THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DIVISION OF ENGINEERING, BUSINESS, AND COMPUTING

AN EXAMINATION OF NON-DOMINANT LEG GAIT AND GAIT SYMMETRY THROUGH AFO AND VO_2 ANALYSIS

TYE A. MORALES

SPRING 2016

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

Reviewed and approved* by the following:

Joseph M. Mahoney
Assistant Professor of Engineering
Thesis Supervisor

Jeanne M. Rose
Associate Professor of English
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

The purpose of this study was to examine the relationship among Ankle Foot Orthoses (AFOs) on the dominant leg, resulting angles of the non-dominant leg, and energy expenditure. Four healthy, young individuals walked on a treadmill for one and one-half minutes at a rate of 2.7 mph for three different trials. A GA200 VO_2 gas analyzer was used to measure and analyze energy expenditure from oxygen-expulsion. A Cannon camera was used to record the motion of the non-dominant. MATLAB programming software was used to analyze the angles of ankle and knee in the participants' non-dominant legs for observation of changes due to AFOs placed on the dominant leg. A second test examined one of the participants as a pilot for the examination of the degree of symmetry among the participants' legs by analyzing the angles of knee and ankle in both legs simultaneously. The data shows the non-dominant leg ankle range of motion (ROM) to increase as AFO stiffness increases on the dominant leg, with the largest difference from the control being over 10%. As examined through the respiratory exchange ratio, there are consistent increases as AFO stiffness increases, signifying increased energy expenditure. Lastly, the gait symmetry experiment resulted in correlation values that show applying AFOs to healthy individuals negatively impacts gait symmetry. While limited to a specific population, this study provides the rationale and experimental processes for studying gait symmetry and non-dominant leg reactions in response to AFO placement through motion capture analysis and energy expenditure.

TABLE OF CONTENTS

LIST OF FIGURES iv

LIST OF TABLES v

ACKNOWLEDGEMENTS vi

Chapter 1 Introduction 1

1.1 Background 1
1.2 Gait Symmetry 4
Parameters of Gait 4
Case Studies Involving Gait Symmetry 5
Gait Summary 7
1.3 Ankle Foot Orthoses 8
AFO Design 8
AFO Design Testing 9
Purpose of AFO Use 10
AFOS and Gait Symmetry 10
1.4 Analysis of Non-Dominant Leg Gait, Gait Symmetry, and AFOs 12
Range of Motion 12
Correlation Analysis Methods 13
Energy Expenditure 14
Analysis Summary 15
1.5 Conclusion 17

Chapter 2 Methods 19

2.1 Participants 19
2.2 Walking Trials 20
Gait Symmetry and AFO Walking Trials 20
Maximum VO_2 Walking Trials 21
2.3 Data Analysis 23
Motion Capture Analysis 23
Gait Analysis 25
Energy Expenditure Analysis 26
2.4 Conclusion 28

Chapter 3 Results 29

3.1 Non-dominant Leg ROM and AFO Results 29
Non-dominant Ankle Results 29
Non-dominant Leg Knee Results 31
3.2 Gait Symmetry Results 33

3.3 VO_2 Results 36
3.4 Summary of Results 38

Chapter 4 Discussion 39

4.1 Overview 39
4.2 Results Analysis 40
Non-dominant Leg ROM and AFO Results 40
VO_2 Results 40
Gait Symmetry Results 41
4.3 Comparison to Previous Studies 43
4.4 Study Limitations 45
4.5 Future Studies Suggestions 46

Chapter 5 Conclusion 47

Appendix A Participant Demographics 48

BIBLIOGRAPHY 49

LIST OF FIGURES

Figure 1. Leg Markers....................20

Figure 2. Ankle Foot Orthoses....................21

Figure 3. Non-dominant Ankle Angle....................30

Figure 4. Non-dominant Knee Angle....................32

Figure 5. Cross Correlation of Knee....................34

Figure 6. Cross Correlation of the Ankle....................35

Figure 7. Mean RER by AFO Condition.....................37

LIST OF TABLES

Table 1. Summary of Participant Demographics. 19

Table 2. Non-dominant Leg Ankle ROM. 30

Table 3. Non-dominant Leg Knee ROM. 31

Table 4. Coefficient of Determination Values 34

Table 5. VO2 Respiratory Exchange Ratio..36

Table 6. Participant Demographics 48

ACKNOWLEDGEMENTS

I would like to first thank Dr. Joseph M. Mahoney for all of his support and guidance during my final year at Penn State Berks as an undergraduate student. His work, along with that of Dr. Benjamin Infantalino, in the fields of biomechanics and study of human motion have been truly insightful and motivating. I am very grateful to have been able to work with both of them in a research capacity. I would also like to thank Ms. Marissa Ruggeiro of our Kinesiology Department for taking the time to train me on our VO_2 analysis machine.

Next, I would like to express my sincere gratitude for all the guidance both of my honors advisors have given me. Dr. Sandy Feinstein helped guide me through my first three years at Penn State and made sure I was always pushing myself. The guidance from Dr. Jeanne M. Rose has been exponentially beneficial my last year. The structure and deadlines created by both of them have helped so much and I will always be grateful to them for all they have done.

I would also like to thank the participants of this study for their willingness to participate and their patience during the experiment. I would like to express my sincere appreciation to Boas Surgical in Wyomissing as well. Their volunteering the use the use of their AFOs in my study made the experiment possible. Lastly and most importantly, I would like to thank my family and friends for their support throughout the entire journey that this thesis has been. Without them, it would have been impossible to get through everything. Thank you to everyone who had a hand in helping and guiding me.

Chapter 1

Introduction

1.1 Background

Gait is a person's manner of walking, a motor skill that for many develops within the first few years of life. While gait may seem a simple function of the human body, the notion is actually contrary to the science that has found there to be a number of factors contributing to how a person's gait actually functions. It is not a simple process of moving one limb at a time. Anatomical factors that affect gait include pelvic rotation, knee flexion, knee mechanisms, and foot mechanisms [4]. In particular, the mechanisms of the ankle and foot are imperative to gait [4]. All of these factors can be specific to the individual in reference to their age, quality of health, and anatomy due to gender. Therefore, gait can vary depending on the individual.

According to research published by the National Center for Biotechnology Information, gait can be divided into two categories: asymmetric or symmetric [18]. Symmetry is "a property of some images, objects, and mathematical equations whereby reflections, rotations, or substitutions cause no change in properties or appearance" [6]. Asymmetry is the opposite or a variation in the correspondence of the objects or images about an axis or dividing line. In the context of gait, symmetry is the mirroring of the right and left leg in comparison to each other as they swing forward, alternating in and out of phase. Asymmetry in gait can cause the swing of the right and left leg to occur at the wrong times, thereby affecting the walking pattern of the individual. Handzic and Reed explain that healthy individuals walk in a *perceptually* symmetric manner with slight changes in gait parameters; such individuals may have an abnormal gait but it is not perceived that way. On the other hand, individuals with physical ailments produce a gait that is both calculable and perceptually asymmetric [8].

Asymmetry in gait can contribute to a lack of balance and muscle deterioration. If a person has an asymmetric gait, physicians will make an effort to correct it so that it becomes more symmetric. Healthy individuals even have a slight variation from perfect symmetry. Perfect gait symmetry would cause an individual to walk rigidly and would be harmful, causing the deterioration of joints. Some degree of asymmetry is observed in normal gait in order for directional changes to occur and for the joints to have smooth movement. Asymmetry in individuals with physical ailments has higher, calculable differences in gait measurements than in healthy individuals [9].

In order to examine the level of symmetry that exists in a person, components of gait on both the right and left side must be analyzed. These components include gait velocity, stance time, swing time, and the overall range of motion (ROM) of the legs. Doing so allows researchers to observe first if a change to one leg affects the other, thereby affecting overall gait. If the changes to one leg do affect the other, then a change in one can be examined in terms of the response in the other. Determining the type of affect a change in one leg has on the other, and quantifying that relationship, allows researchers to begin looking at whether or not this change and response relationship causes the gait to be more symmetric, less symmetric, or remain the same. Part of the first stage, examining components of a dominant side with changes applied to it, has been conducted previously.

A 2015 study conducted at the Pennsylvania State University Berks Campus involved examining changes in the angles of the ankle and knee of the dominant leg of 16 participants as a piece of gait corrective equipment, an ankle foot orthosis (AFO), was attached. With each increase in the stiffness of the equipment, there was a decrease in ankle angle and no significant change in knee angle. This signified less range of motion in the ankle as the final result [20]. If a high degree of gait symmetry exists, then it can be hypothesized that the angles of the knee and ankle in the non-dominant leg would be affected and behave in a similar manner as the dominant leg that has the gait corrective equipment. This study points to the current need to examine the non-dominant leg as changes are applied to the dominant one. Doing so will allow for information about the ROM of the non-dominant leg and any statistical differences to be collected regarding the response of the non-dominant leg due to changes in the dominant leg. With information on both legs, then the symmetry in the gait of an individual can be examined.

This thesis examines three conditions. One with no AFO attached and two with AFOs of increasing stiffness attached to the dominant leg and their effect on the ankle and knee angles of the non-dominant leg. An AFO is a medical device used to correct gait in patients walking in an asymmetric manner. The two AFOs used in this study include the OttoBock AFO, which is the more flexible one, and the Allard Blue Rocker AFO, which is the stiffer one. As a basis for future gait symmetry studies, this study's primary goal is to determine if the dominant leg's change results in a similar change on the non-dominant leg. Ultimately, this study suggests further research in developing analytical measures that have potential use in clinical settings, specifically recommendations for proper corrective devices for patients with gait impairments. Further background information on gait symmetry and AFOs, and a review of the relevant literature is presented in the following sections.

