Rehabilitating Asymmetric Gait Using Asymmetry

by

Tyagi Ramakrishnan

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Department of Mechanical Engineering
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University of South Florida

Major Professor: Kyle B Reed, Ph.D.
Seok Hun Kim, PT, Ph.D.
Stephanie Carey, Ph.D.
Jonathan Gaines, Ph.D.
William Lee, Ph.D.

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DEDICATION

I dedicate this dissertation to my family who have supported me throughout this journey. My parents who took a chance and gave me the support to pursue my passion. My beloved wife who has been patient and supportive of my work for the last few years. This work would not be possible without them.

I dedicate this work to all the researchers who have come before me and will come after me. This dissertation is a small step towards understanding the mysteries of the human body. Do not be afraid to take a leap from the edge of knowledge. Just hope that you will land on your answers and build the new edge. “Life is a travelling to the edge of knowledge, then a leap taken” – D. H. Lawrence

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ABSTRACT

Human gait is a complex process that involves the coordination of the central nervous and muscular systems. A disruption to the either system results in the impairment of a person's ability to walk. Impairments can be caused by neurological disorders such as stroke and physical conditions like amputation. There is not a standardized method to quantitatively assess the gait asymmetry of affected subjects. The purpose of this research is to understand the fundamental aspects of asymmetrical effects on the human body and improve rehabilitation techniques and devices. This research takes an interdisciplinary approach to address the limitations with current rehabilitation methodologies.

The goal of my Doctoral research is to understand the fundamental effects of asymmetry caused by physical and neurological impairments. The methods discussed in this document help in developing better solutions to rehabilitate impaired individuals' gait. I studied four major hypothesis in regards to gait asymmetry. The first hypothesis is the potential of asymmetric systems to have symmetric output. The second hypothesis is that a method that incorporates a wider range of gait parameter asymmetries can be used as a measure for gait rehabilitation. The third hypothesis is that individuals can visually identify subtle gait asymmetries. Final hypothesis is to establish the relationship between gait quality and function. Current approaches to rehabilitate impaired gait typically focus on achieving the same symmetric gait as an able-body person. This cannot work because an impaired person is inherently asymmetric and forcing them to walk symmetrically causes them to adopt patterns that are not beneficial long term. Instead, it is more prudent to embrace the asymmetry of the condition and work to minimize in specific gait parameters that may cause more harm over the long run. Combined gait asymmetry metric (CGAM) provides the necessary means to study the effect of the gait parameters and it is weighted to balance each

parameter's effect equally by normalizing the data. CGAM provides the necessary means to study the effect of the gait parameters and is weighted towards parameters that are more asymmetric. The metric is also designed to combine spatial, temporal, kinematic, and kinetic gait parameter asymmetries. It can also combine subsets of the different gait parameters to provide a more thorough analysis. CGAM will help define quantitative thresholds for achievable balanced overall gait asymmetry.

The studies in this dissertation conducted on able-body and impaired subjects provides better understanding of some fundamental aspects of asymmetry in human gait. Able body subjects test devices that aim to make an individual's gait more asymmetric. These perturbations include a prosthetic and stroke simulator, addition of distal mass, and leg length alterations. Six able-body subjects and one amputee participated in the experiment that studied the effect of asymmetric knee height. The results which consisted of analyses of individual gait parameters and CGAM scores revealed that there is evidence of overall reduction of asymmetry in gait for both able-body subject on prosthetic simulators and transfemoral amputee. The transfemoral amputee also walked with a combination of distal mass with lowered knee height. Although this configuration showed better symmetry, the configuration is detrimental in terms of energy costs. Analyzing the data of gait with the stroke simulator showed that the subject's gait does undergo alterations in terms of overall gait asymmetry. The distal mass and leg length alteration study has revealed some significant findings that are also reflected in the prosthetic study with distal mass. A leg length discrepancy (LLD) or the change of limb mass can result in asymmetric gait patterns. Although adding mass and LLD have been studied separately, this research studies how gait patterns change as a result of asymmetrically altering both leg length and mass at a leg's distal end. Spatio-temporal and kinetic gait measures are used to study the combined asymmetric effects of placing LLD and mass on the opposite and same side. There were statistically significant differences for the amount of mass and leg length added for all five parameters. When LLD is added to longer leg, the temporal and kinetic gait parameters of the shorter limb and the altered limb's spatial parameter become more asymmetric. Contrary to the hypothesis, there was no significant interaction between the amount of mass and leg length added. There were cases in all perturbations where a combination of mass and LLD make a gait parameter more symmetric than a single effect. These cases exhibit the potential for configurations with lower overall asymmetries even though each parameter has a slight asymmetry as opposed to driving one parameter to symmetry and other parameters to a larger asymmetry. CGAM analysis of the results revealed that the addition of distal mass contributes more towards overall asymmetry than LLD. Analyzing 11 gait parameters for LLD and mass on the same side showed that the overall asymmetry decreased for the combination of small LLD and mass. This is consistent with the findings from analyzing five individual gait parameters.

Impaired subjects include individuals with stroke and amputees. The clinical trials for individuals with stroke involve training with the Gait Enhancing Mobile Shoe (GEMS) that provides an asymmetric effect on the subject's step length and time. Training with the GEMS showed improvement in clinical measures such as timed up and go (TUG), six minute walk test (6MWT), and gait velocity. The subjects also showed lower step length symmetry as intended by the GEMS. The ground reaction force asymmetries became more asymmetric as the spatial and temporal parameters became more symmetric. This phenomenon shows evidence that when an individual with stroke is corrected, for spatial and temporal symmetry is at the expense of kinetic symmetry. The CGAM scores also reflected similar trends to that of spatial and temporal symmetry and the r^2 correlation with the gait parameters proved that double limb support asymmetry has no correlation with CGAM while ground reaction force asymmetry has a weak correlation. Step length, step, and swing time showed high correlation to CGAM. I also found the r^2 correlation between the clinical measures and the CGAM scores. The CGAM scores were moderately correlated to 6MWT and gait velocity but had a weak correlation with TUG. CGAM has positive correlation with TUG and has negative correlation with 6MWT and gait velocity. This gives some validation to CGAM as a potential metric that can be used to evaluate gait patterns based on their asymmetries.

Transfemoral amputees were tested for their gait with varied prosthetic knee heights to study the asymmetrical effects and trained split-belt treadmill. Asymmetric knee heights showed improvement in multiple gait parameters such as step length, vertical, propulsive, and braking force asymmetry. It also decreased hip and ankle angle asymmetries. However, these improvements did lead other parameters to become more asymmetric. The CGAM scores reflect this and they show overall improvement. Although the lowest knee height showed improvement, the input from the amputee suggested that the quality of gait decreased with the lowest knee height. These exploratory results did show that a slightly lower knee height may not affect the quality of gait but may provide better overall symmetry. Another exploratory study with split-belt treadmill training, similar to the protocol followed for individuals with stroke, showed definitive improvement in double limb support, swing time, step length and time symmetry. This was also reflected in the improvements seem post training in the CGAM scores as well. I found the r^2 correlation of the CGAM and the gait parameters including gait velocity. Step length and swing time show consistent correlation for individual subjects and all the data combined to CGAM. Gait velocity shows a moderate correlation to CGAM for one subject and a high correlation to the other one. However, the combined data of gait velocities does not have any correlation with CGAM. These results show that CGAM can successfully represent the overall gait parameter asymmetry. The trends seen in the gait parameters is closely reflected in the CGAM scores.

This research combines the study of asymmetry with people's perception of human gait asymmetry, which will help in estimating the thresholds for perceivable asymmetrical changes to gait. Sixteen videos were generated using motion capture data and Unity game engine. The videos were chosen to represent the largest variation of gait asymmetries. Some videos were also chosen based on CGAM values that were similar but had large variation in underlying gait parameters. The dataset consisted of results of perturbation experiments on able-body subjects and asymmetric knee height prosthesis on transfemoral amputee. These videos were rated on a seven point Likert scale by subjects from 7 being normal to 1 being abnormal. Thirty one subjects took part in the experiment, out of which only 22 subject's data was used because they rated at least 3 videos. The results show that the subjects were able to differentiate asymmetric gait with perturbations to able-body gait without perturbation at a self-selected speed. r^2 correlation analysis showed that hip angle had mild correlation to the Likert scale rating of the 16 different gait patterns. Multivariate linear regression analysis with a linear model showed significant contribution of ankle and hip angles, vertical, propulsive, and braking forces. It is interesting that the majority of parameters that showed significance are not perceivable visually. Ankle and hip angles are visually perceivable and this significance revealed that subjects seemed to perceive asymmetric ankle and hip angles as abnormal. However, the subjects do not perceive asymmetric knee angles as completely abnormal with evidence of no significance, no correlation, and neutral Likert rating for gait patterns that perturbed knee angles.

CHAPTER 1: INTRODUCTION

Human gait is one of the most complex neuromuscular phenomenon which requires perfect coordination between the brain, spine, and muscles. It is also a cyclic process that requires visual and sensory feedback to execute the motions effectively. Since, gait is based on cyclic motion, it also depends on physical characteristics such as the length of limbs, mass distribution of the limbs, and ambulatory joints. The cyclic nature of gait is often presented as a close to symmetric gait in able-body individuals. However, if this delicate balance among these factors gets impaired, the gait of the individual gets affected. Gait impairment can be caused by amputation, unequal leg length, adding a mass to the shank, and applying stiffness or damping at the knee. Impairments can also be neurological such as stroke where an individual loses some control over one half of their body.

Rehabilitation devices and techniques are designed to counteract and restore the loss of function of impaired individuals. To develop these rehabilitation methods, it is important to understand the biomechanics of human gait. Researchers collect data on gait patterns by the use of motion capture and force plates. Multiple variables are analyzed in order to portray the various facets of human gait. There are spatial parameters such as step length defined by the distance covered from heel strike of one foot to the heel strike of the opposite foot. There are temporal parameters such as step time defined as the time taken between opposite heel strikes. Then there is swing time the time taken from toe off to heel strike of the same foot. Double limb support is the time spent when both legs are on the ground. The terminal double limb support is used for this research study. There are kinematic parameters associated with joint angles of the ankle, knee, and hip joints. Hip joints in the case of individuals with stroke and amputees also show abduction and adduction. Then there are kinetic parameters such as vertical ground reaction forces, propulsive or push off forces during toe off, braking forces during initial contact or heel strike, ankle, knee, and hip joint moments. Traditionally researchers analyze a small set of gait parameters in order to evaluate the outcomes of their techniques. Researchers either focus on spatial, temporal, or kinematic and sometimes kinetic data. There are few who analyze a larger spectrum of data.

Symmetry is one of the factors that is affected by both physical and neurological impairments. Symmetry is used to evaluate the quality of a gait pattern. Researchers typically use spatial and temporal symmetry as outcome goals for rehabilitating individuals with stroke and amputees. In this study symmetry of multiple types of gait parameters is used to describe gait patterns and the effect of methods used to perturb an individual's gait. With more sophisticated processing power it is possible to examine a larger set of gait parameters and their effects on gait patterns. This form of analysis helps determine the relationships between the various gait parameters and gives more insights for the development of novel methods to balance all gait parameters.

One of the main goals of rehabilitation of an individual with physical impairments is to restore them back to an overall efficient gait pattern and posture. Rehabilitation to restore gait may be characterized as improving functionality, being able to perform tasks with limited or no assistance, and having a good overall quality of life. Since this study focuses on gait rehabilitation, normality translates to improving gait quality and function. Gait quality encompasses several factors such as symmetry, comfort, pain, and posture. Functional gait can be evaluated using velocity, stability, and biomechanical parameters, which include kinetic, kinematic, spatial, and temporal variables.

In contrast to much of the literature that aims to restore symmetry to individuals, this research aims to understand the inherent limitation of gait symmetry to find balanced walking patterns. Embracing one's asymmetric gait allows all of the gait parameters to be slightly asymmetric within limits that will be identified and promotes functional gait patterns that are feasible, achievable, and viable over the long term. Overall, I aim to identify gait patterns that limit the maximum asymmetry in any one measure to balance all aspects of gait and optimize functional mobility.

The motion capture and kinetic data that is collected using various devices such as the Computer Assisted Rehabilitation Environment (CAREN), Vicon motion capture, and Protokinetic zeno gait walkways are used to generate the combined gait asymmetry metric (CGAM). CGAM as a metric offers a method to evaluate the overall asymmetry of a gait pattern. This data is analyzed using Matlab scripts to extract the spatial, temporal, kinematic, and kinetic gait parameters. These parameters will then be used to generate gait asymmetry metrics that represent overall gait asymmetry. Further, the motion capture data will also be used to drive models in the Unity game engine to generate realistic 3D gait playback models. High definition videos of these models will be used to test the perception of individuals to determine their inherent biases of viewing human gait. The perception of individuals plays an important role in determining the amount of asymmetry that is socially acceptable. By combining the understanding derived from the metrics and perception, it is possible to provide social and clinical thresholds. These thresholds can help in defining the level of overall asymmetry in an individual's gait that is beneficial. Figure 1.1 represents the search for the ideal gait pattern that an individual with asymmetric gait can achieve after rehabilitation.

This dissertation contains the research and experiments that have been conducted on human gait asymmetry. There are four major aims for this project which are designed to evaluate rehabilitation devices and techniques on their effect on gait asymmetry, expanded upon in Chapter 2. The first aim focuses on obtaining symmetry from an asymmetric system. This is the focus on experiments that deal with the study with different knee heights on transfemoral amputees and able-body subjects on a prosthetic simulator. It also plays a major part in the study of multiple physical changes. The second aim is analogous to aim one where I aim to study the physical and psychological effects by analyzing the perception of individuals on asymmetric gait patterns. This study of the inherent biases of gait perception will involve walking videos that are generated in Unity game engine. The third aim is the evaluation of the CGAM metric that has been developed to evaluate the progress of overall symmetry of an individual through the rehabilitation process. The final goal aims to explore the balance between gait quality and function. This is addressed by a combination of analyses using results from clinical trials and able-body studies.

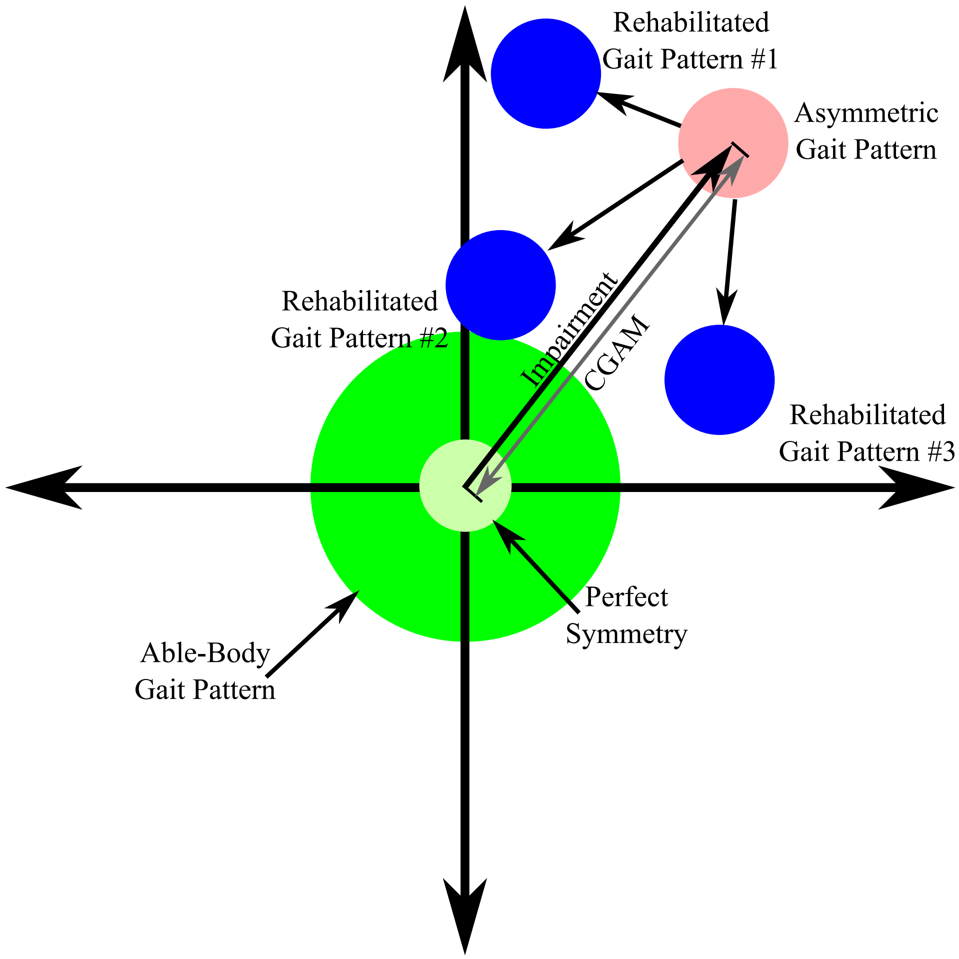

Figure 1.1: Determining Optimized Gait Pattern Post Rehabilitation Training.

To demonstrate that an asymmetric system cannot return to perfect symmetry, the research study looks at physical asymmetries in able-body and impaired individuals. The able-body subjects will be tested with alterations to their legs, and simulators for stroke and prosthetics. These alterations are designed to fundamentally alter an individual's gait and make it more asymmetric. I study the basic effects of these changes to gait parameters as well as discuss the potential benefits of combining asymmetric changes for a better overall gait pattern. In addition to the effects observed in altering able-body subjects, this research will also use data from impaired subjects. I have collected data from amputees and individuals with stroke to analyze the asymmetries of their gait parameters. Each of the impairments affects gait in certain parameters, such as kinematic, kinetic, or spatiotemporal. Gait asymmetries of amputees differ in all of the parameters depending on the characteristics of their prostheses. In this research study, I test amputees with different knee heights, addition of distal mass, and split-belt treadmill training. Stroke patients also show changes in all gait parameters. However, rehabilitation techniques often focus on making their spatial and temporal parameters more symmetric. In this research study, one of the clinical aspects dealing with individuals with stroke involves the Gait Enhancing Mobile Shoe (GEMS) where the subject are trained to learn a new gait pattern similar to a split-belt treadmill.

Perception of different impairments is a social driver in rehabilitation. An individual with an impairment goes to rehabilitation in order to ambulate effectively on a daily basis and to help restore a normal gait pattern. To study the inherent perceptions of individuals, this research study will compose play back videos of motion capture data using the Unity game engine of various types of gait patterns. These videos will be evaluated by users to get a sense of their varied perceptions. This study will help understand the parameters of human perception of gait. For example, a small change in step time is perceived easily compared to a small change in step length. I can also try to correlate the actual changes in gait parameters detected by analyzing data and what subjects detect by visually studying the videos.

In this study, I have also developed the novel CGAM metric to evaluate overall gait symmetry. I have used this metric in evaluating various gait patterns that I have recorded using motion capture and force data. This metric will also be used to evaluate clinical data from the experiments, once enough data has been collected on the studies. I also plan to use these results to correlate the perception of different people. Further, I plan on using all the different gait patterns and their varied parameters to define relationships between gait quality and function. For example, a prosthetic leg that is designed to be functionally superior may not exhibit a symmetric gait or cause excess strain affecting the gait quality.

The document contains seven chapters including the introduction. The design is predicated on providing a coherent narrative. Chapter 2 reiterates the research hypotheses. Chapter 3 analyzes the literature related to various forms of gait asymmetries and identifies the gaps in research. Chapter 4, 5, and 6 explain the experimentation methods and results of various experiments conducted on able-body subjects, amputees, individuals with stroke, and perception experiments on individuals. Chapter 4 summarizes the methods for the experiments conducted on able-body subjects with various perturbations such as stroke simulator, leg length discrepancy, addition of distal mass, and combination of leg leg length discrepancy and distal mass. Chapter 4 also covers the formulation and results of CGAM. The CGAM scores are used to compare able-body gait patterns with prosthetic gait pattern. I also investigate the use of LibSVM based machine learning algorithms to categorize gait patterns based on gait parameter asymmetry. Chapter 5 summarizes the methods and results for clinical experiments with amputees and individuals with stroke. Two types of experiments were conducted on transfemoral amputees which are as follows: asymmetric knee height and split-belt training. In addition to a transfemoral amputee I tested six able-body individuals with prosthetic simulators with asymmetric knee heights. The experiments on individuals with stroke describes the protocol and results of the training with the GEMS. Chapter 6 summarizes the methods and results of the experiment performed to evaluate the perception of gait asymmetry of individuals using motion capture data in computer generated human models. Finally, Chapter 7 discusses the results from Chapters 4, 5, and 6 to draw conclusions on all the experiments and explains the contribution of the results in satisfying the hypotheses. Further, I also discuss how this research can be extended in the future, the questions I have been able to answer, the questions that still remain unanswered, and the new questions that have arisen from this research.

CHAPTER 2: SPECIFIC AIMS

2.1 Goal

The overall goal of this research is to provide novel data driven methodologies to rehabilitate asymmetric gait using asymmetric devices and techniques.

2.2 Aim 1: Symmetry from an Asymmetric System

Hypothesis: It is not possible for an individual with impairments that render their gait asymmetric to achieve a symmetric gait similar to an able-body individual.

When the legs have different physical or control properties, allowing for slight spatial and temporal asymmetries will result in more symmetric forces than a gait with perfect spatial and temporal symmetry.

2.3 Aim 2: Clinical Evaluation Metric

Hypothesis: There exists a gait pattern that an individual with physical or neurological asymmetries can achieve by balancing the effects of multiple gait parameters.

I investigate methods to estimate the optimized asymmetries of various gait parameters. The goal is to design and validate a quantitative method to aid rehabilitation measures based of gait parameter asymmetry.

2.4 Aim 3: Perception of Gait

Hypothesis: Individuals will be able differentiate between asymmetric gait from normal gait.

Humans are inherently capable of noticing asymmetries in gait. The goal is to establish the degree to which they are aware of these differences and to evaluate the impact of visual perception in evaluating gait patterns.

2.5 Aim 4: Relationship between Gait Quality and Gait Function

Hypothesis: Changes in functional gait parameters affect the quality of gait.

Functional gait parameters are used to quantitatively evaluate the dynamic effects of a gait pattern. These include speed, cadence, stability, and all biomechanical parameters. Gait quality signifies the subjective variables that influence gait patterns and also societal perception of gait, some of the variables that influence gait quality are symmetry, comfort, pain, and posture.

CHAPTER 3: BACKGROUND

3.1 Historical Push for Symmetry in Rehabilitation

Since ancient times humans were taken by symmetry. Symmetry is the quality of an object to be unaffected by transformation and maintain the proportions, like a reflection. Symmetry can be found in art [2], engineering [121], communication [46], anatomy [3], and in forms of psychology [63]. Symmetry is encouraged in engineering systems because it is attributed to efficiency and functionality of the system. Symmetry also makes designs easier to visualize and model mathematically. The evolutionary design of the human body is a testament to the importance of symmetry and what is perceived by the society as normal [35]. Leonardo da Vinci's Vitruvian man illustrates the importance of symmetry and perception of symmetry of the human body [76].

