THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF KINESIOLOGY

AN EVALUATION OF CONTROLLED ANKLE MOVEMENT (CAM) BOOT MECHANICS DURING LOCOMOTIVE CHANGES IN ELEVATION.

MARTIN JOSEPH SEDLOCK III
SPRING 2019

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Kinesiology
with honors in Kinesiology

Reviewed and approved* by the following:

John H. Challis
Professor of Kinesiology
Thesis Supervisor

Jinger S. Gottschall
Associate Professor of Kinesiology
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

Controlled ankle movement (CAM) boots are a commonly prescribed treatment in response to a variety of musculoskeletal injuries of the lower limb. However, evidence supporting their efficacy at reducing normal reaction forces experienced by the foot is limited and inconclusive. The experimental portion of this thesis sought to remedy the situation by gauging the effectiveness of CAM boots at reducing the normal reaction forces experienced by the plantar surface of the foot during ambulation. Subjects were tasked with completing nine trials composed of three walking tasks: level surface, inclined/declined ramp, and ascending/descending stairs. Each task was completed under three footwear conditions: Sneakers, CAM boot, and Air CAM boot. Subjects were outfitted with force-sensing insoles that measured the normal reaction forces experienced by the plantar surface of the foot and allowed for the calculation of their derivatives. Four variables were subsequently examined: duration of contact, impact peak force, active peak force, and loading rate. It was hypothesized that CAM boot use will exacerbate asymmetry in all four variables between feet as to offload the injured side, as compared to sneakers. It was predicted this will occur in all walking conditions. For a majority of walking tasks, significant differences were sporadic, leading to rejection of the hypothesis and suggesting no practical benefit of CAM boot use. This excluded the task of ascending/descending stairs. In these trials, both versions of CAM boots were consistently successful at decreasing three of four variables. Results indicated that CAM boots are a valid treatment if regular stair use is unavoidable by the patient. Otherwise, the data suggested CAM boots are not effective at reducing reaction forces.

TABLE OF CONTENTS

LIST OF FIGURES ... v

LIST OF TABLES ... vi

ACKNOWLEDGEMENTS ... vii

Chapter 1 Introduction ... 1

- 1.1 Background ... 1
- 1.2 Purpose ... 2
- 1.3 Aims ... 2
- 1.4 Overview ... 3

Chapter 2 Literature Review ... 4

- 2.1 Overview of Literature ... 4
- 2.2 Epidemiology ... 4
  - 2.2.1 Injuries of the Lower Limb ... 4
  - 2.2.2 Injuries of the Foot and Ankle ... 5
- 2.3 Features of Gait ... 6
  - 2.3.1 Footedness and Asymmetry ... 6
  - 2.3.2 Leg Length Discrepancy ... 7
  - 2.3.3 Balance ... 8
- 2.4 Kinematic Variables ... 8
  - 2.4.1 Duration of Contact ... 9
  - 2.4.2 Step/Stride Length and Frequency ... 9
  - 2.4.3 Gait Velocity ... 10
  - 2.4.4 Range of Motion ... 10
- 2.5 Kinetic Variables ... 11
  - 2.5.1 Ground Reaction Forces ... 11
  - 2.5.2 Plantar Pressure ... 12
  - 2.5.3 Center of Pressure and Center of Mass ... 13
- 2.6 Neuromuscular Factors ... 14
- 2.7 Functional Tests and Clinical Outcome ... 14
- 2.8 Summary of Literature ... 15

Chapter 3 Experimental Method ... 16

- 3.1 Overview of Method ... 16
- 3.2 Subjects ... 16
- 3.3 Data Collection Equipment ... 19
- 3.4 Data Collection Procedure ... 21
- 3.5 Data Processing Procedure ... 22
- 3.6 Statistical Analysis ... 25

3.7 Permissions 25
3.8 Summary of Method 26

Chapter 4 Results 27

4.1 Overview of Results 27
4.2 Kinematics 27
4.3 Gait on a Level Surface 28
4.3.1 Duration of Contact 29
4.3.2 Impact Peak Force 29
4.3.3 Active Peak Force 30
4.3.4 Loading Rate 30
4.4 Gait on an Inclined Slope 30
4.4.1 Duration of Contact 31
4.4.2 Impact Peak Force 32
4.4.3 Active Peak Force 32
4.4.4 Loading Rate 33
4.5 Gait on a Declined Slope 33
4.5.1 Duration of Contact 33
4.5.2 Impact Peak Force 34
4.5.3 Active Peak Force 35
4.5.4 Loading Rate 35
4.6 Gait Ascending Stairs 36
4.6.1 Duration of Contact 36
4.6.2 Impact Peak Force 37
4.6.3 Active Peak Force 38
4.6.4 Loading Rate 38
4.7 Gait Descending Stairs 40
4.7.1 Duration of Contact 40
4.7.2 Impact Peak Force 41
4.7.3 Active Peak Force 42
4.7.4 Loading Rate 43
4.8 Summary of Results 44

Chapter 5 Discussion 45

5.1 Overview of Discussion 45
5.2 Study Findings 45
5.2.1 Kinematics 45
5.2.2 Main Findings 46
5.3 Implications of Findings 49
5.4 Reflection on Method 50
5.4.1 Strengths of Method 50
5.4.2 Weaknesses of Method 51
5.4.3 Areas for Future Research 52

5.5 Conclusion 54
5.6 Summary of Discussion 54

Appendix A: Consent & Debrief Forms 55

Appendix B: Waterloo Footedness Questionnaire 58

Appendix C: Full Asymmetry Index Data Set 59

BIBLIOGRAPHY 60

LIST OF FIGURES

Figure 3.1: Flow chart detailing subject exclusions.. 18

Figure 3.2: United Ortho© USA CAM Walker® (left) and USA Air Walker® (right), both in their short versions 20

Figure 3.3: Novel© Loadsols® in their five sizes (left), and the configuration of force sensors in the Novel© Loadsols® used in this experiment 21

Figure 3.4: An example of the force-time plot produced for both feet........................ 23

Figure 3.5: An example of a force-time plot for a single footfall with the first (impact) and second (active) peaks labeled.. 24

LIST OF TABLES

Table 3.1: Mean (SD), Range, and Median of Initial Subject Demographics 17

Table 3.2: Mean (SD), Range, and Median of Final Subject Demographics 19

Table 4.1: Mean (±SD) of Kinematic Variables 28

Table 4.2: Mean (±SD) Level Duration of Contact Asymmetry 29

Table 4.3: Mean (±SD) Level Impact Peak Force Asymmetry 29

Table 4.4: Mean (±SD) Level Active Peak Force Asymmetry 30

Table 4.5: Mean (±SD) Level Loading Rate Asymmetry 30

Table 4.6: Mean (±SD) Inclined Slope Duration of Contact Asymmetry 31

Table 4.7: Mean (±SD) Inclined Slope Impact Peak Force Asymmetry 32

Table 4.8: Mean (±SD) Inclined Slope Active Peak Force Asymmetry 33

Table 4.9: Mean (±SD) Inclined Slope Loading Rate Asymmetry 33

Table 4.10: Mean (±SD) Declined Slope Duration of Contact Asymmetry 34

Table 4.11: Mean (±SD) Declined Slope Impact Peak Force Asymmetry 34

Table 4.12: Mean (±SD) Declined Slope Active Peak Force Asymmetry 35

Table 4.13: Mean (±SD) Declined Slope Loading Rate Asymmetry 36

Table 4.14: Mean (±SD) Ascending Stairs Duration of Contact Asymmetry 37

Table 4.15: Mean (±SD) Ascending Stairs Impact Peak Force Asymmetry 38

Table 4.16: Mean (±SD) Ascending Stairs Active Peak Force Asymmetry 38

Table 4.17: Mean (±SD) Ascending Stairs Loading Rate Asymmetry 39

Table 4.18: Mean (±SD) Descending Stairs Duration of Contact Asymmetry 41

Table 4.19: Mean (±SD) Descending Stairs Impact Peak Force Asymmetry 42

Table 4.20: Mean (±SD) Descending Stairs Active Peak Force Asymmetry 43

Table 4.21: Mean (±SD) Descending Stairs Loading Rates Asymmetry 44

ACKNOWLEDGEMENTS

Dr. John H. Challis: For his endless patience in dealing with my constant procrastination, inconsistency in productivity, and overall craziness. His friendship and mentorship were invaluable to me during my stay at Penn State. Through him, I have learned a great deal about biomechanics and science, in general. I could not have asked for a better mentor.

Samuel Masters: For his assistance in procuring the insoles, explaining their use, and collecting last minute data.

Danny Davis: For his assistance in rationalization of statistical techniques used in this experiment.

Dr. Jinger S. Gottschall: For her selfless actions in extending the deadline on multiple occasions. Her feedback on the initial draft was crucial in producing a final, polished thesis; and without her leniency, I could not have graduated with honors this semester.

The Participants: For their participation in this experiment. Without them, completion of this thesis would not have been possible.

Chapter 1

Introduction

1.1 Background

When humans walk, there is a subtle interplay between the forces applied to the ground by each foot. In the kinematics and kinetics of healthy human walking, there is some degree of asymmetry between the two sides of the body, as exemplified by Sadeghi, Allard, and Duhaime (2000). If one side of the body has suffered an injury, accentuating this asymmetry may be advantageous, as the injured side of the body can have the loads applied to it and/or its range of motion reduced.

Every year in the United States, there are upwards of 200,000 diagnosed cases of ankle sprains, and to aid in the recovery from the injury, 8.1% of the cases are prescribed a CAM boot, as reported by Feger et al. (2017). These boots are believed to help reduce the loads on the foot wearing the CAM boot, according to Graham et al. (2016). Such load reductions can be useful in certain circumstances. For example, 5% of skeletal fractures occur in the metatarsals, as per data from Buddecke, Polk, and Barp (2010). A question arises as to what extent CAM boots are successful in reducing the load on the human body.

Modern technology in the form of force-sensing insoles now permits the measurement of the forces applied to the plantar surface during human gait. Exploiting this technology permits the determination of various aspects of the kinematics and kinetics of human ambulation on a variety of surfaces and the assessment of asymmetries induced by CAM boots.

1.2 Purpose

The purpose of this study was to test the ability of CAM boots to reduce normal reaction forces experienced by the plantar surface of the foot during three different forms of locomotion: level walking, inclined/declined ramp, and ascending/descending stairs.

The forces were measured using force-sensing insoles which were inserted into sneakers and two types of CAM boots. The insoles sampled force over time during ambulation, allowing for the calculation of four variables: duration of contact, impact peak force, active peak force, and loading rate.

It is hypothesized that CAM boot use will exacerbate asymmetry in all four variables between feet as to offload the injured side, as compared to sneakers. It is predicted this will occur in all walking conditions.

1.3 Aims

This experiment sought to examine to what extent CAM boots are effective at reducing normal reaction forces experiences by the foot during ambulation. Specifically, the research questions are:

1) Do CAM boots reduce load on the foot during level walking?
2) Do CAM boots reduce load on the foot during walking up/down a slope?
3) Do CAM boots reduce load on the foot during walking up/down stairs?

Two different types of CAM boots were examined. One had a built-in air pump to improve snugness of fit, and one did not. Data from both types were compared with sneakers and with each other.

1.4 Overview

This thesis consists of five chapters. This chapter is Chapter 1, which introduces the study and states its purpose and aims. Chapter 2 provides a review of relevant literature. The method employed for data collection and processing and statistical analysis is explained in Chapter 3. The results of the study are displayed in Chapter 4. Finally, Chapter 5 presents the results of the study in context relative to the literature, implications of the results, study weaknesses, potential future study ideas, and overall conclusions.

Chapter 2

Literature Review

2.1 Overview of Literature

In overview, this chapter explores the relevant background literature that supports this thesis experiment. It reviews previously published literature on musculoskeletal epidemiology, features of normal gait, kinematic, kinetic, and neuromuscular variables altered through CAM boot use, and clinical and functional outcomes of CAM boot use. Findings reported by the literature are used to pinpoint a gap in the narrative which this thesis seeks to fill.

2.2 Epidemiology

This section examines the epidemiology of injuries to the lower limb, and more specifically, of injuries to the foot and ankle. It also examines the frequency at which CAM boots are prescribed as a treatment for these injuries.

2.2.1 Injuries of the Lower Limb

Injuries of the lower limb disproportionally contribute to the total number of musculoskeletal injuries. In pediatric sports, Gottschalk and Andrish (2011) found that 53% of musculoskeletal injuries occurr in the lower limb, with odds of lower limb injury increasing with age. Four years earlier, Hootman, Dick, and Agel (2007) examined collegiate sports and a found a similar statistic of 53.75% of musculoskeletal injuries occurring in the lower extremity. This trend is not exclusive to the realm of sports and exercise. Hootman et al. (2002) reported that 66.5% of injuries – 68% in men and 65% in women – occur in the lower limb in a mixed sample of sedentary and physically active adults. When ligamentous and tendinous injuries were singled-out, meniscal tears and Achilles tendon ruptures ranked first and fourth with 22.4% and 10.7% of all ligamentous and tendinous injuries according to data from Clayton and Court-Brown (2008). Injuries to the lower limb are prevalent among a wide range of subpopulations.

