains the stance phase and the swing phase. The stance phase is the phase in which one foot (the right foot, for example) is in contact with the ground, and the swing phase is the phase in which the root foot is not in contact with the ground. The stance phase makes up approximately 60% of one gait cycle (the right gait cycle in this example) and the swing phase makes up approximately 40% of the cycle. The stance and swing phases can be further broken down into more specific stages. The first stage of of stance phase is initial contact, or heel strike, of the right foot. Approximately 10% into the gait cycle, the left foot reaches toe off, which is the beginning of the next stage of stance phase called midstance. Once the heel begins to rise off the ground, at 30% of the gait cycle, the terminal stance stage is reached. Finally, at 50% of the cycle, the left heel strikes and the pre-swing stage is reached. At the toe off of the right foot, swing phase of gait begins. The first stage of swing phase is the initial swing stage. When the feet are adjacent to one another, at 73% of gait cycle, the mid-swing stage begins. When the right tibia becomes vertical, at 87% of gait cycle, terminal swing stage begins. Finally, when the right heel makes next initial contact, the gait cycle has reached 100% and the swing phase has been completed (Öberg & Lamoreux, 1979).

Understanding and recognizing normal values for anatomical variables at each of these phases of gait is crucial in determining if gait is healthy or abnormal. The American College of Sports Medicine (2013) published average and healthy range of motion ranges for each movement at each joint. For the ankle joint, 30 to 50 degrees of plantarflexion and 15 to 20 degrees of dorsiflexion should be expected for the general population. For the knee joint, 130 to 140 degrees of flexion and 5 to 10 degrees of extension should be expected for the general population. For the hip joint, 90 to 135 degrees of flexion and 10 to 30 degrees of extension should be expected for the general population. When individuals have measurements that do not fall into these parameters, abnormal gait can be expected.

A study conducted by Öberg and Lamoreux (1979) more directly addresses the kinematic variables that will be addressed in this research project. The following values of both knee joint and ankle joint angles were measured throughout the gait cycle at moderate walking speed, and are considered normative values plus or minus 5 degrees. At the beginning of the gait cycle, knee joint angle is at -10° and ankle joint angle is at 0°. At 10% (opposite toe off), both knee and ankle angle are at -5°. At 30% of gait cycle (heel rise), knee angle is neutral (=0°) and ankle angle is at 5°. At 50% (opposite initial contact), knee angle is at -5° and ankle angle is at 10°. At 60% of gait cycle (toe off), knee angle is at 10° and ankle angle is at -10°. At approximately 73% (feet adjacent), knee angle is at 35° and ankle angle is at -5°. At approximately 87% of gait cycle (tibia vertical), knee angle is at 10° and ankle angle is at 5°. Finally, at completion of gait cycle when next initial contact is made, knee angle is at -10° and ankle angle returns to neutral. It should be noted that these values are not range of motion measurements, but rather kinematically determined joint angles. Öberg and Lamoreux also found total hip range of motion to be 40 to 50 degrees, total knee range of about 65 degrees, smooth stance-phase knee flexion of 5 to 20 degrees following heel contact, and return to full extension of the knee at about 45% of gait cycle.

Deviations in Gait

Walking is a fundamental movement when it comes to functional daily living. Having a functional gait is more than just successfully ambulating over a distance; it is imperative to carry out the activities of daily life. When deviations occur in the gait cycle, an individual is less efficient and can even experience pain or injury. The foot plays a crucial role in efficient locomotion; the foot cushions the impact force during the loading response, maintains stability and support of the lower limbs, and assists in forward propulsion. Several studies have explored the relationship between abnormal medial longitudinal arches and gait cycles. Kudo and Hatanaka (2016) conducted a study that looked into foot kinematic differences between normal and flat feet during forefoot loading. They utilized 46 feet of 33 subjects and obtained kinematic data via 4 high-definition video cameras. Subjects were categorized into two groups, a normal foot group and flat foot group. Via the kinematic data collected, they found that during forefoot loading, the subjects in the flat arched feet group showed forward splaying, or medial longitudinal arch collapse. Kudo and Hatanaka further suggested that treatment of flat feet needs to be aimed at decreasing forward movement of the cuboid bone and increasing the medial movement of the third metatarsal base in order to minimize forward splaying.

Levinger et al. (2010) also explored foot kinematics in people with normal and flat arched feet by utilizing the Oxford Foot Model. The Oxford Foot model uses markers attached to the foot and lower leg that allows motion of the joints to be measured during gait. Foot posture was determined in 19 subjects to be either normal arched or flat arched by using a screening protocol involving measurements from weight-bearing radiographs. Triplanar motion (motion in the sagittal, frontal, and transverse planes) of the tibia, rearfoot, and forefoot during walking were evaluated using a three-dimensional analysis system incorporating the multi-segmental Oxford Foot Model. The study found that the flat arched group had associations with greater peak forefoot plantar-flexion, forefoot abduction, and rearfoot internal rotation compared to the normal arched group, all indicating excessive pronation. Additionally, the flat arched group had associations with decreased peak forefoot adduction, further indicating excessive pronation. This lead Levinger et al*.* to conclude that individuals with flat arches have altered foot kinematics during gait.