Symmetry is an important factor that is used to evaluate the efficacy of lower limb rehabilitation techniques. Achieving perfect gait symmetry is not possible even amongst able-bodied individuals. Many able-bodied individuals express up to 6% asymmetry in their gait parameters [114]. Gait has to be symmetric in spatial, temporal, and kinematic parameters to be perceived as normal. In addition to these parameters, the walking velocity has to be from 0.8 m/s to 1.14 m/s to be considered community ambulation [66]. Gait symmetry is affected when an individual is impaired physically either due to a stroke or amputation. Stroke affects an individual's nervous system and modifies the motor control pathways rendering the limbs paralyzed and asymmetric in terms of function. Rehabilitating individuals with stroke involves retraining the motor pathways to overcome the effects of neuroplasticity of the brain to correct the subject's gait and posture [16]. Unilateral lower limb amputation, similar to a unilateral stroke, renders the individual physically asymmetric. Rehabilitation of amputees is different from individuals with stroke as the amputees do not posses the physical limb and learn walking with the help of a prosthesis.

3.2 Dynamic Systems

Unimpaired human walking can be represented as two double pendulums that are synchronized to bring about a periodic form of locomotion. Representing human legs as double pendulums simplify the mathematical models required to analyze the dynamics of walking. The study of Passive Dynamic Walkers (PDW) uses the double pendulum to theoretically model these bipedal walkers [70]. PDW models use the force of gravity to propagate their gait over a small (eg. 3°) slope. These models have been used to model unimpaired human gait. This means the PDWs were physically symmetric and displayed more or less symmetric spatial, temporal, and kinetic outcomes. However, this research centers on understanding physically asymmetric systems.

The nine mass asymmetric PDW was put forth by Sushko et al. [111] to help with gait rehabilitation. The asymmetric PDW model can tune the mass and length of the model's segments to bring about various forms of gait. This is significant because asymmetric human walking can be modeled by using a PDW. An experiment conducted by Handzic et al. [30] shows the close trend of the kinetics and kinematics of the human wearing an ankle mass and the PDW model.

This leads to the study conducted by Handzic et al. [30] which looked at double pendulum systems with different mass distributions. The study found that it is possible to obtain symmetric motions from dissimilar double pendulum systems. Due to the differences in mass distribution between the double pendulums, the forces experienced at the joint were different as well. This ties in well with Aim 1 because matching motion can be brought about by different forces. The forces experienced at the joints are important because there is a direct cause of deterioration of bone and synovial fluid volume at the joint leading to orthopedic ailments such as arthritis.

3.3 Prosthetic Rehabilitation

Lower limb amputation is debilitating to an individual's gait because they may lose multiple joints. There are 3 levels of amputations and disarticulations for each of the three joints: hip, knee, and ankle. Transfemoral, amputation above the knee, and transtibial, amputation below the knee, are the most common types of lower limb amputation. Transfemoral prosthetics have more dynamic effects on an individual's gait than a transtibial prosthesis. This is caused by the loss of the knee and ankle joints that are responsible for most of the load bearing and balance during walking. When designing prosthetic systems, factors such as the weight of the prosthesis, kinematics of the joint mechanisms, and length of the prosthesis play major roles in determining the comfort for the prosthetic user.

Prosthetic simulators (PS) are devices that can mimic the effects of wearing a prosthesis on able-bodied individuals [22, 61, 110, 115]. They are usually modified knee braces that have an attached prosthetic knee and foot. PS render the user asymmetric and makes them rely on the prosthetic leg to ambulate. These devices provide an easy platform to test different prosthetic components before testing it on actual amputees. Another important use of this device is to test the adaptation of users to changes in dynamics of the prosthetic system.

In this research, the prosthetic simulator is used to evaluate dynamics of asymmetric knee locations on a transfemoral prosthesis. Moving the knee location to a lower position could be potentially advantageous to a transfemoral amputee who is physically asymmetric. Previous studies by Craig et al. [43] on asymmetric PDW models demonstrated that a lower knee location improves spatial and temporal symmetry of the PDW gait. The gait dynamics of the PDW are defined in terms of mathematical equations which allowed for the study to focus on the passive dynamics of walking. Following this result, a preliminary study using a prosthetic simulator was conducted with 3 different knee height settings [83]. The study found that spatial and temporal symmetry improved when the knee was at the lowest position.

Literature on the gait of prosthetic users show that they tend to exhibit less efficient and unnatural gait patterns [21, 41]. This inefficiency is more evident in transfemoral amputees than transtibial amputees, which results in the users exerting a great deal of effort to compensate for unwanted motions [45]. Since amputees are physically asymmetric, bringing about efficient and symmetric gait depends on multiple factors such as length, weight of the prosthesis, type of socket, the length of residual limb, etc. A study on unilateral transtibial prosthetic users showed that as the mass of the prosthesis gets closer to their intact shank weight, the subject's gait becomes more asymmetric [68].

3.4 Stroke Rehabilitation

Individuals with stroke are similar to unilateral amputees as they lose control of one side of their body rendering them physically asymmetric. Common impairments caused by to stroke include the loss of proprioception in the paretic limbs, loss of flexion control at the knee, loss of dorsiflexion and plantarflexion at the ankle (drop foot phenomenon), increased damping at all upper and lower limb joints, and limited range of motion of the upper body. Due to the considerable effects of stroke, the subjects usually tend to compensate in various ways such as circumduction at the hip to prevent scuffing the floor because of drop foot.

The combination of loss of control and compensation strategies make the individual's gait highly asymmetric [80]. Gait of individuals with stroke is asymmetric in all types of gait measures which include, spatial, temporal, kinetic, and kinematics. Spatial asymmetry is attributed to the dissimilar step length between right and left leg. Similarly, temporal asymmetry is associated with the step time between the paretic and normal leg. The forces the subject exerts and experiences on the joints are also different. Subjects tend to use their non-paretic leg more to keep their balance and hence exert more force. On the other hand, they tend to spend less time on their paretic leg and exert less force [47]. As an effect of this behavior subjects experience more discomfort on their non-paretic limbs. The subjects also tend to have different kinematics on the paretic and non-paretic sides and the dissimilarities in motion coupled with the asymmetric kinetics cause rise to several problems over the long run. A study conducted by Lewek et al. [62] found that gait asymmetry leads to deterioration in balance which leads to falls in patient's with stroke.

Rehabilitation techniques that are used to restore gait impaired by stroke involve some form of asymmetric perturbations that try to restore the symmetry between the paretic and non-paretic sides [93]. Split belt treadmills are a common tool that are used to apply this rehabilitation technique. The split-belt treadmill has two treads that can move at different velocities. This is used by clinicians to change the tread velocity of the impaired side to match the normal leg which exaggerates the asymmetry of the individual. However, if the tread speeds were made the same afterward or the subject is made to walk over ground, the subject will have some carry over effect [95]. The carry-over effects are usually improved spatial and temporal symmetry. Unfortunately, these after-effects are usually temporary due to neuroplasticity, and the subject reverts back to their original walking pattern.

Altering neural patterns to override neuroplasticity requires persistent training by the subjects, similar to professional athletes. Due to the cost and poor carry-over effects, the split-belt treadmill cannot be used for regular training. Hence, the Gait Enhancing Mobile Shoe (GEMS) was developed by Handzic et al. [26] that provides the similar effects as a split-belt treadmill. The GEMS amplifies the spatial and temporal asymmetry of the subject's gait similar to the split-belt treadmill. In essence, the GEMS is a shoe worn by the user on their non-paretic side and when stepped on the shoe moves backward helping the subject to push off properly. This motion also forces the subject to spend less time on their paretic side just like a split-belt treadmill. The GEMS also forces the subject to consciously focus on their posture and accommodate the GEMS during walking which leads to better results compared to the split-belt treadmill.

There are other rehabilitation techniques such as partial suspension of weight training, electro-stimulation, periodic cues, and balance training [7, 14, 97, 113]. Each of the techniques have their merits and train the individual in a specialized manner, which means a combination of this methods may provide beneficial to the subject. In weight suspension training the subject's weight is partially supported by a harness while the subject is made to walk on a treadmill. This kind of training puts the subject at ease and reduced the stress on their body during walking. The recovery period for these subjects takes a longer time. This is because the exercise they receive by relieving some of their total body mass is not as effective as training without suspension. Electro-stimulation therapy involves stimulating the muscles of the subject to perform tasks. This method does have good results in terms of regaining mobility but unfortunately the system does not have lasting results in rehabilitation.

Stroke is one of the leading causes of disability among adults. Patients impaired by stroke have difficulty with ambulation, performing daily activities, communication, and cognition. Walking function for an individual with stroke is a primary indicatior of physical independence [5]. Literature shows that only about 7-22% of individuals with stroke are able to regain sufficient function to be considered independent community ambulators [39, 66].

Gait retraining for individuals with stroke focuses on two main outcome measures: velocity and symmetry. Walking velocity and cadence are used as indicators of overall gait performance and can be used to differentiate the levels of disability among the stroke patient population [66, 81]. A gait speed of 0.8 m/s is considered the required minimum for community ambulation [6, 81], and typically able-body gait velocity was measured to be around 1.14 m/s [66]. Gait symmetry is used as a measure of gait quality [15, 79]. As mentioned above gait asymmetry in able-body gait is often asymmetric of about 4-6% in the spatio-temporal and kinetic parameters [37, 114].

Gait after stroke becomes asymmetric (or hemiparetic) as a consequence of altered neuromuscular signals affecting leg motor areas, typically hyperextension at the knee and reduced flexion at the hip, knee, and ankle [8, 52, 117]. Hemiparetic gait is characterized by a significant asymmetry in temporal (e.g., time spent in double-limb support) and spatial (e.g., step length) measures of interlimb coordination [1, 8, 114]. Propulsive force of the paretic limb is also reduced compared to the non-paretic limb, as are work and power of the paretic plantar flexors [1, 7]. The significant decrease in propulsive force results in smaller overall step lengths, which in turn affects the patient's gait velocity. Finally, vertical ground reaction forces (GRFs) are decreased on the paretic limb relative to the non-paretic limb [53], reflecting diminished weight bearing and balancing capabilities by the paretic limb.

In this research study, I concentrate on understanding the fundamental aspects in which stroke affects gait symmetry. To understand the effects of asymmetry, design better rehabilitation devices, and techniques I require a better understanding of the dynamics of gait impaired by stroke. To fully understand the dynamics I require data from a lot of subjects to analyze the subtle variations in their gait. Unfortunately, acquiring a large population of individuals with stroke is hard and hence I need a device that can simulate stroke like gait

3.5 Effects of Leg Length and Mass

Previous research about asymmetric physical changes reveal a range of different effects on an individual's gait. The literature review for this study looked at various physical changes such as leg length discrepancy (LLD), the addition of mass at the distal end of the leg, amputation, and stroke. It is important to remember that although these physical changes affect every individual differently, they can all be characterized using the asymmetries of biomechanical gait parameters. It is not uncommon to find similar effects on gait asymmetry with different physical changes. To illustrate these differences and similarities, the literature review also focused on prior quantitative gait metrics and the algorithms used to discern between different types of gait.

Approximately 0.001% of people have some form of corrective gear due to LLD [23]. LLD may cause serious long-term consequences based on several variables such as the design of corrective devices, age, weight, posture, and level of activity [24]. An increase of 2 cm or 3.7% in leg length difference has dramatic overall gait asymmetry, especially in vertical reaction forces during push-off and initial contact [51]. Further, LLD causes abnormal changes in foot loading patterns and increases in joint torques/moments, which could lead to long-term effects [82]. Finally, studies have also shown that LLD causes more overall strain on the body and leads to increased expenditure of energy [25].

Limb mass, like limb length, plays an integral role in the dynamics of human walking. Adding mass on limbs, especially towards the distal end, brings about increases in metabolic activity and disrupts spatiotemporal symmetry [9]. Adding mass at the distal end has been shown to force the user to change their walking posture by moving their arms in order to maintain balance [17]. In some cases, simple solutions can correct irregular gait. For example, when individuals with ataxia wore a 2 lb. mass on their chest, unstable motions significantly decreased and the gait was more steady and efficient [19]. These effects may cause adverse changes in walking patterns in able-bodied symmetric individuals, but the addition of weight to the non-paretic limbs of individuals with stroke has shown improvement in walking speed, step length, cadence, and weight bearing in the paretic limb [90].

3.6 Gait Symmetry Metrics

When an individual with an asymmetric impairment walks with symmetric step lengths, other aspects of gait become asymmetric, such as the forces in the joints [11, 30], the amount of time standing on each leg [53], and other temporal variables [38, 101], all of which can be detrimental to efficiency and long-term viability. Understanding how symmetry affects function could change the fundamental nature of clinical gait rehabilitation. The results from this research could also help tailor rehabilitation treatments to target each individual's specific impairment. An overall analysis of multiple gait parameters can bring equilibrium to the different, and sometimes conflicting, requirements of gait. In order to distinguish and characterize the effects of multiple gait parameters, I use metrics that consolidate and quantify the overall change in gait. This paper demonstrates the effectiveness of these quantitative gait metrics in classifying multiple physical asymmetric changes.

Several gait metrics have been used clinically in the evaluation of different gait impairments. These metrics can also be used to classify gait based on different types of information. There are two types: qualitative [69, 108] and quantitative [100, 103, 104] metrics. Many metrics rely on either kinetic or kinematic data to categorize different gait motions and behaviors. Some metrics have the ability to jointly analyze kinetic and kinematic parameters [13, 40]. Most gait metrics use advanced statistical analysis like principle component analysis (PCA) and singular variable decomposition (SVD) to reduce dimensionality to make the running of the data easy [72].

The processed data is then classified using either the Euclidean or Mahalanobis distances [72]. These distances become the scores which form the central part of the gait metric. Another study by Hoerzer et al. [40] proposed the comprehensive asymmetry index (CAI) which combined gait asymmetry using PCA and Euclidean distances. CAI was effective in identifying that shod running reduces gait asymmetry compared to barefoot running. A prior study used a combination of Mahalanobis distances with data reduction techniques on a pre-processed dataset, to analyze kinematic and kinetic gait parameters [13]. They developed several metrics to classify the data and showed that they can successfully classify the abnormal data from standard normal data set. The precursor to the combined gait asymmetry metric (CGAM) used a symmetry index processed using PCA measured using Mahalanobis distances. Without the restrictions of dimensionality reduction, CGAM served as a versatile gait asymmetry metric [86].

3.7 Perception of Human Walking

The perception of human walking is required to establish the fundamental biases that may exist among people. Humans have the innate ability to recognize complex movements of other humans [57, 67]. This generally makes humans better at detecting asymmetric changes in an individual's movement or their own gait beyond a certain threshold [60]. There is precedence for studying the perception of human motion based on motion capture data [56], passive dynamic walker (PDW) models [32], and human vision based morphs to categorize bipedal motion perception [20]. Recent evidence showed that perception of temporal asymmetries in gait due to split-belt treadmills can be associated with spinal level afferent inputs [44]. Humans with anterior cruciate ligament reconstruction detected asymmetry of their own gait differently from able-body subjects while on a split-belt tread mill [98].

Human perception is often biased against abnormal motions or postures. The uncanny valley is a well-documented concept that notes the realistic motion that machines can perform before it appears to be human like and escape the inherent perception biases of humans [71]. The uncanny valley applies to animations, robots, and different walking patterns among humans.

Discrepancies in walking patterns are especially apparent to people when they encounter gait impaired by stroke, cerebral palsy, Friedrich ataxia, and use of prosthetics. This is because humans recognize the slightest variations in discrepancies of step time, length, or other noticeably different changes to the norm [32].

An extensive study conducted by Handzic et al. [32] studied the perception of impairments and uncanniness of 25 different gaits. This study offers precedence to this study to further analyze the inherent biases of naive and experts subjects. The 25 different gaits generated by Handzic et al. [32] used a mix of PDW models and actual human data to create videos in 6 different categories: normal gait, gait cadence, knee height, spatiotemporal asymmetry, Roll Over Shape (ROS) asymmetry, and knee damping with asymmetric shank mass. The study also used videos generated using Matlab code that offers a 2D viewing experience to the subjects. The results presented in Chapter 6 used videos generated using the Unity game engine to generate videos using 3D models to give a sense of realistic appeal to the subjects. The methods and the results obtained by showing the different gait patterns will be elaborated in Chapter 6.

3.8 Computer Assisted Rehabilitation Environments

The experiments involving the stroke & prosthetic simulator, leg length change, distal mass addition, and unilateral transfemoral amputee (different sockets and prosthetic knees) were conducted on the computer assisted rehabilitation environment (CAREN). Kinematic and kinetic data were collected for all the experiments conducted on the CAREN. The CAREN was designed by Motek Medical®, it is a state of the art rehabilitation environment consisting of a Bertec® split-belt treadmill, a MOOG® motion base (*MB-E-6DOF/12/1000KG*) with six degrees of freedom (DOF), a 10 camera Vicon® (*Edgewood, NY*) infrared motion capture system, Bertec® force plates (*FP4060-08-1000*), and a panoramic display for full visual immersion. The subject's motions were captured using reflective markers placed on specific locations on the subject's body.

CHAPTER 4: EFFECT OF MULTIPLE PHYSICAL CHANGES [1]

This chapter on multiple physical changes focuses on Aims 1 and 4 as it analyses asymmetric effects on human gait, and the results of these analyses can help in determining the relationship between the quality of gait and its function. The idea behind testing multiple physical changes is to understand the basic biomechanical characteristics in order to help formulate better rehabilitation technology. Some of the physical asymmetries that were tested are as follow: Stroke Simulator with variable stiffness and damping, change in leg length, adding mass at the distal end, and the combination of leg length and mass. A novel contribution of this research is to reveal the effects of the combination of multiple physical changes, in this case, adding mass to prosthetics to change the dynamics of the gait. The asymmetries of all the changes were quantified using the CGAM to provide the overall gait asymmetry for all types of gait. The summary of information for the experiments performed in this chapter are provided in Table 4.1.

4.1 Stroke Simulator

Individuals impaired by stroke exhibit neuromuscular weakness and paralysis on one side of the body. This is due to the neuromuscular disruption that causes muscles to behave abnormally either under or overexcited. These effects often result in the hyperextension of the knee joint and the inability to plantar flex the ankle joint. The stroke simulator is a small, lightweight, and adjustable knee orthotic device [58, 59]. The device was constructed by Christina-Anne Lahiff and used for her thesis [58].The stroke simulator simulates hemiparetic gait on able-body individuals by impeding the knee joints motion. This device also serves as a means to quantify the Ashworth scale. The Ashworth scale is used clinically to rate knee spasticity in individuals with stroke but it

[1] Part of this chapter was published in Gait and Posture, 2017, Volume 58, Pages 487 - 492. Permission is included in Appendix A

Table 4.1: Experiments Presented in the Chapter.

Experiment	Subjects	IRB	Funding Source	Publications
Stroke Simulator^{*1}				
Able Body	5 Female 5 Male	# Pro00016724	NSF	Lahiff et al. [58, 59]
LLD & Distal Mass^{*2}				
Able Body	7 Female 13 Male	# Pro00016724	NSF	Muratagic et al. [73, 74]
Socket Testing				
Transfemoral Amputee	1 Female	# Pro00026445	AOPA	Kahle et al. [48] Ramakrishnan et al. [84]

^{*1} Christina-Anne Lahiff designed the stroke simulator that was used in these experiments
^{*2} Haris Muratagic completed the first half of the experiments with LLD and distal mass on opposite legs

is extremely subjective to a particular clinician and hence this orthosis can be used to train on the different levels of spasticity. All the gait experiments were performed on the CAREN where the kinematic and kinetic data were collected for all subjects. Previous tests have shown that the gait with and without a stroke simulator are significantly different [59].

The stroke simulator is a portable knee orthosis equipped with a spring-damper mechanism to convey variable stiffness and damping as well as to evaluate the effects of asymmetric dynamics of the knee on the gait patterns of healthy, able-bodied subjects. Damping and stiffness of an individual affected with stroke have been rated by the Modified Ashworth Scale [120], but it has never been quantified in terms of numerical values for stiffness and damping levels. The eventual quantification of the Modified Ashworth Scale would allow for a more personalized design of orthotics that could aid rehabilitation. Figure 4.1 shows the knee orthosis prototype design. Figure 4.2 shows initial results of the effect of the stroke simulator on an individual's gait. The CGAM or modified Mahalanobis distances shown in orange indicate the overall asymmetry of the gait pattern. Normal walking clearly has the lowest CGAM score, while it is highest with the stroke simulator and the magnitude of after wearing the stroke simulator indicates carry over

Figure 4.1: Stroke Simulator on a Subject.

effects. In this preliminary experiment, I study the effects of one of the various combinations of damping and stiffness on the knee orthosis. The rationale behind the device is to simulate knee damping that is typically seen in stroke patients. Recreating the damping and hysteresis on able-body subjects similar to that of an individual with stroke provides researchers the ability to study multiple levels of damping and hysteresis. This also mitigates the recruiting limitations of trials that involving people with stroke. In addition to this the device also can be used to estimate the Ashworth scale. The results section of this chapter has more details of the device using the CGAM metric.

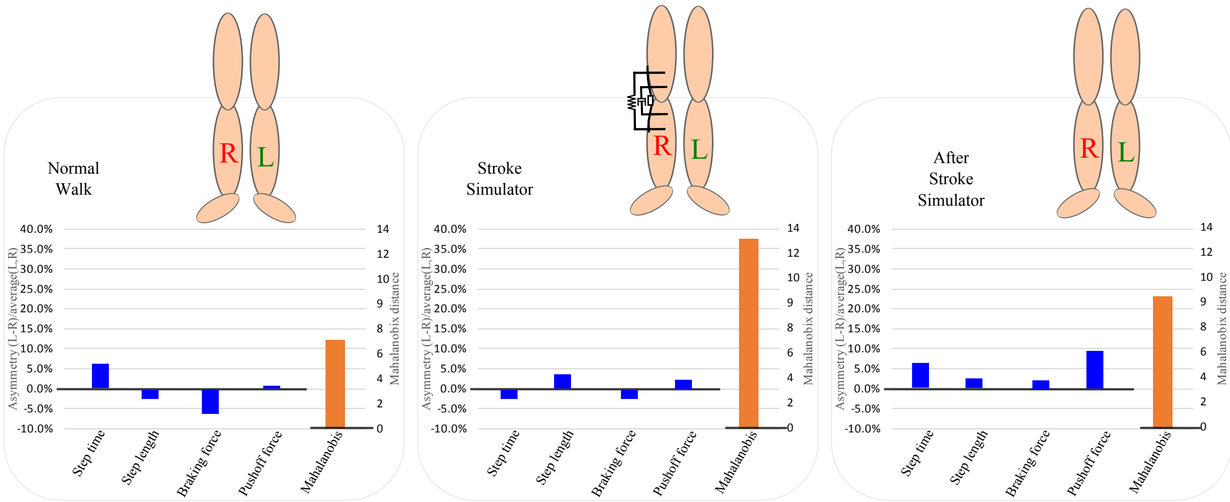

Figure 4.2: Initial Results with the Stroke Simulator.

The majority of the walking process is governed by the passive dynamics of the legs and body [27], which generally leads to symmetric walking when both sides of the body are identical. In an asymmetrically impaired individual, asymmetric control effort is necessary to create symmetric motions. These compensatory motions, such as using alternate arm movements along with abnormal torso and hip flexion, are commonly used by disabled individuals. These adaptations often lead to back pain and premature deterioration of joints in individuals with stroke and also cause stresses at the residual limb socket in amputees.

4.2 Methods: Leg Length and Weight Alterations

Each combination of physical parameters was performed once, with the exception of baseline walking that was performed at the start and end of the experiment. Each combination was tested for approximately two minutes with varying times between trials to apply the physical alterations. To avoid the effects of adaptation from previous physical combinations in the study, only the last thirty seconds was evaluated in each session. The total walking time for the entire experiment was approximately 32 minutes for each subject, and a short break was available to the participants between sessions as needed.