2.2.2 Injuries of the Foot and Ankle

Of note in particular are injuries to the ankle and foot. Hootman, Dick, and Agel (2007) noted that ankle sprains were the most common injury in collegiate sport, comprising 14.9% of all injuries. Feger et al. (2017) conducted a nationwide survey of ankle sprain patients and discovered that there were upwards of 200,000 diagnosed cases of ankle sprains per year in the United States between 2007-2011, 8.1% of which were prescribed a CAM boot as treatment. In addition to ankle sprains, metatarsal fractures are also a significant injury of the foot and ankle. Buddecke, Polk, and Barp (2010) claimed metatarsal fractures were responsible for 35% of all foot fractures and 5% of skeletal fractures, in general. They also noted the overall support of 2-3 weeks of CAM boot use as treatment among podiatrists and orthopedic specialists. In addition, Firoozabadi, Harnden, and Krieg (2015) and Bonness et al. (2018) demonstrated that immediate partial weight bearing using a CAM boot is generally safe for those diagnosed with benign non-specific ankle fractures and benign distal fibula fractures, respectively. Injuries of the ankle and foot are predominant amongst lower limb musculoskeletal injuries, and research has revealed CAM boots as a popular treatment option.

2.3 Features of Gait

This section examines a few features of gait that may be at play but do not fit into the sections on kinetics or kinematics. These features include the following: footedness (limb dominance), gait asymmetry, leg length discrepancy, and balance.

2.3.1 Footedness and Asymmetry

CAM boot prescription is often done in effort to alter some kinematic and kinetic variables which may cause pain and/or re-injury; but before they are examined, other features of gait must be investigated. One of these features is footedness, a mediator often left unconsidered in biomechanics literature. Accounting for footedness is critical, as Sadeghi, Allard, and Duhaime (1997, 2000) uncovered natural functional asymmetry in normal human gait via the roles played by the dominant and non-dominant limbs. They claimed the dominant limb plays a larger role in fine control and balance, while the non-dominant limb contributes more to propulsion. Sadeghi, Allard, Prince, and Labelle (2000) also noticed that many research articles in the field did not offer a clear definition of asymmetry and assumed symmetry despite findings of inherent asymmetrical gait. Asymmetry is an important factor to adequately define and consider, as asymmetry is shown to always be at play, even in natural gait.

Over the years, there have been several methods proposed for measuring limb lateralization. According to Oldfield (1971), the two most frequently utilized methods involved observing limb preferences in menial tasks performed by the subject and having the subject self-report on which limb they would use in a given activity. He argued the latter is more valid and accurate, as such measures are less subject to external factors of a subject's background and that they more accurately represent lateralization in the form of an "unsymmetrical U" (i.e. a bimodal distribution). Elias, Bryden, and Bulman-Fleming (1998) developed one such method, which they named the "Waterloo Footedness Questionnaire," in their paper that revealed footedness is a better predictor of emotional lateralization than handedness. With each limb having a different contribution to overall gait, it is crucial to measure and control for footedness.

2.3.2 Leg Length Discrepancy

Another important factor to contemplate when prescribing and/or wearing CAM boots is the creation of a leg-length discrepancy (LLD). By virtue of the existence of a LLD, natural gait asymmetry is exacerbated, often so much so as to become pathological. Knutson (2005) concluded that LLDs greater than two centimeters are clinically significant. Khamis and Carmeli (2017) later determined that LLDs greater than one centimeter can cause gait asymmetries that lead to statistically different results in experimentation. To combat this concept, Cabral et al. (2016) developed a Global Asymmetry Index that can quickly and reliably measure pathological asymmetries for real-time feedback using variables such as ground reaction forces, duration of contact, or leg length. In assessing leg length and potential LLDs, Sabharwal and Kumar (2008) identified over 40 methods used in published articles and concluded that computerized tomography (CT) scanogram is the recommended method. This method was originally proposed by Helms and McCarthy (1984). Utilization of CAM boots typically induces a LLD, barring rare cases where it may remedy a pre-existing one. Therefore, it is important to be cognizant of this fact, because a great enough disparity in leg length may lead to significant gait asymmetries and potential future complications.

2.3.3 Balance

A third factor of gait to consider, possibly due to an induced LLD, is balance. One is said to be balanced when their center of mass (i.e. the point around which mass is evenly distributed) remains within the confines of their base of support. A LLD may shift center of mass, facilitating deviation from the base of support. Through motion capture, Goodworth et al. (2014) were able to show that CAM boots cause the upper body to tilt and sway in standing tasks. CAM boots also caused exacerbated upper body movement during perturbed and unperturbed ambulation. These phenomena are compensatory alterations in posture and gait as a result of CAM boot application. It is also worth noting that unlike infants, adults did not adopt symmetrical gait in the presence of a LLD, according to data collected by Cole, Gills, Vereijken, & Adolph (2014). This suggests that while compensatory changes in posture and gait will ensue, human adults do not attempt to or are not effective at remedying the asymmetry in real-time.

2.4 Kinematic Variables

This section examines some kinematic variables related to ambulation. Kinematics refers to the motion of objects, ignoring the forces which caused the motion. The variables examined in this section are the following: duration of contact, step/stride length and frequency, gait velocity, and range of motion.

2.4.1 Duration of Contact

Of gait-related kinematic variables, perhaps the simplest is duration of contact (i.e. the timespan in which the foot is in physical contact with the walking surface). In a typical gait cycle, a given foot is in contact for 60% of one cycle, but the absolute time per cycle is dependent on other factors, such as step frequency and gait velocity. One study by Powell, Clowers, Keefer, and Zhang (2012) reported no differences in average duration of contact between CAM boot and shod walking. However, another experiment studying the effects of LLDs and added masses to the distal leg contradicted this. Muratgaic, Ramakrishnan, and Reed (2017) published results that suggest both LLDs and distal added masses increase duration of contact independently of one another. The literature on this variable is limited, conflicted, and inconclusive. More evidence is required before a conclusion can be drawn.

2.4.2 Step/Stride Length and Frequency

Step/stride length and step/stride frequency are more kinematic variables which may be affected by CAM boot use. Step length refers to the distance covered between two footfalls, while step frequency is a measure of how often in time footfalls occur and can be referred to as cadence. A stride is simply two steps - one per side. Muratagic, Ramakrishnan, and Reed (2017) reported no differences in stride length in their experiment examining LLDs and distal added masses. Böhm and Hösl (2010) discovered that the stiffness of a boot’s shaft (i.e. the section from mid-arch to the top of the boot) has no effect on cadence or stride length. Cadence and stride length are also unaffected by the use of several CAM boot designs, as found by Pollo, Gowling, and Jackson (1999). Step/stride length and step/stride frequency appear constant between shod walking and walking in CAM boots.

2.4.3 Gait Velocity

The product of step/stride length and frequency yields gait velocity (i.e. how quickly one is walking). Bohannon (1997) suggested that humans typically walk at an average speed of 1.27-1.46m/s. Several of the experiments listed previously also reported findings on gait velocity. Böhm and Hösl (2010) claimed that boot shaft stiffness has no effect on gait velocity. Pollo, Gowling, and Jackson (1999) discovered that several CAM boot designs have no effect on gait velocity, either. Another study, conducted by Richards, Payne, Myatt, and Chohan (2016), supported this finding that CAM boots do not cause a significant difference in gait velocity. But, one study did contradict these, as Gulgin, Hall, Luzadre, and Kayfish (2018) noted a significant 9-13% decrease in gait velocity when wearing a CAM boot. A majority of the literature reports no difference in gait velocity between shod walking and walking in a CAM boot, but contradictory findings do exist.

2.4.4 Range of Motion

A fourth and final kinematic variable to be considered is range of motion (ROM). Reduction of ROM is one of the two main intended functions of CAM boots. Reduction of ROM is traditionally used in the healing process of tendinous and ligamentous injury (e.g. an Achilles tendon rupture), but it may also be beneficial for certain skeletal fractures. It was suggested by Yang, Fang, He, & Fu (2017) that increased shoe collar height results in decreased dorsiflexion of the ankle. In examining boot shaft stiffness, Böhm and Hösl (2010) found that increased rigidity in boot shaft decreases ankle ROM in all directions. Zhang, Clowers, and Powell (2006) found that CAM boots reduce hip abduction and ankle eversion. McHenry et al. (2017) complemented this research by finding that CAM boots also reduce talocrural and subtalar ROM in the sagittal plane, with the magnitude of the decrease dependent on the height of the CAM boot shaft. Tall CAM boots caused larger decreases in ROM than short CAM boots. In the specific case of a torn Achilles tendon, the foot is commonly fixed in equinus (i.e. immobilized dorsiflexion of the ankle) as part of treatment. MacDonald, Neilly, Littlechild, Harrold, & Roberts (2018) demonstrated that CAM boots are not as effective in this regard as traditional casts. Once more, there is a study to contradict the majority of findings. Pollo, Gowling, and Jackson (2012) showed that CAM boot use results in no significant differences in ROM from shod walking. Prevalent findings suggest that CAM boots are effective at ROM reduction, but the claim is not shared unanimously throughout the literature.

2.5 Kinetic Variables

This section examines some kinetic variables related to ambulation. Kinetics refers to forces which cause motion and their derivatives. The variables examined in this section are the following: ground reaction forces, plantar pressure, and center of pressure and center of mass.

2.5.1 Ground Reaction Forces

The second of the two main intended functions of CAM boots is reduction of ground reaction force (GRF) experienced by the injured foot. Reduction of this variable is critical in the healing process of skeletal fractures. Hayes et al. (1996) established a risk factor for skeletal fractures, ϕ, defined as load/force applied divided by load/force necessary for a fracture to occur. Hayes' team applied this specifically to the femur; but in theory, it holds true for any long bone, including the metatarsals. Therefore, it stands that reducing applied force would reduce risk of fracture or re-injury. Muratagic, Ramakrishnan, and Reed (2017) discovered that both added distal masses and LLDs decrease peak vertical GRF when applied to the same foot. Azizan et al. (2018) took their analysis a bit further and determined that LLDs increase GRFs experienced by the shorter limb. In the case of wearing a CAM boot, this is the non-injured leg.

The literature on the relationship between CAM boot use and GRFs experienced by the foot inside is polarized. Gulgin, Hall, Luzadre, and Kayfish (2018) suggested the peak GRF dropped a significant 2-3% when CAM boots were worn, but Zhang, Clowers, and Powell (2006) provided data that showed no difference in peak GRF between CAM boots and sneakers. Their data, however, displayed significant increases in GRF mid-stance. The current literature on the relationship between CAM boot use and GRF is inconclusive, necessitating the need for further study.

2.5.2 Plantar Pressure

Plantar pressure describes the magnitude of GRF over a specified area of the plantar surface of the foot. A study by DiLiberto, Baumhauer, Wilding, and Nawoczenski (2017) demonstrated that CAM boots reduce plantar pressures compared to shod walking. Hunt et al. (2014) specifically examined planter pressures at the fifth metatarsal, the location of a Jones Fracture. Hunt's team discovered that CAM boots were effective in reducing peak plantar pressure at the fifth metatarsal compared with sneakers and post-operative sandals. Their study was based on research by Petrisor, Ekrol, & Court-Brown (2006), which found that Jones Fractures account for 68% of all metatarsal fractures. In addition, LLDs alter plantar pressure distribution. Both Eliks, Ostiak-Tomaszewska, Lisiński, and Koczewski (2017) and Swathinathan, Cartwright-Terry, Moorehead, Bowey, and Scott (2014) noticed that LLDs shift weight and pressure to the foot of the short leg. While CAM boots appear effective at reducing pressures experienced by the injured foot, they also increase load on the shorter leg.

2.5.3 Center of Pressure and Center of Mass

Center of pressure, in this context, is the point where GRFs can be considered to act through on the plantar surface of the foot. During partial weight bearing, as is often recommended in CAM boot prescriptions, the center of pressure shifted posteriorly, as per data from North, Potter, Kubiak, Morris-Bamberg, and Hitchcock (2012). Furthermore, LLDs can affect these variables, as well. Eliks, Ostiak-Tomaszewska, Lisiński, and Koczewski (2017) reported significant increases in center of pressure velocity in subjects with natural LLDs compared to subjects without them. Center of pressure velocity refers to the speed at which center of pressure translates relative to the plantar surface of the foot during ambulation. LLDs also caused significantly altered center of mass trajectories (i.e. the imaginary line along which center of mass travels during ambulation), according to Azizan et al. (2018). Lee & Farley (1998) claimed the two major determinants in center of mass trajectory are leg touchdown angle and stance limb compression, proposing two possible mechanisms behind the altered center of mass trajectories.