A study conducted by Buldt et al*.* (2015) further researched this topic by including high arch as one of the foot posture groups. The study compared foot kinematics across normal arched, high arched, and flat arched feet. The study utilized 97 subjects (194 feet) the normal arched group having 37 subjects, the high arched group having 30 subjects, and the flat arched group having 30 subjects. Individuals were classified using the Foot Posture Index (FPI), arch height index, and normalized navicular height. The Foot Posture Index is a method of rating foot posture using 6 set criteria and a simple scale; it is often used to quantify the degree to which a foot is pronated, neutral, or supinated. Additionally, a multi-segment foot model (likely similar to the Oxford Foot Model) was utilized. The five-segment model measured triplanar motion of the medial forefoot, lateral forefoot, rearfoot, hallux (big toe), and midfoot. Kinematic variables analyzed were ankle angle at heel contact, peak angle of ankle, time to peak angle, and range of motion. Researchers found individuals in the high arched group had distinctly different motion compared to the normal and flat arched groups; furthermore, they displayed altered angles of the rearfoot as well as minimal midfoot motion. Individuals in the flat arched group displayed decreased midfoot frontal plane motion during the pre-swing phase of gait. These findings further support the notion that individuals with abnormal medial longitudinal arches have altered foot kinematics during gait.

Patellofemoral pain syndrome (PFPS) is a condition in which the cartilage under the kneecap is damaged due to overuse or injury. It is the most common cause of anterior knee pain and the most common cause of knee pain as seen by doctors. Barton, Levinger, Crossley, Webster, and Menz (2011) conducted the first study to examine the relationship between foot posture and three-dimensional kinematics in individuals with patellofemoral pain syndrome. The researchers wanted to investigate the extent to which a stationary foot measurement tool, such as the Foot Posture Index, can predict kinematic variables associated with pronation during walking in both PFPS and asymptomatic individuals. Twenty-six individuals and twenty control participants underwent evaluation via the Foot Posture Index and kinematic analysis of the forefoot and rearfoot during gait using a three-dimensional motion system. In both symptomatic and asymptomatic individuals, there was a fair to moderate correlation between the Foot Posture Index and some parameters of dynamic foot function. A pronated foot type was associated with greater peak forefoot abduction and earlier peak rearfoot eversion in the PFPS group, and was associated with greater rearfoot eversion range of motion in the control group. Through this study, the researchers concluded and suggested that pathology may play a factor in the relationship between static foot posture and dynamic function.

Several studies have analyzed the relationship between foot posture and foot kinematics during gait, but research has also investigated the relationship between foot posture and foot kinematics during running; specifically, research has been conducted on interaction between foot arch type and footwear on running mechanics. A study conducted in 2006 aimed to determine the effects of motion control and cushion trainer shoes on running mechanics in recreational runners (Butler, Davis, & Hamill, 2006). Forty participants were recruited and equally placed into a high arched or low arched group. Runners were recreational and ran less than 10 miles per week. A three-dimensional analysis system collected kinetic and kinematic data as runners ran at 3.5 m/s on a 25 m runway. The motion control shoe utilized was the New Balance 1122 and the cushion trainer shoe utilized was the New Balance 1022. Researchers found significant data on the interaction observed in the instantaneous loading rate, or the force exerted per step. Individuals in the low arched group had lower instantaneous loading rates (which results in less force on the joints) in the motion control shoe, whereas individuals in the high arched group had lower instantaneous loading rates in the cushion trainer shoe. Although this study was conducted on recreational runners, it suggests that shoe type interacts with foot posture. Motion control shoes tend to control rearfoot motion better, whereas cushion trainer shoes attenuate shock better. Shoe types can benefit individuals with different foot mechanics, which can empirically be judged based on arch type.

Orthotic Implications

As research has shown arch type can alter foot kinematics in gait and the impact shoes may also have on foot kinematics, orthotics may have important implications in returning gait to normal values and/or decreasing pain and risk of injury in individuals with abnormal medial longitudinal arches. McCulloch, Brunt, and Vander Linden (1993) examined the interaction between foot orthotics and two walking speeds on the angular changes at the rearfoot, ankle, and knee. Ten subjects were recruited and had to demonstrate sufficient calcaneal (heel) eversion during relaxed standing. Participants walked at 2 mph and 3 mph on a treadmill, and completed trials with and without the orthotic while also wearing personal athletic shoes of choice. The orthotics were designed to restore dynamic stability and reduce compensatory pronation during the stance phase of the gait cycle. Repetitive pronation requires additional rotation of the tibia, increasing knee flexion and potentially resulting in pain. Kinematic data revealed walking with the orthotic significantly reduced the degree of pronation during stance phase. Additionally, orthotic use increased the relative duration of stance, particularly from heel strike to heel rise. The increase in relative duration of stance corresponded with increased dorsiflexion, allowing for a longer period for resupination following maximum pronation, meaning the individual is able to more efficiently stabilize and maintain foot posture. It is biomechanically advantageous to utilize orthotics during walking and potentially during more strenuous exercise, as orthotics have a positive effect on rearfoot, ankle, and knee motion.