1.2 Gait Symmetry

The following sections discuss the subject of Gait Symmetry in further detail. Key terms, parameters, and relevant case studies are examined.

Parameters of Gait

Gait Symmetry is a metric that is being used increasingly more in clinical settings to aid therapists in assisting patients who have suffered a stroke, Parkinson's disease, and many other neuromuscular diseases [14, 15]. For example, Parkinson's patients are more susceptible to falling from the abnormality in their gait. They have small steps or shuffling that negatively impacts their gait velocity, swing time, and stance time [10]. The literature expresses that physically perceived healthier individuals have a more symmetric gait than those whose physical ailments or diseases impair them [12, 15]. The variation in gait (asymmetry) has also been seen due to age and gender differences [12, 15]. Healthy individuals have smooth, fluid strides, perceived symmetric movement of the right and left leg and a more upright posture compared to afflicted individuals [18].

Gait symmetry analysis compares the movement of the right and left leg [10, 17]. Specifically, the ratios of the right to left leg for the parameters of step length, swing time, and stance time are examined. Each leg is a separate limb that will have its own set of values for these parameters [4, 12]. The values are then compared to each other and the resulting ratio of left to right leg sets the individual into the category of symmetric gait, with subcategories of being perfectly symmetric or normal gait, or the category of asymmetric gait. Another analyzable factor is the amount of control an individual has over his or her gait. Gait control is the ability to modify the reflex patterns of the joints independently of one another at the levels of hip, knee, and ankle [5]. In other words, it is the individual's ability to react to a change in environment with their right and left legs, independent of one another, in order to correct their gait. If a stone is in the path of the right leg and not the left, gait control allows the individual to pivot just their right leg and avoid the stone, keeping their left leg in a normal position. Without gait control, the individual would have to move both legs to avoid the stone.

Case Studies Involving Gait Symmetry

The 2012 Patterson et al. study examined the potential connection between gait symmetry and age using the three parameters of step length, swing time, and stance time [15]. The study consisted of 253 individuals, 172 impaired from stroke and 81 healthy. The subjects walked on a walkway for 10 meters, eventually crossing a pressure-sensitive mat located in the middle of the walkway. The plate recorded data and, using a statistical analysis system (SAS 9.1), calculated and projected the values for stance time, swing time, and step length. While this particular study concluded that age was not a significant factor in the symmetry and asymmetry observed in the subjects' gait, the study did conclude that gait symmetry is a good indicator of a person's degree of gait control and overall performance. The study also concluded that the gait components, including swing time, stance time, and step length, could be used by clinicians and researchers to examine how much a disease or bodily trauma has affected a patient's gait.

A study published in the *Journal of Neuro-Engineering and Rehabilitation* examined the effects of age on gait symmetry and added in a second factor of gender to be considered. The study consisted of 87 subjects, 40 of which were elderly with an average age of 70 and 47 of which were younger with an average age of 20. For data collection, a tri-axial accelerometer was used, which measures the acceleration of the subject's gait. The accelerometer was placed on the subject's back and recorded data every 0.02 seconds as the subject walked over a seven-meter length of walkway. Using an autocorrelation function to analyze the recorded acceleration data, by which the correlation between the different time intervals can be compared, the gait components could be quantified [12]. With variations from one to negative one, the autocorrelation value indicated the symmetry between the two legs. The first peak in the data, when graphed over time, identified the symmetry of the steps and the second peak identified the symmetry of the strides. The study concluded that age significantly impacted the symmetry of an individual's gait over a large period of time whereas gender was not as significant a factor. This study, in conjunction with the previous Patterson et. al. study, points to gait symmetry as an indicator of how bodily change, whether that be age or a disease, has affected an individual's gait control. Individuals with a measured symmetric gait are physically healthier and in more control of their gait movements than those with a measured asymmetric gait.

Three of the studies reviewed on gait symmetry, as well as two medical journals examined, focused on using the measurements for swing time, stance time, step length, and gait velocity in order to determine and analyze the subjects' gaits [10, 15, 17]. Another measurement to consider is the heel-strike comparison over time with a continuous relative phase analysis (CRP). Haddad et. al.'s 2010 study involved 12 unaffected participants, six of each gender, and measured the gait velocity as various loads were placed on the participant [7]. This study found that the higher the order of the analysis function used, the more effective and precise the measurement of symmetry or asymmetry will be. The CRP methods are more complex than simple kinetics and kinematics calculations, but these methods are also more adept to discovering and revealing asymmetry. In order to evaluate the ROM of the non-dominant leg and symmetry in this study, continuous phase analysis methods for the knee and ankle angles were implemented in MATLAB.

Gait Summary

Each of the case studies examined in the section above provides a basis for this thesis' examination of gait symmetry as well as non-dominant leg response to dominant leg changes. Based on the aforementioned literature, gait in the non-dominant leg will be examined to determine if it is affected by changes in the dominant leg. Furthermore, this study will also pilot an examination of gait symmetry through dual motion capture analysis and cross-correlation analysis. As in the case studies, the parameters to consider are knee and ankle ROM, as well as gait velocity and swing time. The following section will provide information on a corrective piece of medical equipment for patients with an unhealthy gait, which the studies cited thus far have not involved.

1.3 Ankle Foot Orthoses

Ankle foot orthoses (AFOs) are pieces of medical equipment typically made of plastic or carbon fiber and resemble a shin guard with a foot plate. The purpose of an AFO is to correct the gait of patients who have suffered a stroke or other condition resulting in gait abnormalities. These abnormalities include misplacement of the foot when making contact with the ground and reduced stability [2]. AFOs correct these by giving the ankle more support and holding both the ankle and foot in a rigid position to allow for proper foot drop and increased clearance when walking. The following sections discuss AFO design, testing, and application.

AFO Design

In a clinical setting, there are various types of AFOs in terms of design and material stiffness. Depending on the health system and equipment available, physicians will recommend an AFO to patients through a process of trial and error. A patient will try an AFO on and walk for the physician to observe. Then the physician will try to make the best recommendation based on what was seen with the response in plantarflexion and dorsiflexion. An individual who holds his or her heel on the ground and flexes their foot back toward them is said to be in dorsiflexion, if they were to point their foot forward instead, they would be in plantarflexion. Individuals who are in too much dorsiflexion or plantarflexion when walking may be in need of a more rigid AFO to control the flexion. The same may not be true of an individual who does not have enough movement in either direction and may need a more flexible AFO to help adjust the movement of the foot.

AFO Design Testing

Methods of analysis have included bench-tests in which the analysis is mainly on the mechanical properties of the hardware. A force is created to examine the deflection of the AFO [13]. Applying an artificial force at different locations and loads will test the strength of the material. Doing so will cause deflection at certain points, so areas, where the material breaks in the design can be targeted and redesigned. The purpose of the AFO is to provide some rigid support so that the gait is corrected; having too stiff or too flexible of an AFO can result in more harm to the patient and longer periods of rehabilitation. Therefore, the rigidity becomes a factor of concern in AFO design. Ideally, the ROM of the ankle is completely restricted by the AFO. One study examined a 2-D analysis method for analyzing AFO deflection. In this study, the ankle movement was recorded in two dimensions in the sagittal plane using five physical markers and four virtual markers. The markers served to create the ankle angles among the tibia, heel, and foot [17]. The study resulted in expressing a relationship between ankle ROM and AFO deformation, thus providing measurement values in order to make recommendations for the AFO best suited to the patient.

A second method for analyzing AFOs is to use 3-D motion capture software along with a data interpretation tool. This method has been shown to be effective in pilot studies for helping clinicians to fine-tune the AFOs they are recommending for their patients. These systems, such as a Vicon system, are used in animation and biomechanical industries and can measure walking velocity, lower limb kinematics, step length, and symmetry ratio [3]. As studies have begun to indicate, the aforementioned measurements would also be very useful in analyzing gait symmetry and physical health of the patient.

Purpose of AFO Use

Since AFOs correct gait, it is conceivable that these devices would have an impact on both legs as well as gait symmetry. The following three sections explain recent studies involving gait as affected by AFOs, a method of analysis for non-dominant leg angle comparisons, and a mathematical method of analysis for gait symmetry. All three sections support and provide further basis for this thesis's goal of analyzing the non-dominant leg in response to changes in the dominant leg. The present study also provides preliminary evidence of the level of existence of gait symmetry in healthy individuals using an AFO.

AFOS and Gait Symmetry

As discussed previously, a 2015 Pennsylvania State University study examined the ROM in the ankle and knee of the dominant leg as participants walked in four different situations. The first trial for each served to provide a control, where no AFO was placed on the participant. In subsequent trials AFOs with increasing stiffness were placed on the right leg. In each trial, motion capture was used to obtain the locations of the markers that determine the ankle and knee angle, specifically distal and proximal thigh, shank, and foot. The study conclusively found that AFOs do affect gait significantly in terms of ankle ROM [20].