2.6 Neuromuscular Factors

The kinetic and kinematic variables discussed above arise via a chain of command in the central nervous system. In order to uncover the mechanism behind some of the changes described above, any neuromuscular alterations must be investigated. Powell, Clowers, Keefer, and Zhang (2012) used electromyography and found that CAM boot use leads to earlier activation of motor neurons and prolonged activation with no difference in amplitude. This one study is enough to raise concern, because Matijevich, Branscombe, Scott, and Zelik (2019) discovered that loads applied to bone are not strongly correlated with GRF but with internal muscle forces. This new study suggested that reducing GRFs are less critical in preventing re-injury or discomfort than is lowering internal muscle forces. If CAM boots prolong the duration of motor neuron activation, then they also prolong the exposure of bone to these massive internal forces produced by muscle contraction.

2.7 Functional Tests and Clinical Outcome

Despite all the conflicting experimental evidence, studies on functional and clinical outcomes can shed light as to whether or not CAM boots are perceived as effective by the patients using them. Shahid, Punwar, Boulind, and Bannister (2013) noticed that Jones Fracture patients whom were prescribed CAM boot reported better function and less pain than patients whom were prescribed a cast. CAM boot patients also returned to work after an average of 31.5 days - 7.7 days earlier than those in casts. Efforts were also made to resolve the issue of LLD creation associated with CAM boot use. The Evenup™ shoe lift aimed to eliminate LLDs by extending the shorter leg. Kipp, Village, and Edwards (2017) examined this tool and found that patients using it reported less pain, better function, and better ankle strength than those not using the device. However, these differences were found to be statistically insignificant. Patients report CAM boots as effective tools, but the mechanism(s) behind why they promote better outcomes is/are not quite understood. Additionally, attempts to remedy the LLDs created by CAM boots appear ineffective.

2.8 Summary of Literature

In summary, injuries of the lower limb, and especially those of the foot and ankle, are overrepresented amongst musculoskeletal injuries. Epidemiological data suggest that improving treatment of these injuries would be beneficial to many. However, evidence on the efficacy of one orthopedic device in particular – CAM boots – is inconsistent. It is known that much of the current literature surrounding these devices ignores footedness and wrongfully assumes symmetry. It is also known that CAM boots tend to cause LLDs, have no effect on step/stride length and frequency, reduce ROM, reduce plantar pressure on the injured foot, shift load and plantar pressure to the opposite leg, alter center of mass trajectories, and increase duration of motor neuron activation. But, it is less certain whether CAM boots lead to measurable differences in duration of contact, gait velocity, and normal reaction forces experienced by the plantar surface of the foot and prove to be more than just a placebo. Further investigation is necessary to determine the usefulness of these devices and if their prescription rate is warranted.

Chapter 3

Experimental Method

3.1 Overview of Method

In overview, this study examined the reaction forces normal to the plantar surface of the foot in subjects during ambulation with and without a CAM boot in three different walking tasks. In the following sections of this chapter, the subject sample is described, followed by descriptions of the data collection equipment, data collection procedures, methods used for data processing, procedures for statistical analysis, and permissions granted.

3.2 Subjects

Twenty healthy subjects were initially recruited for this study. They were recruited from the local community at The Pennsylvania State University via word-of-mouth. Exclusion criteria were the following: existing musculoskeletal injury and/or neurological disorder currently resulting in visibly altered gait, pre-existing musculoskeletal injuries and/or neurological disorder that has permanently visibly altered gait, and a reported age of under 18 years. Subjects confirmed the absence of these criteria during the consent process. All subjects implied informed consent when they opted to participate (see Appendix A). The initial study sample included eight males and twelve females. The subjects had a mean age of 25.3 ± 7.4 years, height of 1.72 ±

0.09m, and mass of 84.9 ± 27.5kg. Of the twenty subjects, nineteen were determined right-footed and one was determined left-footed (see Table 3.1).

Table 3.1: Mean (SD), Range, and Median of Initial Subject Demographics

Initial Subject Demographics				
Overall (n=20):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	25.2 (±7.4)	1.72 (±0.09)	84.9 (±27.5)	NA
Range	20-52	1.46-1.87	58.9-172.0	NA
Median	22	1.71	76.0	NA
Males (n=8):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	23.9 (±3.6)	1.79 (±0.07)	95.4 (±19.5)	10.9 (±1.3)
Range	21-30	1.65-1.87	78.6-125.5	9-13
Median	22	1.79	89.4	11
Females (n=12):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	26.2 (±9.1)	1.67 (±0.07)	77.9 (±30.5)	8.8 (±1.6)
Range	20-52	1.46-1.74	58.9-172.0	6-13
Median	22	1.68	70.7	9

Note: Shoe sizes are respective to sex.

Due to various circumstances, twelve subjects were excluded post-consent. All excluded subjects were compensated in accordance with protocol. A total of eight subjects' data sets was left to be included in the final data analysis (see Figure 3.1).

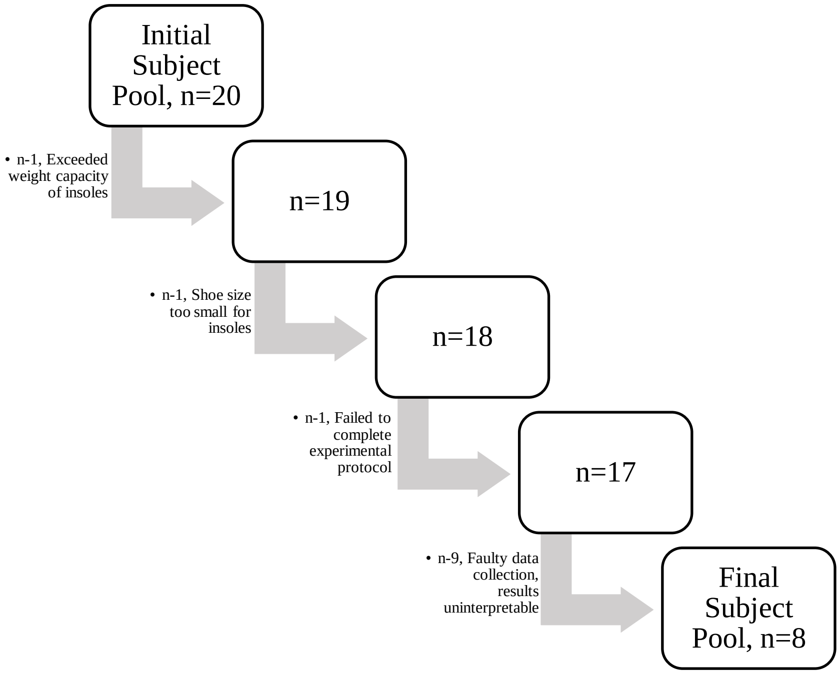

Figure 3.1: Flow chart detailing subject exclusions

The final study population included three males and five females, for a total of eight subjects to be included in data analysis. The subjects had a mean age of 24.3 ± 3.5 years, height of 1.71 ± 0.08m, and mass of 79.9 ± 19.2kg. Of the remaining eight subjects, all eight were determined right-footed (see Table 3.2).

Table 3.2: Mean (SD), Range, and Median of Final Subject Demographics

Final Subject Demographics				
Overall (n=8):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	24.3 (±3.5)	1.71 (±.08)	79.9 (±19.2)	NA
Range	21-30	1.64-1.87	63.5-123.6	NA
Median	23	1.69	76.0	NA
Males (n=3):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	25.3 (±3.2)	1.78 (±0.11)	93.2 (±26.3)	10.3 (±1.5)
Range	23-29	1.65-1.87	77.5-123.6	10-12
Median	24	1.81	78.6	10
Females (n=5):				
	Age (yr)	**Height (m)**	**Mass (kg)**	**Shoe Size (U.S.)**
Mean (SD)	23.6 (±3.8)	1.68 (±0.03)	71.8 (±9.3)	8.6 (±0.5)
Range	21-30	1.64-1.71	63.5-86.5	8-9
Median	22	1.68	70.0	9

Note: Shoe sizes are respective to sex

3.3 Data Collection Equipment

CAM walker boots – The CAM walker boots purchased for the purposes of this experiment were United Ortho© USA Walker and United Ortho© USA Air Walker. Three of each boot were purchased in three sizes: small (men’s 5-6, women’s 5.5-7), medium (men’s 6.5-10, women’s 7.5-11), and large (men’s 10.5-12, women’s 11.5+). The “short” versions of each boot were used in the experiment, each a shortened boot shaft with three fitting straps. The USA Air Walker includes a built-in air pump for better fitting and further reduction of ROM (see Figure 3.2).

Figure 3.2: United Ortho© USA CAM Walker® (left) and USA Air Walker® (right), both in their short versions

Insoles – Subjects were fitted with force-sensing insoles on both feet, so the reaction forces normal to the plantar surface of the foot could be measured. The insoles were Loadsol® insoles from Novel©. The following size insoles were used: small, medium, large, extra-large. The insoles' force measurements were sampled at 100Hz with a 5N resolution over a force range of 0-2250N. Samples were transmitted to a smartphone via Bluetooth using the "pedoped loadsol" application created by Novel©, version 1.4.88. The insoles included three force-sensing areas: heel sensor (40% of area), anteromedial sensor (30%), and anterolateral sensor (30%) (see Figure 3.3). Previous research by Barnett, Cunningham, and West (2001) concluded that these insoles are equally accurate and precise as conventional force plates.

Figure 3.3: Novel© Loadsols® in their five sizes (left), and the configuration of force sensors in the Novel© Loadsols® used in this experiment

3.4 Data Collection Procedure

After measuring subject mass and height, footedness was determined via the Waterloo Footedness Questionnaire created by Elias, Bryden, and Bulman-Fleming (1998). Footedness results were confirmed by the subject (see Appendix B). Each subject then performed three activities: walking on a level surface, walking up and down a ramp, and walking up and down a set of stairs. Each of these three tasks was performed three times: once in sneakers, once in the USA Walker® boot, and once in the USA Air Walker® boot. The order of these conditions and tasks was randomized per subject, as was the direction order, using a random number generator. The specific details for each walking condition were:

Level Surface - 25m at 0° slope

Ramp – 25m at a 2.4° slope

Stairs – 54 stairs at 0.15m high by 0.32m long with two 1.8m landings resulting in a 22.4m hypotenuse at 21.2°

During all trials, the CAM boot was worn on the dominant foot, as Sadeghi, Allard, and Duhaime (2000) have demonstrated the dominant and non-dominant limbs have been shown to play different roles - one of propulsion and one of fine control - during ambulation. Subjects were given one or two minutes to acclimate to walking in CAM boots before data collection began. Subjects were not instructed to alter their gait in any way. All subjects were determined right-footed and wore the CAM boots on their right foot.

3.5 Data Processing Procedure

From the distance traveled and time in motion, mean gait velocity was determined. From the insoles the following variables were determined for each combination of condition and task:

- Number of footfalls
- Step frequency (cadence)
- Duration of foot contact
- Impact peak force
- Active peak force
- Loading rate to impact peak

For four of these variables, the data created a time series. These were created separately for the CAM foot and non-CAM foot (see Figure 3.4 and Figure 3.5). Even for the condition where a CAM boot was not worn, the feet are still referred to a CAM foot and non-CAM foot so comparisons could be made between the corresponding feet during all conditions.