Further studies have examined the effect of interventions such as taping the arches and customized orthotics. Bishop, Arnold, and May (2016) aimed to identify any effects of taping and orthoses on multi-segment foot biomechanics in adults with flat arches. Eighteen participants were recruited and four walking conditions were administered in random order: neutral athletic shoe, neutral shoe with tape (low-Dye taping method), neutral shoe with tape (modified low-Dye taping method), and neutral shoe with customized foot orthoses. Low-Dye taping method covers more surface area of the sole of the foot than the modified low-Dye taping method. Kinematic data revealed deformations across the midfoot and in the medial longitudinal arch was reduced in both taping methods. Additionally, orthotics significantly delayed peak eversion compared to the neutral shoe (control). All interventions increased peak dorsiflexion of the first metatarsophalangeal joint (ability to lift the big toe). While taping interventions were superior in supporting the midfoot and medial longitudinal arch, the orthotics more efficiently altered the timing of hindfoot motion.

Arnold, May, and Bishop (2018) conducted yet another study to further research customized foot orthoses in adults with flat arched feet. Their goal was to identify any and all biomechanical responses to customized orthotics in a flat arched population. Eighteen subjects, all with flat feet, were recruited and all were symptom free. In-shoe foot biomechanics were analyzed during walking with and without customized foot orthotics using three-dimensional analysis. Kinematic and kinetic data during baseline walking were compared to groups who displayed diminished calcaneal eversion with orthotics to those with no change in calcaneal eversion. In addition to their original research, they concluded individuals with increased dynamic foot pronation, which occurs in most flat arched individuals, were more likely to show a positive biomechanical response to customized foot orthotics; meaning, customized foot orthotics were effective in biomechanically reducing the instantaneous loading rates in adults with flat arches.

A study conducted by Burns, Crosbie, Ouvrier, and Hunt (2006) aimed to analyze the evidence of the efficacy of custom foot orthotics for individuals with high arched feet as well. High arched individuals often exhibit foot pain and orthotics are widely prescribed to treat such pain, but little evidence existed to show their efficacy. One hundred fifty-four participants with chronic musculoskeletal foot pain and high arches in both feet were randomly assigned to a custom foot orthotic or a control group. Individuals were given a Foot Health Status Questionnaire to evaluate foot pain, function, quality of life, and plantar pressure loading. At 3 months, foot pain scores improved more with custom foot orthotics than with the control group. Function scores also improved and quality of life data supported the efficacy of the custom foot orthotics. Much of the research conducted regarding the efficacy of custom foot orthotics supports the notion that orthotics are more effective than a control for the treatment of abnormal medial longitudinal arches and associated foot pain/limitations in function, but further research can and should be carried out to determine to what extent.

Orthotics therefore may prove to be beneificial in those with abnormal arches, as abnormalities in the medial longitudinal arch have shown to have impact on foot kinematics during the gait cycle. These abnormalities may be harmless, but they also have the potential to lead to pain and/or injury. Further research should be conducted on the direct relationship between foot arch type and kinematic variables such as joint angles during heel strike and toe off, duration of stance phase and angular velocity of the ankle during this phase, and stride lengths, velocities, and frequencies. Better understanding of the relationships between foot arch type and each of these variables can facilitate the understanding of how arch type may affect the entire lower body kinetic chain throughout movements as fundamental as walking.

The Gap in the Research

Sufficient research has been conducted on structural abnormalities of the medial longitudinal arch of the foot in the last two decades. Determining an individual’s arch height and type and how these factors contribute to deviations in foot kinematics is well understood.

However, a majority of the research on abnormalities of the medial longitudinal arch is focused on how the arch alters foot kinematics during gait, and does not ask how abnormalities may contribute to deviations in knee kinematics as well. Research has concluded that varying arch heights do have an impact on movement of the foot during regular walking. There is no research conducted on how varying arch heights have an impact on movement of the knee and hip joints. Although it is not thought to analyze how the structure of the foot arch impacts the knee and hip joints, it is important to take this into account during gait. Furthermore, it has not been researched how arch type may have an effect on characteristics of gait such as stride velocity and frequency.

When an individual is walking, the ankle, knee, and hip joints are working together to propel an individual forward across a distance. This motion starts at the foot. The foot makes initial contact with the ground, but on the opposite limb, the knee and hip are working together to move the opposite foot forward. There is an intricate connection between all three lower limb joints that impacts the way in which an individual walks. If there is an abnormality in the foot, which makes the initial contact with the ground during gait, imagine how this may affect the other two joints in succession. There are no previous studies connecting structural abnormalities of the medial longitudinal arch of the foot and deviations in knee biomechanics during gait. This study was intended to begin filling the gap in the research on how arch height may affect deviations in otherwise healthy biomechanical gait.

CHAPTER III: METHODOLOGY

Research Design

This study examining the effect of arch height on variances in gait phases utilized kinematic analysis.

Research Participants

The target population was healthy college-aged students at the University of Northern Iowa. Nine students, four males and five females, participated in foot screening procedures as well as completed a video walking trial. The average age of the participants was 20.44 years old and ranged from 19-22. Participants were screened to ensure healthy ankle joint range of motion and healthy BMI.