This study's results confirmed a 2010 study that examined the effects of AFOs on the ankle, knee, and hip joint kinematics in walking. The 2010 study similarly concluded that AFOs do significantly impact the kinematics and kinetics while walking [14]. Both of the aforementioned studies involved placing an AFO on the dominant leg and observing and capturing the joint angles of that same leg. Since gait symmetry can be said to be the level of similarity between the right and left leg, it is expected that the left leg will change while the right leg is being affected. The aim of this thesis examines that potential relationship. Its existence will also help in providing further information about gait symmetry. This study would support the idea that non-dominant leg changes resulting from applied changes to the dominant leg exist and show if the changes are similar or distinctly different.

1.4 Analysis of Non-Dominant Leg Gait, Gait Symmetry, and AFOs

The gait of the non-dominant leg, gait symmetry, and Ankle Foot Orthoses are the components of the research that will be observed. While the three do seem to relate to each other, there is not a direct connection that says a specific amount of gait symmetry qualifies a patient as needing an AFO. Because there is more than one factor influencing both the need for an AFO and the symmetry of one's gait, the three can be related using correlation analysis methods, range of motion comparison, and volume of oxygen (VO_2) analysis methods. The following sections will briefly describe each method. Chapter 2 will go into further detail and calculations.

Range of Motion

ROM is the measure of how far limbs can move based on joint angles. For example, a human can rotate the shoulder a full 360 degrees, whereas the forearm can pivot about the elbow from 0 to under 180 degrees. In the leg, the ROM of the knee and ankle are the two measurements that can be used to identify changes that may be significant.

In terms of the non-dominant leg, the ROM can be calculated by taking the range of the knee and ankle angles with each change in the right leg. Comparing the values to one another will then show if there is a consistent difference in the non-dominant leg due to changes in the dominant leg. Standard deviation and the average values of ROM are also informative measurements.

Correlation Analysis Methods

Simple correlation is a basic statistical approach used to examine how closely associated two variables are. A variable X and a variable Y will each have their own set of data where standard deviations and covariance values are calculated. Covariance helps in comparing the degree that X varies to the degree that Y varies. Using the three calculations of covariance, and standard deviations, a correlation coefficient is calculated. The correlation coefficient will be between one and negative one. The coefficient will never reach negative one or one in calculations unless the same variable is being compared to itself, resulting in a perfect correlation value of one. The second possibility is that the two variables are perfectly opposite of each other, resulting in a negative one correlation coefficient.

Based on the size and sign of the correlation coefficient, the level of association between the two variables is determined. For example, if the correlation coefficient between X and Y was determined to be -0.64, this would indicate a strong probability that the two variables are not related. In contrast, a value of 0.61 would indicate a strong probability that the two variables are strongly related to one another. The drawbacks to the method of simple correlation are that correlation does not show causality and can be subject to randomness. The variables X and Y may be related, but that does not mean that X causes Y to occur. Another possibility is that the specific data may pertain to a unique instance in time and is therefore not an accurate representation of the variables' characteristic relationship. There are too many unanswered questions to rely on simple correlation alone.

Cross-correlation analysis is a more complex version of simple correlation and incorporates signal data. Cross-correlation can be used to examine the similarity of two signals at different time lag positions. The cross-correlation method will allow for the determination of a cross-correlation sequence as a ratio of the two variables, or signals, being observed. Similarly, a Pearson Correlation method will also measure a linear correlation between two variables, resulting in values of one, zero, or negative one depending on the type of correlation. One study specifically used a Pearson's Correlation method to evaluate its recorded motion capture data of the leg motion of 16 participants, eight patients of recent lower limb surgery and eight healthy volunteers. This method allowed the researchers to evaluate the symmetry of the patients' gait and use their results as a predictive treatment protocol [11].

The right and left ankle angles, and the right and left knee angles represent the variables being considered in gait symmetry. By comparing the individual knee and ankle angles, with a time lag being applied to the left ligament in both cases, a cross-correlation method can be implemented. The cross-correlation values, based on the sign and strength of the value, provide an indication of the gait symmetry of the ankles and knees, and ultimately the person's gait.

Energy Expenditure

Aerobic exercise is any exercise that requires the host to take in oxygen to create the energy that will be expelled. Energy expenditure (EE) is the measure of energy spent during rest or a period of steady exercise. To calculate energy expenditure in aerobic exercise or movement, the most common practice is to measure oxygen consumption (VO_2) and carbon dioxide production (VCO_2), which is known as indirect calorimetry [1]. This technique is commonly used in sports medicine to assess the level of fitness in athletes during field conditions. If a person was connected to a metabolic cart that measures VO_2 and VCO_2 while performing an aerobic exercise, then EE could be calculated. Changes that are administered then would be seen to have a positive, negative, or null effect on the EE of the person. It can be said that those changes either made the person work less, more, or no differently than before, with respect to the calculated value.

One unit of measurement to examine when determining energy expenditure is the respiratory exchange ratio (RER). This measure represents the ratio of oxygen consumption to carbon dioxide production. RER increases and decreases throughout an exercise indicating what fuel the body is using, for example, fats instead of carbohydrates for higher intensity workouts. The distinction is seen in the typical RER values that range from 0.7 to 1.0, where the lower represents rest and the higher represents a higher intensity workout. This measure is a simpler, yet effective way to quantitatively see if EE is increasing or decreasing, and it is the EE measure examined in this study.

If gait symmetry is said to identify a degree of the physical health of an individual, then it can be hypothesized that the more symmetric the gait, the less energy needed to walk. Additionally, assuming a patient has a non-symmetric gait that is corrected with the use of an AFO, the EE value should be less for the patient when they are wearing an AFO as compared to when they are not. Since the patient is using less energy to move, this would indicate the chosen AFO is an appropriate choice for that patient.

Analysis Summary

Using ROM analysis, the non-dominant leg will be examined to determine its change as AFOs with increasing stiffness are placed on the dominant leg. Using cross-correlation analysis, the existence of gait symmetry and the strength of gait symmetry between the right and left leg in a participant can be determined. Using a metabolic cart that implements indirect calorimetry, the energy expenditure of a participant wearing a mask can be simultaneously calculated while the participant is moving. Combining both measures when the participant is walking without an AFO and with each of two AFOs will create two categories of data. The first category will go towards showing whether the participant has a more or less symmetric gait with each AFO implementation, as well as how the non-dominant leg is changing. The second will then point towards whether or not the changes cause the participant to expend more or less energy. Chapter 2 will discuss the implementation of this data analysis further.

1.5 Conclusion

In 2011, Gait & Posture published a study concerning the use of a wireless inertial device that was used to examine how AFOs, given to patients with equinus foot as a corrective measure, would affect various parameters of a patient's gait [19]. Equinus foot is the inability of a person to flex their foot forward at the ankle, and one of the parameters, in particular, was gait symmetry. It is reasonable to conclude that gait symmetry would be affected by the use of an AFO. As detailed previously some studies have examined either gait symmetry on its own, AFOs on their own, or gait symmetry as one of many examined parameters of a patient with an AFO. Furthermore, the methods of analysis used present a wide range of potential candidates for examining step length, stance time, dorsiflexion, plantar flexion, and gait symmetry.

This study focuses on examining the effects of AFOs on the gait observed in the non-dominant leg as a basis for studying gait symmetry. Specifically, three of the examined methods and similar instrumentation from this introduction were used, which will be further examined in Chapter 2. This study will validate a relationship between dominant leg AFO placement and changes in the non-dominant leg ankle and knee angles. Through AFO usage and energy expenditure measurements the relationship will be qualitatively and quantitatively examined. Lastly, this study aims to use the aforementioned results from the non-dominant leg angles and begin comparison with captured dominant leg angles in one participant for further validation concerning the existence of a relationship between gait symmetry and AFO stiffness.

Chapter 2 will describe the experiment to be run using volunteer participants, as well as the instrumentation for data capture for motion analysis. This section will also explain the mathematical interpretations and analysis methods to be run using MATLAB software for examination of chosen gait and AFO parameters. Chapter 3 will focus on the results of the experiment and how it compares to previous experiments.

Chapter 4 will discuss the results with the intent of making recommendations for further research and for clinicians currently in need of a system to evaluate AFOs and gait symmetry.

Chapter 2

Methods

2.1 Participants

Four participants (two males, two females) took part in this study. The participants' age ranged from 20 to 21 years, had a mass average of 147.1 pounds, and a mean height of 65 inches. The footedness (foot preference) of each participant was found by asking the participant to stand on his or her leg of choice, step forward with his or her leg of choice, and kick a soccer ball with his or her foot of choice. Each of these tests were performed three times for each participant to observe the dominant side of the participant, which is recorded below. All participants signed and provided written consent for participation in this study.

Gender	Mean Age (years)	Mean Height (in)	Mean Weight (lbs.)	Dominant Side	n
Men	20.6	65.4	147.8	Right	2
Women	20.1	64.6	146.4	Right	2

Table 1. Summary of Participant Demographics - Gender as well as average age, height, weight, dominant side, and number of participants are listed above.

2.2 Walking Trials

Gait Symmetry and AFO Walking Trials

The walking trials of this experiment took place in three parts. All parts involved a treadmill, colored physical markers, and a stopwatch. For both trials with and without an AFO, the participant stood on the treadmill in an upright position while a still image was taken of the non-dominant leg to obtain the initial position of the markers. The markers were placed to represent the points corresponding to distal thigh, proximal thigh, distal shank, proximal shank, distal foot (ankle) and proximal foot (fifth base metatarsal) as seen in Figure 1. The first walking trial for every participant was performed to obtain control data. The participant walked for 90 seconds at a speed of 2.7 miles per hour with six different markers attached to each leg. The participants walked for 15 seconds both before and after each trial to ensure the data was recorded properly.