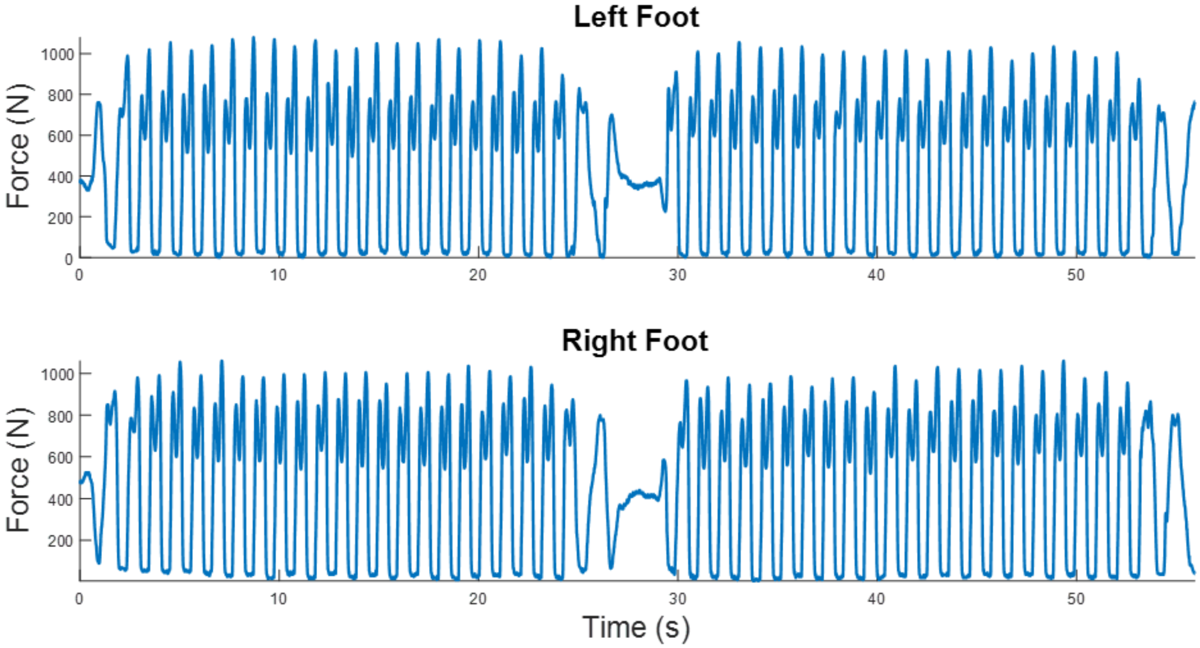

Figure 3.4: An example of the force-time plot produced for both feet

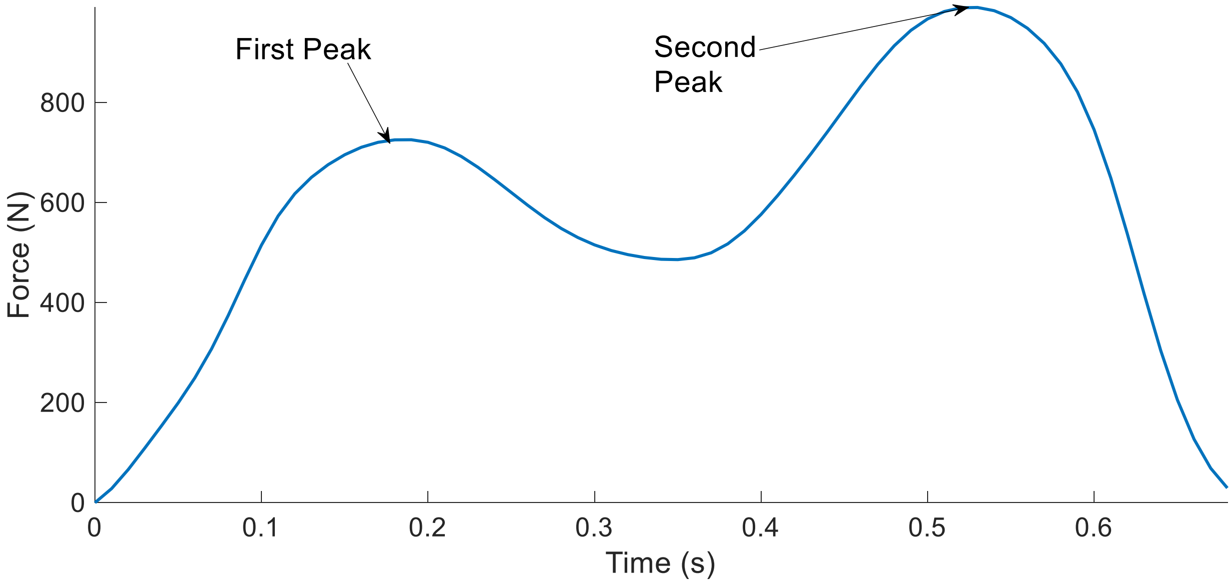

Figure 3.5: An example of a force-time plot for a single footfall with the first (impact) and second (active) peaks labeled

The first and last four footfalls were manually removed to combat interference due to accelerating to and from a standstill. The force insole data were filtered in forward and backward directions with a second-order low-pass Butterworth filter. By using the filter in both directions, it doubled the filter order and removed phase lag. The filter cutoff used was 25Hz. A force threshold of 20N was used to determine initial foot contact and cessation of contact. Forces were normalized for every subject using their weight.

To assess symmetry or asymmetry between footfalls, the Bland and Altman (1986) method of differences was used. This method requires the graphical analysis of a sequential pair of footfalls, left and right, the mean of the metrics of the two footfalls, and the difference between the metrics for each pair of footfalls. To determine if there was a proportional bias with increasing size of a given metric, a regression line was fit to the data from the Bland and Altman analysis, and the gradient of the line was assessed to see if it was statistically different from zero.

To assess if there was a relative bias between the left and right footfalls, the differences in the Bland and Altman analysis were compared to zero using a one-sample t-test.

In addition, the Symmetry Index (SI) from Sadeghi, Allard, Prince, and Labelle (2000) was computed to determine differences between feet within a condition, where XR and XL are the gait variables measured for the right and left limb respectively. The index outputs a percentage by which the right foot is greater or less than the left (see equation below).

$$SI=100 \text{ x } [(XR-XL)/0.5(XR+XL)]$$

3.6 Statistical Analysis

Descriptive statistics were determined for all measured variables. All statistical analyses were performed in MATLAB©. Wilcoxon Matched Pairs Signed Rank tests were used to determine significant differences in Symmetry Index scores between conditions.

3.7 Permissions

This study was approved by the Institutional Review Board at The Pennsylvania State University. Subjects implied consent upon their decision to participate and were not required to fill out consent forms.

3.8 Summary of Method

In summary, eight subjects participated in an experiment to examine reaction forces normal to the plantar surface of the foot between sneakers and two types of CAM walker boots during ambulation under three different walking conditions. Subjects were of at least 18 years of age and lacked visually abnormal gait. Following consent, a footedness questionnaire was used to determine the dominant foot. Subjects were then asked to walk on a flat surface, walk up and down a 2.4° sloped ramp, and walk up and down a flight of stairs, all while fitted with force-sensing insoles and wearing sneakers or a CAM boot on their dominant foot. The insoles output normal reaction forces over time, allowing for analysis of the following variables: number of footfalls, step frequency (cadence), duration of foot contact, gait velocity, impact peak force, active peak force, and loading rate to impact peak.

Chapter 4

Results

4.1 Overview of Results

In overview, this chapter presents the analyzed data. Sections of this chapter are separated by walking task, then further separated by the variable being analyzed. Kinematic data are presented first, followed by level walking, walking on an inclined/declined ramp, and ascending/descending stairs. Excluding kinematic data, each section is divided into four sections: duration of contact, impact peak force, active peak force, and loading rate. A full data set is included (see Appendix C). In this chapter, smaller pieces of the table are dissected in their corresponding sections.

4.2 Kinematics

Several kinematic variables are reported here, but statistical analysis was not done on them. Number of footfalls was greatest during the walking trials on the stairs, averaging 52.25–55.75 footfalls across both directions. The least number of footfalls occurred during the trials on the ramp, which averaged 30.57–33.5 footfalls across both directions. There was little variation in number of footfalls between directions and between footwear conditions.

Cadence, measured in steps per minute, was consistently greatest on the ramp. Average cadences on the ramp ranged from 106.18–113.74 steps/min. The stair trials produced the slowest cadences, with averages ranging from 87.09–108.39 steps/min. The sneaker condition consistently demonstrated higher average cadences than both CAM boots, which differed little from one another. Sneaker averages spanned 102.2–113.74 steps/min, while both boots demonstrated a range of 87.09–110.43 steps/min. There appeared to be little difference between directions.

Gait velocity, expressed in meters per second, exhibited more drastic variation than the previous two variables. Gait velocities were fastest across the board in the ramp trials, with average velocities of 1.39-1.66m/s. They were slowest on stair trials, with a range of 0.58-0.78m/s. Outside of the ramp trials, the Sneaker condition resulted in marginally quicker gait velocities in the flat and stair trials. CAM and Air CAM conditions proved similar in gait velocity across all three conditions. Little difference was found between directions.

A full table of kinematic data is listed below (see Table 4.1). Step/stride length was not examined but could be found by dividing the distance covered by the number of footfalls.

Table 4.1: Mean (±SD) of Kinematic Variables

Mean (±SD) of Kinematic Variables										
		Sneaker Flat	**Sneaker Ramp**	**Sneaker Stairs**	**CAM Flat**	**CAM Ramp**	**CAM Stairs**	**Air Flat**	**Air Ramp**	**Air Stairs**
Up	**# of Footfalls**	38.25 (±3.45)	31.5 (±1.41)	53.75 (±1.98)	40.00 (±1.85)	30.57 (±1.90)	55.5 (±2.33)	39.5 (±1.77)	31.25 (±2.37)	54.5 (±2.07)
	Cadence (steps/min)	107.82 (±5.23)	112.63 (±3.70)	102.02 (±6.20)	101.19 (±5.68)	106.18 (±5.98)	87.09 (±9.49)	101.62 (±6.09)	107.74 (±3.41)	91.13 (±6.06)
	Gait Velocity (m/s)	1.17 (±0.08)	1.49 (±0.08)	0.71 (±0.06)	1.05 (±0.06)	1.45 (±0.11)	0.59 (±0.06)	1.07 (±0.07)	1.44 (±0.13)	0.64 (±0.05)
		Sneaker Flat	**Sneaker Ramp**	**Sneaker Stairs**	**CAM Flat**	**CAM Ramp**	**CAM Stairs**	**Air Flat**	**Air Ramp**	**Air Stairs**
Down	**# of Footfalls**	39 (±3.55)	33.43 (±1.51)	52.25 (±3.62)	41.25 (±5.01)	31.14 (±9.01)	54.75 (±2.38)	36.5 (±8.47)	33.5 (±2.07)	55.75 (±1.98)
	Cadence (steps/min)	107.86 (±4.62)	113.74 (±3.02)	108.39 (±6.68)	100.67 (±6.17)	108.16 (±7.54)	93.46 (±13.53)	101.55 (±5.52)	110.43 (±3.68)	97.56 (±13.05)
	Gait Velocity (m/s)	1.16 (±0.11)	1.42 (±0.06)	0.78 (±0.05)	1.03 (±0.14)	1.66 (±0.90)	0.64 (±0.09)	1.27 (±0.57)	1.39 (±0.10)	0.65 (±0.09)

Note: While briefly described, no statistical examination was performed on these variables.

4.3 Gait on a Level Surface

This section examines asymmetry in the four values (duration of contact, impact peak force, active peak force, and loading rate) during ambulation on a level surface.

4.3.1 Duration of Contact

There was one significant difference in asymmetry in duration of contact between footwear conditions during gait on a level surface (see Table 4.2).

The difference was found between CAM vs. Air CAM conditions. In the CAM condition, duration of contact was 0.77 (±0.05) seconds for the non-CAM foot and 0.72 (±0.05) seconds for the CAM foot. The non-CAM foot was favored with a 6.20% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001). In the Air CAM condition, duration of contact was 0.76 (±0.05) seconds for the non-CAM foot and 0.73 (±0.04) seconds for the CAM foot. The non-CAM foot was favored with a 4.01% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.2: Mean (±SD) Level Duration of Contact Asymmetry

Mean (±SD) Level Duration of Contact Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM***	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-2.44 (±4.23)	-6.20 (±2.85)	-2.44 (±4.23)	-4.01 (±2.51)	-6.20 (±2.85)	-4.01 (±2.51)

Note: * denotes significance at p<.05

4.3.2 Impact Peak Force

There were no significant differences in asymmetry between footwear conditions for impact peak force while walking on a level surface (see Table 4.3).

Table 4.3: Mean (±SD) Level Impact Peak Force Asymmetry

Mean (±SD) Level Impact Peak Force Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
4.79 (±12.11)	5.17 (±13.41)	4.79 (±12.11)	9.80 (±12.56)	5.17 (±13.41)	9.80 (±12.56)

Note: * denotes significance at p<.05

4.3.3 Active Peak Force

There were no significant differences in asymmetry between footwear conditions for active peak force while walking on a level surface (see Table 4.4).

Table 4.4: Mean (±SD) Level Active Peak Force Asymmetry

Mean (±SD) Level Active Peak Force Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
3.94 (±12.60)	0.49 (±17.36)	3.94 (±12.60)	3.55 (±17.69)	0.49 (±17.36)	3.55 (±17.69)

Note: * denotes significance at p<.05

4.3.4 Loading Rate

There were no significant differences in asymmetry between footwear conditions for loading rate while walking on a level surface (see Table 4.5).

Table 4.5: Mean (±SD) Level Loading Rate Asymmetry

Mean (±SD) Level Loading Rate Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
7.09 (±15.02)	1.16 (±22.20)	7.09 (±15.02)	8.76 (±16.08)	1.16 (±22.20)	8.76 (±16.08)

Note: * denotes significance at p<.05

4.4 Gait on an Inclined Slope

This section examines asymmetry in the four values (duration of contact, impact peak force, active peak force, and loading rate) during ambulation on an inclined slope.

4.4.1 Duration of Contact

There were two significant differences in asymmetry in duration of contact between footwear conditions during ambulation on an inclined ramp (see Table 4.6).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, duration of contact was 0.68 (±0.03) seconds for the left foot and 0.58 (±0.02) seconds for the right foot. The left foot was favored with a 1.42% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, duration of contact was 0.74 (±0.05) seconds for the non-CAM foot and 0.69 (±0.04) seconds for the CAM foot. The non-CAM foot was favored with a 6.49% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001).