Instrumentation

Before participants completed a video walking trial, foot arch types were screened using two protocols. The first was determining the participant's arch height index; arch height index is determined by dividing dorsum height at 50% foot length by truncated foot length (McCrory, Young, Boulton, & Cavanagh, 1997). The participant's arch height index was found via the researcher taking manual measurements of the individual's right foot in a non weight-bearing position. The second was via a Foot Levelers 3D Body View (Foot Levelers, 3D Body View, Roanoke, Virginia) imaging unit. This scanning unit generated an image to identify asymmetries in the feet with arch height mapping, illustrating how the feet impact the entire kinetic chain.

In the next part of the research process, participants were filmed with a video camera (JVC, GC-PX1, Japan) while walking a distance of approximately 5 meters. Participants were filmed from the side. Then, film was kinematically digitized and analyzed via a computer program (Innovision Systems Inc., MaxTRAQ, Lapeer, Michigan) in order to quantify several gait variables: ankle joint angle, knee joint angle, center of mass location, duration of stance phase and angular velocity of the ankle during this phase, stride length, stride velocity, and stride frequency. The data obtained from the completion of the kinematic gait analysis was compared across the three groups to determine the effect among results.

Procedures for Collecting Data

After Institutional Review Board (IRB) approval, the researcher contacted several individuals about participation in this study. If individuals expressed interest, the researcher sent an email with an explanation of the study as well as asked for the individual's schedule to set up appointments to complete feet screening and video walking trials. After securing nine participants, a schedule was made and sent out to participants informing them when to come in to complete feet screening and video walking trials.

Upon arrival at the data collection site, the individual was presented with an informed consent form. At this time the participant was informed that the research study was being conducted to examine the relationship between arch height and gait variables. They were also informed that the information in the study was confidential and no compensation was offered for participation. By signing the informed consent form, they agreed to participate in the study and began screening protocols.

After completion of screening protocols and video walking trials, data was kinematically analyzed using MaxTRAQ computer software. Within the computer software, markers were placed on the participant's hip, knee, ankle, and third metatarsophalangeal joints. Video was analyzed frame by frame, beginning with the frame in which the participant's right heel first made contact with the floor, and ending with the frame in which the participant's right heel again made contact with the floor after one full gait cycle. Stride length was measured by use of four plungers being placed one meter apart each, and then being converted into pixels using a pixel conversion factor. A stride is measured from heel strike to heel strike of the same foot. After analysis of data was completed, video data was destroyed to ensure participant confidentiality. Participants' identities were also protected by using pseudonyms (ex: Subject A, Subject B, etc.) in all remaining data.

CHAPTER IV: RESULTS

Summary statistics for participant demographics can be found in Table 1. Summary statistics for research question variables can be found in Table 2. Across all data, the mean normal arch group values were either on the high or the low end of the spectrum, dependent upon the variable. Normal arch group values were used as a standard when making comparisons with the two abnormal arch groups. The data showed that the normal arch group had the smallest ankle angle at heel strike (M=105.17°) and had the largest knee angle at heel strike (M=178.57°). The normal arch group had the largest ankle joint angle at toe off (M=122.20°) while having the smallest knee joint angle at toe off (M=131.73°). The normal arch group had the longest stance phase duration with a mean time of 0.92 seconds, as well as the greatest ankle joint angular velocity (M=18.82°/s) and knee joint angular velocity (M=-51.00°/s) during stance phase. The normal arch group had a mean stride length of 1.23 meters, which was the shortest mean stride length across the three groups. The normal arch group had a mean stride velocity of 0.95 meters per second and a mean stride frequency of 45.75 strides per minute, both of which were the smallest variables across the three groups, respectively.

Table 1

Summary Statistics Table for Participant Demographics Split by Arch Type

Variable	*M*	*SD*	SE_M
Age			
Cavus	20.00	1.00	0.58
Planus	20.00	1.00	0.58
Normal	21.33	0.58	0.33
Height (cm)			
Cavus	178.67	14.49	8.37
Planus	158.33	6.29	3.63
Normal	173.00	3.46	2.00
Weight (kg)			
Cavus	70.93	19.11	11.03
Planus	63.07	8.41	4.86
Normal	72.57	2.25	1.30
BMI			
Cavus	21.84	2.70	1.56
Planus	25.09	1.99	1.15
Normal	24.25	0.48	0.28

Note. No significant difference between groups ($p < 0.05$).

There were no significant differences between groups for age ($F(2,6)=2.29$, $p=0.18$), height ($F(2,6)=3.79$, $p=0.09$), weight ($F(2,6)=0.53$, $p=0.62$), and BMI ($F(2,6)=1.92$, $p=0.23$).