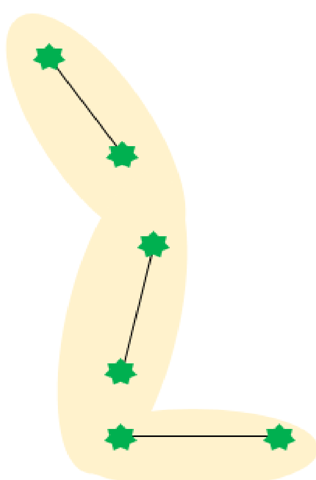

Figure 1. Leg Markers **-** The representation of the right leg with all six anatomical markers indicating the locations of distal and proximal thigh, shank, and foot is shown above. The black connection between the markers indicates the limb segments the MATLAB software will determine in order to calculate the angles of the knee and ankle.

The second set of walking trials was performed with each patient using each of the two AFOs shown in Figure 2. The two AFOs are made of carbon fiber and differ in stiffness. The Otto Bock Walk-On AFO is less stiff and is a posterior AFO, whereas the Allard Blue Rocker AFO is stiffer and an anterior AFO. The six markers were placed at the same locations on the participant as they were in the initial trial without the AFO. Care was taken to avoid placing the markers in an area that the AFO would block during data capture. The participants walked for 90 seconds at 2.7 mph with the motion being captured by a recording device. The participants, as in the initial trial, walked for an additional 15 seconds before and after the trial.

Figure 2. Ankle Foot Orthoses - The AFOs used in this experiment include the Allard Blue Rocker AFO (right) and the Otto Bock Walk-On AFO (left). The Allard Blue Rocker is an anterior AFO while the Otto Bock Walk-On is a posterior AFO.

Maximum VO_2 Walking Trials

During the walking trials, VO_2 testing was run using a metabolic cart comprised of an iWorx Teaching Assistant device, an iWorx GA-200 Gas Analyzer, a gas chamber, an A-M Systems Spirometer, a face mask, and a laptop running Labscribe software. Initially, the system was calibrated to ensure the expired air volume under standard temperature and pressure conditions was initially set between 2.75-2.85. CO_2 levels and O_2 levels were each calibrated afterward to be within their standard values. Once calibrated, a clean facemask was attached to the oxygen chamber using a clean hose, and then attached to each participant's face by strapping it around the ears. The participants walked at 2.7 mph for 90 seconds. The trials were run with no AFO on, and each type of AFO (OttoBock and Allard Blue Rocker) on. The oxygen chamber was calibrated after each trial using the A-M Systems spirometer. Data was stored in both a readable format for Labscribe, and as a comma delimited file for plotting in MATLAB and Excel.

2.3 Data Analysis

The data from the experiment was captured and analyzed in multiple ways. The first involved capturing motion of the non-dominant leg while walking to determine the angles of the knee and ankle. The second involved capturing the motion of the dominant leg for symmetry comparison to the non-dominant leg in one participant. The last involved measuring the maximum VO_2 output of each participant to determine energy expenditure through respiratory exchange ratio. The following sections detail each method of capture and analysis.

Motion Capture Analysis

Motion Capture Analysis occurred in two different approaches. The first involved motion capture of solely the non-dominant leg, and the second involved simultaneous motion capture of the right and left leg for gait symmetry analysis.

For non-dominant leg motion capture analysis, the gait of the non-dominant leg was captured using a Canon r600 video camera. The camera was placed on a tripod mount at an eight-foot distance from the treadmill and a height large enough to capture the full image of the thigh, shank, and foot. Before recording any of the walking trials, the camera was used to take a still shot of the non-dominant leg. Doing so allowed the initial position of all the markers to be obtained. With these initial positions, the zero mark, or resting position, for the knee and ankle angles were determined. After initial image capture, the participants began walking on the treadmill; after 15 seconds the camera was started and recorded 90 seconds of each trial. The recording was saved in a mp4 format.

For gait symmetry motion capture analysis of one of the participants, the same process of non-dominant leg motion capture analysis was used on the dominant leg. This process ran simultaneously to the capture of hiss non-dominant leg motion capture in order to provide accurate time representations of the collected data. To synchronize the videos for processing, a loud clapping sound was generated and recorded by the cameras simultaneously.

MATLAB (Mathworks R2015a) software was used to analyze the recorded videos. The custom MATLAB code converts the recorded video from mp4 format into a readable video reader object format. Initially, the code reads the video object for a frame rate of 60 frames per second. A random frame from the static image is chosen by the code and displayed so the leg markers can be clicked on, to allocate a centroid, and then re-entered for further analysis. Using the chosen points, the code calculates the angles between each set of limb segments the thigh, shank, and foot markers determine. The code uses these initial measurements as the zero or resting position before movement begins. The code saves the data, then uses it in the subsequent code for the recordings of the non-dominant and, when applicable, dominant leg motion.

The recorded leg motion data was similarly converted into a video object, and the code used the previously determined centroid from the corresponding static image as a starting point for finding the markers. Using *k-means* clustering, the centroids of the markers were tracked frame by frame at a rate determined by the code as the most time efficient for processing. Through this tracking, the motion of the legs was analyzed. From the stored location of the markers over time, the range of motion (ROM) of the ankle and knee were measured. ROM was seen to be affected if the values of ROM changed in the non-dominant leg after each change in AFO condition of the dominant leg. ROM was tracked and compared graphically to see if ROM was affected. Additionally, the ROM of the non-dominant and dominant leg, including knee and ankle angles, of participant M02 was tracked for comparison to one another for gait symmetry analysis through cross correlation.

Gait Analysis

Range of Motion (ROM)

Using the discussed MATLAB code the angles of knee and ankle for the trials involving the non-dominant leg and the trial that involved both legs were calculated and stored. A comparison of these values allowed for an examination of change in ROM as each AFO stiffness increase. Statistical measures for comparison in both cases were mean, standard deviation, and range.

Gait Symmetry through Correlation

The cross-correlation function of the right and left leg time series is a function of the lag between them. If *n* is the number of samples taken, then transmitted signal one is represented by the right leg information (ankle and knee angles).

$$\boldsymbol{X_i}$$

Transmitted signal two is represented by the left leg information with a time delay for comparison based on the right leg.

$$\boldsymbol{Y_{(i+m)}}$$

Using both signals the covariance function can be designed for m = (0, 1, 2, …. N-1) as

$$\boldsymbol{C_{XY}(m) = \frac{1}{N}\sum_{i=1}^{N-m}(X_i - \bar{X})(Y_{i+m} - \bar{Y})}$$

Combining the covariance function with the variances of X and Y initially, allows the cross-correlation coefficient to be calculated as

$$\boldsymbol{r_{XY}(m) = \frac{C_{XY}(m)}{\sqrt{C_{XX}C_{YY}}}}$$

which measures the strength and direction of the relationship between the two.

MATLAB code is used to take the determined knee and ankle angles from the first code and run all the values of the right while comparing them to the left values that have a lag added to them. The correlation values are found using the *corr* function and then squared to find the r^2 values. The r^2 values represent the coefficient of determination, or the amount of variation in one leg's measures that is described by the variation in the other.

Energy Expenditure Analysis

To evaluate energy expenditure, an iWorx GA-200 metabolic cart was used. The metabolic cart consists of a gas chamber, the GA-200 modem, a spirometer, and a laptop running the program Labscribe. Initially, the entire system is calibrated by using the spirometer to clear the gas chamber, and an oxygen tank that when connected injects the chamber with pure oxygen to calibrate the CO_2 and O_2 levels. The entire calibration process takes twenty to thirty minutes to run entirely. Once calibrated, each participant has a facemask placed over his or her mouth with a tube connecting on one side of the mask. The participant walks for one minute to reach a steady pace and allow his or her body time to adjust. At the one-minute mark, the system is set to record data, and then the participants' mask and tube are connected to the gas chamber. After an additional thirty seconds, the camera is started for the motion capture analysis and the metabolic cart records data for the duration of the experiment, which is ninety additional seconds.

After each experiment, the system was calibrated to clear the gas chamber and tube for future use. While in Labscribe, the collected data was processed using the offline calculations function. The data was exported to Excel and the energy expenditure over the duration of the experiment was observed. The values of RER over the recorded period of time is the measure specifically examined in each participant for this study.

2.4 Conclusion

Using the previous methods of motion capture and data analysis, the results reported in Chapter 3 were found. Each experiment, the non-dominant leg experiments and the simultaneous left and right leg experiment, ran the same process, once to obtain a control and two subsequent times for the AFOs for each participant. All data was recorded and stored in Excel and evaluated using MATLAB.

Chapter 3

Results

3.1 Non-dominant Leg ROM and AFO Results

Non-dominant Ankle Results

In MATLAB, the ankle angles of the non-dominant leg were plotted against each other on the same graph. As shown in Figure 3, there are differences between the ankle angles of the non-dominant leg as an AFO is attached to the dominant leg. Figure 3 represents the result of one participant, identification M02. This participant's data is represented to show not only the trends that occurred in non-dominant leg angles for each participant but also for his participation in the gait symmetry trial to be discussed later in section 3.1. Each participant consistently showed a larger difference between the control trial and the Allard Blue Rocker AFO trial, than between the control trial and the OttoBock AFO Trial.