The second difference was found between CAM vs. Air CAM conditions. In the CAM condition, duration of contact was 0.74 (±0.05) seconds for the non-CAM foot and 0.69 (±0.04) seconds for the CAM foot. The non-CAM foot was favored with a 6.49% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001). In the Air CAM condition, duration was 0.71 (±0.03) seconds for the non-CAM foot and 0.69 (±0.02) seconds for the CAM foot. The non-CAM foot was favored with a 3.18% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.6: Mean (±SD) Inclined Slope Duration of Contact Asymmetry

Mean (±SD) Inclined Slope Duration of Contact Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM***	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-1.42 (±1.03)	-6.49 (±2.57)	-2.35 (±2.80)	-3.66 (±3.68)	-6.49 (±2.57)	-3.18 (±3.69)

Note: * denotes significance at p<.05

4.4.2 Impact Peak Force

There were no significant differences between footwear conditions for impact peak force during ambulation on an inclined slope (see Table 4.7).

Table 4.7: Mean (±SD) Inclined Slope Impact Peak Force Asymmetry

Mean (±SD) Inclined Slope Impact Peak Force Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
8.60 (±8.66)	8.68 (±11.96)	5.18 (±12.56)	7.19 (±19.27)	8.68 (±11.96)	12.94 (±11.17)

Note: * denotes significance at p<.05

4.4.3 Active Peak Force

There was one significant difference in asymmetry in active peak force between footwear conditions during ambulation on an inclined ramp (see Table 4.8).

The difference was found between CAM vs. Air CAM conditions. In the CAM condition, active peak force was 1.24 (±0.21) Newtons of force per Newton of bodyweight for the non-CAM foot and 1.16 (±0.20) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 6.63% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001). In the Air CAM condition, active peak force was 1.19 (±0.18) Newtons per Newton of bodyweight for the non-CAM foot and 1.18 (±0.18) Newtons per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 1.43% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05).

Table 4.8: Mean (±SD) Inclined Slope Active Peak Force Asymmetry

Mean (±SD) Inclined Slope Active Peak Force Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM***	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
8.40 (±13.00)	-6.63 (±24.01)	7.82 (±12.14)	-0.44 (±20.29)	-6.63 (±24.01)	-1.43 (±21.70)

Note: * denotes significance at p<.05

4.4.4 Loading Rate

There were no significant differences between footwear conditions for loading rate during ambulation on an inclined slope (see Table 4.9).

Table 4.9: Mean (±SD) Inclined Slope Loading Rate Asymmetry

Mean (±SD) Inclined Slope Loading Rate Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
10.66 (±10.76)	15.37 (±18.74)	7.68 (±13.03)	12.06 (±22.31)	15.37 (±18.74)	18.68 (±13.07)

Note: * denotes significance at p<.05

4.5 Gait on a Declined Slope

This section examines asymmetry in the four values (duration of contact, impact peak force, active peak force, and loading rate) during ambulation on a declined slope.

4.5.1 Duration of Contact

There was one significant difference in asymmetry in duration of contact between footwear conditions during ambulation on a declined ramp (see Table 4.10).

The difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, duration of contact was 0.68 (±0.04) seconds for the left foot and 0.65 (±0.02) seconds for the right foot. The left foot was favored with a 1.69% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, duration of contact was 0.71 (±0.05) seconds for the non-CAM foot and 0.67 (±0.04) seconds for the CAM foot. The non-CAM foot was favored with a 5.61% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.10: Mean (±SD) Declined Slope Duration of Contact Asymmetry

Mean (±SD) Declined Slope Duration of Contact Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-1.69 (±0.68)	-5.61 (±3,74)	-3.65 (±5.22)	-5.56 (±2.78)	-5.55 (±3.41)	-5.21 (±2.63)

Note: * denotes significance at p<.05

4.5.2 Impact Peak Force

There were no significant differences in asymmetry between footwear conditions for impact peak force during ambulation on a declined slope (see Table 4.11).

Table 4.11: Mean (±SD) Declined Slope Impact Peak Force Asymmetry

Mean (±SD) Declined Slope Impact Peak Force Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
13.02 (±9.43)	11.49 (±18.48)	8.64 (±14.44)	5.03 (±19.17)	13.50 (±17.69)	12.52 (±12.67)

Note: * denotes significance at p<.05

4.5.3 Active Peak Force

There was one significant difference in asymmetry in active peak force between footwear conditions during ambulation on a declined ramp (see Table 4.12).

The difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, active peak force was 1.11 (±0.10) Newtons of force per Newton of bodyweight for the left foot and 1.16 (±0.14) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 7.35% asymmetry. Bland-Altman analysis indicated a relative bias (p<.01). In the CAM condition, active peak force was 1.06 (±0.10) Newtons of force per Newton of bodyweight for the non-CAM foot and 1.06 (±0.17) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 4.62% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.12: Mean (±SD) Declined Slope Active Peak Force Asymmetry

Mean (±SD) Declined Slope Active Peak Force Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
7.35 (±13.23)	-4.62 (±16.34)	5.99 (±12.60)	-3.55 (±18.05)	-2.03 (±16.41)	-3.96 (±17.78)

Note: * denotes significance at p<.05

4.5.4 Loading Rate

There were no significant differences in asymmetry between footwear conditions for loading rate during ambulation on a declined slope (see Table 4.13).

Table 4.13: Mean (±SD) Declined Slope Loading Rate Asymmetry

Mean (±SD) Declined Slope Loading Rate Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
18.87 (±12.91)`	17.82 (±20.80)	15.73 (±17.12)	7.70 (±25.90)	16.95 (±21.08)	15.03 (±18.30)

Note: * denotes significance at p<.05

4.6 Gait Ascending Stairs

This section examines asymmetry in the four values (duration of contact, impact peak force, active peak force, and loading rate) while ascending stairs.

4.6.1 Duration of Contact

There were two significant differences in asymmetry in duration of contact between footwear conditions while ascending stairs (see Table 4.14).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, duration of contact was 0.75 (±0.05) seconds for the left foot and 0.74 (±0.05) seconds for the right foot. The left foot was favored with a 0.78% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, duration of contact was 0.91 (±0.11) seconds for the non-CAM foot and 0.83 (±0.09) seconds for the CAM foot. The non-CAM foot was favored with an 8.58% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between CAM vs. Air CAM conditions. In the CAM condition, duration of contact was 0.91 (±0.11) seconds for the non-CAM foot and 0.83 (±0.09) seconds for the CAM foot. The non-CAM foot was favored with an 8.58% asymmetry. Bland-Altman analysis indicated no bias. In the Air CAM condition, duration of contact was 0.85

(±0.07) seconds for the non-CAM foot and 0.82 (±0.04) seconds for the CAM foot. The non-CAM foot was favored with a 2.96% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.14: Mean (±SD) Ascending Stairs Duration of Contact Asymmetry

Mean (±SD) Ascending Stairs Duration of Contact Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM***	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-0.78 (±3.63)	-8.58 (±2.46)	-0.78 (±3.63)	-2.96 (±4.35)	-8.58 (±2.46)	-2.96 (±4.35)

Note: * denotes significance at p<.05

4.6.2 Impact Peak Force

There were two significant differences in asymmetry in impact peak force between footwear conditions while ascending stairs (see Table 4.15).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, impact peak force was 1.04 (±0.09) Newtons of force per Newton of bodyweight for the left foot and 1.10 (±0.11) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 5.98% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05). In the CAM condition, impact peak force was 1.05 (±0.07) Newtons of force per Newton of bodyweight for the non-CAM foot and 0.95 (±0.12) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 10.85% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, impact peak force was 1.04 (±0.09) Newtons of force per Newton of bodyweight for the left foot and 1.10 (±0.11) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 5.98% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05). In the Air CAM condition, impact peak force was 1.06 (±0.06) Newtons of force per Newton of bodyweight for the non-CAM foot and 0.96 (±0.10) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 9.54% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05).

Table 4.15: Mean (±SD) Ascending Stairs Impact Peak Force Asymmetry

Mean (±SD) Ascending Stairs Impact Peak Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
5.98 (±13.05)	-10.85 (±14.02)	5.98 (±13.05)	-9.54 (±14.40)	-10.85 (±14.02)	-9.54 (±14.40)

Note: * denotes significance at p<.05

4.6.3 Active Peak Force

There were no significant differences in asymmetry between footwear conditions for active peak force while ascending stairs (see Table 4.16).

Table 4.16: Mean (±SD) Ascending Stairs Active Peak Force Asymmetry

Mean (±SD) Ascending Stairs Active Peak Asymmetry					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
6.87 (±12.66)	0.28 (±17.55)	6.87 (±12.66)	3.17 (±17.59)	0.28 (±17.55)	3.17 (±17.59)

Note: * denotes significance at p<.05

4.6.4 Loading Rate

There were two significant differences in asymmetry in loading rate between footwear conditions while ascending stairs (see Table 4.17).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, loading rate was 5.39 (±0.81) Newtons of force per second per Newton of bodyweight for the left foot and 5.84 (±0.94) Newtons of force per second per Newton of bodyweight for the right foot. The right foot was favored with a 7.69% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05). In the CAM condition, loading rate was 5.28 (±0.79) Newtons of force per second per Newton of bodyweight for the non-CAM foot and 4.21 (±1.10) Newtons of force per second per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 21.54% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, loading rate was 5.39 (±0.81) Newtons of force per second per Newton of bodyweight for the left foot and 5.84 (±0.94) Newtons of force per second per Newton of bodyweight for the right foot. The right foot was favored with a 7.69% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05). In the Air CAM condition, loading rate was 5.41 (±059) Newtons of force per second per Newton of bodyweight for the non-CAM foot and 4.29 (±0.81) Newtons of force per second per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 24.15% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.17: Mean (±SD) Ascending Stairs Loading Rate Asymmetry

Mean (±SD) Ascending Stairs Loading Rate Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
7.69 (±13.18)	-21.54 (±24.97)	7.69 (±13.18)	-24.15 (±15.42)	-21.54 (±24.97)	-24.15 (±15.42)

Note: * denotes significance at p<.05

4.7 Gait Descending Stairs

This section examines asymmetry in the four values (duration of contact, impact peak force, active peak force, and loading rate) while descending stairs.

4.7.1 Duration of Contact

There were two significant differences in asymmetry in duration of contact between footwear conditions while descending stairs (see Table 4.18).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, duration of contact was 0.69 (±0.05) seconds for the left foot and 0.70 (±0.05) seconds for the right foot. The right foot was favored with a 1.62% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, duration of contact was 0.83 (±0.14) seconds for the non-CAM foot and 0.77 (±0.13) seconds for the CAM foot. The non-CAM foot was favored with a 7.99% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, duration of contact was 0.69 (±0.05) seconds for the left foot and 0.70 (±0.05) seconds for the right foot. The right foot was favored with a 1.62% asymmetry. Bland-Altman analysis indicated no bias. In the Air CAM condition, duration of contact was 0.79 (±0.13) seconds for the non-CAM foot and 0.75 (±0.13) seconds for the CAM foot. The non-CAM foot was favored with a 5.44% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.18: Mean (±SD) Descending Stairs Duration of Contact Asymmetry

Mean (±SD) Descending Stairs Duration of Contact Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
1.62 (±4.26)	-7.99 (±3.86)	1.62 (±4.26)	-5.44 (±5.44)	-7.99 (±3.86)	-5.44 (±5.44)

Note: * denotes significance at p<.05

4.7.2 Impact Peak Force

There were two significant differences in asymmetry in impact peak force between footwear conditions while descending stairs (see Table 4.19).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, impact peak force was 1.31 (±0.14) Newtons of force per Newton of bodyweight for the left foot and 1.47 (±0.19) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 9.87% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001). In the CAM condition, impact peak force was 1.36 (±0.13) Newtons of force per Newton of bodyweight for the non-CAM foot and 1.18 (±0.19) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 14.16% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05).

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, impact peak force was 1.31 (±0.14) Newtons of force per Newton of bodyweight for the left foot and 1.47 (±0.19) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 9.87% asymmetry. Bland-Altman analysis indicated a relative bias (p<.001). In the Air CAM condition, impact peak force was 1.37 (± 0.12) Newtons of force per Newton of bodyweight for the non-CAM foot and 1.20 (±0.18) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 13.43% asymmetry. Bland-Altman analysis indicated both relative and proportional biases (p<.05).

Table 4.19: Mean (±SD) Descending Stairs Impact Peak Force Asymmetry

Mean (±SD) Descending Stairs Impact Peak Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
9.87 (±12.73)	-14.16 (±14.32)	9.87 (±12.73)	-13.43 (±15.11)	-14.16 (±14.32)	-13.43 (±15.11)

Note: * denotes significance at p<.05

4.7.3 Active Peak Force

There were two significant differences in asymmetry in active peak forces between footwear conditions while descending stairs (see Table 4.20).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, active peak force was 0.94 (±0.08) Newtons of force per Newton of bodyweight for the left foot and 1.00 (±0.07) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 6.26% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, active peak force was 1.06 (±0.12) Newtons of force per Newton of bodyweight for the non-CAM foot and 0.92 (±0.10) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 14.41% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, active peak force was 0.94 (±0.08) Newtons of force per Newton of bodyweight for the left foot and 1.00 (±0.07) Newtons of force per Newton of bodyweight for the right foot. The right foot was favored with a 6.26% asymmetry. Bland-Altman analysis indicated no bias. In the Air CAM condition, active peak force was 1.03 (±0.11) Newtons of force per Newton of bodyweight for the non-CAM foot and 0.89 (±0.10) Newtons of force per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 15.10% asymmetry. Bland-Altman analysis indicated a relative bias (p<.05).