The 16 different physical combinations of this walking study are shown in Figure 4.3 and described in Table 4.2. The leg length device was attached to the non-dominant foot of the participant and is shown in Figure 4.3. The two settings for the applied leg length change were small and large, measuring 27 mm(1.05 inches) and 52 mm (2.05 inches) respectively. It was designed to be under 0.350 kg (0.77 lb) for the high setting and under 110 g (0.25 lb) for the lower setting. These small mass values ensured that this shoe would only simulate pure leg length change and not add unwanted weight. For the application of weighted walking, a weighted ankle strap with several lead weight inserts was attached to the dominant leg. There were two distinct mass values for this parameter, as shown in Figure 4.3. The small weight size was approximately 2.3 kg (5.07 lb), and the large was 4.6 kg (10.14 lb). The leg lengths were chosen to represent a larger than 2 cm discrepancy as per the literature. The masses were selected based on a PDW study conducted by Handzic et al. [28] that used a linear relationship of x and 2x to test the scenarios used in this study for leg length and distal mass. An additional strap was included to avoid interfering with any infrared position sensing markers.

4.3 Methods: Participants for LLD, Distal Mass, and Stroke Simulator

There were twenty subjects (13 male, 7 female) that participated in the walking study, all with limited to no exposure with physically induced asymmetric walking [73]. The complete experiment was conducted in two different phases. The first phase consisted of 10 subjects (8 male and 2 female) where nine of the ten participants in the study were right foot dominant. The data of the left foot dominant subject was mirrored to be included in the analysis. Note, the dominant foot was always used for the applied weight and, in this phase, the leg length change was always applied to the non-dominant foot for consistency. The subjects walked with the weights on their right leg, heights on their left leg, and the combinations were on opposite sides as seen in Table 4.2 and Figure 4.3 (f – l). The second phase consisted of 10 subjects (5 male, 5 female) who were all right leg dominant. The subjects walked with all the perturbations on their left leg as seen in Table 4.2 and Figure 4.3 (d,e & j – o). The age of all participants ranged from 18 to 30 years old, with no

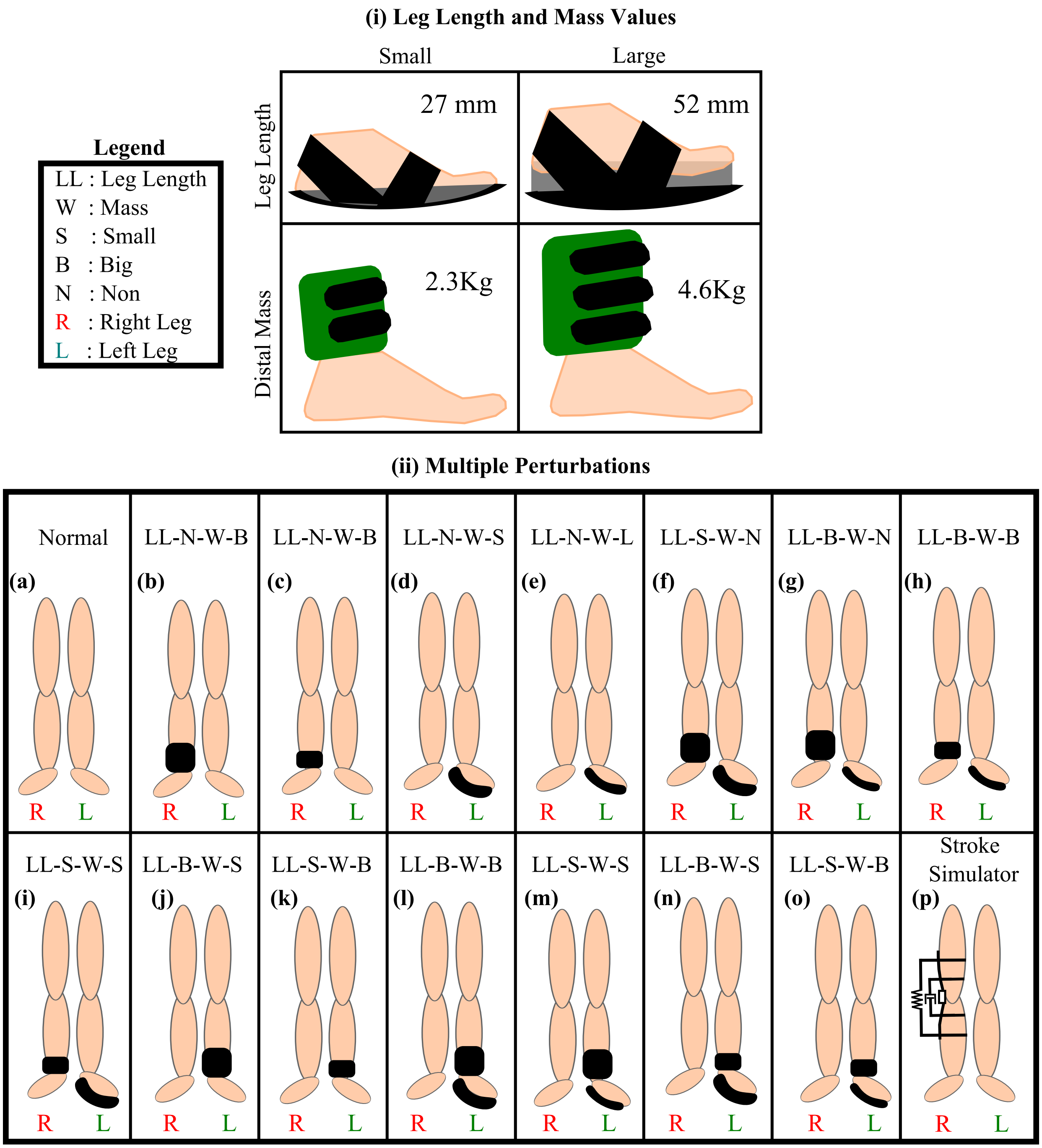

Figure 4.3: Multiple Physical Perturbations. (i) Leg Length and Mass (ii) Different Perturbations

Table 4.2: All Combinations of Settings That Were Applied to the Participants. Note: Combinations 2 - 15 Were Randomized for Each Participant

Combination	Leg Length Change	Weight Applied	Side
LL_N-W_N	None	None	None
LL_N-W_B	None	Big	Left
LL_N-W_B	None	Big	Right
LL_N-W_S	None	Small	Right
LL_N-W_S	None	Small	Left
LL_S-W_N	Small	None	None
LL_B-W_N	Big	None	None
LL_S-W_S	Small	Small	Same Side
LL_B-W_S	Big	Small	Same Side
LL_S-W_B	Small	Big	Same Side
LL_B-W_B	Big	Big	Same Side
LL_S-W_S	Small	Small	Opposite Side
LL_B-W_S	Big	Small	Opposite Side
LL_S-W_B	Small	Big	Opposite Side
LL_B-W_B	Big	Big	Opposite Side
LL_N-W_N2	None	None	None

physical impairments, past knee injuries, or large leg length discrepancies. The average height, leg length, weight, and walking speed of the participants was 1.785 m (70.3 in), 0.981 m (38.6 in), 82.8 kg (182.5 lbs), and 1.22 m/s (48.03 in/s), respectively. All experiments were conducted with the approval of the Institutional Review Board at the University of South Florida after informed consent and signing the consent form.

4.4 Results: LLD and Distal Mass Perturbations

The altered gait patterns are measured using the percentage of asymmetry between each leg, calculated using Equation 4.1, for step length, step time, peak vertical force, push off force, and braking force. These biomechanical parameters were chosen because they are related to an individual's gait pattern and are generally impacted by physical and neurological asymmetries. Since, I am interested in the changes from the baseline gait patterns, all the graphs shown below are normalized to the baseline walking pattern of the subjects such that baseline walking is always

Table 4.3: Summary of the Statistics. (Bold implies Statistical Significance)

Measure	Mass Effect	Height Effect	Interaction Effect
Step Time	**$p < .0001$** $F(4, 165) = 87.5$	**$p < .0001$** $F(2, 165) = 56.0$	$p = .08$ $F(8, 165) = 1.8$
Step Length	**$p < .05$** $F(4, 165) = 2.9$	**$p < .0001$** $F(2, 165) = 15.3$	$p = .97$ $F(8, 165) = 0.29$
Peak Vertical Force	**$p < .0001$** $F(4, 165) = 9.6$	**$p < .0001$** $F(2, 165) = 22.6$	$p = .84$ $F(8, 165) = 0.53$
Peak Pushoff Force	**$p < .0001$** $F(4, 165) = 137.0$	$p = .26$ $F(2, 165) = 1.35$	$p = .18$ $F(8, 165) = 1.44$
Peak Braking Force	**$p < .0001$** $F(4, 165) = 137.0$	**$p < .05$** $F(2, 165) = 4.1$	$p = .73$ $F(8, 165) = 0.66$

at zero asymmetry. The baseline condition means no added mass and no added height difference. The gait data is normalized to the baseline/unaltered walking pattern of the subjects such that baseline/unaltered gait is always at zero asymmetry (i.e., 0 on y-axis with no added length of mass). The means of step length (-2.9%), step time (-0.39%), vertical force (-1.6%), propulsive force (-4.3%), and braking force (-3.5%) were subtracted from all of the respective graphs to normalize the plots. This normalization was done to ensure continuity between the length and mass perturbations being applied to the same and opposite limbs to focus on the change in gait pattern [73].

To determine statistical significance, SPSS statistics software was used to perform a two-way ANOVA with asymmetry in each parameter as the dependent variable and the independent variables were LLD and added mass with interaction effects. The summary of these results with the statistical significance of each gait parameter is shown in Table 4.3. Figures 4.4 – 4.8 show each of the parameters as a function of mass added and leg length change. The X-axis represents the mass added and is split between mass added to the same or opposite side as the leg length increase (leg length increase was always applied to the subjects' left legs). The three lines represent the different leg lengths added.

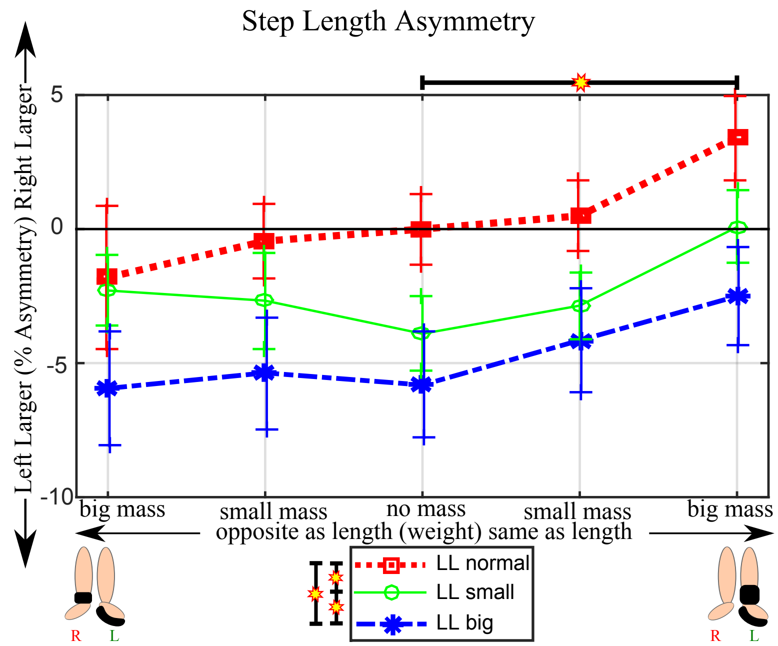

Figure 4.4: Step Length for All the Conditions. (Bars Show Standard Error)

Step length asymmetry showed a statistically significant main effect on both the amount of mass added, $F(4, 165) = 2.9$, $p < 0.05$, and size of leg length added, $F(2, 165) = 15.3$, $p < 0.0001$. There was not a statistically significant interaction between the amount of mass added and the size of the leg length added on the step length asymmetry, $F(8, 165) = 0.29$, $p = 0.97$.

Step length shows distinct non-overlapping trends for each of the leg length conditions, as seen in Figure 4.4. Without any mass added, increasing the LLD causes an increase in the asymmetry. Adding mass causes a change in the asymmetry, but to a smaller extent than the LLD [64, 68]. When mass and LLD were tested together, the mass added to the opposite leg had less of an effect than the mass added to the same foot as the LLD. The effect of change for the combination seems to be more pronounced when they are on the same side as opposed to opposite sides, which is also seen in the case of a big leg length change. However, in this case, the small mass on the opposite side is slightly less asymmetric while the big mass and length change was slightly more asymmetric. It is interesting to note that a small LLD and a large mass on the same foot result in a symmetric step length. This indicates that there is a configuration for symmetry in an asymmetric individual, but none of the other parameters are symmetric in that configuration.

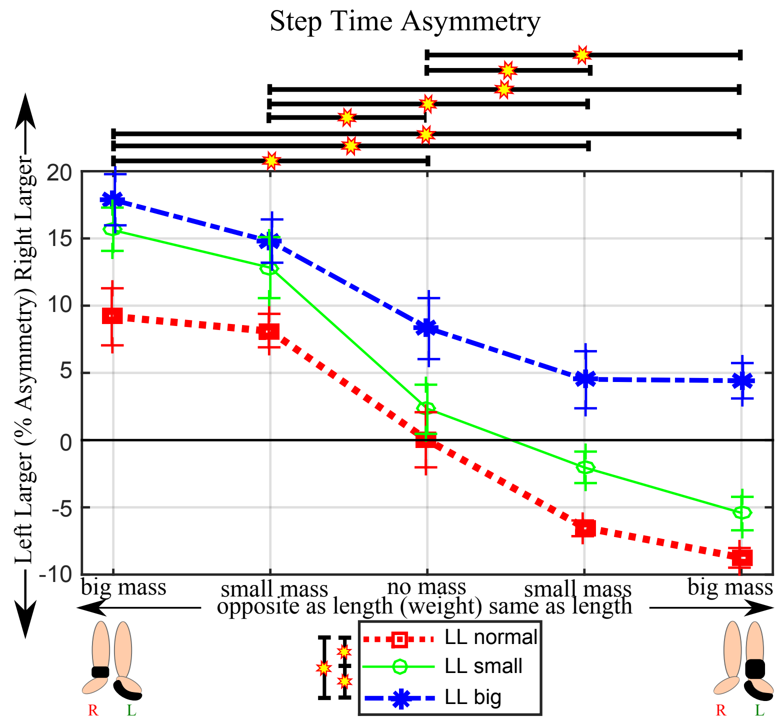

Figure 4.5: Step Time for All the Conditions. (Bars Show Standard Error)

Step time asymmetry showed a statistically significant main effect on both the amount of mass added, $F(4, 165) = 87.5$, $p < 0.0001$, and the size of leg length added, $F(2, 165) = 56.0$, $p < 0.0001$. There was not a statistically significant interaction between the amount of mass added and the size of the leg length added on the step time asymmetry, $F(8, 165) = 1.8$, $p = 0.08$.

The curves for step time show a dissimilar trend as for step length, because the asymmetries are flipped, as seen in Figure 4.5. A small addition in mass has a large magnitude of asymmetric change and, unlike step length, the asymmetry changes in the same direction as the leg to which the mass is added. Adding a small leg length shifts the pattern of asymmetry towards the right leg. This is because the leg length alterations were always performed on the subject's left leg. This is opposite to the shift noticed in step length as it shifted towards left asymmetry. The change in magnitude with a small mass on the opposite side is much larger than the change in the same side for the small leg length condition. The curve becomes highly asymmetric with the big leg length condition [64].

Peak vertical force asymmetry showed a statistically significant main effect on both the amount of mass added, $F(4, 165) = 9.6$, $p < 0.0001$, and the size of leg length, $F(2, 165) = 22.6$, $p < 0.0001$. There was not a statistically significant interaction between the amount of mass added and the size of the leg length added on vertical force asymmetry, $F(8, 165) = 0.53$, $p = 0.84$.

The plots for the vertical peak ground reaction forces shift towards the right asymmetry with an increase in leg length, seen in Figure 4.6. Previous research has shown that the addition of asymmetric mass at the ankle caused a decreased single support time and increased swing time [106]. This is similar to Figure 4.5 where the asymmetry of step times shift towards the leg the masses were added. The condition with no added leg length has an interesting trend where on both legs the small mass seems to be more asymmetric than the large mass condition. This is seen again on the same side condition with a small change in leg length. Although the flattening out of the asymmetry at larger masses, this may indicate a change in the compensation mechanism when walking. When the leg length and mass were on opposite legs with the small leg length condition, the asymmetry of gait was proportional to the mass. Any change in leg length of the same side mass loading condition is more symmetric than the opposite side loading condition. When a large mass is added to the same side condition it results to be more symmetric than no mass for both leg length changes [50, 68].

Pushoff force asymmetry showed a statistically significant main effect on the amount of mass added, $F(4, 165) = 137.0$, $p < 0.0001$, but not on the size of leg length added on pushoff force asymmetry, $F(2, 165) = 1.35$, $p = 0.26$. There was not a statistically significant interaction between the amount of mass added and the size of the leg length added on pushoff force asymmetry, $F(8, 165) = 1.44$, $p = 0.18$.

The peak push off forces showed little change when the leg length was increased, seen in Figure 4.7. There is also research showing an increase in vertical force asymmetry proportional to the height of the leg length change [50]. This can be seen in Figure 4.6 with the no mass condition the asymmetry is clearly moving towards the right leg which in this case is the unaltered leg. The normal and small leg length change condition have an extremely similar pattern where the small

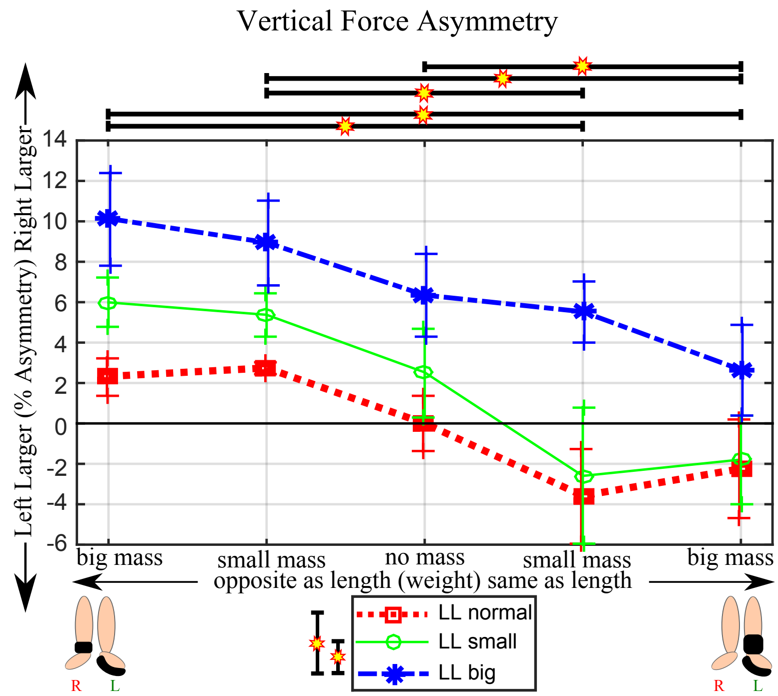

Figure 4.6: Peak Vertical Force for All the Conditions. (Bars Show Standard Error)

leg change curve is slightly offset towards the right leg. The big leg length follows a similar trend for the same side mass conditions, but for the opposite mass condition, the big leg length change was more symmetric than the other two condition. This is because of the opposite effects of mass on one leg and a drastic increase in leg length on the other. Other interesting aspects to note are that the changes from no mass to small mass is much larger than the change from small to large mass for all leg length changes [25, 107].

Braking force asymmetry showed a statistically significant main effect on both the amount of mass added, $F(4, 165) = 137.0$, $p < 0.0001$ and on the size of leg length added, $F(2, 165) = 4.1$, $p < 0.05$. There was not a statistically significant interaction between the amount of mass added and the size of the leg length added on the braking force asymmetry, $F(8, 165) = 0.66$, $p = 0.73$.

Braking force curves for all leg length conditions follow the same pattern with an offset towards the right with each alteration, as seen in Figure 4.8. Changing leg lengths has been shown to affect plantar flexion in the opposite limb thus indicating a higher push off force and higher quadricep activity in the altered leg [24, 25]. This can be observed in Figure 4.7 where the push

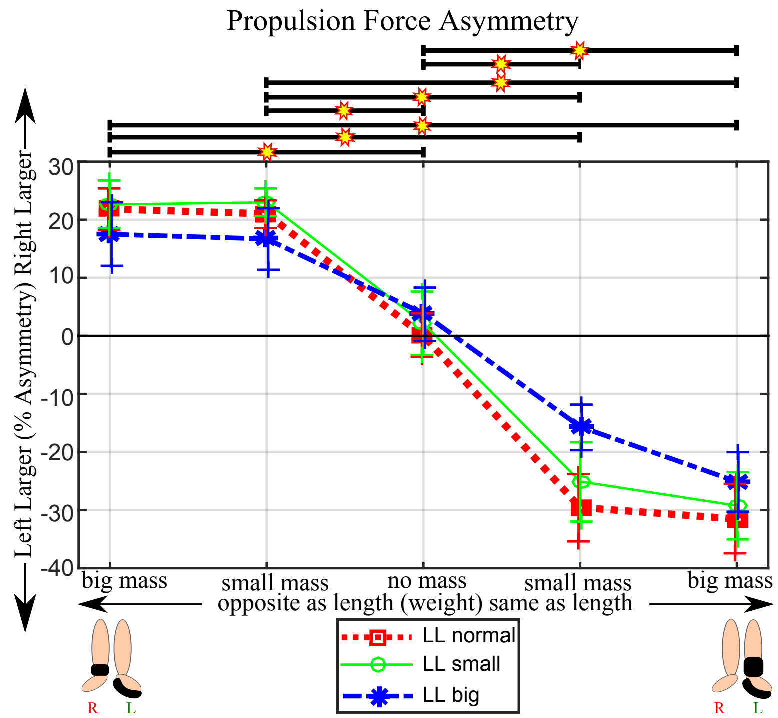

Figure 4.7: Peak Push off Force for All the Conditions. (Bars Show Standard Error)

off force with change in leg length shifts towards the right because the leg lengths were changed on the subject's left leg. The increased quadraceps activity may also explain the asymmetries caused by the other parameters, especially spatial and temporal changes. On the same side mass loading condition, the small and large mass conditions are progressively more symmetric with the change in leg length compared to the normal leg length curve. This is reversed in the opposite mass loading condition, and it can also be seen that the deflection of asymmetry is larger with the leg length change. This seems to be a linear relationship in the opposite loading condition and an inverse relationship in the same side loading [64].