Table 2

Summary Statistics Table for Research Question Variables Split by Arch Type

Variable	*M*	*SD*	SE_M
Ankle Joint Angle at Heel Strike			
Cavus	110.97	6.31	3.65
Normal	105.17	1.78	1.03
Planus	113.20	1.85	1.07
Ankle Joint Angle at Toe Off			
Cavus	110.20	7.27	4.20
Normal	122.20	9.31	5.37
Planus	119.63	6.75	3.90
Knee Joint Angle at Heel Strike			
Cavus	175.30	6.70	3.87
Normal	178.57	11.46	6.61
Planus	178.43	2.54	1.47
Knee Joint Angle at Toe Off			
Cavus	134.37	6.46	3.73
Normal	131.73	7.01	4.04
Planus	138.23	6.32	3.65
Stance Phase Duration (s)			
Cavus	0.86	0.06	0.03
Normal	0.92	0.15	0.09
Planus	0.83	0.02	0.01
Ankle Joint Angular Velocity at Stance Phase			
Cavus	-1.28	15.36	8.87
Normal	18.82	11.20	6.47
Planus	7.68	7.20	4.16
Knee Joint Angular Velocity at Stance Phase			
Cavus	-47.90	11.62	6.71
Normal	-51.00	16.06	9.27
Planus	-48.16	8.96	5.17

Stride Length (m)			
Cavus	1.33	0.21	0.12
Normal	1.23	0.19	0.11
Planus	1.39	0.14	0.08
Stride Velocity (m/s)			
Cavus	1.03	0.20	0.12
Normal	0.95	0.28	0.16
Planus	1.10	0.11	0.06
Stride Frequency (strides/min)			
Cavus	46.32	1.98	1.14
Normal	45.75	6.14	3.54
Planus	47.82	0.88	0.51

Note. No significant difference observed for all variables ($p < 0.05$).

There were no significant differences between groups for ankle joint angle at heel strike ($F(2,6)=3.33$, $p=0.12$), ankle joint angle at toe off ($F(2,6)=1.94$, $p=0.22$), knee joint angle at heel strike ($F(2,6)=0.17$, $p=0.85$), knee joint angle at toe off ($F(2,6)=0.74$, $p=0.52$), stance phase duration ($F(2,6)=0.60$, $p=0.58$), ankle joint angular velocity at stance phase ($F(2,6)=2.21$, $p=0.92$), knee joint angular velocity at stance phase ($F(2,6)=0.06$, $p=0.95$), stride length ($F(2,6)=0.58$, $p=0.59$), stride velocity ($F(2,6)=0.41$, $p=0.68$), and stride frequency ($F(2,6)=0.24$, $p=0.79$).

CHAPTER V: DISCUSSION

Effect on Joint Angle

The data showed that the normal-arch group had the smallest ankle joint angle at heel strike (M=105.20°), followed by the high-arch group (M=111.00°), ending with the low-arch group having the greatest angle (M=113.20°). This supports the idea that an abnormal arch affects foot kinematics during walking. In this case, the angle at the ankle joint in individuals with abnormal arches is larger than in individuals with a normal arch when the foot is in the heel strike position. In other words, the ankle is not as flexed in individuals with abnormal arches. When the ankle performs dorsiflexion, or pulling the foot up closer to the shin, four muscles are used: the tibialis anterior, the extensor hallucis longus, the extensor digitorum longus, and the peroneus tertius. Each of these muscles inserts somewhere on the dorsal side of the foot. The tibialis anterior inserts on the medial cuneiform and base of the first metatarsal, the extensor hallucis longus inserts on the distal phalanx of the great toe, the extensor digitorum longus inserts on phalanges two through five, and the peroneus tertius inserts on the fifth metatarsal. When a medial longitudinal arch is abnormal, the insertion site of each of these muscles may be located differently in space. This could result in altered activation of the muscles that cause ankle dorsiflexion, therefore altering the ankle joint angle at heel strike.

Also at heel strike, the high-arch group had the smallest knee joint angle (M=175.30°), followed by the low-arch group (M=178.40°), ending with the normal-arch group having the greatest angle (M=178.60°). This data shows that an abnormal arch may affect not only foot kinematics, but may also affect knee kinematics during walking. In this case, the angle at the knee joint in individuals with abnormal arches is smaller than in individuals with a normal arch when the foot is in the heel strike position. This reflects how the knee is more bent, or flexed, in individuals with abnormal arches. This is likely a result of compensation for the ankle joint. When the ankle is not as flexed, the knee must be more flexed in order to ensure the heel clears the floor during swing phase before heel strike occurs.

The data showed that the high-arch group had the smallest ankle joint angle at toe off (M=110.20°), followed by the low-arch group (M=119.60°), ending with the normal-arch group having the greatest angle (M=122.20°). This again supports the idea that foot kinematics are altered during walking. In this case, the angle at the ankle joint is smaller, or less extended, in individuals with abnormal arches during toe off. When the ankle performs plantarflexion, or pointing the foot away from the shin, eight muscles are involved: the gastrocnemius, the soleus, the plantaris, the flexor hallucis longus, the flexor digitorum longus, the tibialis posterior, the peroneus longus, and the peroneus brevis. All of these muscles have an insertion site somewhere on the foot. The gastrocnemius, soleus, and plantaris all insert into the Achilles tendon which inserts into the calcaneus; the flexor hallucis longus inserts on the plantar side of the distal phalanx of the great toe; the flexor digitorum longus inserts on phalanges two through five; the tibialis posterior inserts on the medial cuneiform and the navicular bone; the peroneus longus inserts on the plantar side of the medial cuneiform and the first metatarsal; and the peroneus brevis inserts on the lateral side of the fifth metatarsal. Again, when a medial longitudinal arch is abnormal, these insertion sites may be located differently in space, resulting in altered activation of the muscles that cause plantarflexion.