Table 4.20: Mean (±SD) Descending Stairs Active Peak Force Asymmetry

Mean (±SD) Descending Stairs Active Peak Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
6.26 (±9.27)	-14.41 (±13.08)	6.26 (±9.27)	-15.10 (±13.73)	-14.41 (±13.08)	-15.10 (±13.73)

Note: * denotes significance at p<.05

4.7.4 Loading Rate

There were two significant differences in asymmetry in loading rate between footwear conditions while descending stairs (see Table 4.21).

The first difference was found between Sneaker vs. CAM conditions. In the Sneaker condition, loading rate was 9.10 (±1.57) Newtons of force per second per Newton of bodyweight for the left foot and 10.14 (2.03) Newtons of force per second per Newton of bodyweight for the right foot. The right foot was favored with a 10.37% asymmetry. Bland-Altman analysis indicated no bias. In the CAM condition, loading rate was 9.07 (±1.98) Newtons of force per second per Newton of bodyweight for the non-CAM foot and 7.51 (±2.03) Newtons of force per second per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 18.90% asymmetry. Bland-Altman analysis indicated no bias.

The second difference was found between Sneaker vs. Air CAM conditions. In the Sneaker condition, loading rate was 9.10 (±1.57) Newtons of force per second per Newton of bodyweight for the left foot and 10.14 (±2.03) Newtons of force per second per Newton of bodyweight for the right foot. The right foot was favored with a 10.37% asymmetry. Bland-Altman analysis indicated no bias. In the Air CAM condition, loading rate was 9.83 (±2.12) Newtons of force per second per Newton of bodyweight for the non-CAM foot and 7.85 (±2.44) Newtons of force per second per Newton of bodyweight for the CAM foot. The non-CAM foot was favored with a 25.37% asymmetry. Bland-Altman analysis indicated no bias.

Table 4.21: Mean (±SD) Descending Stairs Loading Rates Asymmetry

Mean (±SD) Descending Stairs Loading Rate Asymmetry					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
10.37 (±10.45)	-18.90 (±30.91)	10.37 (±10.45)	-25.37 (±24.88)	-18.90 (±30.91)	-25.37 (±24.88)

Note: * denotes significance at p<.05

4.8 Summary of Results

In summary, this section presented asymmetry results for each of the four variables analyzed between footwear conditions under each walking task. Significantly different asymmetry results between footwear for level walking and inclined/declined ramp were sparse. It was concluded that for all intents and purposes, asymmetry incurred through CAM boots are equivalent to sneakers in these walking tasks. In ascending/descending stairs, there were consistent decreases in three of the four variables as a result of CAM boot use compared to the non-CAM foot. It was also concluded that CAM boots and Air CAM boots are equivalent. More in-depth discussion of these results takes place in the next chapter.

Chapter 5

Discussion

5.1 Overview of Discussion

In overview, this chapter further explores the results listed in the previous chapter. It acknowledges trends in the data, compares the data to current literature, identifies irregularities and peculiarities in the data, proposes rationales to explain the data, recognizes literature that could add to the data interpretation, reflects on experimental protocol, and derives a final conclusion from the results.

5.2 Study Findings

This section explains the findings present in the results. It includes a summary of both kinematic findings and asymmetry findings of the four variables (duration of contact, impact peak force, active peak force, and loading rate).

5.2.1 Kinematics

Kinematic data on number of footfalls aligned with expectations of the principal investigator to a degree. Despite the stairs having the shortest overall distance, subjects had to overcome a larger vertical distance. This required more footfalls than distances traversed in the primarily horizontal tasks. Though, by the same logic, level walking trials should have had the fewest footfalls. This was not the case, as that honor belonged to the ramp trials. The principal investigator proposes that this result was due to overcompensation to walking on an incline and to assistance from gravity when walking on a decline.

Data on cadence is similar to that of number of footfalls. Cadence was slowest in stair trials and fastest in ramp trials. Again, the slow cadence in the stair trials was expected, but level walking was predicted to be the quickest. There was also a difference between footwear conditions in this variable. As might be expected, cadence was quickest in sneaker trials. A possible rationale behind this is that CAM boots induce LLDs, cause asymmetrical gait, add mass to one leg, and may affect stability.

Gait velocity logically followed the trends seen in the previous two kinematic variables. The stairs presented the slowest gait velocities, as expected. However, the ramp trials exhibited the quickest gait velocities rather than the predicted level walking trials. With exception of the ramp trials, sneakers demonstrated slightly faster velocities than both CAM boots. This was to be expected for many of the same reasons listed previously. Compared to the data from Bohannon (1997), gait velocities derived in this study danced around Bohannon’s range of 1.27-1.46 m/s. Ramp gait velocities averaged at or slightly above the upper limit of Bohannon’s range, while the level walking averaged at or below Bohannon’s range, and the average gait velocities during the stair trials clearly fell short of typical human gait velocity.

5.2.2 Main Findings

Results for asymmetry in the four variables analyzed were separated by walking task. In level walking, there was one significant finding. In walking on an inclined ramp, there were three, and in walking on a declined ramp, there were two. Among these six findings, there were no discernable trends. For all intents and purposes, these findings may be considered unimportant in consideration of the effectiveness of CAM boots. The stair trials were where a vast majority of significant findings occurred.

In ascending stairs, there were six total findings, and in descending stairs, there were eight. In most of these findings, both types of CAM boots resulted in significant reductions of a variable compared to the non-CAM foot of each trial. This trend suggests their usefulness lies in attenuating normal reaction forces and derivatives while ascending and descending stairs. Overall, impact peak forces, active peak forces, and loading rates for stair trials were less than those seen in ramp trials. In addition, as discovered by Sheehan and Gottschall (2012), ambulation on ramps involved a higher fall risk than ambulation on stairs when the two are at similar angles. In the case of this experiment, the angle of the stairs was roughly nine times larger than the ramp angle; however, their findings and those of this study may advocate for stair use over ramp use. In this case, CAM boots are recommended.

In regard to duration of contact, the non-air-filled CAM boots reduced time in contact during ascent, and both types of CAM boots reduced time in contact during descent. These reductions were in relation to the non-CAM foot. When examining the overall magnitudes of time in contact, it was discovered that they were still greater than those of the sneaker trials. These data contrast the data from Powell, Clowers, Keefer, and Zhang (2012) but support the data from Muratgaic, Ramakrishnan, and Reed (2017). Since overall duration of contact may extend feelings of pain and/or discomfort when walking, CAM boot use may actually cause more pain despite their tendency to offload to the non-injured foot. It is unknown whether the increased contact times were due to lack of acclimation to walking in the CAM boots. CAM boot use is not recommended in this matter.

In regard to impact peak force, both types of CAM boots successfully reduced impact peak forces in both ascent and descent compared to the non-CAM foot. In the case of impact peak force, the overall magnitude of force was also decreased compared to the Sneaker condition. These findings support those of Muratagic, Ramakrishnan, and Reed (2017), Gulgin, Hall, Luzadre, and Kayfish (2018), and Azizan et al. (2018). They also contrast the findings of Zhang, Clowers, and Powell (2006). Given that CAM boots not only reduced impact peak forces in comparison with the non-injured foot, but also in comparison with sneaker trials, they are certainly recommended in this context.

In regard to active peak force, both types of CAM boots were successful in reducing active peak forces compared to the non-CAM foot, but only in descent. They also decreased the overall magnitude of active peak forces in comparison to sneaker trials. Because the studies referenced above in the section on impact peak forces were unspecific about the type of ground reaction forces, the same studies are supported and contradicted. CAM boots are once again recommended in this context.

In regard to loading rate, both types of CAM boots successfully reduced loading rates in both ascent and descent compared to the non-CAM foot. Loading rates were also decreased in magnitude compared to sneaker trials. There were no articles found that examined loading rate in standing and/or walking tasks with CAM boots. This study appears to be the first, and the data provided indicate that CAM boots are effective at attenuating loading rate while ascending and descending stairs.

5.3 Implications of Findings

Based on the summary provided above, CAM boots were successful at attenuating impact peak forces and loadings rates during ascent and descent of stairs, and they were successful at attenuating active peak forces during descent only. However, this comes at a trade-off, for duration of contact is increased through CAM boot use. The extent to which each of the four variables facilitates pain and affects the risk of reinjury is unknown. Evidence from Matejevich, Branscombe, Scott, and Zelik (2019) suggests duration of contact may be more important than the external forces. Still, the principal investigator proposes the CAM boots have an overall positive effect on the well-being of the patient during stair use. Outside of stair use, CAM boots are not significantly different than shod walking.

Implications based on these results are as follows: use of stairs is preferred over use of a ramp in changing elevation, patients who routinely use stairs or have the option to use stairs should wear a CAM boot, and patients who do not have access to stairs or choose not to take them do not need a CAM boot. In the event that stairs and ramps are avoidable (i.e. the patient can use an elevator or does not need to change elevation all too often), then CAM boots are not necessary. Often, CAM boots are not covered by insurance policies, meaning the money being saved here is money that patients would otherwise have to pay out-of-pocket. So, these findings could collectively save patients thousands of dollars in out-of-pocket healthcare expenses.

5.4 Reflection on Method

This section reflects on the experimental method utilized in this study. Experimental protocol is judged, and both its strengths and weakness are addressed. In addition, strategies to avoid mistakes made by this experiment are proposed, as well as options for future research.

5.4.1 Strengths of Method

There were a number of positive points in the experimental protocol. The first was the extent of randomization. A random number generator was utilized to randomize the order of the walking tasks, footwear conditions, and direction. For convenience, randomization occurred per subject (i.e. one randomized order was set per subject). Randomization could have occurred per data collection (i.e. a new randomized order between every collection). However, this is unrealistic, as it would involve constant changing of footwear and recalibration of insoles, introducing another source of error.

The second strength of the protocol was the relatively constant conditions of the walking surfaces. Both the stairs and ramp were concrete. The level surface was granite. Both surfaces are of similar hardness and should not have much of an effect on force measurements.

The third strength, which could also be a weakness depending on perspective, was that subjects were allowed to wear their own sneakers. This could be considered a strength, as subjects are already acclimated to walking in their own sneakers. However, the downside of this decision is detailed in the following section.

The fourth strength of the protocol was the within subject design. By having all subjects complete all walking tasks under all footwear conditions, differences in gait mechanics were controlled. Data were able to be normalized per subject based on weight before being averaged and analyzed.

The fifth and final strength of this experiment was the use of force-sensing insoles. This new technology can be used as a replacement for conventional force plates. While equivalent in accuracy and precision to a force plate, force-sensing insoles directly measure the normal reaction forces experienced by the plantar surface of the foot, as opposed to the bottom of the sneaker or CAM boot. Use of these insoles also removed bias in the form of force plate targeting and allowed for data collection on non-level surfaces outside of a laboratory setting.

5.4.2 Weaknesses of Method

There were many imperfections in the experimental protocol. For one, the distances of each walking task varied slightly. While the level surface and hypotenuse of the ramp were each 25m, the hypotenuse of the stairs was only 22.4m. In addition, the stairs had two horizontal landings, which split the staircase into three sets of stairs. Finding a 25m hypotenuse staircase without any type of landing proved difficult. The few steps that did not include a change in vertical distance could have altered the overall means of stair data.

Second, the insoles were subject to drift with changes in temperature. The level surface and stair trials both occurred indoors, where the temperature was 20-22°C. On the other hand, the ramp trials occurred outside, during the months of February and March. Temperatures outside were typically around 0-5°C on data collection days. The amount of drift is supposedly minimal, but it still exists.

Third, subjects were not given much time to acclimate to walking in the CAM boots. At most, each subject took 1-2 minutes to get a feel for the boots. This was due to time constraints, as subjects were scheduled in 60-90 minute timeslots. Longer acclimation periods of 5-10 minutes would likely have sufficed, but allowing subjects to walk in the boot for up to a day prior to data collection would have been optimal.

Fourth, as mentioned in the prior section, subjects were allowed to wear their own sneakers during trials. While they were already acclimated to their own shoes, the soles of the shoes varied. Some may have been softer/harder than others, made of different materials, or more flat/rounded than others. It is not unreasonable to think that different shoe designs may incur variations in force distribution over time or magnitude of forces, in general.

Fifth, the force-sensing insoles used in this experiment were only capable of measuring vertical GRF. In contrast, conventional force plates have the ability to record GRF vectors in three dimensions. Obviously, studying the magnitude of forces experienced in one of three dimensions ignores the magnitude of forces experienced in the other two.

The sixth and final weakness was the subject demographics. The original subject sample was more diverse than the final sample. The final sample included in statistical analysis was strictly young adults aged 18-24, and they were all right-footed. Had the original sampled not been nullified, this may have been a strength of the protocol.