Table 2 lists the data collected for the range of motion (ROM) of all four participants. The maximum and minimum mean values of the ankle angle of all four participants, as well as the total ROM averages, were calculated in degrees using basic statistical analysis. This data shows a larger maximum ROM in the non-dominant leg overall when the Allard Blue Rocker AFO was applied to the dominant leg, as compared to the other two conditions. Figure 3 was created by taking the mean of the ankle coordinates, which creates the angle values plotted along the y-axis over the total phase of the gait from zero to one-hundred percent of the phase.

Condition	Max. Ankle Angle (°)	Min Ankle Angle (°)	ROM (°)
No AFO	11.66	-7.864	19.53
OttoBock AFO	11.46	-7.210	18.67
Allard Blue Rocker AFO	12.20	-10.20	22.40

Table 2. Non-dominant Leg Ankle ROM - In the second column the mean values of the maximum angle the non-dominant leg ankle reach for all four participants was taken for each condition. Column two lists the mean minimum angle the non-dominant ankle reached. Lastly, column three lists the total ROM the non-dominant leg ankle had over the gait cycle.

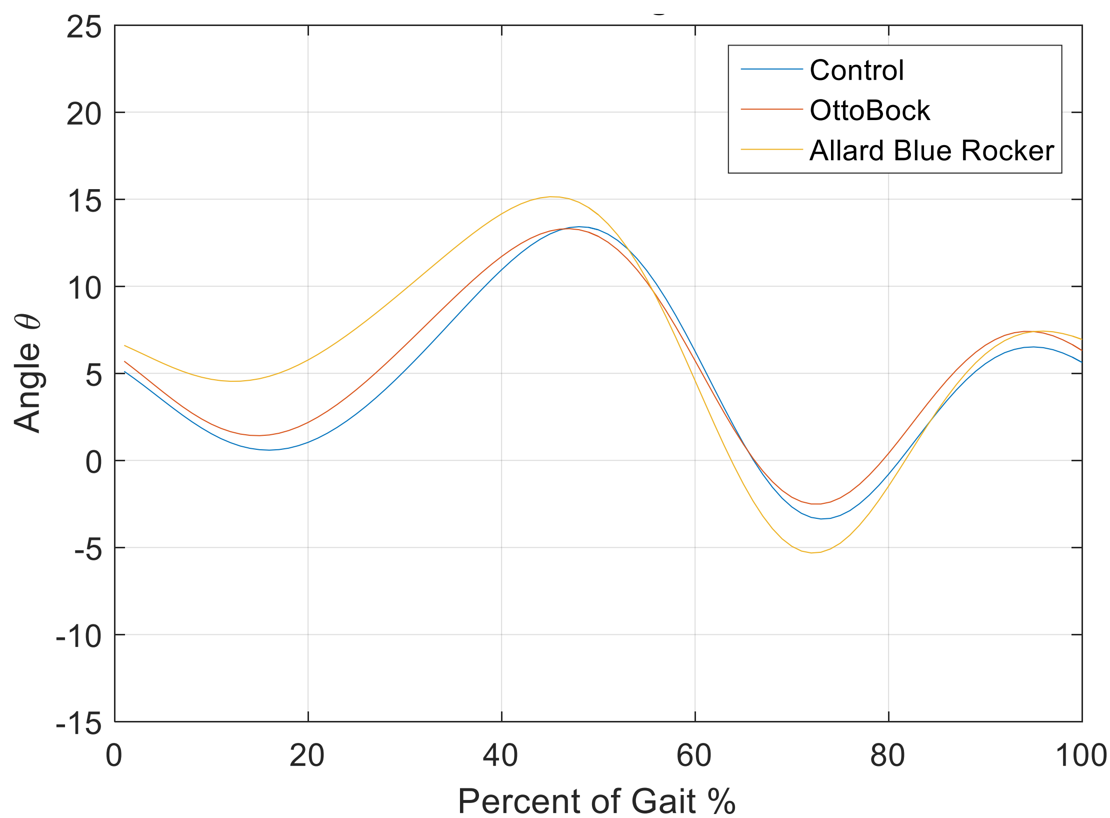

Figure 3. Non-dominant Ankle Angle - Participant M02's left leg ankle angle changed in response to AFOs being placed on the right leg. The maximum and minimum angles were larger with increasing AFO stiffness.

Non-dominant Leg Knee Results

In MATLAB, the knee angles of the non-dominant leg were also plotted against each other on the same graph. As shown in Figure 5, there are differences between the knee angles of the non-dominant leg as an AFO is attached to the dominant leg. Figure 5 shows the result of participant M02. In this case, the knee angles showed a larger difference between the OttoBock AFO and control trial, rather than the Allard Blue Rocker and control trial.

Table 3 lists the data collected for the ROM of all four participants. The mean maximum and minimum values of the knee angle, as well as the total ROM averages, were calculated in degrees using basic statistical analysis of averages and standard deviation. This data shows larger ROM in the non-dominant leg when the Allard Blue Rocker AFO is applied to the dominant leg, as compared to the other two conditions.

Condition	Max. Knee Angle (°)	Min Knee Angle (°)	ROM (°)
No AFO	60.60	-7.77	68.36
OttoBock AFO	61.13	-9.351	70.48
Allard Blue Rocker AFO	56.83	-12.89	69.72

Table 3. Non-dominant Leg Knee ROM - In the second column, the mean values of the maximum angle the non-dominant leg knee reached for all four participants were taken for each condition. Column two lists the mean minimum angle the non-dominant knee reached. Lastly, column three lists the total ROM the non-dominant leg knee had over the gait cycle.

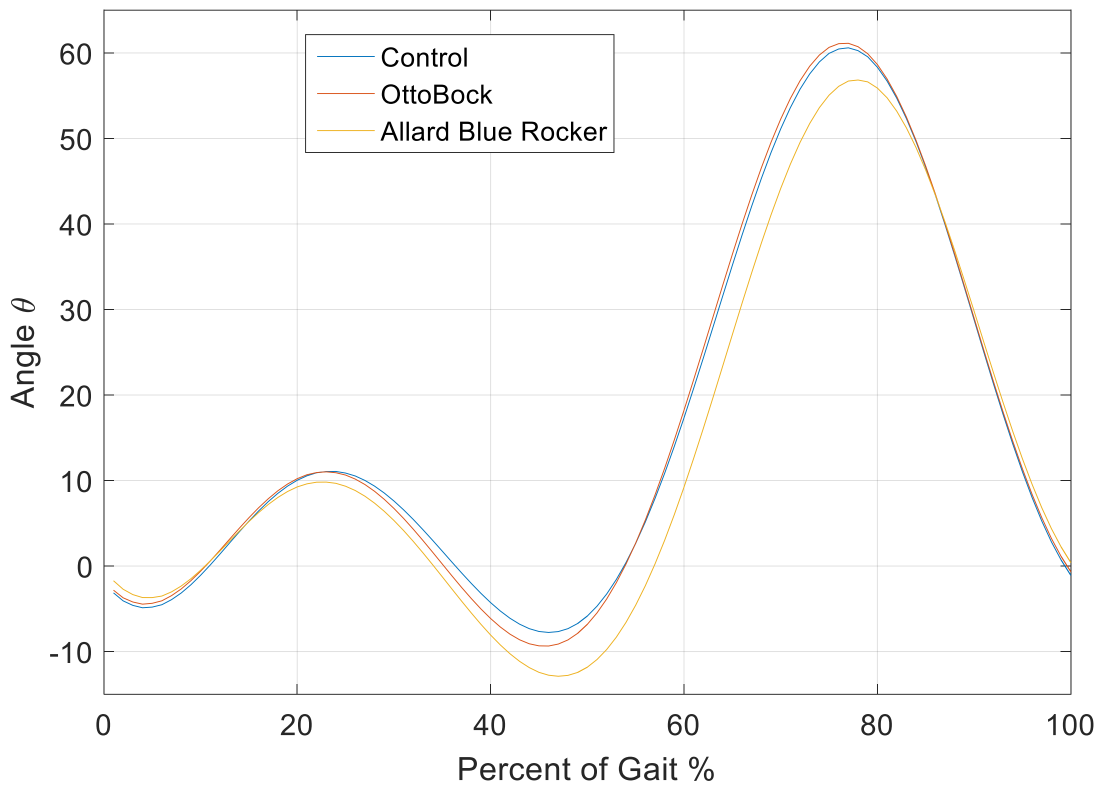

Figure 4. Non-dominant Knee Angle- Participant M02's non-dominant leg ankle angle changed in response to AFOs being placed on the right leg. The maximum and minimum angles the ankle moved in were larger with increasing AFO stiffness.

3.2 Gait Symmetry Results

Participant M02 was used in the sole gait symmetry test run as an experimental trial for future work. In MATLAB, the ankle and knee angles of both the dominant and non-dominant leg were calculated using the same process as in the non-dominant leg trials. Using the *corr* function and the cross-correlation method outlined in Chapter 2, the coefficients of determination (cross-correlation values) were found and plotted over lag times equal to half the total number of sampling points. Additionally, the maximum correlation values were found for comparison over all three conditions. Table 4 outlines these results.

Figure 7 shows the coefficient of determination for the knee over the time lags applied to the left leg with no AFO placed on the dominant leg, the OttoBock AFO placed on the dominant leg, and the Allard Blue Rocker AFO placed on the dominant leg. Figure 8 shows the same measures with the same conditions, but with regards to the ankle correlation coefficients. The ankle coefficients are consistently lower than those of the knee and reach a maximum correlation of 0.7740 under the no AFO condition, whereas the knee reaches a maximum correlation of 0.9614. The OttoBock AFO condition caused the coefficients of both the knee and ankle to gradually decline and rise in intensity as the time lag increased. Focusing on the maximum values, the knee correlation was higher under the OttoBock condition when compared to the no AFO condition. The maximum ankle correlation coefficient was lower compared to the no AFO condition. Lastly, the Allard Blue Rocker AFO condition caused the correlation values of the knee and ankle to gradually decline. When comparing the maximum values of this condition to the previous two, it is noteworthy that the correlation values were lowest with this AFO applied to the dominant leg.