There are overall trends in the direction of the asymmetric change that seem to be dependent on the mass loading condition. The asymmetry in step length follows a different trajectory in both loading conditions when compared to the other four biomechanical parameters. That said, for the same side mass loading condition, the addition of a small mass drives both leg length conditions to be more symmetric. In the case of step length and peak vertical force, the addition of a big mass on the same side drove both leg length conditions to be more symmetric than the small mass

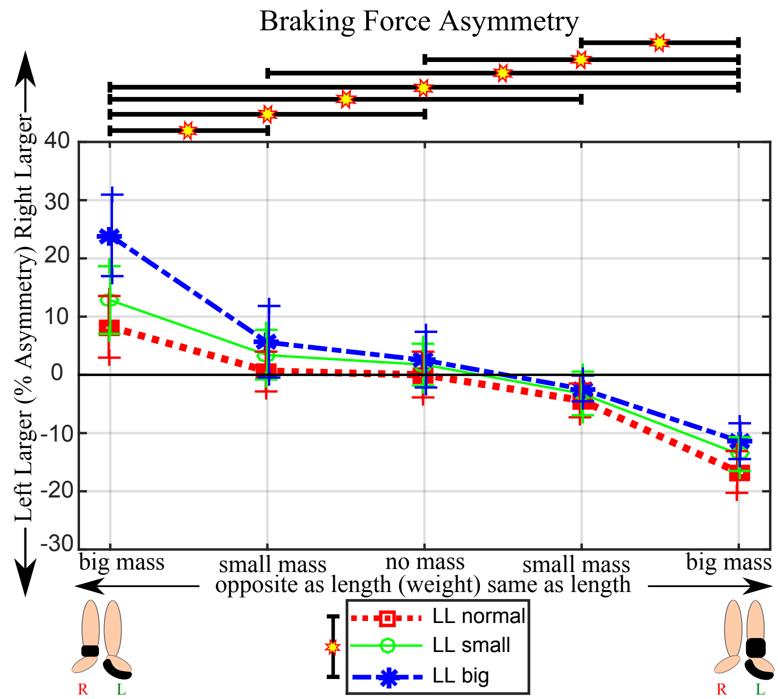

Figure 4.8: Peak Braking Force for All the Conditions. (Bars show standard error)

condition. However, the step time, peak push off, and braking force became more asymmetric with the addition of the big mass on the same side condition.

The trends for the opposite leg mass loading show that the curves become more asymmetric with the addition of mass except for a few curves in step length and peak vertical force. The pattern seems to be that the normal leg compensates by generating large forces to maintain the gait. This is confirmed in one study that found an increase in joint kinetics during gait with leg length asymmetry [105]. The addition of mass on the opposite side of a small leg length increase improved symmetry of the step length compared to a no mass condition. There is a slight improvement with the small mass and large leg length change in the opposite combination, but when a big mass is added the step length becomes more asymmetric. When a large mass is added to the opposite leg at the normal leg length, it is slightly more symmetric than the addition of small mass. All other curves than the anomalous ones discussed above have a general trend of becoming more asymmetric with the increase in mass added to the opposite side.

The results indicate that there is a configuration for symmetry in an asymmetric individual, but none of the other parameters are symmetric in that configuration. For example, step length is close to symmetry when the big mass and small leg length were added to the same leg, but this resulted in a highly asymmetric step time, vertical, push off, and braking forces. This is backed by a preliminary study exploring the interaction between LLD and addition of mass, which showed that there were significant changes in parameters between leg lengths changes and kinetics associated with these configurations [75].

There is a statistically significant difference between no mass and the big mass in all measures, with the exception of step length and vertical force on the opposite condition [73]. Step time and propulsion forces have the same pattern for significances. Braking forces show significance between big and small masses in both opposite and same side conditions.

There is statistical significance between all three leg length conditions for step length and time. There is no statistical significance between all conditions for propulsive forces. Vertical forces show statistical significance for the normal and large leg length condition and for small and big leg lengths. Braking forces only display significance between normal and large leg length.

4.5 Discussion: Effect of LLD and Addition of Distal Mass

An important finding from this experiment is that there is no significant interaction effect between the addition of mass and leg length for all gait parameter asymmetries, Table 4.3 (f). I initially expected interaction between these mass and leg length alterations because they both affect the gait patterns, but in different ways. There was significance for all parameters for mass effect and leg length with the exception of propulsion forces. These results imply that the addition of mass will have the same gait change regardless of whether there is a LLD or not and similarly for the addition of a LLD with an added mass on one side. Interaction effects may be found with larger perturbations, but the magnitudes used here span the range of asymmetries typically seen [42, 99, 109, 119]. The results of this study contain evidence that differences in asymmetric gait patterns can drive some gait parameters to symmetry while causing the inverse effect on the rest of the paramaters. This shows that a balance of multiple gait parameter asymmetries might be beneficial clinically. Designing rehabilitation protocols with this in mind will help improve the quality of gait patterns post training.

The results show there are configurations where one parameter is symmetric in an asymmetric individual. For example, step length is close to symmetry (0.075%) when a big mass and small leg length were added to the same leg, but this resulted in a highly asymmetric step time (-5.4%), vertical (-1.78%), propulsion (-29.24%), and braking forces (-13.61%). This is consistent to other studies exploring LLD and addition of mass, which found significant changes in parameters between leg lengths and kinetics associated with these configurations [75, 116]. The same side conditions tend to have the symmetric parameters more so than the opposite side conditions.

With no mass added, the forces show an approximately linear increase in their asymmetry with leg length change. In the no-mass condition, the unaltered leg compensates by generating large forces to maintain the gait, Figures 4.6, 4.7& 4.8. The increase in forces has been observed in prior studies with simulated LLD [105, 118]. However, subjects with a natural LLD tend to exhibit more force on their longer limb [4, 24]. I believe this difference in behavior can be attributed to the adaptation period of simulated and natural LLD subject populations.

Subjects with LLD and amputees with shorter prosthetics have smaller step times on their shorter limbs compared to longer limbs [24, 96]. This is not consistent with my findings. The step times show a linear increase with change in leg length towards the shorter limb. However, the same studies also found subjects with LLD take smaller steps with their shorter limbs. This does correlate with my findings. The general behavior of the subjects with simulated leg length is to spend more time on their unaltered limb and use that leverage to swing their altered limb to maintain the stability required for their gait on a constant velocity treadmill. They also spend less time on their altered limb and quickly switch to their unaltered limb.

Compensatory motions influence gait asymmetries with mass and leg length alterations. This is clinically relevant because patients with impairment tend to adapt with compensatory movement. This results in long term effects such as chronic back pains in amputees with asymmetric prosthetic lengths [96]. Adding mass to prosthetics increase step length and swing time asymmetry of the prosthetic compared to the intact limb [68]. Amputees swing their prosthetics out and hence have larger step length and swing time. Able body subjects tend to take smaller steps and spend more time on the altered limb to conserve energy while taking longer steps with the unaltered limb. Long term effects of these gait alterations may lead to completely different gait mechanics than reported in the results. This is because over a long term subjects tend to use different compensation strategies than the short term tested for this research.

The results of adding both leg length and mass demonstrate that driving one of the gait parameters to symmetry will cause the other gait parameters to become more asymmetric. There are instances where a gait parameter can be symmetric when walking with asymmetric height and weight, but I did not find a configuration where several of the measured gait parameters became more symmetric in an asymmetric individual. Although there is a statistically significant effect between the addition of mass and leg length, there was not a significant interaction between the mass and leg length change. The kinetic and temporal parameters exhibit higher asymmetry on the shorter limb for leg length condition while the spatial parameter shows that asymmetry moves towards the altered leg. Similarly, the addition of mass shifts the trend towards the affected leg in the temporal and kinetic parameters but they affect the opposite leg spatially. Finally, although there was no statistically significant interaction effect, this study has shown the behavior of multiple gait parameters. This gives an overall perspective of the effects of LLD and addition of distal mass in multiple perturbations.

4.6 CGAM to Analyze Multiple Physical Effects

Symmetry in gait rehabilitation is used to evaluate the quality of an individual's gait. Symmetry has also been used as a metric to measure the improvement of gait patterns due to intervention [34, 77]. Inter limb symmetry of post stroke patients is used to determine the walking patterns after training on a split-belt treadmill [95]. CGAM offers a method to combine multiple gait parameter asymmetries. The rationale behind this method is to offer a single measure for the overall quality of a gait pattern. Using symmetry as a measure helps to homogenize different types of gait parameters such as spatio-temporal, kinematic, and kinetic variables. This uniform dataset then can be combined to be used as a metric of overall symmetry. CGAM score and overall asymmetry are directly proportional, i.e, higher CGAM score indicates higher overall asymmetry while a lower CGAM score indicates smaller overall asymmetry. CGAM is also relative to the number of gait parameters used to calculate the CGAM score, for example, a five parameter analysis cannot be compared to a eleven parameter analysis. Finally, CGAM is also relative to the type of variables used in the analysis, for example, a five parameter analysis of spatio-temporal and kinetic asymmetries cannot compared to a five parameter analysis of spatio-temporal and kinematic asymmetries.

4.6.1 Methods: Formulation

Physical changes such as leg length discrepancy, the addition of a mass at the distal end of the leg, the use of a prosthetic, and stroke frequently result in an asymmetric gait. The metric presented here has the potential to help categorize and differentiate between multiple asymmetric gaits. CGAM is based on Mahalanobis distances, and it utilizes the asymmetries of gait parameters obtained from motion capture and force data recorded during human walking, calculated using Eqn. 4.1. The gait parameters that were used in this analysis represent spatiotemporal, kinematic, and kinetic parameters. This form of a consolidated metric will help researchers identify overall gait asymmetry and to improve rehabilitation techniques to provide a well-rounded gait post training. The CGAM metric successfully served as a measure for overall symmetry with 11 different gait parameters and successfully showed differences among gait with multiple physical asymmetries. The mass at the distal end had a larger magnitude on overall gait asymmetry compared to leg length discrepancy. Combined effects are varied based on the cancellation effect between gait parameters. The metric was also successful in delineating the differences of prosthetic gait and able-bodied gait at three different walking velocities. Aim 3 and 4 can be fulfilled using this metric to define an overall achievable symmetry using rehabilitation techniques.

To further describe how the CGAM metric combines the gait parameters into one measure, the 11 gait parameters are shown in Figure 4.9 with their respective CGAM score for four of the gait alterations. An important aspect for interpreting this metric is the covariance of the asymmetry matrix, which serves to weight the measures based on how much variability is present. From Equation 4.2 it is clear that the covariance of the data plays a major role in calculating the Mahalanobis distances from ideal symmetry. The measures that have more variability get weighted less and more consistent measures are weighted more heavily. These weights generally account for the variations in magnitudes across all the parameters. For example, push off and braking forces tend to show much higher magnitude asymmetry than other measures, but they also show more variability; scaling them based on their variability makes the influence comparable to the other measures.

$$Percentage\ of Asymmetry = \frac{Right - Left}{\frac{1}{2} * (Right + Left)} \tag{4.1}$$

$$CGAMDistance = \sqrt{(Data) * inv(\Sigma) * (Data)'} \tag{4.2}$$

$$\text{Modified CGAM} = \sqrt{\frac{(Data) * inv(\Sigma) * (Data)'}{\sum(inv(\Sigma))}} \tag{4.3}$$

where,

- *Modified CGAM Distance* = Weighted Distance from Ideal Symmetry
- *CGAM Distance* = Mahalanobis Distance from Ideal Symmetry
- *Data* = Matrix with n columns (11) and m rows (Number of Steps)
- Σ = Covariance of the Data.

I have updated the formulation to Equation 4.3 from Equation 4.2. The new formula works similar to weighted means. In this case the weights are inverse covariances that are multiplied

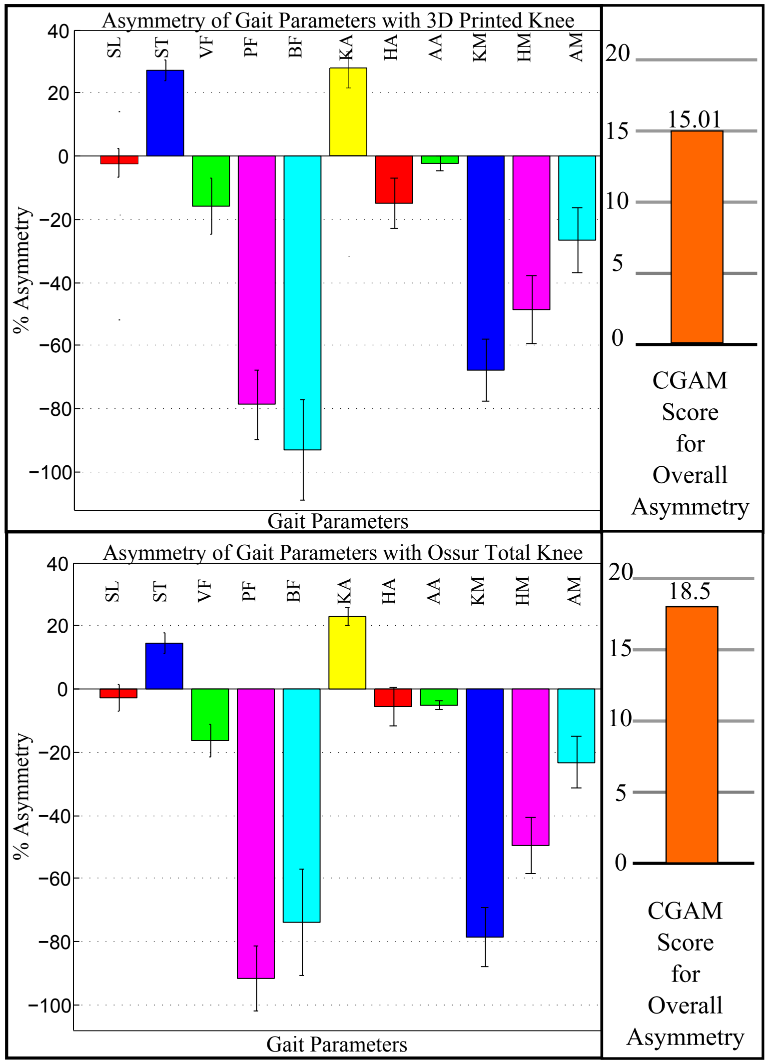

Figure 4.9: CGAM Scores for Prosthetic Knees. (Legend: SL–Step Length, ST–Step Time, VF–Vertical Force, PF–Push Off Force, BF–Braking Force, KA–Knee Angle, HA–Hip Angle, AA–Ankle Angle, KM–Knee Moment, HM–Hip Moment, AM–Ankle Moment)

across the data set in the numerator, Equation 4.2. To balance the influence of the inverse of covariance it is divided by the sum of the inverse covariance matrix, Equation 4.3. This change to the formulation make the modified CGAM to represent the scores closer to the percent asymmetry while still serving as a combined measure of all the gait parameter asymmetries.

4.6.2 Results: CGAM Scores for Multiple Physical Changes

Figure 4.9 shows the comparison of two different systems in overall gait asymmetry between a 3D printed biomimetic prosthetic knee [87, 88] and an Ossur Total knee [89]. The representation shows the 11 gait parameter asymmetries on the left that are combined using CGAM to represent overall asymmetry on the right. Notice, that the pattern for both systems in terms of asymmetry are the same as the step time, and knee angles express left asymmetry (positive) while the rest of the parameters express right asymmetry (negative). This is because the data was collected on a single amputee walking on two different prosthetic knees. The magnitudes and variances of asymmetry affect the combination of all the parameters as they are weighted by the inverse of their covariances to find their distances in 11-dimensional space. CGAM was also used to characterize the differences in overall gait asymmetry between gait with the addition of leg length, shown in Figure 4.10 (a), and distal mass and in the classification of gait with prosthetics at three different speeds testing different socket technologies, shown in Figure 4.10 (b) [10]. This shows the diversity of gait patterns that can be analyzed using the CGAM metric. CGAM streamlines the understanding of the overall asymmetry of a gait pattern, thus, enabling easy classification.

Machine learning has been used in data-driven industries to find patterns in large amounts of disparate datasets. The two datasets that were collected during this study represent gait with multiple asymmetrical changes and hence, can be used to find patterns. For this study, the LibSVM library [12] was used because it is easy to implement and it is widely used for research data. The machine is trained using labels and a training dataset. The labels are long vectors with a single number and the training datasets are ground truths. In the case of this study, the labels were 0 and 1. Label 0 was used for the perfect symmetry which is a zero matrix with 11 columns and multiple rows. Label 1 was used for training asymmetry data. Figure 4.11 shows the results of grouping predictions from 2 different asymmetry training datasets.

The pattern of the LibSVM grouping Index seen in Figure 4.11 (a) is very similar to the pattern of the CGAM Mahalanobis distance in Figure 4.10 (a). Although the specific values cannot

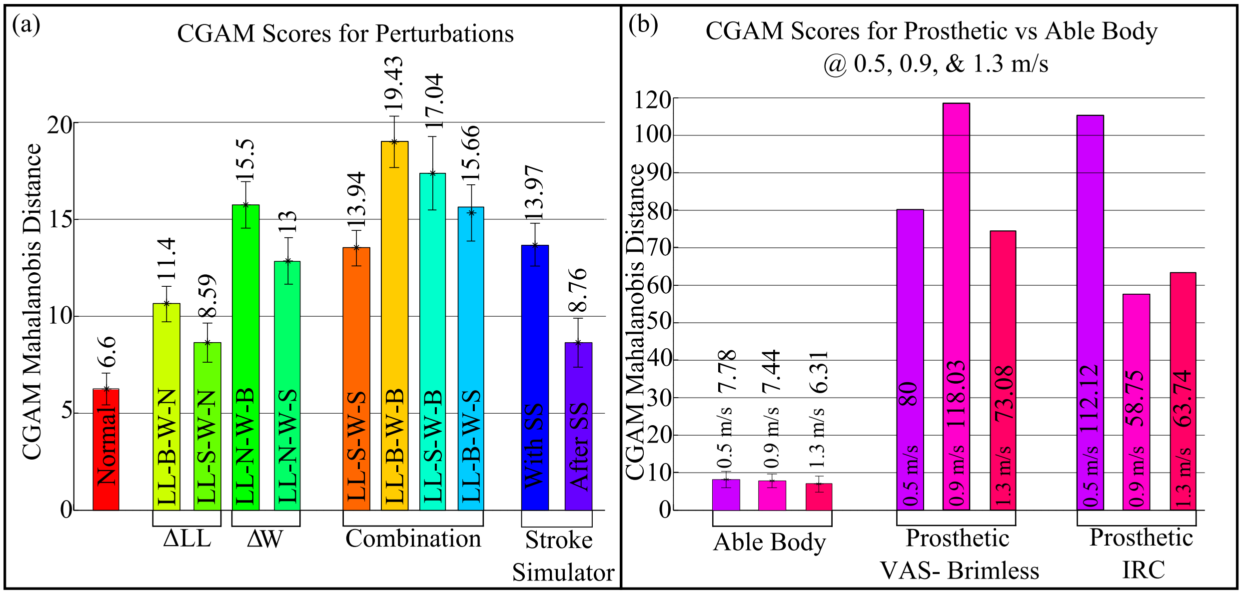

Figure 4.10: CGAM Scores for All Perturbations. (a) Able-bodied Subjects with Multiple Physical Asymmetries (b) Comparison of Able-body Subjects to Prosthetic User at Three Different Speeds (0.5, 0.9, & 1.3 m/s)

be compared directly because the modes by which they arrive at the results are inherently different, the trends highlight the differences between these two methods. The CGAM metric uses a simple Mahalanobis distance calculated from ideal symmetry while the more complex machine learning metric groups the data based on training datasets. LibSVM is not as reliable at this stage for being considered as a gait asymmetry metric because, based on the training datasets, the results vary substantially. This can be seen by comparing Figure 4.11 (a & b) where the training datasets were different and the grouping predictions are completely different. This can be attributed to the different asymmetries present in the SS data and the weight/LL datasets. CGAM does not get affected by these differences and offers a more objective metric that can be used to classify the asymmetric changes. Another problem with Machine Learning as a metric is the requirement of large datasets.

Analyzing multiple physical asymmetries in one method requires a special form of metric. This is because every perturbation of physical change that impairs an individual's gait has to be accounted for and kept track of following clinical procedures. The consolidated metrics such as CGAM and Machine learning can be quantitative data analysis tools that can help researchers

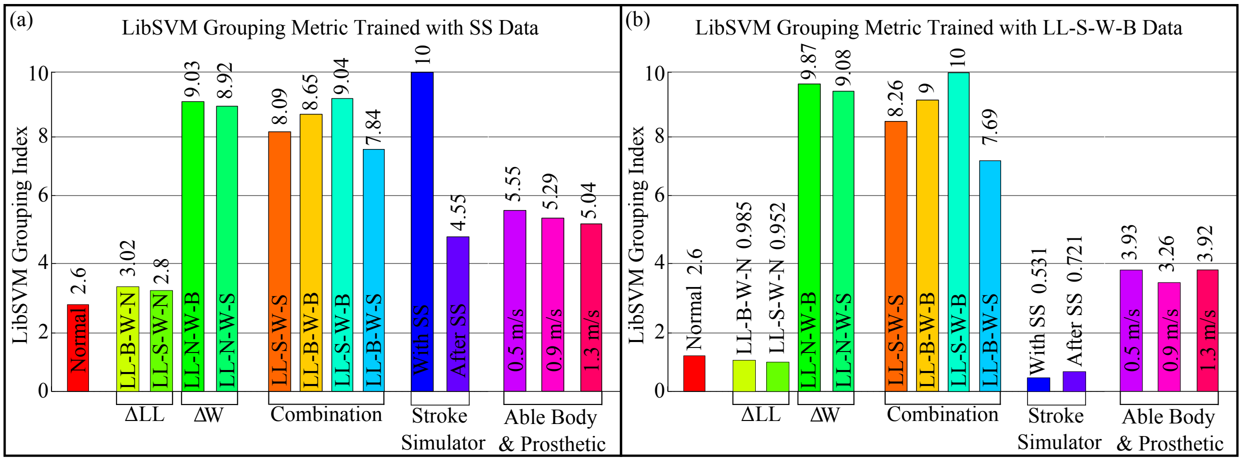

Figure 4.11: Machine Learning (LibSVM) Grouping Metric Using Two Different Datasets for Training. (a) Uses the Asymmetry Data for Walking with Stroke Simulator (b) Uses the LL-S-W-B Data which was Found to have the Largest CGAM Score Notice the Differences in Grouping

keep track of an individual's overall gait asymmetry. These metrics can be obtained using all gait asymmetry parameters such as spatiotemporal, kinematic, and kinetic or by using subsets and combinations of any or all of these parameters. This versatile platform allows researchers to have many options for generating metrics to represent the progress or regression of an individual over a period of training and time.