5.4.3 Areas for Future Research

Future research can improve upon this study design by fixing any of the weaknesses in experimental protocol mentioned above. First, walking task distances and/or number of footfalls can be better controlled. Second, the trials could all take place inside or outside, if possible. Otherwise, data collection could take place when the temperature outside is more similar to room temperature to prevent potential drift in the insoles. Third, subjects could be given a CAM boot a day in advance of data collection. They would then have a full day to acclimate to walking in the boot, rather than a minute or two. Fourth, if it is decided that controlling for shoe design is more important than allowing subjects to wear their own shoes to which they are acclimated, a certain model shoe could be provided in various sizes for subjects to wear for trials. Fifth, subject demographics could be improved by recruiting age ranges outside that of typical college students and recruiting subjects more diverse in respect to limb dominance. Lastly, a future study may opt to recruit patients with an injury, as injured subjects' gaits would likely differ from healthy subjects' gaits.

However, there is more to the story than is portrayed here. The prime focus of this study was CAM boots. In the future, researchers may opt to use a different type of orthotic device. Or, they may opt to add in other variables, such as partial weight bearing. Likewise, the four variables analyzed in this experiment are not the full story. Statistical analysis could be done on step/stride length and frequency, gait velocity, and impulse. Furthermore, the Novel© Loadsol® configuration utilized in this study analyzed three zones of the foot: hindfoot, anteromedial, and anterolateral. The sums of the three areas were used in this study, but deeper analysis could show if the force distributions change between footwear conditions. In the current study, many subjects reported instability and a lack of balance when wearing the CAM boot, especially the one which lacked an air pump. Future experiments may opt to use Novel© Pedar® insoles, which measure pressure distribution over time, to determine center of pressure differences between sneakers and CAM boots.

5.5 Conclusion

This thesis experiment sought to judge the efficacy of CAM boots at reducing normal reaction forces and derivatives which are experienced by the plantar surface of the foot during gait in three different walking tasks. It was determined that CAM boots are only effective in reducing these variables when ascending and descending stairs; however, they also increased duration of contact in these same trials. If this activity is part of daily living, then CAM boots are recommended. However, if stairs are avoidable, then CAM boots are not necessary. They demonstrate no advantage over sneakers in ambulation on a level surface or ramp, outside of a possible placebo effect.

The study hypothesis was rejected. CAM boot use did offload the injured side through increased asymmetry in three of four variables in the stair trials; however, for the other two walking tasks, CAM boot use proved ineffective in this regard. And, in the context of duration of contact in the stair trials, CAM boots had the opposite effect. As such, the original hypothesis was considered rejected.

5.6 Summary of Discussion

In summary, this chapter summarized the results, discussed the implications of the results, reflected upon the experimental method, pointed out strengths and weaknesses in said method, proposed directions for future experimentation, and drew an overall conclusion. This chapter ends the thesis.

Appendix A:

Consent & Debrief Forms

Participant #:_____ **Date:_____**

Recruitment Statement & Implied Consent (Front)

“An evaluation of controlled ankle movement (CAM) boot mechanics during locomotive changes in elevation.”

This study requires the participant to walk on a level surface, walk up and down a ramp, and walk up and down a set of stairs. Each set of actions will be performed a minimum of three times: once in the participant’s sneakers, once in a CAM boot without air padding, and once in a CAM boot with air padding. During each trial, a force-sensing insole will be inserted in the shoe/boot of the participant’s dominant foot. These force-sensing insoles will output data on the reaction forces normal to the plantar surface of the foot, and this data can show which method of changing elevation produces the lowest magnitude of reaction forces. This can show if the boots are effective in the first place, and it can also suggest which method of changing elevation is safest for traveling upwards and downwards. This data could be useful in reducing discomfort and preventing re-injury in those with a recent musculoskeletal injury of the lower limb.

Participant #:_____ **Date:_____**

Recruitment Statement & Implied Consent
(Back)

1. I, the participant, confirm that I do not have any neuromuscular disorders that affect my gait (e.g. muscular dystrophy, myopathies, ataxias . . .).

2. I, the participant, confirm that I do not have any current musculoskeletal injuries that affect my ability to walk normally or have had any past musculoskeletal injuries which have permanently affected my gait (e.g. bone fractures, ankles sprains . . .).

3. I, the participant, verify that I am 18 years of age or older.

Participant's answer:

YES NO

Participant #:_____ **Date:_____**

Debriefing Statement

"An evaluation of controlled ankle movement (CAM) boot mechanics during locomotive changes in elevation."

This study required the participant to walk on a level surface, walk up and down a ramp, and walk up and down a set of stairs. Each set of actions was performed a minimum of three times: once in the participant's sneakers, once in a CAM boot without air, and once in a CAM boot with air. During each trial, a force-sensing insole was inserted in the shoe/boot of the participant's dominant foot. These force-sensing insoles output data on the reaction forces normal to the plantar surface of the foot, and this data can show which method of changing elevation produces the lowest magnitude of reaction forces. This can determine if the boots are effective in the first place, and it can also suggest which method of changing elevation is safest for traveling upwards and downwards. This data could be useful in reducing discomfort and preventing re-injury in those with a recent musculoskeletal injury of the lower limb.

Thank you for taking the time to participate in this study. Your time and efforts are much appreciated, and your data will be very helpful, not only to the principal investigator, but also to anyone who may one day find themselves in a CAM boot following an injury. If you have any questions about the data gathering process that occurred here today or would like to request the results of the study in the future, feel free to reach out to the principal investigator, **Martin Sedlock**, at **mjs6935@psu.edu.**

Appendix B:

Waterloo Footedness Questionnaire

Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

---

1. Which foot would you use to kick a stationary ball at a target straight in front of you?
La Lu Eq Ru Ra
2. If you had to stand on one foot, which foot would it be?
La Lu Eq Ru Ra
3. Which foot would you use to smooth sand at the beach?
La Lu Eq Ru Ra
4. If you had to step up onto a chair, which foot would you place on the chair first?
La Lu Eq Ru Ra
5. Which foot would you use to stomp on a fast-moving bug?
La Lu Eq Ru Ra
6. If you were to balance on one foot on a railway track, which foot would you use?
La Lu Eq Ru Ra
7. If you wanted to pick up a marble with your toes, which foot would you use?
La Lu Eq Ru Ra
8. If you had to hop on one foot, which foot would you use?
La Lu Eq Ru Ra
9. Which foot would you use to help push a shovel into the ground?
La Lu Eq Ru Ra
10. During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?
La Lu Eq Ru Ra
11. Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?
YES NO (circle one)
12. Have you ever been given special training or encouragement to use a particular foot for certain activities?
YES NO (circle one)
13. If you have answered YES for either question 11 or 12, please explain:

Appendix C:

Full Asymmetry Index Data Set

Asymmetry Results											
Level Asymmetry Results											
Mean (±SD) Level Duration of Contact Asymmetry						**Mean (±SD) Level Impact Peak Force Asymmetry**					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM***		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-2.44 (±4.23)	-6.20 (±2.85)	-2.44 (±4.23)	-4.01 (±2.51)	-6.20 (±2.85)	-4.01 (±2.51)	4.79 (±12.11)	5.17 (±13.41)	4.79 (±12.11)	9.80 (±12.56)	5.17 (±13.41)	9.80 (±12.56)
Mean (±SD) Level Active Peak Force Asymmetry						**Mean (±SD) Level Loading Rate Asymmetry**					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
3.94 (±12.60)	0.49 (±17.36)	3.94 (±12.60)	3.55 (±17.69)	0.49 (±17.36)	3.55 (±17.69)	7.09 (±15.02)	1.16 (±22.20)	7.09 (±15.02)	8.76 (±16.08)	1.16 (±22.20)	8.76 (±16.08)
Ramp Asymmetry Results											
Mean (±SD) Inclined Slope Duration of Contact Asymmetry						**Mean (±SD) Inclined Slope Impact Peak Force Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM***		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-1.42 (±1.03)	-6.49 (±2.57)	-2.35 (±2.80)	-3.66 (±3.68)	-6.49 (±2.57)	-3.18 (±3.69)	8.60 (±8.66)	8.68 (±11.96)	5.18 (±12.56)	7.19 (±19.27)	8.68 (±11.96)	12.94 (±11.17)
Mean (±SD) Declined Slope Duration of Contact Asymmetry						**Mean (±SD) Declined Slope Impact Peak Force Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM**		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-1.69 (±0.68)	-5.61 (±3,74)	-3.65 (±5.22)	-5.56 (±2.78)	-5.55 (±3.41)	-5.21 (±2.63)	13.02 (±9.43)	11.49 (±18.48)	8.64 (±14.44)	5.03 (±19.17)	13.50 (±17.69)	12.52 (±12.67)
Mean (±SD) Inclined Slope Active Peak Force Asymmetry						**Mean (±SD) Inclined Slope Loading Rate Asymmetry**					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM***		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
8.40 (±13.00)	-6.63 (±24.01)	7.82 (±12.14)	-0.44 (±20.29)	-6.63 (±24.01)	-1.43 (±21.70)	10.66 (±10.76)	15.37 (±18.74)	7.68 (±13.03)	12.06 (±22.31)	15.37 (±18.74)	18.68 (±13.07)
Mean (±SD) Declined Slope Active Peak Force Asymmetry						**Mean (±SD) Declined Slope Loading Rate Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM**		**Sneaker vs CAM**		**Sneaker vs Air CAM**		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
7.35 (±13.23)	-4.62 (±16.34)	5.99 (±12.60)	-3.55 (±18.05)	-2.03 (±16.41)	-3.96 (±17.78)	18.87 (±12.91)`	17.82 (±20.80)	15.73 (±17.12)	7.70 (±25.90)	16.95 (±21.08)	15.03 (±18.30)
Stairs Asymmetry Results											
Mean (±SD) Ascending Stairs Duration of Contact Asymmetry						**Mean (±SD) Ascending Stairs Impact Peak Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM**		**CAM vs Air CAM***		**Sneaker vs CAM***		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
-0.78 (±3.63)	-8.58 (±2.46)	-0.78 (±3.63)	-2.96 (±4.35)	-8.58 (±2.46)	-2.96 (±4.35)	5.98 (±13.05)	-10.85 (±14.02)	5.98 (±13.05)	-9.54 (±14.40)	-10.85 (±14.02)	-9.54 (±14.40)
Mean (±SD) Descending Stairs Duration of Contact Asymmetry						**Mean (±SD) Descending Stairs Impact Peak Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**		**Sneaker vs CAM***		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
1.62 (±4.26)	-7.99 (±3.86)	1.62 (±4.26)	-5.44 (±5.44)	-7.99 (±3.86)	-5.44 (±5.44)	9.87 (±12.73)	-14.16 (±14.32)	9.87 (±12.73)	-13.43 (±15.11)	-14.16 (±14.32)	-13.43 (±15.11)
Mean (±SD) Ascending Stairs Active Peak Asymmetry						**Mean (±SD) Ascending Stairs Loading Rate Asymmetry**					
Sneaker vs CAM		**Sneaker vs Air CAM**		**CAM vs Air CAM**		**Sneaker vs CAM***		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
6.87 (±12.66)	0.28 (±17.55)	6.87 (±12.66)	3.17 (±17.59)	0.28 (±17.55)	3.17 (±17.59)	7.69 (±13.18)	-21.54 (±24.97)	7.69 (±13.18)	-24.15 (±15.42)	-21.54 (±24.97)	-24.15 (±15.42)
Mean (±SD) Descending Stairs Active Peak Asymmetry						**Mean (±SD) Descending Stairs Loading Rate Asymmetry**					
Sneaker vs CAM*		**Sneaker vs Air CAM***		**CAM vs Air CAM**		**Sneaker vs CAM***		**Sneaker vs Air CAM***		**CAM vs Air CAM**	
Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM	Sneaker	CAM	Sneaker	Air CAM	CAM	Air CAM
6.26 (±9.27)	-14.41 (±13.08)	6.26 (±9.27)	-15.10 (±13.73)	-14.41 (±13.08)	-15.10 (±13.73)	10.37 (±10.45)	-18.90 (±30.91)	10.37 (±10.45)	-25.37 (±24.88)	-18.90 (±30.91)	-25.37 (±24.88)

BIBLIOGRAPHY

Azizan, N. A., Basaruddin, K. S., Salleh, A. F., Sulaiman, A. R., Safar, M. J. A., & Rusli, W. M. R. (2018). Leg length discrepancy: Dynamic balance response during gait. *Journal of Healthcare Engineering, 2018,* 1-9. doi:10.1155/2018/7815451

Barnett, S., Cunningham, J. L., & West, S. (2001). A comparison of vertical force and temporal parameters produced by an in-shoe pressure measuring system and a force platform. *Clinical Biomechanics, 16,* 353-357. doi:10.1016/S0268-0033(01)00026-2

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet, 327(8476),* 307-310. doi:10.1016/S0140-6736(86)90837-8

Bohannon, R. W. (1997) Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. *Age & Ageing, 26,* 15-19. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/9143432

Böhm, H. & Hösl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *Journal of Biomechanics, 43,* 2467-2472. doi:10.1016/j.jbiomech.2010.05.029