Condition	Max. Knee r^2	Max. Ankle r^2
No AFO	0.9614	0.7740
OttoBock AFO	0.9783	0.6811
Allard Blue Rocker AFO	0.7538	0.5261

Table 4. Coefficient of Determination Values - Listed above are the values of the maximum coefficients of determination as found in each AFO condition. The column represents the knee and the third column represents the ankle.

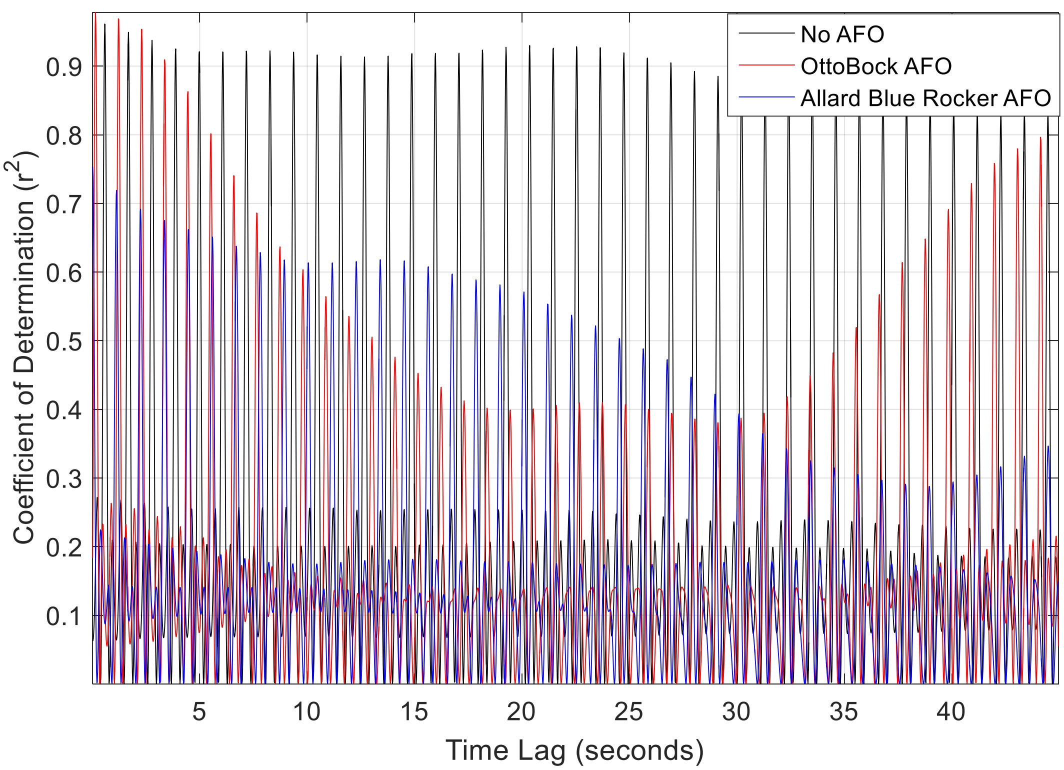

Figure 5. Cross Correlation of Knee - The correlation of the knee angles of the right and left leg with no AFO (black), OttoBock AFO (red), and Allard Blue Rocker AFO (blue) placed on the dominant leg are represented above. The knee angle correlation shows higher correlation values associated with no AFO throughout different time lags. The OttoBock AFO placement results in a gradual fall and rise in correlation values of the knees and the Allard Blue Rocker AFO shows a gradual decline with increasing lag time.

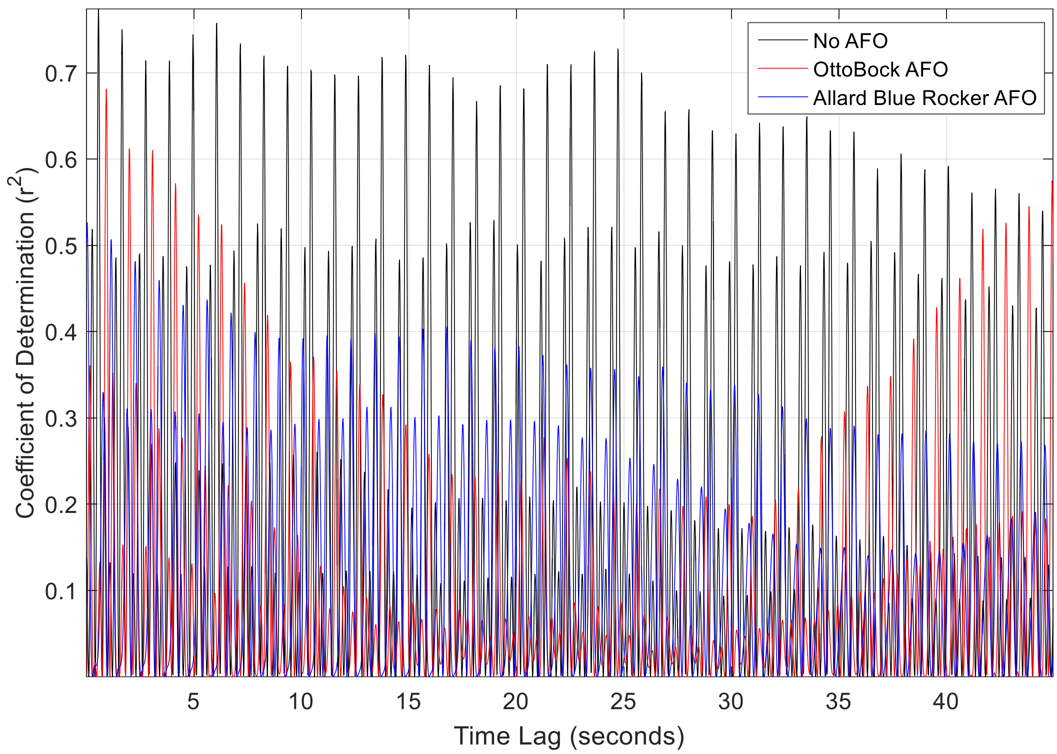

Figure 6. Cross Correlation of the Ankle - The correlation of the ankle angles of the right and left leg with no AFO (black), OttoBock AFO (red), and Allard Blue Rocker AFO (blue) placed on the dominant leg are represented above. The ankle angle correlation shows higher correlation values associated with no AFO throughout different time lags. The OttoBock AFO placement results in a gradual fall and rise in correlation values of the knees and the Allard Blue Rocker AFO shows a gradual decline with increasing lag time.

3.3 VO_2 Results

VO_2 RER data was collected and stored in Excel and analyzed in MATLAB. Figure 5 shows the increase in difference from the mean RER value of the control condition, no AFO, with each increase in AFO stiffness. The average differences of the normalized RER values among all four participants for each trial was graphed using a *boxplot* function in MATLAB. The mean values are represented by the solid red lines in the box and whisker plot. The mean values and standard deviations are shown in Table 2. The result shows a rise in normalized mean RER and percent difference from control with increasing AFO stiffness.

AFO TRIAL	**Mean RER**	**Standard Deviation RER**	**% Diff. from Control**
No AFO	0.7876	0.0135	-
OttoBock AFO	0.7913	0.0059	0.47 %
Allard Blue Rocker AFO	0.7933	0.0160	0.72 %

Table 5. VO2 Respiratory Exchange Ratio - Displayed in the second column are the values for average normalized RER of all four participants. In the third column, the standard deviation from average RER is listed as well as the percent difference from the average normalized RER value of the control trial, which is listed in column three.