4.6.3 Discussion: Relationship of CGAM and Multiple Physical Asymmetries

The results discussed above show that the metric is able to successfully catagorize the extent of asymmetric changes caused by different perturbations. For example the CGAM scores for walking with the SS, which is designed to cause asymmetric gait, has a significantly larger value compared to the value that was gathered for gait immediately after the device was taken off. The after-effects of the SS are also more asymmetric than a normal gait pattern, which shows that the individuals adapted to the SS. Classification of gait based on overall symmetry will help clinicians keep track of a subject's progress, such as pre and post physical therapy regiments. The SS can be examined as an impeding exoskeleton. Hence, the gait with and after the SS is asymmetric overall. Conversely, in robot-assisted locomotion therapy the outcomes are expected to be more symmetric [65]. CGAM could provide researchers the tools to measure the overall

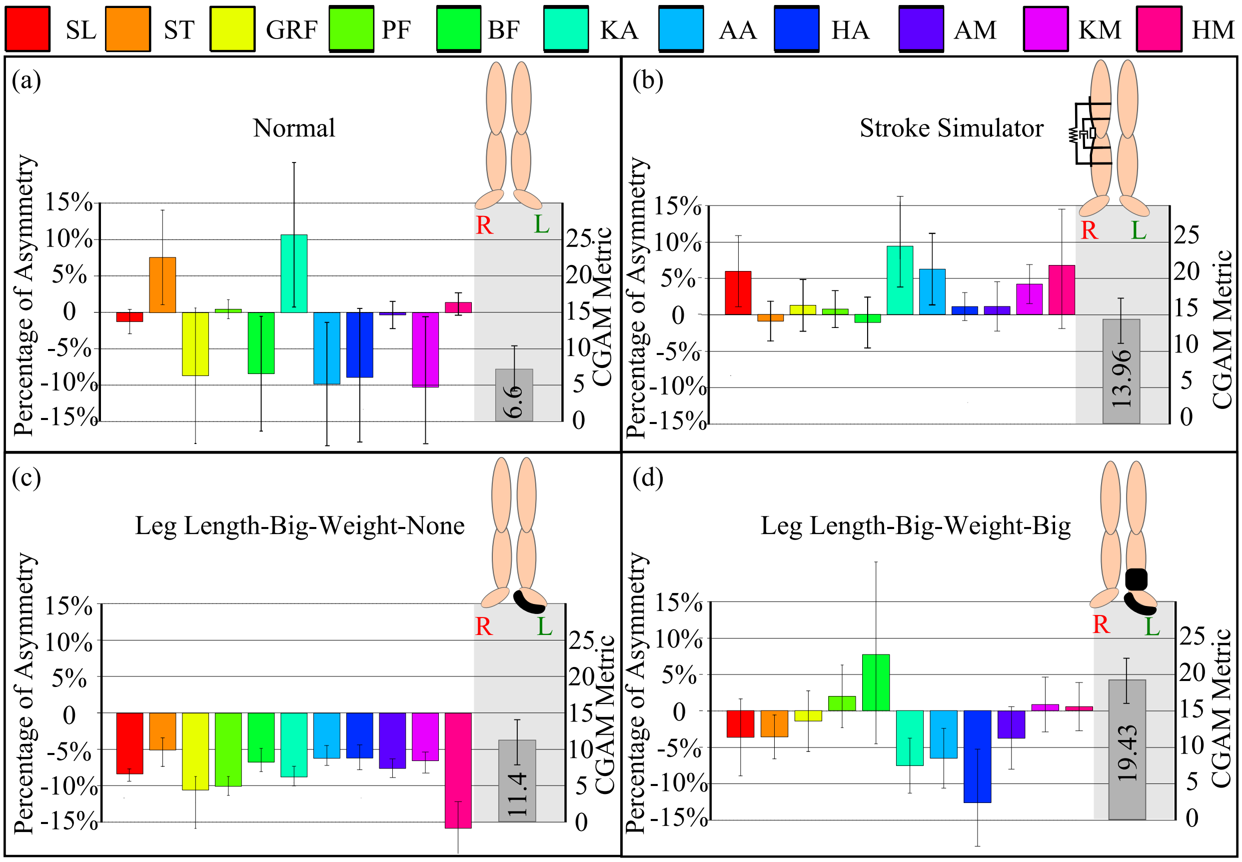

Figure 4.12: Comparing Variation of Mean, Standard Deviation, and CGAM Metric among Perturbations. (a) Normal Walking without any Alterations, (b) Walking with SS or the Variable Stiffness and Damping Knee Orthosis, (c) Walking with Big Leg Length and No Weight Addition at the Ankles, and (d) Walking with Big Leg Length and Weight
(Legend: SL - Step Length, ST - Step Time, GRF - Ground Reaction Forces, PF - Push Off Forces, BF - Braking Forces, KA - Knee Angle, AA - Ankle Angle, HA - Hip Angle, AM - Ankle Moment, KM - Knee Moment, and HM - Hip Moment)

change in gait asymmetry and modify their rehabilitation techniques to induce better gait patterns. This approach is different from prior research practices that limited their study to either spatio-temporal, kinematic, or kinetic data.

Another approach is analyzing an individual's gait parameters separately. This method could reveal insights on specific comparisons, but the complexity increases with the number of gait parameters. It is difficult to determine if the gait has improved when separately examining 11 parameters. The CGAM could make this evaluation easier since it can be used to represent a range of gait parameters, and is not just limited to the 11 parameters that were used in this study.

Figure 4.12 shows the means and standard deviation of the 11 gait parameters. The patterns of gait parameter asymmetry for each of the perturbation is different. The magnitude and the direction (left or right asymmetry) of the gait parameter asymmetry influence the magnitude of CGAM score. The subsets of the gait parameters can be made to fit the requirements of the clinicians such as reporting on improvements in only spatiotemporal parameters or only in kinematics. For example, in a prior study with CGAM, only 5 gait parameters were used to analyze the data [86]. The parameters were step length, step time, vertical forces, push off forces, and braking forces. Using these five asymmetry parameters, the CGAM was able to classify the different perturbations of leg length and addition of masses on separate legs.

Consolidated metrics such as CGAM and Machine Learning offer a unique and simplified perspective into categorizing gait data between multiple asymmetric datasets. CGAM has the potential of serving as a benchmark in representing overall gait asymmetry using multiple different parameters. The multidimensionality that CGAM offers makes it versatile and as shown in this dissertation I can assess multiple gait patterns with different causations. These metrics have to be field tested in clinical trials in order to be formally proposed for clinical use. It is important to remember that these metrics could direct researchers to help patients achieve a well rounded gait. A well rounded gait can be characterized as a sustainable gait that an individual adopts that has the least overall asymmetry, not just a decrease in one parameter. Some parameters would remain asymmetric so that other parameters could become closer to symmetry. In case of an individual who is physically asymmetric, this would mean adopting a gait and posture that will have a balance between all the gait parameters. This adaptation of a well rounded gait will help a physically impaired individual to sustain a long-term gait that may not necessarily be as symmetric as an able-bodied gait, but it is subjectively beneficial to their specific physical asymmetry. A well rounded gait will alleviate long-term problems caused by asymmetric forces and moments acting on the individual's body.

In this study the 11 parameters were chosen because they represent important gait parameter information and have clear symmetry values between each limb. With both metrics it is clearly seen that the addition of mass at the distal end has a larger effect on the overall symmetry than leg length discrepancies. The combined effect of leg lengths and mass addition did not reveal a clear pattern but the results were as expected in most cases. For example, the combination of big leg length and mass had a slightly larger effect than small mass and leg length. However, the combination of a small leg length and big mass had a lot more deviation than big leg length and big mass. This is caused by the cancellation effects between gait parameters, which in turn resulted in a larger or smaller CGAM value.

The prosthetic gait at the three different speeds showed that the overall symmetry improves with increases in speed. It has been shown in literature that amputees achieve better spatio-temporal and kinematic symmetry at higher speeds, but at the expense of kinetic symmetry which can cause long-term degeneration effects [78]. A bigger patient population is required in order to gather all variations of prosthetic gait and leave that to future studies.

The CAREN is a versatile device that was used to collect all the data for this study and has been used in other similar studies [74, 83]. To further understand the effects and dynamics of physical asymmetries, the split-belt treadmill can be used to exaggerate asymmetries. Split belt treadmills are used to rehabilitate gait affected by hemiplegia by having the treads move at different velocities. This exaggeration of hemiplegic gait temporarily restores the individual's gait closer to symmetry. However, successfully returning an individual's gait to spatio-temporal symmetry does not necessarily guarantee an overall effective gait with a healthy ratio of symmetry between all gait parameters. To further explore how physical asymmetries combine, the split-belt treadmill could be used in conjunction with an added mass and/or LLD.

Analyzing multiple physical asymmetries in one platform requires a special form of metric. This is because every perturbation of physical change that impairs an individual's gait has to be accounted for and kept track of following clinical procedures. The consolidated metrics such as CGAM and Machine learning can be quantitative data analysis tools that can help researchers keep track of an individual's overall gait asymmetry. These metrics can be obtained using all gait asymmetry parameters such as spatio-temporal, kinematic, and kinetic or by using subsets and combinations of any or all of these parameters. This versatile platform allows researchers to have many options for generating metrics to represent the progress or regression of an individual over a period of training and time.

CHAPTER 5: CLINICAL TRIALS

Experiments involving asymmetric rehabilitation techniques were conducted on subjects with transfemoral amputation and stroke. The effects of asymmetric knee height on unilateral transfemoral amputee and able-body subjects using prosthetic simulators was evaluated. Analysis was performed on the gait parameter data collected on transfemoral amputees who completed a split-belt treadmill training protocol. Stroke subjects were evaluated on the GEMS which exaggerates the asymmetry of one leg to help in the overall rehabilitation. The gait analysis from the subjects was used to determine the effects of the asymmetric rehabiliation techniques. Clinical evaluation measurements such as Timed Up and Go (TUG), six minute walk tests, and gait velocity collected on the individuals with stroke, were also collected for this study. Further, the data from all three experiments was also used to estimate the overall asymmetry scores using CGAM.

The information of all the studies described in this chapter are summarized in Table 5.1. There are three major experiments that are presented in this chapter. The methods, results, and discussion of each experiment is explained. The first experiment evaluates the effects of asymmetric knee height on a transfemoral amputee and able-body subjects with prosthetic simulators. This experiment is designed to bring about symmetry from an asymmetric system corresponding to Aim 1 and it gives a glimpse into the relationship between gait symmetry and function corresponding to Aim 4. This experiment is aimed to show evidence that simple asymmetric changes made to prosthetics can result in better overall symmetry. I also explore the combination of distal mass in combination of distal mass and asymmetric knee height on a transfemoral amputee. The asymmetries of eleven gait parameters which include spatio-temporal, kinematic, and kinetic types are analyzed. The differences in kinematics for both transfemoral amputee and able-body subjects

Table 5.1: Experiments Presented in the Chapter.

Experiment	Subjects	IRB	Funding Source	Publications
Asymmetric Knee Height				
Prosthetic Simulator	5 Male 1 Female	# Pro00016724	NSF	Ramakrishnan [83]
Transfemoral Amputee	1 Female	# Pro00026445		
Split Belt Training*[1]				
Transfemoral Amputee	1 Female 1 Male	# Pro00017820	RFA OPERF 2014-SGA-1	Kim et al. [55]
GEMS Training				
Individuals with Stroke	2 Female 4 Male	Western IRB #20140915	Moterum Technologies	Kim et al. [54]

*[1] I did not help with data collection, but was allowed access to relevant data by Dr. Kim for the purposes of this dissertation

on prosthetic simulators are also described. Finally, the CGAM scores are calculated for all the different gait patterns and the results are discussed.

The second experiment presented in this chapter is gait adaptation patterns of transfemoral amputees after split-belt treadmill training. This experiment is based on the same split-belt treadmill protocol applied on individuals with stroke [93]. Two subjects, male and female, underwent a two week training protocol. The data is collected on a Protokinetic zeno walkway. A total of four data sets were collected on each subject that were collected before training, after first week of training, after completing training, and a follow up after two months. The data presented in this chapter was analyzed using CGAM. Further, I also calculated the correlation between the CGAM scores and each of the gait parameters. This experiment corresponds to Aims 1,2, and 4 as it explores a simple asymmetric means to result in an overall symmetric gait. The dataset is used to validate the use of CGAM as an index of overall asymmetry. It also shows the relation between gait velocity and gait symmetry.

The third experiment is a clinical evaluation study of the GEMS on individuals with stroke. I worked with Dr. Kim and Dr. Reed on the clinical trials of the Gait Enhancing Mobile Shoe (GEMS). Clinical trials offer a new perspective on the requirements for rehabilitation. It gives a glimpse into the standard practices and the potential gaps in technology that can make rehabilitation techniques more effective. The data that was collected during the clinical trials is used to validate important characteristics of gait asymmetries in patients with physical impairments. The data is analyzed using conventional metrics and statistical analysis as well as the CGAM metric. This analysis is carried out to correspond with Aim 2 to validate CGAM clinically.

GEMS emulates a split-belt treadmill but it is worn by the subject who walks overground. The GEMS aims to improve spatial and temporal symmetry similar to split-belt training. This chapter describes the methods of the experimental protocol and the results obtained via the Protokinetic zeno walkway. Spatial, temporal, and kinetic gait parameter asymmetries were analyzed for the results. The CGAM scores for all the trials were also calculated using the gait parameter asymmetries. Clinical measures such as Timed up and Go (TUG), six minute walk test (6MWT), and Gait velocity were collected for this study. The goal of this analyzes in regards to this dissertation is to validate the CGAM scores with the clinical measures, which is directly related to Aim 2. In order to validate CGAM I find r^2 correlation between the clinical measures and the CGAM scores. Further, I also find the r^2 correlation of clinical measures and individual gait parameters to analyze underlying relationships. This study is also directly related to Aim 1 and 4 because it uses a simple asymmetric device to alter gait to improve overall asymmetry. I also discuss the relationship

5.1 Methods for Experiments with Prosthetics

5.1.1 Effect of Knee Height in Transfemoral Prosthesis

Prosthetics offer a perfect platform to test different gait dynamics because they can be modified to have various joints locations, weights, and leg lengths. The human legs can be modeled as a double pendulum system and the knee forms the integral joint in this system. The location of the knee and the mass of the shank both contribute to the dynamics of the system. Previous research has shown that two dissimilar systems can exhibit symmetric motion and a prosthetic

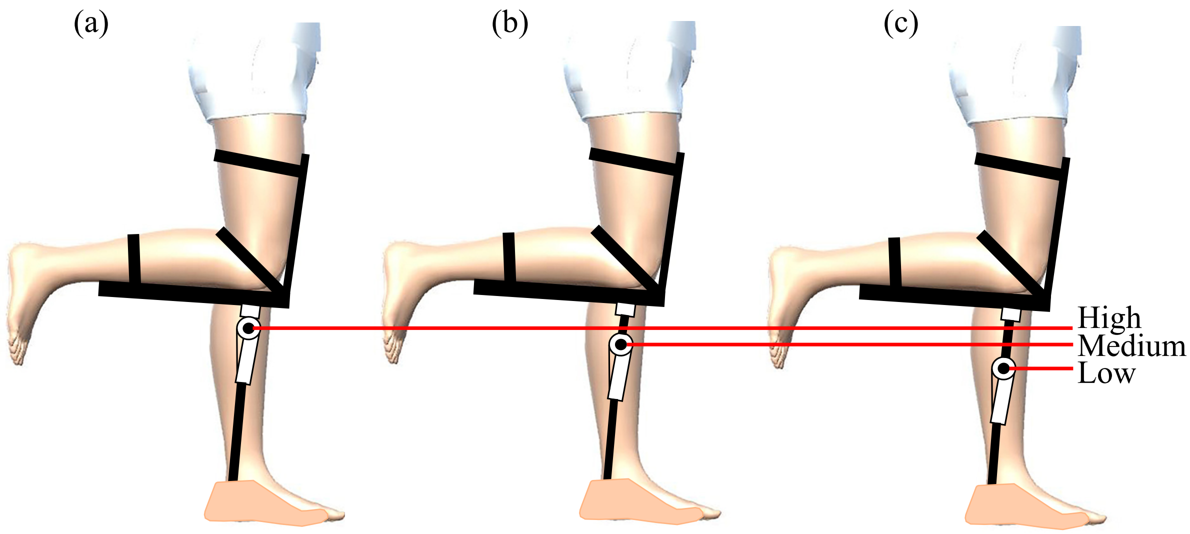

Figure 5.1: Prosthetic Simulator with Different Knee Heights.

with a lower knee height exhibits better overall symmetric gait than a prosthetic with similar knee height to the normal leg [30].

5.1.2 Prosthetic Simulator

This experiment is an extension of a previous study [83]. The prior experiment was a evidence of concept and had only 3 subjects tested on 3 different knee height conditions [85]. The current study for this dissertation had 6 subjects with 3 different knee height positions. An example of the knee height changes is shown in Figure 5.1. The positions range from 1 - 40% asymmetry of the subject's knee height. This range of asymmetry in knee height was chosen based on a perception trial conducted using simulated gait videos based on PDW models. The research showed that knee height discrepancy was perceived to be higher when the knee height difference is above 26% [32].

Prosthetic simulators have been successfully used in other studies to simulate gait with a prosthetic [22, 61, 110, 115]. Recruiting amputee subjects is difficult which lead to the use prosthetic simulators to help evaluating outcomes of altering prosthetic components. The prosthetic simulator used for the experiment consisted of a knee brace (I-Walk), pediatric knee (ST&G 4 bar

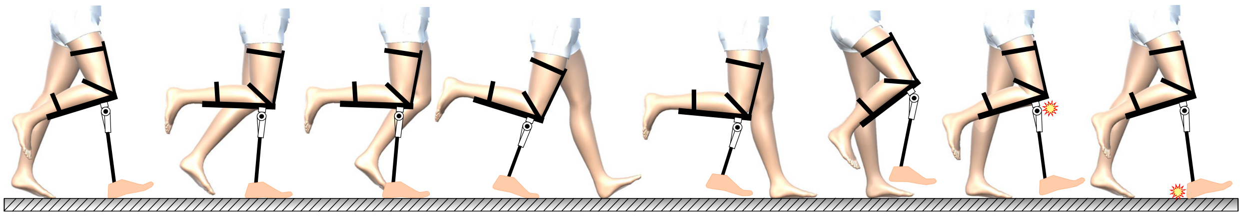

Figure 5.2: Able Body Subject Walking on Prosthetic Simulator.

mechanism), off the shelf prosthetic foot, and Aluminum piping for achieving the different knee heights; Figure 5.2 and 5.3 show the different phases of walking with a prosthetic simulator.

This study was conducted under IRB # Pro00016724. The subjects were tested on the CAREN system where the kinematic and kinetic data was collected to aid in the calculating the various biomechanical parameters. The kinematic data was recorded using reflective markers placed on the joints of the subjects.

5.1.3 Amputee Tested with Asymmetric Knee Heights

An extension of the prosthetic simulator study for the effects of different knee heights is to test the alteration on a unilateral transfemoral amputee. The test was conducted on the CAREN system under IRB # Pro00026445. The subject is a 37 year old high functioning unilateral transfemoral amputee, shown in Figure 5.4 walking on the CAREN system. The amputee was tested on 4 different perturbations with every change corresponding to 7% decrease in knee height. Figure 5.6 shows the different perturbations that were applied to the amputee. Figure 5.5 shows the subject on the CAREN with lowered knee height and the combination of lowered knee height with addition of distal mass.

5.1.4 Combination Asymmetric Knee Heights with Distal Mass

An extension of this simple alteration to gait takes the form of adding masses to a prosthetic to improve symmetry. In this study, I add a distal mass in combination with different knee heights. This combination is a similar attempt to evoke better overall asymmetry such as the combination of leg length and distal mass [73]. The alterations are necessary to understand the overall effects

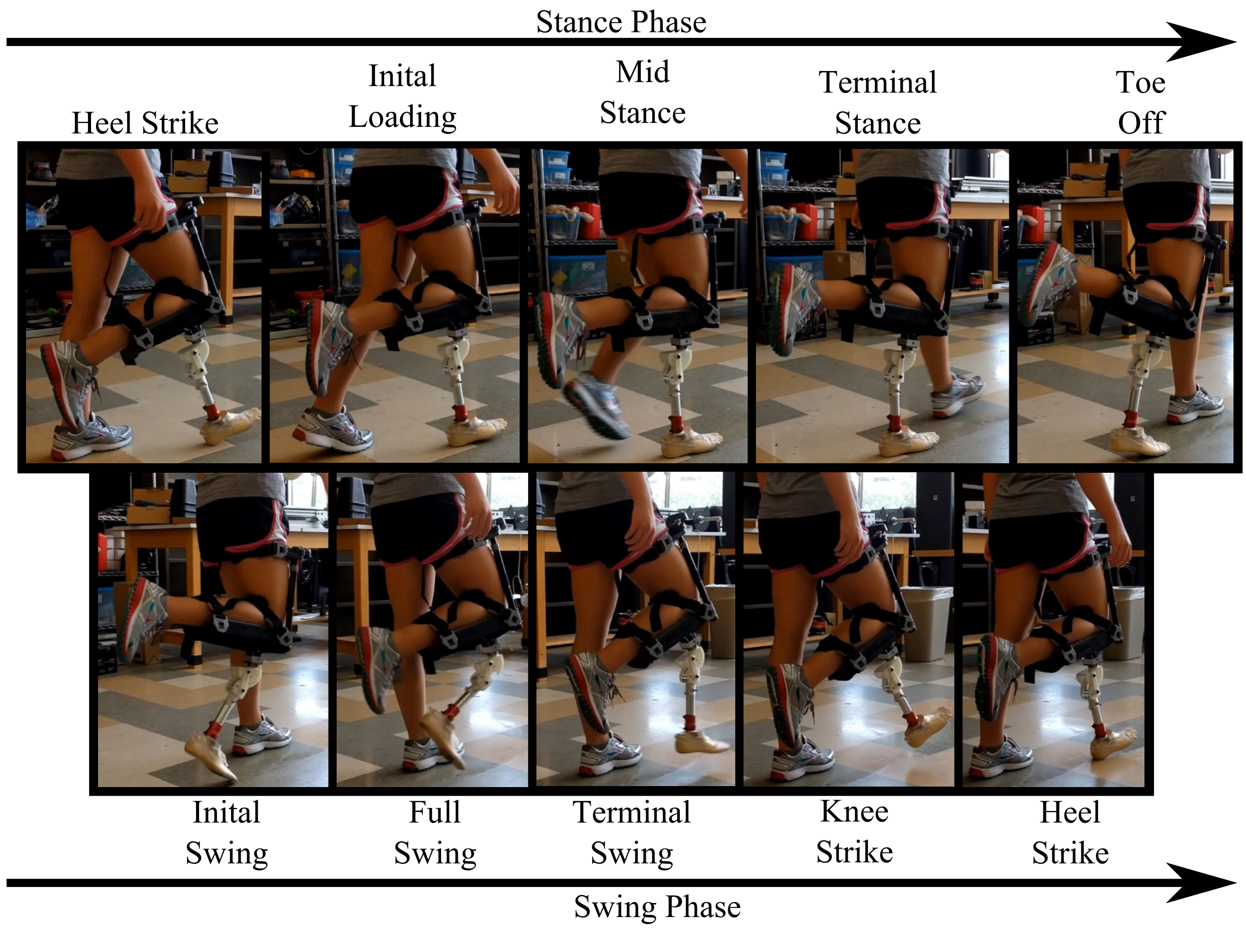

Figure 5.3: Able Body Subject Walking on Prosthetic Simulator with Gait Phases.

of asymmetric changes and to investigate if a combined effect of altering knee heights and distal mass is beneficial to the prosthetic user. To gather the required data, the experiments are performed on transfemoral amputees, Figure 5.6.

The experiment was conducted on a unilateral transfemoral amputee at three different knee heights at 3, 6, and 9 cm. There were noticeable changes to gait as reported by the amputee, Figure 5.5. The subject walked on the CAREN system at a predetermined speed. Speed was determined with a 10 m walk test prior to the experiment. Due to the smaller and lighter shank, the time from flexion to extension increased. This is because the leg behaves like a double pendulum and the altered thigh link which is now longer and heavier swings much faster than the smaller and lighter shank link. A distal mass of 1 kg was added in combination of every different knee heights. This is interesting because the literature suggests that prosthetics that are lighter show better gait

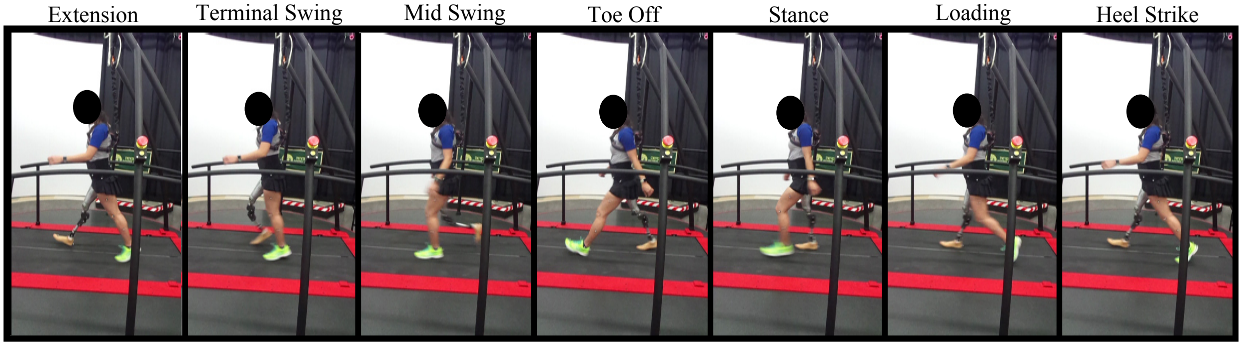

Figure 5.4: Transfemoral Amputee User on CAREN System.

symmetry [9]. The knee heights were fitted on the subject in a random order to avoid adaptation effects.