Bonness, E.K. Siebler, J. C., Reed, L. K., Lyden, E. R., & Mormino, M. A. (2018). Immediate weight-bearing protocol for the determination of ankle stability in patients with isolated distal fibular fractures. *Journal of Orthopaedic Trauma, 32,* 534-537. doi:10.1097/BOT.0000000000001268

Buddecke, D. E., Polk. M. A., & Barp, E. A. (2010). Metatarsal fractures. *Clinics in Podiatric*

Medicine and Surgery, 27, 601-624. doi:10.1016/j.cpm.2010.07.001

Cabral, S., Resende, R. A., Clansey, A. C., Deluzio, K. C., Scott-Selbie, W., & Veloso, A. P. (2016). A global gait asymmetry index. *Journal of Applied Biomechanics, 32,* 171-177. doi:10.1123/jab.2015-0114

Clayton, R. A. E. & Court-Brown C. M. (2008). The epidemiology of musculoskeletal tendinous and ligamentous injuries. *Injury, 39,* 1338-1344. doi:10.1016/j.injury.2008.06.021

Cole, W. G., Gills, S. V., Vereijken, B., & Adolph, K. E. (2014). Coping with asymmetry: How infants and adults walk with one elongated leg. *Infant Behavior and Development, 37,* 305-314. doi:10.1016/j.infbeh.2014.04.006

DiLiberto, F. E., Baumhauer, J. F., Wilding G. E., & Nawoczenski, D. A. (2007). Alterations in plantar pressure with different walking boot designs. *Foot & Ankle International, 28,* 55-60. doi:10.3113/FAI.2007.0010

Elias, L. J., Bryden, M. P., & Bulman-Fleming, M. B. (1998). Footedness is a better predictor than is handedness of emotional lateralization. *Neuropsychologia, 36,* 37-43. doi:10.1016/S0028-3932(97)00107-3

Eliks, M., Ostiak-Tomaszewska, W., Lisiński, P., & Koczewski, P. (2017). Does structural leg-length discrepancy affect postural control? *BMC Musculoskeletal Disorders, 18,* 346-352. doi:10.1186/s12891-017-1707-x

Feger, M. A., Galviano, N. R., Donovan, L., Hart, J. M., Saliba, S. A., Park, J. S., & Hertel, J. (2017). Current trends in the management of lateral ankle sprains in the United States. *Clinical Journal of Sport Medicine, 27,* 145-152. doi:10.1097/JSM.0000000000000321

Firoozabadi, R., Harnden, E., & Krieg, J. C. (2015). Immediate weight-bearing after ankle fracture fixation. *Advances in Orthopedics, 2015,* 1-6. doi:10.1155/2015/491976

Goodworth, A. D., Kunsman, M., DePietro, V., LaPenta, G., Miles, K., & Murphy, J. (2014). Characterization of how a walking boot affects balance. *Journal of Prosthetics and Orthotics, 26,* 54-60. doi:10.1097/JPO.0000000000000014

Gottschalk, A. W. & Andrish, J. T. (2011) Epidemiology of sports injury in pediatric athletes. *Sports Medicine and Arthroscopy Review, 19,* 1-6. doi:10.1097/JSA.0b013e31820b95fc

Graham, C. S., Stephens, D. M., Dietz, K. C., & Winter, S. L. (2016). Are current methods of partial weight-bearing instruction accurately translating to crutch-assisted gait? *International Journal of Therapy and Rehabilitation, 23,* 215-220. doi:10.12968/ijtr.2016.23.5.215

Grieve, D. W. & Gear, R. J. (1966). The relationships between length of stride, step frequency, time of swing, and speed of walking for children and adults. *Ergonomics, 5,* 379-399. doi:10.1080/00140136608964399

Gulgin, H., Hall, K., Luzadre, A., & Kayfish, E. (2018). 3D gait analysis with and without an orthopedic walking boot. *Gait & Posture, 59,* 76-82. doi:10.1016/j.gaitpost.2017.09.024

Hayes, W. C., Myers, E. R., Robinovitch, S. N., Van Den Kroonenberg, A., Courtney, A. C., & McMahon, T. A. (1996). Etiology and prevention of age-related hip fractures. *Bone, 1 Suppl.,* 77-85. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/8717551

Helms, C. A. & McCarthy, S. (1984). CT scanograms for measuring leg length discrepancy. *Radiology, 151,* 802. doi:10.1148/radiology.151.3.6718746

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training, 42,* 311-319. Retrieved from: www.ncbi.nlm.nih.gov/pmc/articles/PMC1941297/

Hootman, J. M., Macera, C. A., Ainsworth, B. E., Addy, C. L., Martin, M., & Blair, S. N. (2002). Epidemiology of musculoskeletal injuries among sedentary and physically active adults. *Medicine & Science in Sports & Exercise, 34,* 838-844. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/11984303

Hunt, K. J., Goeb, Y., Esparza, R., Malone, M., Shultz, R., & Matheson, G. (2014). Site-specific loading at the fifth metatarsal base in rehabilitative devices: Implication for Jones Fracture treatment. *Physical Medicine and Rehabilitation, 6,* 1022-1029. doi:10.1016/j.pmrj.2014.05.011

Khamis, S. & Carmeli, K. (2017). Relationship and significance of gait deviations associated with limb length discrepancy: A systematic review. *Gait & Posture, 57,* 115-123. doi:10.1016/j.gaitpost.2017.05.028

Kipp, D., Village, D., & Edwards, K. J. (2017). Effectiveness of Evenup(TM) shoe-lift use among individuals prescribed a walking boot. *Journal of Allied Health, 46,* 104-110. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/28561867

Knutson, G. A. (2005). Anatomic and functional leg-length inequality: A review and recommendation for clinical decision-making. Part I, anatomic leg-length inequality: Prevalence, magnitude, effects, and clinical significance. *Chiropractic & Osteopathy, 13,* 1-10. doi:10.1186/1746-1340-13-11

Lee, C. R. & Farley, C. T. (1998). Determinants of center of mass trajectory in human walking and running. *The Journal of Experimental Biology, 201,* 2935-2944. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/9866878

MacDonald, D. R. W., Neilly, D., Littlechild, J., Harrold, F., & Roberts, S. C. (2018). Acute

Achilles tendon rupture: Do cast boots produce adequate equinus when used for functional rehabilitation? *The Foot, 37*, 1-4. doi:10.1016/j.foot.2018.07.004

Matejevich, E. S., Branscombe, L. M., Scott, L. R., & Zelik, K. E. (2019). Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *Plos One.* doi:10.1371/journal.pone.0210000

McHenry, B. D., Exten, E. L., Cross, J. A., Kruger K. M., Law, B., Fritz, J. M., & Harris, G. (2017). Sagittal subtalar and talocrural joint assessment during ambulation with controlled ankle movement (CAM) boots. *Foot & Ankle International*, *38*, 1260-1266. doi:10.1177/1071100717723129

Muratagic, H., Ramakrishnan, T., & Reed, K. B. (2017). Combined effects of leg length discrepancy and the addition of distal mass on gait asymmetry. *Gait & Posture, 58,* 487-492. doi:10.1016/j.gaitpost.2017.09.012

North, K., Potter, M. Q., Kubiak, E. N., Morris-Bamberg, S. J., & Hitchcock, R. W. (2012). The effect of partial weight bearing in a walking boot on plantar pressure distribution and center of pressure. *Gait & Posture, 36,* 646-649. doi:10.1016/j.gaitpost.2012.04.015

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97-113. doi:10.1016/0028-3932(71)90067-4

Petrisor, B. A., Ekrol, I., and Court-Brown, C. (2006) The epidemiology of metatarsal factures. *Foot & Ankle International, 27,* 172-174. doi:10.1177/107110070602700303

Pollo, F. E., Gowling, T. L., & Jackson, R. W. (1999). Walking boot design: A gait analysis study. *Orthopedics*, *22*(5), 503-507. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/10348111

Powell, D., Clowers, K., Keefer M., & Zhang, S. (2012). Alterations in neuromuscular activation patterns associated with walking in short-leg walking boots. *Journal of Sport and Health Science, 1,* 43-48. doi:10.1016/j.jshs.2012.02.003

Richards, J., Payne, K. Myatt, D., & Chohan, A. (2016). Do orthotic walkers affect knee and hip function during gait? *Prosthetics and Orthotics International, 40,* 137-141. doi:10.1177/0309364614546525

Sabharwal, S. & Kumar, A. (2008). Methods for assessing leg length discrepancy. *Clinical Orthopaedics and Related Research, 466,* 2910-2922. doi:10.1007/s11999-008-0524-9

Sadeghi, H., Allard, P., & Duhaime, M. (2000). Contributions of lower-limb muscle power in gait of people without impairments. *Physical Therapy, 80*, 1188-1196. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/11087305

Sadeghi, H., Allard, P., & Duhaime, M. (1997). Functional gait asymmetry in able-bodied subjects. *Human Movement Science, 16*, 243-258. doi:10.1016/S0167-9457(96)00054-1

Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000). Symmetry and limb dominance in able-bodied gait: A review. *Gait & Posture, 12,* 34-45. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/10996295

Shahid, M. K., Punwar, S., Boulind, C., & Bannister, G. (2013). Aircast walking boot and below-knee walking cast for avulsion fractures of the base of the fifth metatarsal. *Foot & Ankle International, 34,* 75-79. doi:10.1177/1071100712460197

Sheehan, R. C. & Gottschall, J. S. (2012). At similar angles, slope walking has a greater fall risk than stair walking. *Applied Ergonomics, 43,* 473-478. doi:10.1016/j.apergo.2011.07.004

Swathinathan, V., Cartwright-Terry, M., Moorehead, J. D., Bowey, A., & Scott, S. J. (2014). The effect of leg length discrepancy upon load distribution in the static phase (standing). *Gait & Posture, 40,* 561-563. doi:10.1016/j.gaitpost.2014.06.020

Yang, Y., Fang, Y., Zhang, X., He, J., & Fu, W. (2017). Does shoe collar height influence ankle joint kinematics and kinetics in sagittal plane maneuvers? *Journal of Sports Science and Medicine, 16,* 543-550. Retrieved from: www.ncbi.nlm.nih.gov/pubmed/29238255

Zhang, S., Clowers, K. G., & Powell, D. (2006). Ground reaction force and 3D biomechanical characteristics of walking in short-leg walkers. *Gait & Posture, 24,* 487-492. doi:10.1016/j.gaitpost.2005.12.003

ACADEMIC VITA

Education:

The Pennsylvania State University: **University Park, PA**
B.S Kinesiology – Movement Science **Fall 2015 - Spring 2019**
UMNR Psychology

Schreyer Honors College:
Schreyer honors scholars are enrolled in more rigorous courses inside and outside their fields of study and tasked with completing an honors thesis, which includes an independent research project.

Academic Awards, Honors, & Scholarships:
Recipient of the following: Dean's List x8, President's Freshman Award, Evan Pugh Scholar Award, Noll Endowment for Undergraduate Research, Merenda Family Trustee Scholarship, & Schreyer Family Scholarship.

Medical and Allied Health Professions Experience:

Cadaver Anatomy & Dissection Technique
Participated in cadaver dissection and identification of anatomical structures in vivo.

Principal Investigator in Research Projects in Psychology & Biomechanics

- Psychology research in behavioral economics concerning dynamic pricing schemes.
- Biomechanics research concerning foot and ankle mechanics during ambulation.

Research Assistant in Research Projects in Exercise Psychology

- Contributed to a systematic literature review in exercise psychology.
- Assisted in conduction of several other research projects in exercise psychology.

Physical Therapy Shadows
Observed outpatient physical therapy techniques, including: **Dr. Danny Singles, DPT**

- Practical identification of anatomical structures Elite Physical Therapy
- Physical manipulation Wilmington, DE
- Dry needling & electric stimulation dannypt11@gmail.com

Operating Room Shadows
Observed several operations in a hospital setting, including: **Beth Risser, RN, CNOR**

- Total joint replacements WellSpan Good Samaritan Hospital
- Gallbladder & appendix removals Lebanon, PA
- Anaesthetization techniques Brisser@wellspan.org

Work & Volunteer Experience:

Autozone, Inc. **Hazleton, PA**
Distribution center maintenance and recycling. Summer 2016

Wal-Mart Stores, Inc. **Lehighton, PA**
3rd shift cashier, stocker, customer service, and asset protection. Fall 2014 – Summer 2015

Berks Benefitting THON **Reading, PA**
Volunteered in canning, canvassing, donating, and other fundraising events. Fall 2015 – Fall 2017

Berks Blue & White Society **Reading, PA**
Volunteered in alumni tailgates, homecoming parades, and events for children. Fall 2015 – Spring 2017

Big Brothers / Big Sisters **Tamaqua, PA**
Volunteered as "big brother" to a child with divorced parents. Fall 2012 – Spring 2013

Certifications:

Bloodborne Pathogens Training
Via The Pennsylvania State University Spring 2016 - Current

CPR/AED Certification
Via The American Red Cross Fall 2018 - Current