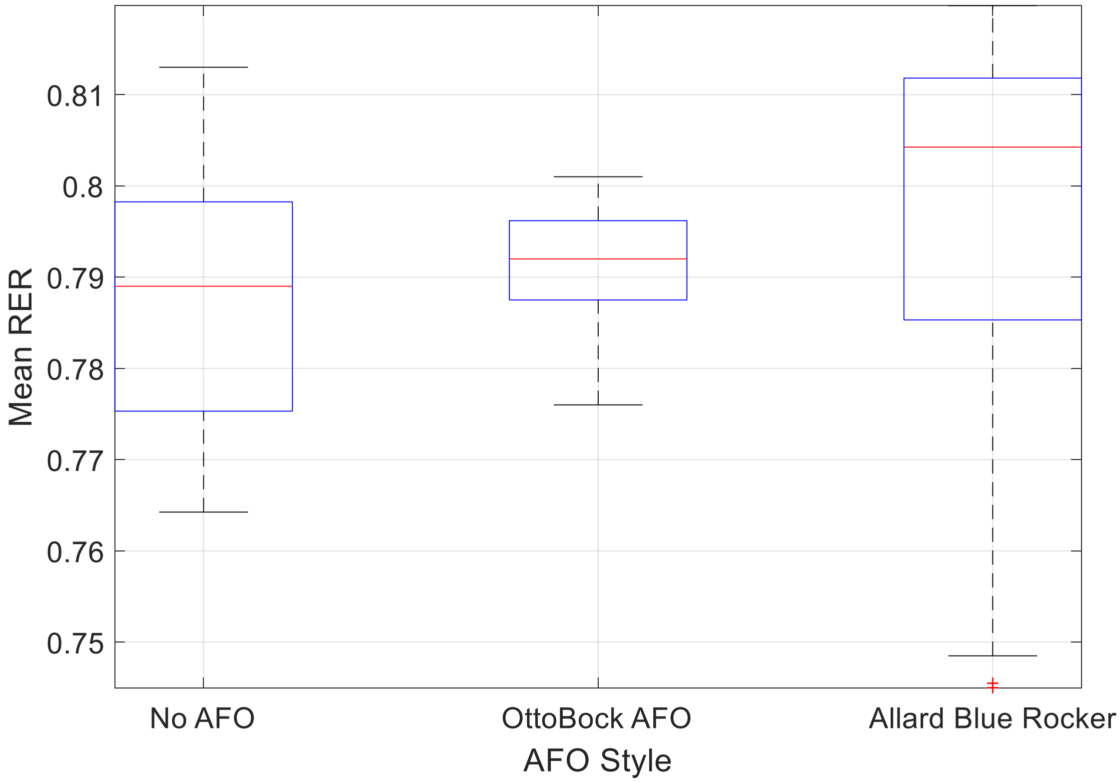

Figure 7. Mean RER by AFO Condition - The resulting RER values of the average of all subjects per AFO style is displayed above. As displayed in the figure above there is a consistent increase in the mean RER value from the first condition with no AFO on the right leg, to the OttoBock AFO being attached, and lastly the Allard Blue Rocker AFO being attached.

3.4 Summary of Results

In both the VO_2 trials and the walking trials that examined the non-dominant leg's knee and ankle angles, there were observable changes from one condition to the other. The results found from the motion capture data show a significant change in ROM between the non-dominant leg ankle angles that consistently increase with AFO stiffness increase. The non-dominant knee angles show a trend of ROM changing with an AFO placement, but not as statistically significant as the ankle. The results obtained from the metabolic cart present increased mean RER values that continually increase as the stiffness in AFO increase, signifying a larger amount of energy expenditure. Both graphically and numerically, the analytical measures used were able to calculate these differences in terms of percent difference, the mean value, and standard deviation.

In the gait symmetry experimental trial performed on participant M02, there was an observable consistent decrease in maximum correlation coefficient values of the ankle as the stiffness of the AFOs was increased. The maximum knee angle correlation coefficients did not follow this trend, although the lowest value did result from the stiffest AFO being placed on the dominant leg.

Chapter 4

Discussion

4.1 Overview

This chapter discusses the results of the study, as well as its limitations, and the potential for future studies. The following sections analyze the results collected in Chapter 3 concerning changes in the ankle and knee angles of the non-dominant leg in response to placement of AFOs on the dominant leg, as well as changes in energy expenditure based on the RER measurements. Lastly, this chapter discusses the rationale for examining these non-dominant leg changes as a basis to study gait symmetry, and the results of the gait symmetry experiment conducted.

4.2 Results Analysis

Non-dominant Leg ROM and AFO Results

The goal of the non-dominant leg analysis segment of the study was to examine if there exists a relationship between the non-dominant leg ankle and knee ROM as changes to the dominant leg were applied. Ultimately, the results do support a trend that exists among AFO placement on the dominant leg and ankle angles changes in the non-dominant leg. The stiffer the AFO on the dominant leg, the larger the range of motion in the non-dominant ankle. This occurred in all four participants. Furthermore, the Allard Blue Rocker AFO had a significantly larger impact on ROM change when compared to the OttoBock. The Allard Blue Rocker AFO had a 12% increase compared to control ROM while the OttoBock had a 4.4% decrease in ROM. This change only occurred in the ankle angle. While the knee angles of the non-dominant leg were also affected by the placement of an AFO on the dominant side, the results show there was no consistent increase or decrease in knee angle as it relates to increasing AFO stiffness.

VO_2 Results

The aim of the VO_2 experimentation was to provide evidence that oxygen consumption and carbon dioxide production would show a trend among energy expenditure and AFO condition changes. The results in Chapter 3 do support the existence of such a relationship through the use of a metabolic cart. RER in the participants under each increased AFO stiffness condition also increased in value. Based on the rise in respiratory exchange ratio it is suggested that the participants had small, but increased ratios of oxygen consumption to carbon dioxide production with increased AFO stiffness. Therefore, the participants were expending more energy when walking with the AFOs on than without them.

Combining these results with those found in the gait symmetry experiment also show a second relationship to exist. There is a direct relationship between RER and gait symmetry. The next section will explain in this relationship in further detail using the VO_2 results and the gait symmetry results from participant M02.

Gait Symmetry Results

The gait symmetry experiment served to be a baseline for potential future work. The aim was to examine in one participant if AFO placement on the dominant side would increase or decrease the level of symmetry existing in that participant's gait. Using the method of motion capture used in the non-dominant leg portion, participant M02's left and right leg were recorded and the joint angles compared to one another using cross-correlation. The maximum coefficient of determination (r^2) values were found to be largest for the ankle in the condition with no AFO and smallest in the condition with the stiffest AFO. The r^2 values for the knee were found to be largest in the condition with the OttoBock AFO and smallest in the condition with the Allard Blue Rocker AFO.

Based on the results of this pilot, it is evident that participant M02 had a high degree of symmetry between the right and left leg without the AFO on. The correlation coefficient maximum under this condition was the second highest of the three conditions, but it was the most consistent throughout multiple time lags. It is also clear that AFOs do have an effect on gait symmetry. The correlation coefficients were seen to change with each of the AFO conditions, mostly decreasing as stiffness in AFO increased. This was expected since AFOs are meant to correct gait in patients who have a physical ailment that causes the asymmetry in his or her gait. A healthy individual should have a symmetric gait, and anything that affects that should show a decrease in symmetry. This data supports that hypothesis.

4.3 Comparison to Previous Studies

J. Weir's 2015 study on ROM on the dominant leg supported the trends of decreasing ROM in the ankle with increasing AFO stiffness and little impact on the knee ROM with increasing AFO stiffness [20]. The study conducted in this thesis observed trends that are both similar and distinct. The ankle angles of the non-dominant leg were affected by the AFO placement on the dominant leg. In contrast to the decreasing angles observed in the 2015 study, the angles of the non-dominant leg found in the present study increased. Rather than decreasing with increasing AFO stiffness, they increased. While the knee angles did change with changes to AFO stiffness, they changed in a manner that was not significantly conclusive in showing increased AFO stiffness causes an increase or decrease in non-dominant leg knee angles. This occurrence is similar to Weir's study. Therefore, based on the results of this study and Weir's, AFO placement on the dominant leg, while decreasing dominant leg ROM, results in the opposite occurrence in the non-dominant leg.

Considering the results of the VO_2 RER portion of the study, it was found that there were small but observable changes in RER with the increased stiffness in each AFO condition. A 2009 study conducted in Japan also examined AFO placement, in this case on individuals with post-stroke hemiparesis. These individuals walked on a treadmill with AFOs placed on their affected side, similar to the present study. The Japanese study did not find significant RER changes when these individuals walked at the same speed, rather the significant changes occurred when the individuals walked at different speeds [1]. The present study also did not find very significant changes in the participants while walking at the same speed, but the changes were measurable and increasing. This comparison in study results actually serves to raise another question. The studies each examined a different population. This shows that in individuals who suffer from a physical ailment, RER changes may not be significantly observed at the same walking speed, and healthy individuals have behaved similarly. The remaining information to consider would be to vary the walking speed of the healthy individuals to see if the response is the same as the previous study.

Lastly, the results of the present study's pilot of gait symmetry analysis and AFOs are supported by the previous studies examined in the literature review. Gait symmetry was seen in two studies that considered age, gender, and gait velocity. The results showed that the health of individuals examined were directly correlated, while not showing causality, to their gait symmetry [12, 14]. The pilot of gait symmetry analysis of participant M02 also resulted in data that supports this trend. The normal condition, with no AFO, showed much higher correlation values of the right and left legs, participant M02's gait symmetry, than with the AFOs placed on the non-dominant leg. This was expected. Since the individual was considered healthy, the non-dominant leg was shown to change in the opposite direction of the dominant leg, and a change in gait resulted in higher RER.

4.4 Study Limitations

This study was limited in several ways. Its examined population and the amount of AFOs used, as a product of time constraints, were limited. The focus of the study was the statistical changes that were calculated in the non-dominant leg, the differences in RER, and a pilot of gait symmetry changes. This study does accomplish that focus successfully, however increasing the number of participants would serve to increase confidence in the results obtained. The studies examined in the literature review involving gait had a participant pool of 16 to 253 participants [16, 17, 20]. Doing so allowed them to be qualitatively and quantitatively conclude whether or not their studies initial theories were supported. Furthermore, the participants were very similar in terms of their demographics. It occurred that all four of the participants were dominant on their right side, leaving the left leg always the focus of the non-dominant leg portion of the study. They were all healthy 20 to 21-year-old college students. Broadening the population to individuals of different demographics would help in seeing if the trends observed in this study would occur for other types of individuals.

Although there were limitations to this study, the work performed and results collected should not be overlooked. This study does show trends in non-dominant leg ROM as affected by dominant leg AFO placement, as well as explain multiple measures that can be taken to examine the trend. Further, this study explains how RER can be used as a measure to examine if an individual is expending more or less energy with AFO placement. Lastly, the study lays the groundwork for further studies to examine AFOs, gait symmetry, and energy expenditure through its gait symmetry analysis pilot.