5.2 Results: Prosthetic with Asymmetric Knee Height

The experiments were conducted to evaluate if a lower asymmetric knee height in a unilateral transfemoral amputee improve the overall symmetry of the gait. The results in Figure 5.7 indicate that a lowered knee height can help bring some gait parameters to symmetry and make others more asymmetric. For example, the vertical forces of the amputee with distal mass move towards symmetry as the knee height lowers while the opposite effect takes place with knee angles, Figures 5.7 (D & B). Since there are many parameters, it is convenient to also look at the CGAM scores that combine all of these metrics; in essence, it determines if the gait is globally getting more symmetric even if one parameter is not. The CGAM scores for each gait pattern are shown in Figure 5.7 (L).

Generally, the behaviors show that lower knee heights do make some gait parameters more symmetric. There are exceptions where the alterations lead to higher asymmetries or show no change; for example, the moments for the amputee with distal mass and the prosthetic simulator show no change in peak vertical force asymmetry. In the case of using prosthetic simulators, they showed distinct differences from the amputee and normal able-body gait asymmetry. This was expected but generally the behaviors are not drastically different. This is also reflected in the CGAM scores where lowering knee height clearly improves the overall asymmetry of the amputee

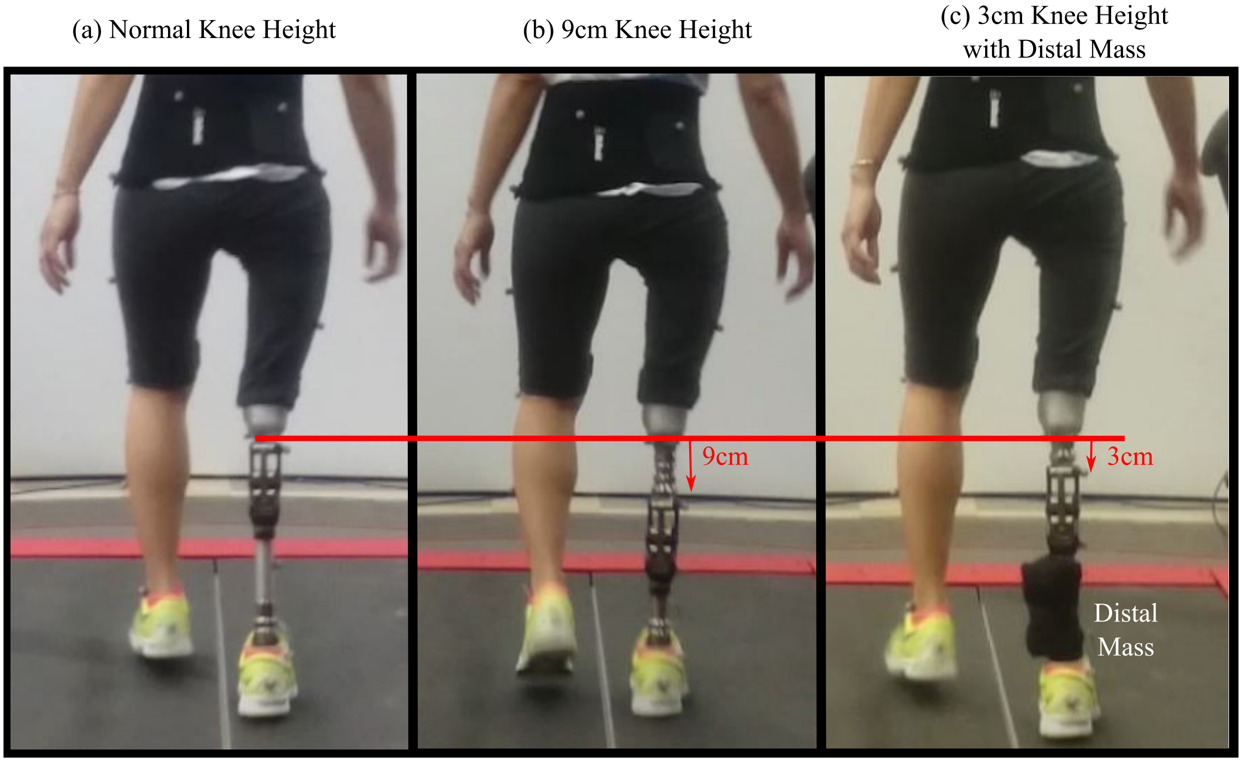

Figure 5.5: Amputee with Different Knee Heights and Distal Mass.

without the distal mass. There is an improvement in the overall asymmetry with respect to the gait with prosthetic simulators as well. However, this shows that the lowest knee height is not always the best dynamically for gait patterns.

Figure 5.7 (L) shows the CGAM scores representing the overall symmetry of each perturbation. The results show that the knee at the normal height has a score slightly larger than the perturbation with the distal mass. A 3 cm drop makes the gait more asymmetric than normal but the distal mass improves the overall symmetry to become slightly better than normal with the distal mass condition. A 6 cm drop in knee height seems to be the most symmetric setting among the lower knee heights. The addition of mass seems to make the 6 cm drop more asymmetric. The 9 cm drop is the most asymmetric perturbation and the combination of distal mass makes it slightly symmetric and it is closer to the 3 cm drop in knee height. The subject walked again with normal knee height and the dynamic changes seem to have had an effect on the gait to make it a lot more symmetric.

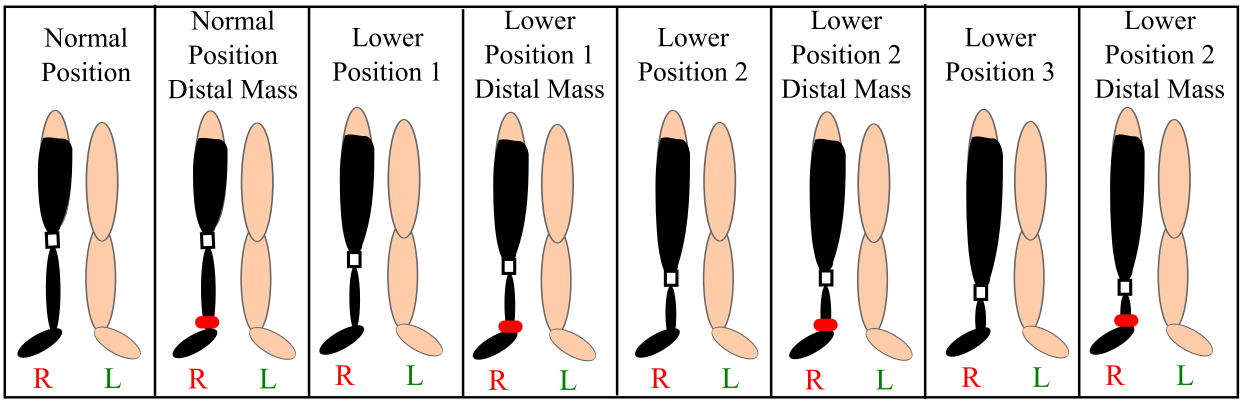

Figure 5.6: Different Perturbations of Knee Heights with a Combination of Distal Mass.

I also recorded the subjective opinions of the subject. The experiment with the 6 cm drop increased the pressure in the socket and at the distal femoral end of the residual stump. When the distal mass was added in combination to the 6 cm drop, the subject reported the terminal impact of the knee just before heel strike. The subject personally did not prefer this but reported that many prosthetic users do. Terminal knee impact is used by amputees to ascertain the position of their prostheses at the end of swing so that they can trigger the necessary functions to aid in the stance phase. The subject did not realize any change in dynamics with the 3 cm drop and the CGAM scores reflect this in terms of overall symmetry. The 9 cm drop made the user perceive the prostheses to be heavier than normal. This led the user to recruit more muscles and constantly fire them to maintain stable gait. This effect became worse when the distal mass was added.

The joint angles for the amputee subject are shown in Figure 5.8. The largest deviation of changes from normal patterns is seen at the hips. The subject compensates for the changes in swing time due to the smaller moment arm at the shank, which is exhibited in the form of altered hip angle patterns. The knee angles for both limbs display consistent patterns with little deviation from the baseline knee angles. The peak knee flexion angles for the 6 cm decrease and symmetric height with distal mass for the prosthetic are considerably smaller than the baseline prosthetic knee flexion. This decrease is also seen in the sound side but not to the extent of the prosthetic which is to be expected. The sound side ankle angles shows higher plantar flexion in the 6 cm asymmetry while all other settings show a decrease compared to the symmetric setting. The ankle angles for

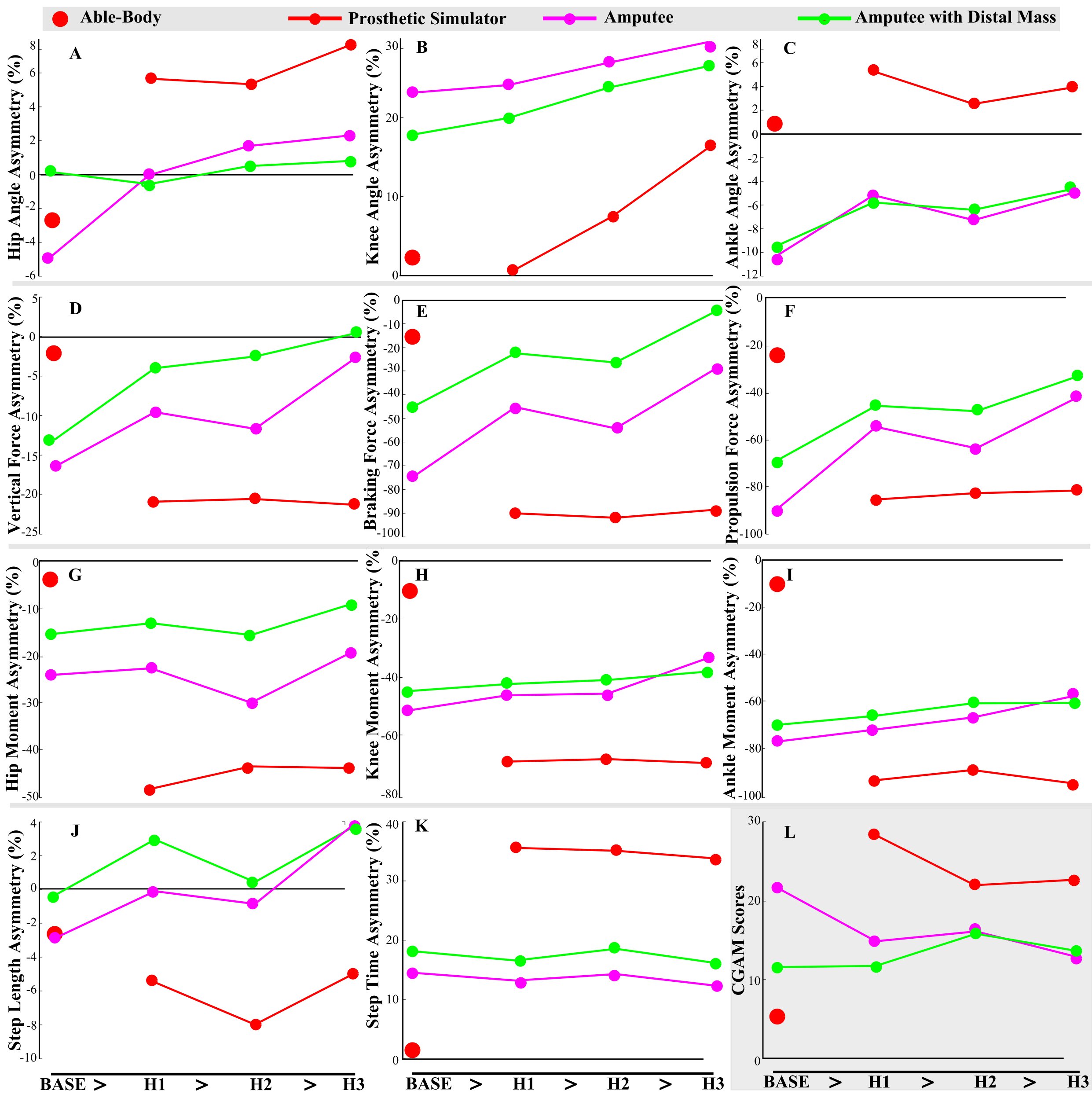

Figure 5.7: 11 Gait Parameter Asymmetries and CGAM Scores.

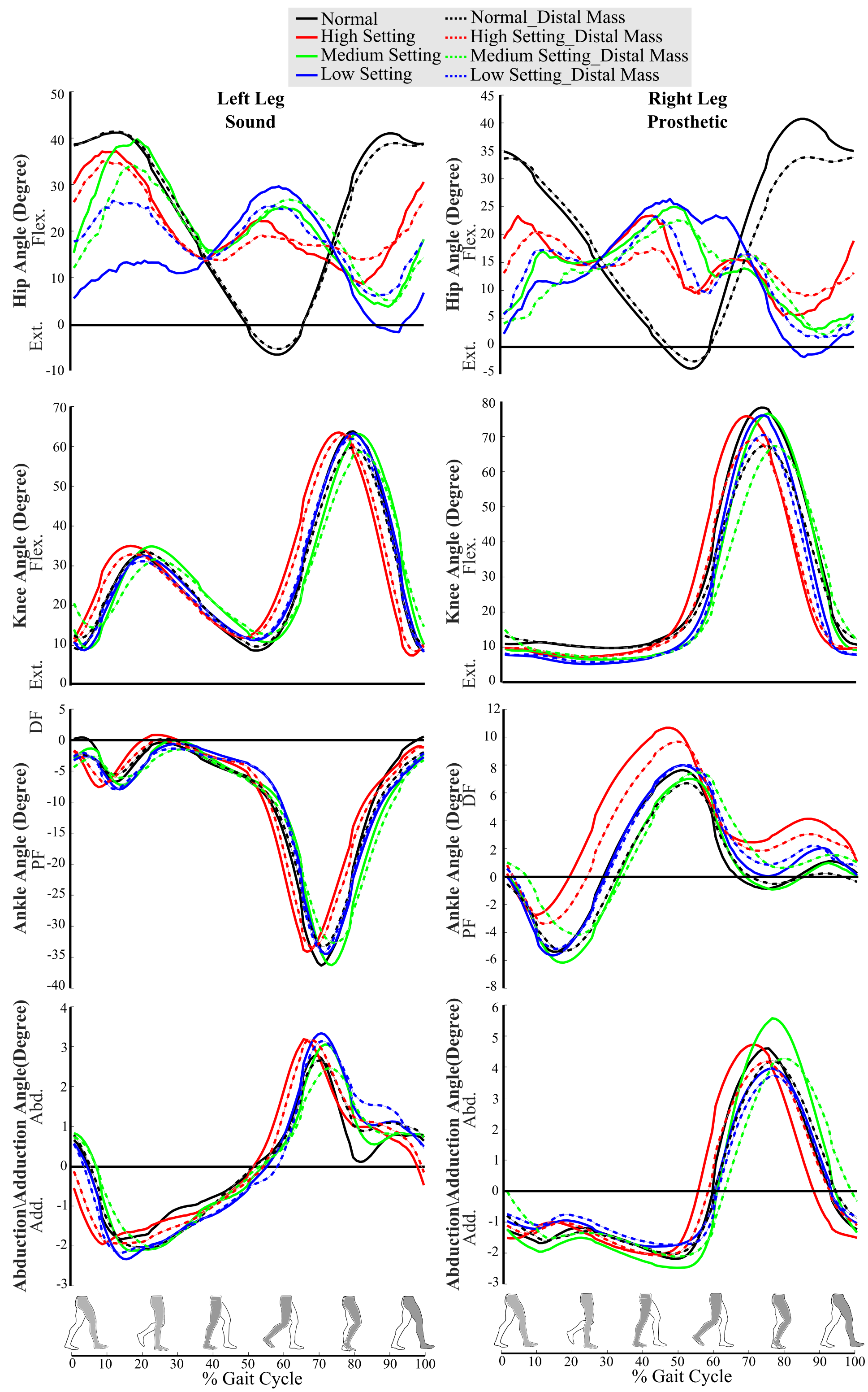

Figure 5.8: Joint Kinematics of Amputee with Asymmetric Knee Height.

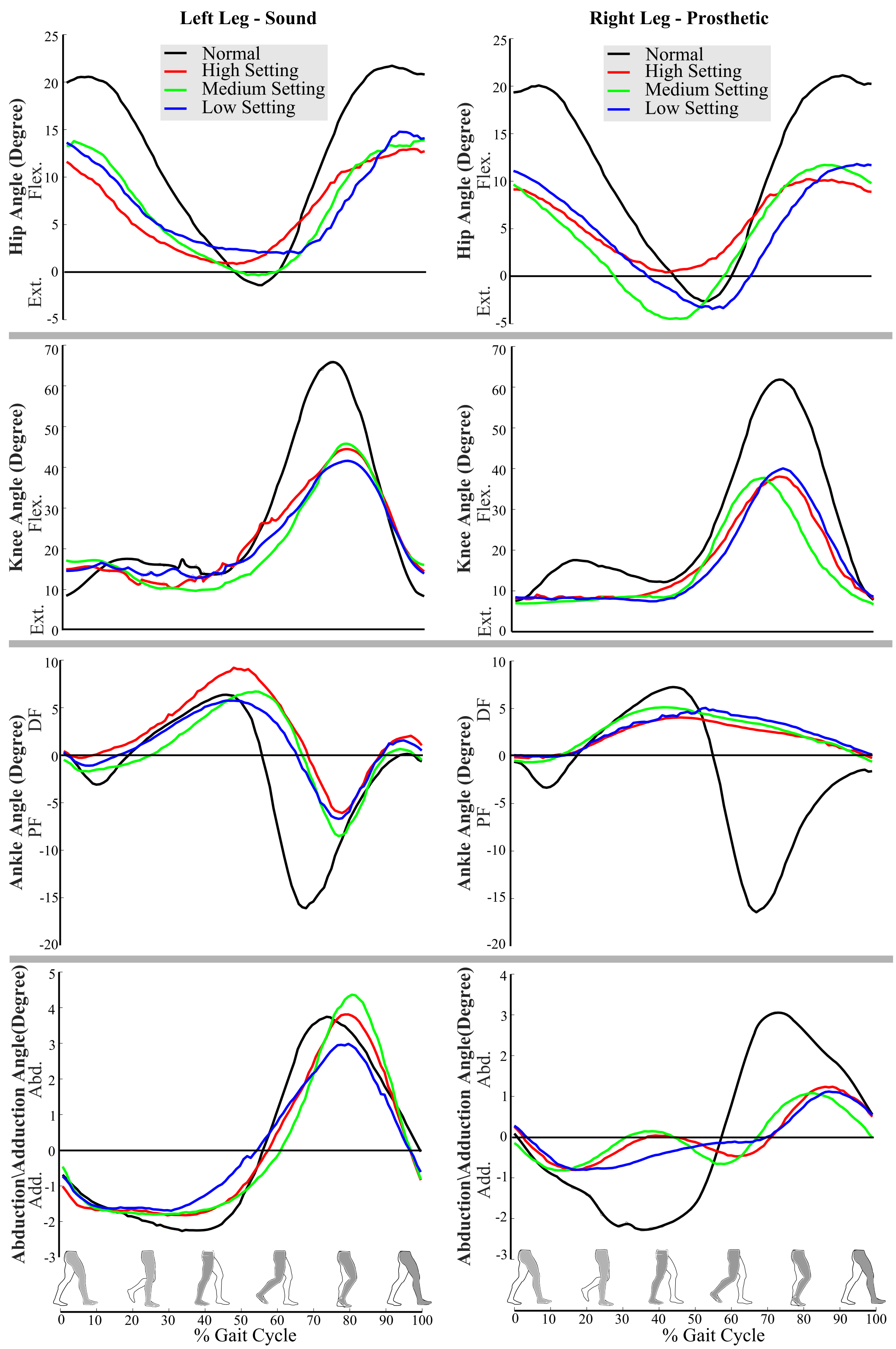

Figure 5.9: Joint Kinematics of Able-body Subjects Wearing Prosthetic Simulator with Asymmetric Knee Height.

the prosthetic side show higher dorsiflexion for the 3 cm asymmetry with and without distal mass compared to the symmetric knee height. The plantar flexion of the ankle decreased with the change in knee height. Hip abduction of the sound leg increases when the knee height is lowered except for the case of 6 cm asymmetry with distal mass, in which case the peak abduction angle is lower than baseline value. In the case of the prosthetic, the 3 cm and 6 cm asymmetries cause the peak abduction angle to be larger than baseline. However, with the addition of distal mass, abduction angles are lower than baseline and the 9 cm asymmetry without distal mass also shows a lower abduction angle.

The able-body subjects walking with the prosthetic simulator were allowed to familiarize themselves with the simulator in order to display stable gait. They were only permitted to practice on the high knee height setting. Figure 5.9 shows the joint kinematics obtained for the prosthetic simulator trial. No distal mass was added to this set of experiments because the additional distal mass could further alter the dynamics of walking more than the alteration caused by the prosthetic simulator. Hip angles for the sound side show a decrease in peak extension, whereas the prosthetic side shows an increase in peak extension angles for the medium and low settings. There is an overall decrease in the hip and knee flexion angles with lower knee height for both limbs. Ankle angles showed larger dorsiflexion with the high setting, but the other settings resulted in no change for the sound leg. Lower knee heights showed decreases in peak plantar flexion in the sound leg. The prosthetic ankle showed lower dorsiflexion angles and no sign of plantar flexion. Hip abduction increased with the medium setting on the sound leg, no change at the high setting, but a decrease with the low knee height setting. Both abduction and adduction showed to decrease on the prosthetic side.

5.3 Discussion: Prosthetic with Asymmetric Knee Height

Lowering the knee height of a prosthesis is counter intuitive in rehabilitation where the goal is to achieve the physical ability prior to ones amputation. In a unilateral transfemoral amputation, an individual loses their knee and ankle joints that are critical to walking, which renders them physically asymmetric. Rehabilitating physical asymmetry with symmetric prosthesis often leads to spatiotemporal and kinetic asymmetries [38, 49]. This study shows that gait asymmetry can be mitigated by asymmetric alterations such as lowering the knee height, adding distal mass, or a combination of the effects.

Evaluating the different asymmetries and kinematics of the gait reveal that there are distinct differences that arise due to lowering knee height. The most important of the effects being the shorter moment arm which in-turn causes longer swing times from flexion to extension. Since the study was conducted on a treadmill at constant velocity, the step time asymmetries do not change with the different knee heights. However, the step length become more symmetric with the 3 cm and 6 cm change in knee heights for the amputee. The prosthetic simulator at the highest and lowest settings were more asymmetric than the medium knee height. The spatiotemporal parameters are also visual indicators and, from Figure 5.7 (J-K), it can be seen that a lowered knee height pushes the step length to be symmetric. Step time shows no change between baseline and different knee heights in both amputee and prosthetic simulator gait.