Also at toe off, the normal-arch group had the smallest knee joint angle (M=131.70°), followed by the high-arch group (M=134.40°), ending with the low-arch group having the greatest angle (M=138.20°). This further supports the idea that knee kinematics are also altered during gait, likely as a result of compensation for the ankle joint. When the ankle joint is more flexed during toe off, which is the case in the individuals with abnormal arches, the knee joint is less flexed, or bent, as a result. This is likely to achieve the same amount of forward propulsion even with a lessened degree of plantarflexion at the ankle.

Effect on Joint Angular Velocity

The data showed that the normal-arch group had the longest stance phase duration (M=0.92s), followed by the high-arch group (M=0.86s), ending with the low-arch group having the shortest stance phase duration (M=0.83s). Stance phase duration is the amount of time one foot is in contact with the ground, starting at heel strike and ending at toe off. Stance phase duration is likely shorter in individuals with abnormal arches due to the fact that ankle and knee kinematics during gait are altered in these individuals. The diminished degree of dorsiflexion at the ankle during heel strike in combination of the diminished degree of plantarflexion at the ankle during toe off would result in less forward propulsion and therefore shorter stance phase duration.

During stance phase, the high-arch group had the smallest ankle joint angular velocity (M=1.28°/s), followed by the low-arch group (M=7.68°/s), ending with the normal-arch group having the greatest angular velocity (M=18.82°/s). Ankle joint angular velocity during stance phase shows how quickly the ankle moves from dorsiflexion (toes flexed) to plantarflexion (toes pointed). Another way of looking at this is how quickly the plantar side of the foot rolls from heel strike through toe off. The data shows that individuals with normal arches roll from heel strike through toe off more quickly than individuals with abnormal arches. This is likely related to the diminished ability of the ankle to perform plantarflexion, which was discussed in the previous section.

Also during this phase, the high-arch group had the smallest knee joint angular velocity (M=47.90°/s), followed by the low-arch group (M=48.16°/s), ending with the normal-arch group having the greatest angular velocity (M=51.00°/s). Knee joint angular velocity during stance phase shows how quickly the knee moves from extension at heel strike to flexion at toe off. The data shows that individuals with abnormal arches have a smaller knee joint angular velocity during stance phase, meaning the knee does not flex as quickly as it does in individuals with normal arches. This is likely related to the angular velocity of the ankle during stance phase. If the ankle joint angular velocity is diminished in individuals with abnormal arches, the knee joint angular velocity is also diminished.

Effect on Stride

The data showed that the normal-arch group had the lowest values for all stride variables, followed by the high-arch group, followed by the low-arch group. The normal-arch group had the shortest stride length (M=1.23m), followed by the high-arch group (M=1.33m), ending with the low-arch group having the longest stride length (M=1.39m). Although the normal-arch group had the shortest stride length, stride length is likely just a result of an individual's height. The difference in stride lengths across the three groups was not substantial and it was likely coincidental that the normal-arch group had the shortest stride length.

The normal-arch group had the slowest stride velocity (M=0.95 m/s), followed by the high-arch group (M=1.03m/s), ending with the low-arch group having the greatest stride velocity (M=1.10m/s). The stride velocity is the relationship between the length of the individual's stride and the amount of time it takes the individual to go through one gait cycle (heel strike of one foot through heel strike of the same foot). This data suggests that individuals with abnormal arches have a quicker stride velocity than individuals with normal arches. This result is again likely affected by the fact that ankle and knee kinematics are altered in individuals with abnormal arches. With diminished dorsiflexion at heel strike and diminished plantarflexion at toe off comes with lessened forward propulsion and therefore shorter stance phase duration. When stance phase duration is shorter, the stride velocity is increased as the amount of time one foot is in contact with the ground is shorter.

The normal-arch group had the smallest stride frequency (M=45.74st/min), followed by the high-arch group (M=46.32st/min), ending with the low-arch group having the greatest stride frequency (M=47.82st/min). This data suggests that individuals with abnormal arches take more strides in a minute than individuals with normal arches do. This is again a result of stance phase duration. With less forward propulsion in individuals with abnormal arches, stride velocity is greater, and more strides are taken in one minute.

Implications of Results

This study revealed that in addition to altered foot kinematics during gait, knee joint kinematics are also altered during gait. The bones of the foot are the insertion site of many important muscles of the lower leg, specifically those that result in plantarflexion and dorsiflexion of the ankle. When the medial longitudinal arch of the foot is abnormal, the bones of the foot may be slightly altered in position, resulting in the insertion sites of many muscles slightly altered in position as well. This could possibly lead to an altered ability of the ankle to perform adequate plantarflexion and dorsiflexion during gait. Furthermore, due to the kinetic chain of the lower extremities during gait, knee kinematics are also altered in individuals with abnormal arches. The idea of the kinetic chain is that joints and segments have an effect on one another during movement. During gait, for example, the ankle joint affects the knee joint, which in turn affects the hip joint. This supports the idea that abnormal arches may contribute to non-specific low back pain, which is a vast problem in adults in the United States (Neely, 1998).

The results of this study also revealed that stride velocity and stride frequency are altered in individuals with abnormal arches. With diminished dorsiflexion at heel strike and diminished plantarflexion at toe off comes with decreased forward propulsion and therefore shorter stance phase duration. This matches the research conducted by McCulloch, Brunt, and Vander Linden (1993), who noted that the increase in relative duration of stance corresponded with increased dorsiflexion in individuals with normal arches. This allowed for a longer period for resupination following maximum pronation, meaning the individual was able to more efficiently stabilize and maintain foot posture.