4.5 Future Studies Suggestions

As mentioned in the previous section, there were limitations to this study. While not harmful to the purpose of the study, acknowledging these limitations and changing them does allow for the potential for future additive studies. Three areas of this study can be reexamined and changed for future work.

First, the study was limited in its participants' age and health. It would serve this research well to examine individuals of different ages to see if age is a factor that influences gait symmetry and if non-dominant legs respond differently. Health differences are another area to be considered. As discussed, the physically-affected individuals showed different results than the healthy individuals in terms of gait symmetry. Examining affected individuals with VO_2 analysis, and dual motion capturing allows for a study that can serve clinicians in determining the best gait correcting and energy saving AFO for a patient.

The second area involves using a larger number of participants. Simply doing so allows for further statistical analysis and power behind the results found in this study. The third area would be in varying the walking speeds of the participants. One study specifically focused on the effects of walking speed on bilateral coordination and found slowed walking to cause differences in gait from normal and fast walking [16]. RER will change as examined in previous studies, but whether the RER trend examined in this study remains would be observed. Further, ROM could also change at different speeds, so whether or not this causes gait symmetry changes could also be examined.

Chapter 5

Conclusion

This study demonstrates three different aspects of gait symmetry. The first is that non-dominant leg ROM does change when an AFO is placed on the dominant leg. The more significant changes are observed in the ankle, rather than the knee, but there are calculable changes. Furthermore, these differences are larger with each increase in AFO stiffness as compared to the expected decreasing dominant side ROM. The second is that VO_s analysis through respiratory exchange ratio (RER) examination is an effective method for determining if an individual is using more or less energy when wearing an AFO, although varied walking speeds may improve statistical significance of the differences. Lastly, the study's pilot gait-symmetry experiment demonstrates that dual motion capture and correlation analysis can be used to examine the symmetry of an individual's gait.

Although the statistical analysis is limited in size, it shows observable changes that should not be ignored. The implications of this study point to areas of research that need to be filled for clinicians. This study along with the future study suggestions mentioned in the previous section serve to provide a useful, quantitatively assured tool to analyze gait in afflicted patients and determine the proper AFO design to use in order to improve the patients' quality of life.

Appendix A

Participant Demographics

Table 6. Participant Demographics

Participant	Age (years)	Gender	Height (in.)	Weight (lbs)	Dominant Side
M01	20.1	F	64.6	146.4	R
M02	20.1	M	65.4	137.3	R
M03	20.1	F	64.6	124.8	R
M04	21	M	65.4	158.3	R

BIBLIOGRAPHY

[1] J. Attal-Singer, D. Dvir and P. Singer, "Determination of Resting Energy Expenditure by VO2 Alone in Normal and Obese Subjects," Clinical Nutrition, vol. 22, pp. S11-S12, 2003.

[2] D. Bregman, A. Rozumalski, D. Kroops, V. de Groot, M. Schwartz and J. Harlaar, “A New Method for Evaluating Ankle Foot Orthosis: BRUCE,” Elsevier, vol. 30, pp. 144-149, 2009.

[3] B. Carse, R. Bowers, B. Meadows and P. Rowe, “Visualization to Enhance Biomechanical Tuning of Ankle-Foot Orthoses (AFOs) in Stroke: Study Protocol for a Randomized Controlled Trial,” Trials, vol. 12, no. 1, p. 254, 2011.

[4] A. Dubin, “Gait,” Medical Clinics of North America, vol. 98, no. 2, pp. 205-211, 2014.

[5] J. Gage, R. Lin, “The Neurological Control System for Normal Gait,” American Academy of Orthotists and Prosthetists, vol. 2, no. 1, pp. 1-13, 1989.

[6] L. Gilman, Symmetry, 3rd ed. Detroit: Gale, 2004, pp. 3941-3942.

[7] J. Haddad, R. van Emmerik, J. Wheat, J. Hamill and W. Snapp-Childs, “Relative Phase Coordination Analysis in the Assessment of Dynamic Gait Symmetry,” Journal of Applied Biomechanics, vol. 26, pp. 109-113, 2010.

[8] I. Handzic, K. Reed, “Perception of Gait Patterns that Deviate from Normal and Symmetric Biped Locomotion,” Frontiers in Psychology, vol. 6, pp. 199, 2015.

[9] J. Hayfron-Acquah, M. Nixon and J. Carter, “Automatic Gait Recognition by Symmetry Analysis,” Pattern Recognition Letters, vol. 24, no. 13, pp. 2175-2183, 2003.

[10] X. Huang, J. Mahoney, M. Lewis, Guangwei Du, S. Piazza and J. Cusumano, “Both Coordination and Symmetry of Arm Swing Are Reduced in Parkinson's Disease,” Gait & Posture, vol. 35, no. 3, pp. 373-377, 2012.

[11] I. Jang, K. Nam, H. Park, Y. Jo, H. Kang, J. Park and K. Kim, “Gait Symmetry Analysis Protocol for Whole Leg Movement Symmetry Evaluation,” J. Mech. Med. Biol., vol. 12, no. 04, p. 1250073, 2012.

[12] H. Kobayashi, W. Kakihana and T. Kimura, “Combined Effects of Age and Gender on Gait Symmetry and Regularity Assessed by Autocorrelation of Trunk Acceleration,” Journal of Neuro-Engineering and Rehabilitation, vol. 11, no. 1, p. 109, 2014.

[13] T. Kobayashi, A. Leung and S. Hutchins, “Techniques to Measure Rigidity of Ankle-Foot Orthosis,” Journal of Rehabilitation Research and Development, vol. 48, no. 5, pp. 565-576, 2011.

[14] P. Nair, K. Rooney, S. Kautz and A. Behrman, "Stepping with an Ankle Foot Orthosis Re-Examined: A Mechanical Perspective for Clinical Decision Making," *Clinical Biomechanics*, vol. 25, no. 6, pp. 618-622, 2010.

[15] K. Patterson, N. Nadkarni, S. Black and W. McIlroy, “Gait Symmetry and Velocity Differ in their Relationship to Age,” Gait & Posture, vol. 35, no. 4, pp. 590-594, 2012.

[16] M. Plotnik, R. Bartsch, A. Zeev, N. Giladi and J. Hausdorff, “Effects of Walking Speed on Asymmetry and Bilateral Coordination of Gait,” Gait & Posture, vol. 38, no. 4, pp. 864-869, 2013.

[17] E. Ridgewell, M. Sangeux, T. Bach and R. Baker, “A New Method for Measuring AFO Deformation, Tibial and Footwear Movement in Three Dimensional Gait Analysis,” Clinical Key, vol. 38, no. 4, pp. 1074-1076, 2013.

[18] H. Sadeghi, P. Allard, F. Prince and H. Labelle, "Symmetry and Limb Dominance in Able-Bodied Gait: A Review", *Gait & Posture*, vol. 12, no. 1, pp. 34-45, 2000.

[19] M. Sicari, M. Benedetti, M. Manca, G. Ferraresi, G. Casadio, F. Buganè, S. Toska and A. Leardini, “A New Inertial Wireless Dispositive for Gait Analysis: Functional Outcome Measures in Patients with AFO,” Gait & Posture, vol. 33, pp. S65-S66, 2011.

[20] J. Weir, B.S. Thesis, Department of Kinesiology., The Pennsylvania State University, Reading, PA, 2015

ACADEMIC VITA

Tye A. Morales

tatmts@msn.com

Education

The Pennsylvania State University, Berks Campus
Bachelor of Science Degree in Mechanical Engineering
Minor in Biology
Honors in Mechanical Engineering

Thesis Title **An Examination of Non-Dominant Leg Gait and Gait Symmetry through AFO and VO_2 Analysis**

Thesis Supervisor Joseph M. Mahoney, Assistant Professor of Engineering

Honors & Awards

- Schreyer Honors Scholar (2012 – Present)
- Recipient of the Chancellor's Scholarship (Penn State Berks)
- Recipient of the Stanley M. and Ruth Heck Detterline Scholarship
- Recipient of the J. Dean Stephens Memorial Award

Leadership Experience

- **Lion Ambassadors** - Penn State Berks
  Executive Director, Summer 2015 – May 2016
  Member, Spring 2013 – May 2016

- **New Student Orientation** - Penn State Berks
  Lead Captain, Fall 2014 – Fall 2015
  First Year Group Leader Captain, Fall 2013 – Fall 2014
  Student Coordinator, Spring 2014 – Spring 2015
  Orientation Leader Spring 2013 – Fall 2015

- **Peer Mentor** – Penn State Berks
  Fall 2013 – Fall 2015

- **Teaching Assistant** for Counselor Education – Penn State Berks
  Fall 2014 – Fall 2015

Publications

- "To Tell the Story of Black Culture in Reading: The Central Pennsylvania African American Museum"

Presentations

- "Outside Sound Level Reduction of Library Study Rooms" - Higher Education Council of Berks County Conference

Community Service

- **Community Service Officer** – Penn State Berks Honors Club
  Opportunity House of Reading, Fall 2012 – Fall 2013
  MaPaw Siberian Husky Rescue, Spring 2013
  Hawk Mountain, Spring 2013

- **Lion Ambassador Member –** Penn State Berks
  Lion Ambassador Conference Community Service
  Sponsored by Gilmore Henne Foundation, Spring 2015