Joint moments also do not show large deviations. Adding distal mass seems to consistently make the moments slightly more symmetric in the amputee. The prosthetic simulator does not show large changes except the medium setting is slightly more symmetric for the hip and ankle moments. This behavior is observed again with the kinetics. Lower knee heights clearly make the forces more symmetric and the addition of distal mass seems to improve it further. Although the distal mass causes higher metabolic strain [68] on the individual, it seems to help balance the asymmetric forces. Prosthetic simulator gait showed no visible deviation in asymmetry for the kinetics. It is possible that combining a lower knee height with heavier shank may alleviate some of the asymmetric forces that amputees experience in their gait.

Joint kinematics show differences in asymmetries while hip and ankle angles become more symmetric the knee angles tend to be more asymmetric with lower knee height for the amputee. In the case of the prosthetic simulator, the lowest knee height has more asymmetric hip and knee angles but not in ankle angles. Joint kinematics are also visually perceived and this anomalous behavior is easily detected. Even if these patterns are better overall, there may be issues with the perception of the gait patterns visually.

The hypothesis for this study originated from robotics with the PDW simulation models. From a purely dynamic perspective from the PDW models it showed that a lower knee height with an asymmetric mass distribution much like an amputee showed better spatiotemporal symmetry [112]. This was evident in this study with step length, but step time did not show improvement. I expect simple asymmetric changes in prosthetic design can bring about much better gait patterns for amputees. Lowering the knee height by a few percent (under 26% of knee height) with a slightly heavier shank may improve the kinetic symmetry. This is contrary to the pursuit of lighter prostheses but optimizing and customizing asymmetric prosthetics has potential for better gait patterns. More testing performed with a larger amputee population with and without weighted prostheses would further determine if a combination of lowered knee height and addition of mass can bring out better outcomes in terms of overall asymmetry and quality of gait.

5.4 Methods: Split Belt Treadmill Training for Transfemoral Amputees

This clinical trial uses a split-belt treadmill to correct the asymmetries in the gait of a unilateral transfemoral amputee. This study was completed by Dr. Kim. This procedure is similar to the split-belt therapy used for individuals with stroke. The reasoning behind this goes back to the inherent physical asymmetry of an amputee which causes their gait to be asymmetric as well. By forcing amputees to spend more time on their prosthetic, the study seeks to improve spatiotemporal gait symmetry. The study also analyses the retention of gait when the amputee adapts to over ground walking. The study uses a split-belt treadmill and a Protokinetic gait mat to measure the kinematics and spatiotemporal parameters of the amputee's gait. This study gives insight into gait adaptation strategies of unilateral transfemoral amputees. I also study the effect of spatiotemporal symmetry on the symmetry of double limb support and ground reaction forces.

The study was conducted over a period of two weeks with a 1 month followup testing. Baseline gait data is collected prior to the split-belt training, then the data is collected again post

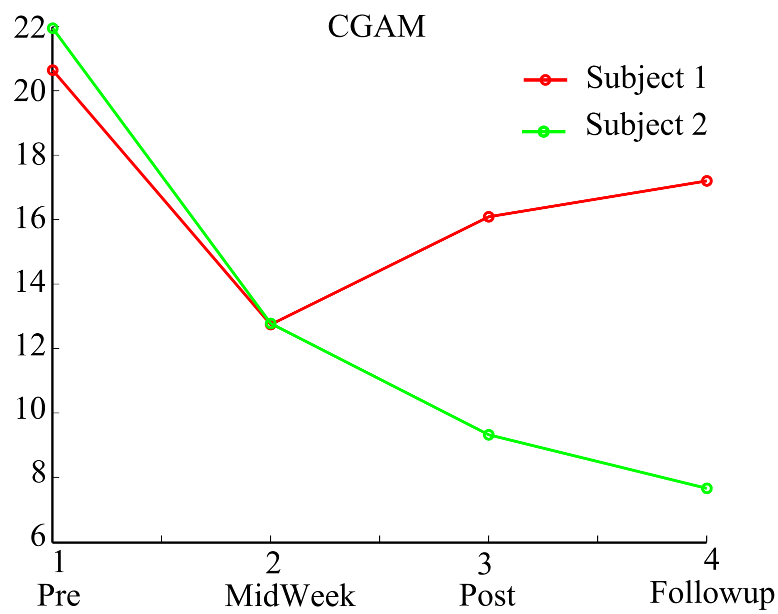

Figure 5.10: CGAM Scores of Two Amputees Before and After Split Belt Training.

training, and finally the subject is tested after a month to check for retention of the training. Each subject went through six training sessions on the split-belt treadmill based on the protocol followed by Reisman et al. [91–93]. The split-belt sessions last 30 minutes to ensure complete adaptation. The prosthetic side is slowed down while the sound side is sped up. This forces the prosthetic leg to take a longer step compared to the sound leg. The resulting expected effect from this training is to force the gait pattern to be more symmetric in the spatial and temporal parameters. Subject 1 was female and Subject 2 was male both under 40 years of age and both have their amputation on the right side.

5.5 Results: Split Belt Treadmill Training for Transfemoral Amputees

The goal of implementing the split-belt treadmill training protocol for transfemoral amputees is to improve in better spatiotemporal symmetry. A previous publication by Kim et al. [55] showed that there was definite improvement in the spatiotemporal parameters for both subjects. All five gait parameter asymmetries became more symmetric post training. However, the effects did not last over a long period of time. The results for the followup tests showed subject 1's step length and time became more asymmetric and subject 2's step time became more asymmetric.

Table 5.2: Modified CGAM vs Gait Parameter r^2 Correlation for Amputee Data. (Bold implies correlation that is mild or above))

Gait Parameter	r^2 (Subject 1)	r^2 (Subject 2)	r^2 (Combined)
Step Length Asymmetry	**0.77**	**0.72**	**0.24**
Step Time Asymmetry	0.13	0.01	0.16
Swing Time Asymmetry	**0.33**	**0.93**	**0.63**
DLS Asymmetry	0.00	**0.66**	0.03
GRF Asymmetry	0.014	**0.87**	0.01
Velocity (cm/sec)	**0.32**	**0.92**	0.018
6MWT (cm/sec)	**0.96**	**0.99**	**0.36**

The CGAM scores were calculated for the two subjects using the ground reaction force, double limb support, swing time, step length, and time asymmetries. These parameters were chosen based on the importance and availability of data. Figure 5.10 shows the CGAM scores for both subjects. The post test scores show that the overall asymmetry of the amputee's gait patterns are lower than pre trial. This is consistent with the clinical assessment. To further assess the validity of the CGAM scores, the correlation between the gait parameters and the CGAM scores were calculated, shown in Table 5.2. Subject 2's results show high correlation of CGAM scores with all gait parameters. CGAM has a positive correlation with step length, step, and swing time. It has a negative correlation with double limb support and ground reaction force. This is because of the Equation 5.1 where the prosthetic side is subtracted from the intact side. Since, terminal double limb support is used DLS tends to be negatively correlated to CGAM as it moves from a high negative towards zero. Similarly, ground reaction force is typically lower on the prosthetic side compared to the intact side.

$$100 * \frac{abs(M_{prosthetic} - M_{intact})}{0.5 * (M_{prosthetic} + M_{intact})} \tag{5.1}$$

Subject 1 showed high correlation with Step length, moderate correlation with swing time, and weak correlation with step time asymmetry. Subject 1 did not show any correlation with ground reaction forces and double limb support. Subject 2 did not show any correlation with step time but showed high correlation with all other parameters. Combining both subjects data to find the r^2 showed that there is no correlation between step length and CGAM. Step length and time show weak correlation while double limb support and ground reaction forces show no correlation with CGAM scores. Swing time asymmetry showed high correlation for all data points vs CGAM scores. Gait velocity increased for both subjects over the course of the training. The correlation between the gait velocity and the CGAM is moderate for subject 1 and high correlation with subject 2. It was surprising that when the data was combined there was no correlation, and indicates that the underlying correlation for each subject is different. 6MWT was also calculated for the experiments for pre-test, post-test, and followup for both subjects. The r^2 correlation of CGAM with 6MWT showed high correlation for each subject, this is because there are only three points in the plot. However, CGAM showed moderate correlation with the six data points by combining both subjects.

5.6 Discussion: Split Belt Treadmill Training for Transfemoral Amputees

Transfemoral amputees often exhibit spatiotemporal asymmetry due to the lack of refined control [102]. This is usually due to the passive prosthetics that do not offer active control and propulsive assistance. The amputees tend to rely on their intact leg more and hence spend less time on their prosthetic and in turn do not shift their load to the prosthetic. Training on the split-belt essentially forces the amputee to spend more time on their prosthetic and shift more weight on to the prosthetic. This was achieved by destabilizing the intact leg by speeding up the tread.

Double limb support, ground reaction force, swing time, step length, and time asymmetries were analyzed from the gait. Out of the five gait parameter asymmetries four showed clear improvement in symmetry for both subjects. Ground reaction force was inconclusive as one subject showed improvement in symmetry while the other displayed higher asymmetry. More data from a larger subject population will show better trends in regard to the behavior of ground reaction force symmetry. GRF asymmetry is expected to become better because the subject is trained to shift more weight on their prosthetic limb. Gait velocity increased for both subjects consistently over the training period. The subjects also showed retention of gait velocity after a long period [55].

The CGAM scores that were calculated for all four phases of the experiment showed a similar behavior for the overall asymmetry of the gait patterns, Figure 5.10. There is a big improvement of overall gait symmetry when the data was collected after the first week of training. This also is corroborated by the individual gait parameters. The post training session data shows a slight increase in asymmetry for both subjects. The followup data overall symmetry is inconclusive as one subject shows improvement while others become slightly more asymmetric. However, even becoming slightly more asymmetric in the post training session, both subjects showed overall improvement in gait symmetry. Further, analyzing the correlation between CGAM that expresses overall asymmetry and each gait parameter revealed that the combined data of both subjects have moderate correlation with step and swing time and high correlation with swing time asymmetries. It showed no correlation with ground reaction force and double limb support asymmetry. This reveals that the overall asymmetry score of CGAM is moderately influenced by spatial characteristics and has large influence contributed by swing time asymmetry. This is good because the swing time asymmetry had large magnitudes and the behaviors for improvement or decline of symmetry were also similar to the CGAM scores. This shows that gait parameters with large magnitude and smaller variances have more influence on CGAM than small magnitude and large variances.

Gait velocity also showed no correlation when the data is combined, but it does show high correlation with subject 2 and moderate correlation with subject 1. The CGAM scores also showed high to moderate correlation with the 6MWT data. The correlation of CGAM with the different gait parameters and the clinical measures such as 6MWT and gait velocity show that CGAM has potential to be used as an index in analyzing gait patterns based on gait parameter asymmetries. DLS and GRF asymmetries show inconsistant correlation with CGAM score which means that either they do not have enough data points to correlate or they do not have a large influence on the magnitude of the CGAM score.

Individuals with stroke exhibit a loss of control due to neurological issues whereas amputees have a loss of control due to physical asymmetry caused due to the amputation. The mechanisms for rehabilitation for stroke and amputees are different. Split belt treadmill training for individuals with stroke helps to re-train their intact but damaged nervous system [93]. This is different from retraining the coordination of transfemoral amputees with no neurological issues. Amputees instead learn to spend more time and shift more weight on to their prosthetic side. Individuals with stroke often do not retain their split-belt treadmill training [95]. This is because of their inherent neuro-plasticity thresholds are changed due to the stroke which makes it difficult for them to retain new information. The results for the split-belt training on amputees does show retention for the first two weeks. Overall, both subjects also show retention of overall symmetry when tested a month after training. This is consistent with the clinical measures as well.

5.7 Methods: GEMS Training

The GEMS can generate a motion to a foot that is capable of changing interlimb coordination while walking over ground, seen in Figure 5.11. The generated motion is similar to that felt when walking on a split-belt treadmill, but while walking over ground where the sensory information of the real-world task will be experienced. Six subjects with a unilateral stroke walked on the GEMS for 12 sessions over 4 weeks with pre- and post-training tests. The results from this ongoing study show that the subject's step length and double limb support symmetry improved following the training.

The Gait Enhancing Mobile Shoe (GEMS) is designed to change interlimb coordination and strengthening the paretic leg of individuals with asymmetric walking patterns caused by stroke. The concept of the GEMS is similar to that of a split-belt treadmill [92], but allows the individual to walk over ground, which is hypothesized to help with long-term retention of the altered gait pattern [29]. In addition, the GEMS can be manufactured for a lower price and can, thus, be made available in more locations and could enable a home-based gait rehabilitation solution.

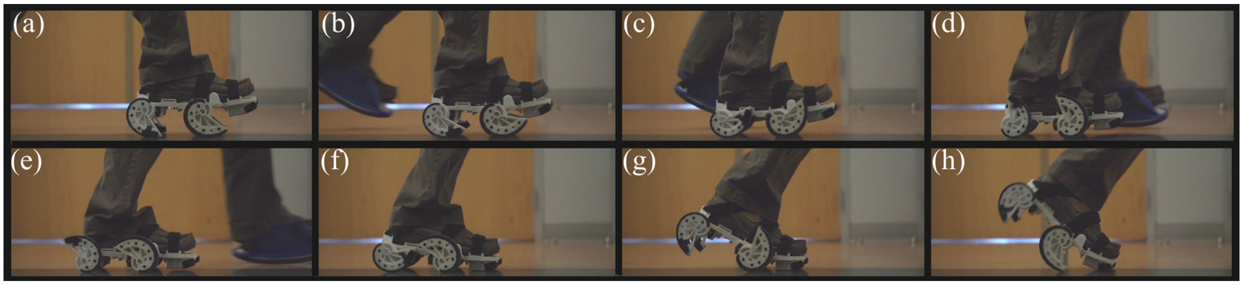

Figure 5.11: GEMS Walk.

The GEMS is completely passive and uses spiral-like (nonconstant radius) wheels [31], which redirect the downward force generated during walking into a backward force that generates a consistent motion. By not utilizing actuators and fabricating the shoe using rapid manufactured glass filled nylon, the GEMS weighs approximately 900 g. Small unidirectional dampers on the front and back axels prevent uncontrolled motions. After the shoe stops moving backward, the user toe-off, and springs attached to the axles reset the position of the wheels for the next step. The front of the GEMS is able to pivot to more naturally conform to the user's toe-off. The motion of the shoe can be seen in Figure 5.11.

The experiment is based on protocol NCT02185404 as listed on ClinicalTrials.gov . Before training, subject's gait patterns are evaluated using a ProtoKinetics Zeno Walkway (ProtoKinetics, Havertown, PA). They then complete 4 weeks of training 3 times a week under the guidance of a physical therapist. Each of the 12 sessions includes 6 bouts of walking on the GEMS for approximately 5 minutes with breaks between bouts. The subject's gait is measured on Protokinetic zeno walkway along with motion capture data before the training begins, this data will be referred here forth as pre-test data. Then gait data is collected on the walkway without motion capture every week starting the week after the first three training sessions, this data will be referred to as midweek data. Their gait is tested again one week after the completion of the training protocol on the walkway and motion capture data is collected, this data will be referred to as post-training.

All subjects agreed to participate in this study and signed a consent form that was approved by the Western Institutional Review Board. Three subjects (4 male and 2 females), aged 57-74 years old with right hemisphere stroke, completed the training thus far and the length of time since stroke ranged from 1.2 to 5.4 years. Subject 6 was atypical compared to other subjects as he took longer steps with his paretic limb. Therefore, the decision was made to fit the GEMS on his paretic side. The logic being it would train him to take longer steps with his non-paretic leg and shorter step with the paretic leg. Hence, balancing out the step length asymmetry which is the inverse of the regular protocol.

5.8 Results: GEMS Training

Symmetry was calculated using equation 5.2 where M is one of the five measures shown in Table 5.3, and a value of 0 indicates symmetry. The five measures comprise of step length, step time, swing time, double limb support (DLS), and ground reaction forces (GRF). Comparisons were made between gait evaluations conducted before training and after completion of training. Subject 3 will not be included in all the analyses because the subject is an outlier for all gait parameters which makes it harder to draw conclusions overall.

$$100 * \frac{abs(M_{paretic} - M_{nonparetic})}{0.5 * (M_{paretic} + M_{nonparetic})} \tag{5.2}$$

The results, summarized in Table 5.3, demonstrate that all subjects improved in step length asymmetry, except subject 2. Similarly, except subject 4 all other subjects showed improved step and swing time symmetry. Subject 3, 4, and 6 show display more asymmetry in double limb support. Subject 2 is the only one who becomes more asymmetric with ground reaction forces. These results are in line with the expected change in gait patterns based on split-belt treadmill studies using the same number of training sessions [91].

Clinical measurements such as Timed Up & Go (TUG) and six minute walk test were also collected for the study, Table 5.3. The TUG measures the time taken for an individual to stand up from a seated position walk six feet, turn around, walk back, and resume a seated position. The mark of improvement for this test is the subject takes less time after training than before which is evident for subjects 1-4 and 6. Subject 5 was unable to complete this task due to other issues. Subjects who completed the study showed improvement in TUG times. Six minute walk

Table 5.3: Participant Clinical Results Pre and Post Training.

Measure	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**
Timed Up and Go - Pre (sec)	27.7	21.4	105.4	24.1	28.6	11.6
Timed Up and Go - Post (sec)	26.5	20.4	90.6	19.6	-	10.5
Six Minute Walk Test - Pre (meters)	144.0	150.2	33.6	149.4	137.9	404.2
Six Minute Walk Test - Post (meters)	144.5	182.6	42.4	161.1	-	430.5
Gait Velocity - Pre (cm/sec)	41.4	47.0	9.0	35.9	38.6	113.5
Gait Velocity - Post (cm/sec)	45.9	61.1	12.8	43.9	-	145.1
Cadence - Pre (steps/min)	56.1	87.0	59	88.0	83.7	106.6
Cadence - Post (steps/min)	66.3	97.2	57.5	94.1	-	118.8
Step Length - Pre (%)	19.3	7.2	261.5	40.8	18.4	11.6
Step Length - Post (%)	14.9	7.8	242.2	36.5	-	4.4
Step Time - Pre (%)	31.0	37.7	98.5	47.9	34.3	22.1
Step Time - Post (%)	24.5	33.1	95.4	52.4	-	6.2
Swing Time Asymmetry - Pre (%)	41.1	34.7	71.7	69.9	61.8	34.8
Swing Time Asymmetry - Post (%)	40.8	34.0	51.9	78.8	-	4.1
DLS Asymmetry - Pre (%)	29.8	42.1	107.6	21.1	21.9	15.8
DLS Asymmetry - Post (%)	14.0	31.2	109.8	22.7	-	20.0
GRF Asymmetry - Pre (%)	22.7	14.8	42.9	14.7	15.1	15.9
GRF Asymmetry - Post (%)	20.3	20.3	40.9	11.8	-	11.7
Modified CGAM - Pre (%)	26.7	23.2	103.3	53.1	29.1	14.8
Modified CGAM - Post (%)	23.3	22.7	110.7	50.4	-	7.1

test measures the total distance the subject can cover in six minutes. All subjects who completed the trial showed improvement in the amount of distance they are able to cover. Parameters related to clinical measures such as Gait velocity and Cadence also showed improvement for all subjects except for subject 3 who showed a slight decrease in cadence post training.

All subjects displayed larger walking velocity post training, as seen in Table 5.3. Related to this increase in gait velocity results in lower Timed up and Go times (secs), higher distance covered during Six minute walk test (meters), and higher cadence (steps/min). Since SBT training is performed on a treadmill, the majority of the studies do not evaluate the gait velocity of walking over ground, so it cannot be compared directly. However, the SBT had almost no effect on double limb support asymmetry, and the GEMS showed decrease of double limb support asymmetry except in the case of subject 4 [54]. Step length and time asymmetry decreased for all subjects except subject 6, who was an atypical case since he wore the GEMS on the paretic side. Swing time asymmetry increased for subjects 1, 4, and 6 while it decreased for subject 2 and 3. Ground reaction force asymmetry decreased for all subjects except subject 6.

The joint kinematics for subject 2 and 4 are depicted in Figure 5.12 and showed mild changes between pre and post training. There are no significant changes observed in the paretic and non-paretic limb for the hip flexion/extension for both subjects. Hip abduction/adduction did not show any changes for the paretic limb for pre and post training for both subjects. The non-paretic limb displayed an increase in abduction post training for subject 4 while it did not change for subject 2. The non-paretic limb showed an increase in ankle plantar-flexion after the training while there was no difference in the paretic limb for subject 4. While subject 4 showed a large increase in plantar flexion in the paretic foot post training and showed no changes in the non-paretic foot. A small increase in peak knee flexion is also seen both limbs for both subjects.

The gait parameter asymmetries are shown in Figure 5.13. Subject 3 showed large deviations in asymmetries in step length, double limb support, swing time, and ground reaction force asymmetries and hence, is not included in the figure. This is reflected in the CGAM score where subject 3 was clearly far deviated from the other subjects. The CGAM scores for all subjects showed overall agreement with the changes in the gait parameters. Some CGAM scores reflected the overall changes closer than others which is to be expected given the small sample size.

Subject 1 shows good improvement in step length asymmetry after the first week but becomes more asymmetric after that but post-test shows the lowest step length asymmetry. Subject 1 shows a consistent decrease in step time and double limb support symmetry. Swing time asymmetry remains almost constant through all the weeks and ground reaction forces show a decrease in asymmetry the first two weeks followed by an increase in asymmetry. The CGAM scores that represents overall asymmetry shows a pattern close to step and swing time symmetry with small improvement in overall symmetry.