As a result of a shorter stance phase duration, stride velocity is greater and more strides are taken in one minute. Some important deviations from healthy gait have been noted through this current study. If this piece of evidence holds true across a range of populations, this information would be very important to health care professionals. If individuals with abnormal arches are taking more strides per minute than individuals with normal arches, imagine how many more strides they are taking in a week, in a month, or even in a year. This is an increase in the stress put on each of the involved joints that could build up and have long term damage over time.

Understanding the impact of abnormal arches on the kinetic chain during activities as simple as walking has a great deal of implications for health care professionals. If a slightly flat or high arch affects foot kinematics, the kinetic chain further shows how it alters knee kinematics, and likely contributes to effected hip and low back kinematics as well. Having a knowledge of the kinetic chain gives health care professionals direction of where to start for both diagnosis and treatment for patients with arch-attributed pain. This especially holds true when a patient presents with non-specific pain, meaning the pain is not attributed to injury, surgery, etc. It is important for the health care professional to assess the feet, then the ankle joints, then the knee joints, etc. to determine where the source of the problem may lie. Then, the health care professional can start treatment with correction at the source of the problem. This may include prescribing general or customized orthotics, providing a home exercise program for ankle strengthening, and/or adding hip flexor stretching to a daily routine, even if the patient’s diagnosis is low back pain. Without the knowledge of the kinetic chain, a health care professional may potentially be treating the problem rather than the source of the problem.

Limitations

Two important limitations must be taken into account in the current study. This first is the small sample size (n=9). A larger sample size is advantageous because there is always the possibility of outliers when collecting data. The sample size also determines the margin of error for a statistic, or how accurate the statistic can be calculated to be. With a larger sample size, the confidence interval should get smaller, meaning the researcher can be more sure about the accuracy of the mean. The larger the sample size, the smaller the margin of error. In order for this study to be more representative, a larger sample size would have to be used (ideally, n>100).

The second is the very specific sample population. All participants were college students between the ages of 19 and 22. Additionally, all participants were regularly physically active and none of the participants were obese. Results may have greatly varied in a different population. It is suspected that results would vary in populations such as the elderly and in those who are obese. When individuals age, it is not uncommon for the body to lose muscular tone and have diminished bone strength. This would likely result in a change in structure of the medial longitudinal arch and could impact the results of the current study. In individuals who are obese, there is more weight distributed down through the feet. This often results in a flattening of the structure of the medial longitudinal arch and would likely mirror the results found in the low arch group. This study represented only a small and quite specific population to answer the research questions at hand. Results could be expected to be different in a larger, more representative sample.

Future Recommendations

Existing research in conjunction with the current study has shown that foot kinematics are altered in individuals with abnormal arches (Levinger et al., 2010) . Furthermore, due to the nature of the kinetic chain of the lower extremities during gait, other body segments are impacted by abnormal arches. This includes the knee and hip joints, and supports the notion that abnormal arches may contribute to non-specific low back pain. However, it would be beneficial for more research to be done in a greater population to note if these deviations have any long term effects on individuals with abnormal arches. Existing research has further shown the implications and benefits of orthotics for individuals with abnormal arches. Research has shown that general orthotics can significantly reduce the degree of pronation of the foot. This is important because in individuals with flat feet, repetitive pronation can result in additional rotation of the tibia, increasing knee flexion and potentially resulting in pain (McCulloch, Brunt, & Vander Linden, 1993).

Research has also shown that general orthotics increase the relative duration of stance phase (McCulloch, Brunt, & Vander Linden, 1993). This has implications with the current study as well, as the abnormal arch groups both had decreased duration of stance phase as compared to the normal arch group. The diminished duration of stance phase in the current study also related to the altered ankle and knee joint angular velocities during stance phase, as well as the altered stride velocities and frequencies in the abnormal arch groups. By increasing the relative duration of stance phase by means of a general orthotic, the feet are allowed more time to reach peak dorsiflexion, returning the lower extremities to a more healthy pattern of gait.

What is most notable, though, is how research has shown how effective custom orthotics can be for an individual with abnormal arches. Customized orthotics more effectively biomechanically reduced instantaneous loading rates in adults with low arches as compared to general orthotics (Arnold, May, & Bishop, 2018). Customized orthotics also have shown to decrease pain scores in individuals with high arches as well (Burns, Crosbie, Ouvrier, & Hunt, 2006). This existing research shows how important the implications of orthotics can be for individuals with abnormal arches. Ideally, individuals with abnormal arches should consult with a physician to find a solution that meets their specific body's need. Customized orthotics have been shown to be more effective than general orthotics, but general orthotics are much more cost efficient and are still effective in correcting foot kinematics during gait.

Conclusion

Existing research has shown that foot kinematics are altered during gait and the foot has a diminished ability to perform both dorsiflexion and plantarfexion. Orthotics have had important implications in correcting unhealthy biomechanical gait and effectively altering foot kinematics. However, the current study adds that knee kinematics are also altered during gait in individuals with abnormal arches. This study also showed that individuals with abnormal arches exhibited shorter stance phase duration, resulting in a greater stride frequency. This means that these individuals are taking more strides per minute, and therefore more strides in a day, in a week, in a month, and in a year. There is a large gap in the research explaining how abnormal arches may alter the entire kinetic chain of the lower extremities during walking. This is concerning, as it is thought that low arches may be a large contributor to non-specific low back pain.

Understanding the biomechanics and kinematics of the lower extremities during gait is incredibly important for health care professionals. It is important that these individuals have a great deal of knowledge of the kinetic chain nature of the human body. The idea of the kinetic chain is that joints and segments have an effect on one another during movement; during gait, the ankle joint affects the knee joint, which in turn affects the hip joint, which in turn affects the low back. Health care professionals must be able to assess the entire kinetic chain, beginning at the feet, in order to gain direction as to where to start for both diagnosis and treatment of patients. This way, providers can ensure they are treating the source of the problem rather than just symptoms of the problem. Having a better idea of how ankle and knee kinematics are altered in individuals with abnormal arches will further assist health care professionals in diagnosing and treating said individuals and ultimately aiding in the decrease of arch-attributed pain.

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APPENDIX A

UNIVERSITY OF NORTHERN IOWA
HUMAN PARTICIPANTS REVIEW
INFORMED CONSENT

Project Title: The Effect of Arch Height on Variances in Gait Phases: A Kinematic Analysis

Name of Investigator: Mackenzie Haag

Invitation to Participate: You are invited to participate in a research project conducted through the University of Northern Iowa. The University requires that you give your signed agreement to participate in this project. The following information is provided to help you make an informed decision about participating in the project.

Nature and Purpose: The purpose of this research project is to determine correlations between foot arch types and deviations in healthy biomechanical gait in addition to the implications of orthotics in order to ultimately aid in the decrease of arch-attributed pain.

Explanation of Procedures: You should plan to allow at least 30 minutes to complete the required tasks. This time allowance is suggested in order to ensure that sufficient time is given to complete screening procedures and adequate film is obtained for analysis by the researcher. It is likely, however, that the procedures will take less than 30 minutes to complete. You will first be asked to disclose your height, weight, and self-classified foot arch type to the researcher. You will then have three screening measures taken of your right foot. The researcher will first use a goniometer to ensure you have baseline range of motion measurements in the right ankle joint. Second, the researcher will manually take measurements of the right foot to determine arch height index. Finally, you will have an assessment completed by a Foot Levelers 3D Body View scanner. You will stand on the scanner for approximately 60 seconds and follow prompts to ensure the scanner generates an accurate image of the arches and also provides an accurate score. You will then be asked to complete a short walk, 25 total feet, while being filmed. You will be filmed from the side; additionally, it is possible that you may be asked to complete the trial one or twice more to ensure a clear video is obtained. Video recordings will not be shared and will be destroyed upon the project's completion of data analysis. The project's results will only reference pseudonyms (example: Subject A) in order to protect your identity. The researcher has the training and experience to direct the study's procedures. Specifically, the researcher has received training and valid certification in CPR and First Aid.

Discomfort and Risks: Risks to participation are minimal. You may decide to stop the foot screening or to stop the walking trial at any time. You will be allowed adequate time to rest while completing the walking trial if necessary for any reason including, but not limited to, physical exhaustion or pain. With any exercise, there is the possibility that abnormal responses could occur. These include unexpected changes in blood pressure, irregular heart rate, fainting, shortness of breath, fatigue, muscle cramps, muscle soreness or joint injury, and in rare cases, a cardiac event. An emergency plan is in place and will be followed if needed. A copy of this emergency plan may be given to you upon request. It is your responsibility to notify the researcher if you experience any response that you find unusual or unexpected during or after exercise. In the unlikely event that any injury or illness occurs as a result of participation in this research, you will be responsible for the cost of medical care.

Benefits and Compensation: There are no direct benefits associated with this study.

Confidentiality: Information obtained during this study which could identify you will be kept confidential. A report of the summarized findings may be published in Rod Library UNI Scholarworks or other publications without any identifying information of participants. Only the researcher will view the obtained videos.

Right to Refuse or Withdraw: Your participation in this research project is completely voluntary. You are free to withdraw from participation at any time or to choose not to participate at all, and by doing so, you will not be penalized or lose benefits to which you are otherwise entitled. You may request at the time of withdrawal that all of your data be excluded from the research.

Questions: If you have questions about the study you may contact or desire information in the future regarding your participation or the study generally, you can contact Mackenzie Haag by email at haagm@uni.edu or the project investigator's faculty advisor jacob Reed at the Department of Kinesiology, 319-273-6275. You can also contact the office of the IRB Administrator, University of Northern Iowa, at 319-273-6148, for answers to questions about rights of research participants and the participant review process.

Agreement: I am fully aware of the nature and extent of my participation in this project as stated above and the possible risks arising from it. I hereby agree to participate in this project. I acknowledge that I have received a copy of this consent statement. I am 18 years of age or older.

______________________________________ __________________
(Signature of participant) (Date)

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(Printed name of participant)

______________________________________ __________________
(Signature of investigator) (Date)

______________________________________ __________________
(Signature of instructor/advisor) (Date)