Subject 2 shows almost a constant step length asymmetry which is slightly more asymmetric post-test. Step time shows lower asymmetry after the first week of training and continues till

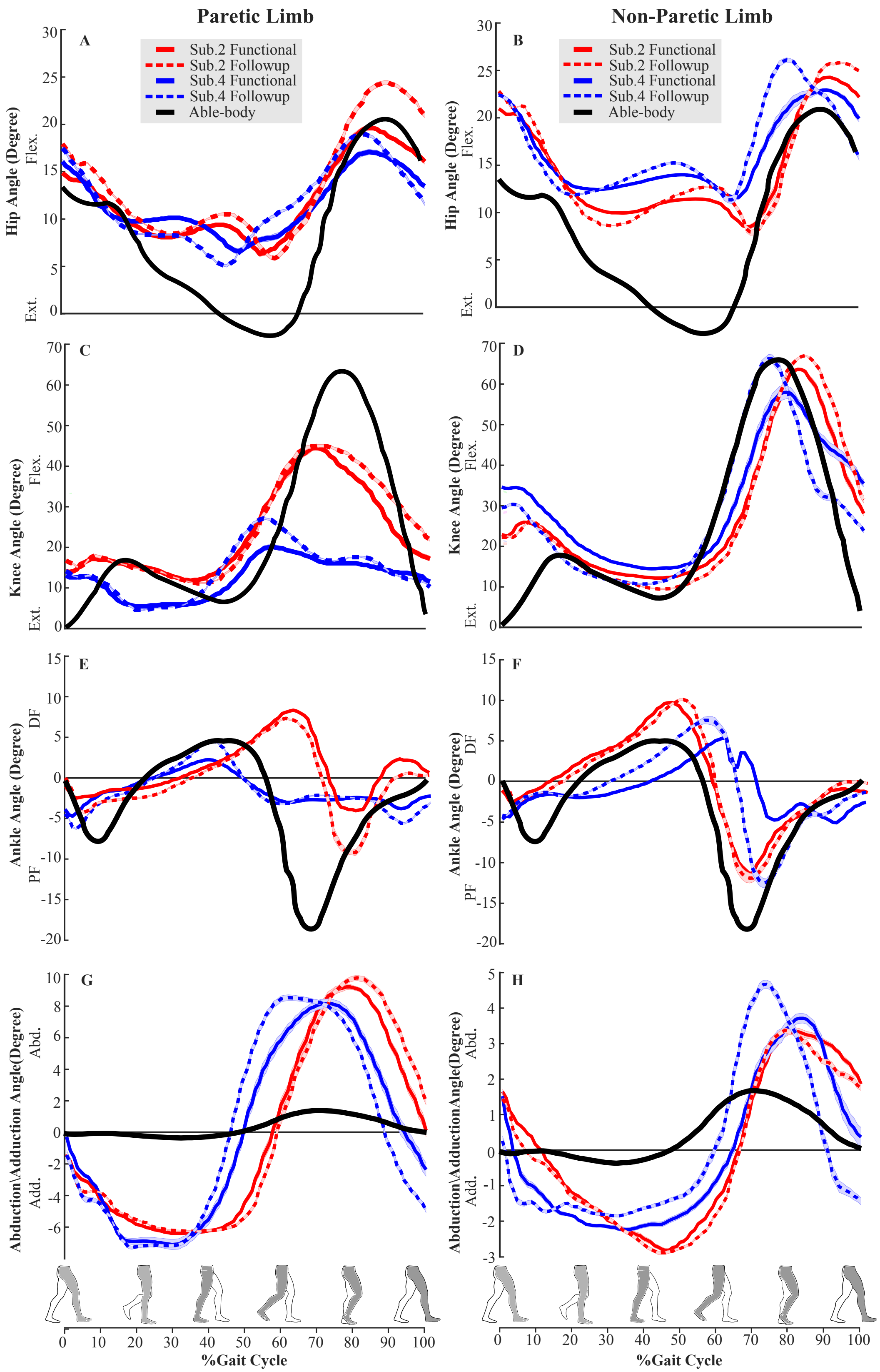

Figure 5.12: Joint Kinematics of Two Subjects Pre and Post-Test Using the GEMS.

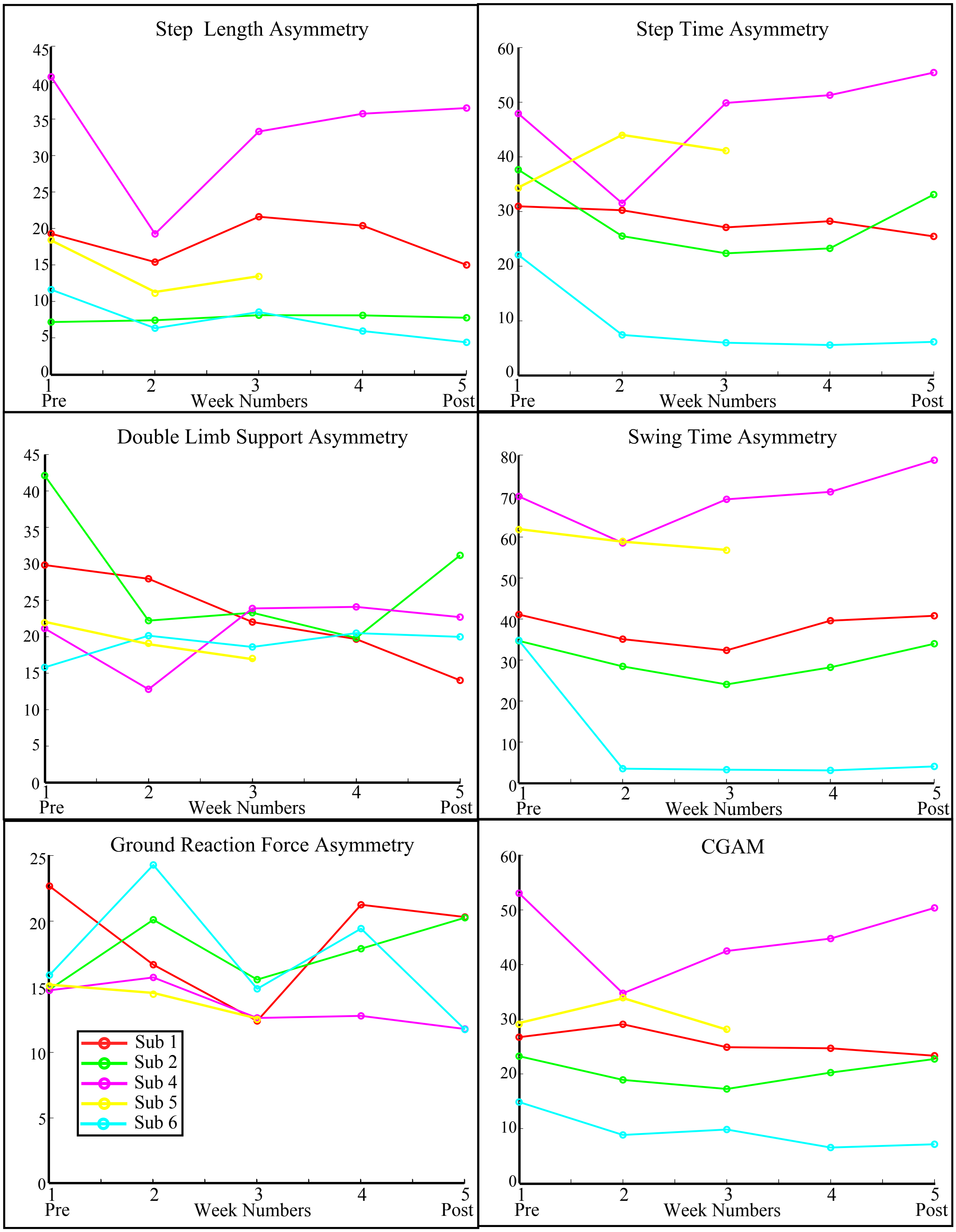

Figure 5.13: GEMS Gait Parameter Asymmetry.

week three but is shows slight increase post-test which is still lower than pre-test asymmetry. A similar behavior is seen in double limb support and swing time asymmetry. Ground reaction force asymmetry for subject 2 increases after the first week of training, then improves in the second week. However, it becomes worse the third week and post-test. The CGAM scores of subject 2 is lower than subjects 1, 4, and 5 due to the smaller magnitude of most of the gait parameter asymmetries. It shows improvement over the midweek but becomes worse towards the end of the training.

Subject 4 shows improvement after the first week but after which the asymmetries increase for step length, step time, double limb support, and swing time asymmetry. Step length post-test is lower than pre-test but the rest of the parameters with the similar pattern show larger asymmetry post-test. Ground reaction force asymmetry consistently decreases for subject 4. The CGAM scores represent the pattern seen in four of the gait parameters but the post-test CGAM is score is lower than pre-test indicating a slight improvement in overall symmetry.

Subject 5 did not complete all of the GEMS training sessions. The pre-test and two midweek data of subject 5 show improved symmetry in step length, swing time, double limb support, and ground reaction forces. Subject 5 does show large asymmetry in the midweek. This also has influence on the CGAM score which shows the overall asymmetry increases after the first week of training with slight improvement over pre-test in the second midweek.

Subject 6 was atypical as he wore the GEMS on the paretic side. He showed improvement is step length, step, and swing time symmetry through out all the weeks and had low asymmetry in post-test. Double limb support remained fairly constant with a slight increase in asymmetry. Ground reaction force symmetry varied midweeks but post-test showed lower asymmetry than pre-test. CGAM shows a behavior of continuous improvement for subject 6 and he also possess the lowest score overall.

The r^2correlation between the CGAM scores and the gait parameters with the TUG, 6MWT, and gait velocity clinical measures are shown in Table 5.3. Subject 3 was not considered for the correlation because of the extreme variation in the gait parameter data. Table 5.4 shows

Table 5.4: Clinical Data vs Gait Parameter and CGAM r^2 Correlation. (Bold Implies Correlation That is Mild or Above)

Gait Parameter	TUG (Sec)	6MWT (m)	Velocity(cm/sec)
Step Length Asymmetry	0.14	**0.21**	**0.31**
Step Time Asymmetry	**0.23**	**0.53**	**0.63**
Swing Time Asymmetry	**0.29**	**0.43**	**0.57**
Double Limb Support Asymmetry	0.03	0.14	0.10
Ground Reaction Force Asymmetry	**0.26**	0.14	0.13
Modified CGAM	**0.22**	**0.41**	**0.51**

Table 5.5: Modified CGAM vs Gait Parameter and CGAM r^2 Correlation. (Bold Implies Correlation That is Mild or Above)

Gait Parameter	r^2 (Pre & Post)	r^2 (All Weeks)
Step Length Asymmetry	**0.93**	**0.81**
Step Time Asymmetry	**0.95**	**0.88**
Swing Time Asymmetry	**0.98**	**0.89**
Double Limb Support Asymmetry	0.01	0.01
Ground Reaction Force Asymmetry	0.03	0.18

the complete list of r^2 values for the gait parameters and CGAM. CGAM scores show a weak correlation to TUG, moderate correlation with 6MWT, and gait velocity. Step time asymmetry shows similar pattern of correlation with CGAM with a high correlation with velocity. Swing time shows moderate correlation with all three clinical measures. TUG shows moderate correlation with ground reaction force asymmetry while the other measures have weaker correlation with a high correlation to velocity. Step length and ground reaction force show moderate correlation for all three clinical measures. Figure 5.14 shows the CGAM vs the clinical measures. TUG and CGAM show a positive slope for correlation which is the expected behavior as both metrics decrease with improvement. 6MWT and gait velocity show negative slopes for correlation which is again the expected behavior as 6MWT and gait velocity increase with improvement while CGAM decreases with better gait patterns.

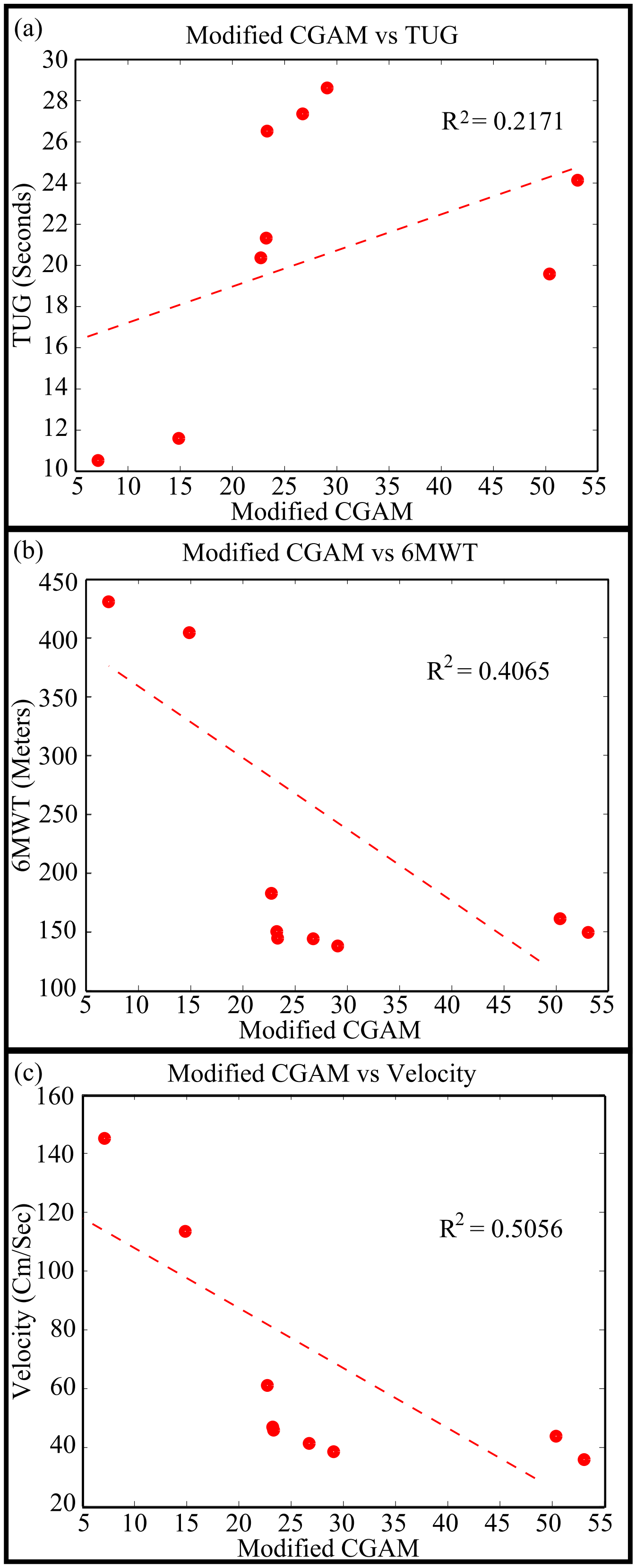

Figure 5.14: CGAM vs Clinical Measures. (a) CGAM vs TUG, (b) CGAM vs 6MWT, and (c) CGAM vs Gait Velocity

The r^2 values between CGAM scores and individual gait parameters were also calculated. Table 5.5 shows the correlation values between the pre and post test data of each gait parameter for all subjects correlated with the corresponding CGAM scores. This was important since the pre and post test performance is more important clinically. However, it is also critical to analyze the correlation for all the week's data points for the gait parameters. It is interesting to note that swing time, step length, and time show high correlation while double limb support and ground reaction force asymmetry show no correlation. This is consistent with both the total data set containing all the weeks of testing and when the data set consisted of only pre and post test data. Step length and swing time showed lowered correlation for all weeks data compared to the just the pre and post test data. Ground reaction force asymmetry showed a weak correlation with all weeks which was interesting. Double limb support showed no correlation in both cases.

5.9 Discussion: GEMS Training

The GEMS is designed to improve step length symmetry of an hemiparetic patient [29]. The wearer of the GEMS has spatial context and optic/visual flow, of their surroundings during training which helps them overcome their inherent neuroplasticity. The patient does not receive this additional information that helps with retraining their body function during SBT training. This results in the lack of retention of learned motor function after the SBT training [94]. This is also an indicator that neuroplasticity of an individual with stroke may need more stimuli to successfully relearn a certain task [18, 36].

The GEMS's main application is as a rehabilitative device to assist patients in improving gait and mobility that are suffering from a variety of ailments that induce hemiparetic related mobility hindrances. The ability to treat hemiparesis will not only improve the physical, mental, and emotional health of the patients themselves, but it will also benefit the quality of life of the nearest relatives and caregivers and improve healthcare economics.The GEMS can also be used as a transitional device which would allow it to serve as an intermediate step between the SBT training and walking over ground. Another alternative for the GEMS is to function as a compensatory motion device, where it would compensate for a patient's asymmetric motion. As a compensatory motion device, the GEMS's goal would no longer be rehabilitation, but rather to compensate for incorrect gait and establish a more symmetric gait by decreasing the step length of the unaffected leg. The training with the GEMS also encouraged the subjects to utilize their paretic limb. Hence, it also pushes the subjects to take longer steps with their paretic limb.

To accurately discuss the results of this experiment, it is important to keep in mind that subject three exhibited atypical gait pattern that resulted in extremely high asymmetries. Subject six is atypical because he took longer steps with paretic limb and hence, the GEMS was fit on his paretic limb which is the opposite of the protocol followed with the other five subjects. The purpose of the GEMS is to improve spatial and temporal symmetry. During the training protocol the subjects were also asked to shift more weight on their paretic limb in order to improve their kinetic symmetry as well.

Comparing the asymmetry behavior of parameters helps understand the relationship between the different parameter asymmetries. This corresponds to the hypothesis of Aim 1: there exists a balance of asymmetry between gait parameters. For example, for the data of midweek 1 most subjects show decrease in spatial and temporal parameters but have high ground reaction for asymmetry. The reverse is observed in midweek 2 where most subjects show low ground reaction force but high spatial and temporal asymmetry. Although not all subjects display the exact changes and there were variation, it offers evidence regarding the balance of gait parameter asymmetry. A large improvement in spatial and temporal characteristics portrayed a large increase in kinetic asymmetry. Subject 4 shows a peculiar pattern as they get better in spatial and kinetic parameters but get worse in temporal parameter. Subject 6 gets better in all parameters except double limb support asymmetry, which may be attributed to wearing the GEMS on the paretic side.

CGAM scores calculated using the spatial, temporal, and kinetic parameters showed behaviors similar to the gait parameter asymmetries, Figure 5.13. However, it does not validate the metric and hence, r^2 correlations were calculated between CGAM and clinical measures. The overall asymmetry measure represented by CGAM showed a weak correlation with timed up and go test. Gait parameter asymmetries also showed weak to moderate correlation with the clinical measures. CGAM also showed moderate correlation with 6MWT and gait velocity which are negatively correlated to CGAM. 6MWT and gait velocity also represent functional parameters as they clearly show that the subject is able to cover more distance in six minutes and can also ambulate faster. Having moderate correlation with these measures shows evidence that a measure of overall symmetry which is used as factor for gait quality is related to gait function signified by gait velocity and 6MWT. This findings offers some evidence to Aim 2, which aims to validate the CGAM metric.

CGAM shows high correlation with swing time, step length, and time. This was consistent when the only the pre and post test data was considered or all the data points were analyzed. This means that these three parameters have similar behaviors to their CGAM scores while double limb support and ground reaction force asymmetry have large variation in the data. However, when all the data is considered ground reaction forces show a weak correlation to the CGAM behavior.

CHAPTER 6: VISUAL PERCEPTION OF GAIT ASYMMETRY

This experiment is conducted to fulfill Aim 2. I seek to understand the capacity of an individual's visual perception to differentiate gait patterns. These gait patterns were generated using the Unity game engine with a visually symmetric human model that is based on human motion capture data. This is different from the previous research study conducted by Handzic et al. [32, 33] that used a combination of symmetric and asymmetry passive dynamic walker models. I also want to check the effect of physical alteration of gait perception. In this experiment, the subjects view videos with different gait patterns and evaluate them based on symmetry and normality. This visual classification will help in understanding how humans fundamentally perceive subtle gait asymmetries. This information will also elucidate the psychological aspects that influence research practices. I hope to garner more specific feedback from trained physical therapists and untrained individuals to further improve the model in the future. One of the goals of this experiment is to determine if individuals are more perceptive to asymmetric gait than more symmetric gait.

6.1 Methods

The videos for the perception experiment are made using Unity game engine. Unity is a game engine that allows users to import and control objects in a programmable environment. The human character model was created using an open source software called 'makehuman' which outputs a rigged character in the filmbox (FBX) format. In this study, I use data that was obtained via motion capture on the CAREN system to animate the characters. The joint angles are calculated from the data and are fed into the model using a C# script. The videos consists of an anterior view of the gait for half the time and the other half shows the same gait pattern in the sagittal view. Figure 6.1 is an example of the quality of the 3D video that the subjects viewed. They then filled

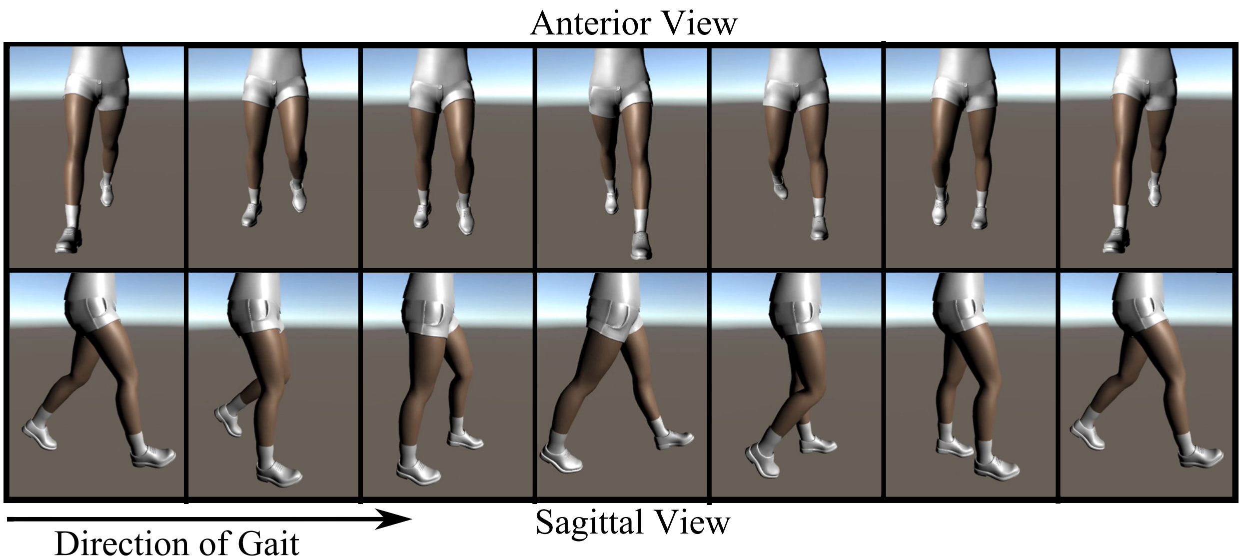

Figure 6.1: Unity Based Walking Video. (Anterior View on Top)

out a questionnaire. The questionnaire had the subjects assess the gait on a 7 point Likert scale to evaluate their perceived normality and symmetry. The graphic user interface (GUI) for the user is shown in Figure 6.2. The GUI is designed to record the user's input for normality of the gait pattern. The first page of the GUI asks the user to fill in demographic information such as sex, age group, and Occupation. Finally, the users are also provided a text box to enter their comments.

The experiment was conducted under USF IRB #Pro00016301. The study is in the form of a survey where the subjects are required to view videos of multiple gait patterns. Once the subjects view a gait pattern they proceed to rate the video on a 7 point Likert scale ranging from Normal to Abnormal. The subjects are also provided with a text box to type in any extra comments they may have regarding the asymmetries of the gait patterns shown in Figure 6.2.

6.1.1 Perception Catagories

The objective of featuring a variety of different gait patterns is to ascertain a viewer's biases. I want to understand the relationship between the perceptions and alteration to the gait. This correlation helps find ranges of asymmetry that can be beneficial and can still be under the threshold of public perception. Although, the subjects are not be aware of the exact nature of change, they should be able to notice the changes.

The subjects were shown videos that portray multiple physical changes such as:

- Normal Walking
- Able body walking with step length and time variations
- Able body walking with distal mass
- Able body walking with altered leg length
- Able body walking with combination of mass and leg length on the same side
- Able body walking with combination (dominant & non-dominant effects)
- Able body walking with stroke simulator and perception disruptor
- Prosthetic gait with different knee heights
- Prosthetic gait with different knee heights in combination with distal mass

6.1.2 Selection Protocol

The means of all gait parameters and respective CGAM scores of the data of all 10 subjects who participated in the study involving three different speeds, leg length change, addition of distal mass on the same leg, prosthetic and stroke simulator experiment was organized into a large data set. I also added the gait parameters of all the perturbations of different knee heights of amputee to this data set. A Matlab script was used to measure the largest determinant of every possible combination of the various perturbations. The logic behind this methodology is to evaluate the largest variation of a given set of gait parameters. As a result the selected gait patterns represent the largest distribution of different gait patterns. Another smaller subset was chosen based on the CGAM scores. The selected gait patterns had similar CGAM scores for different perturbations. Sixteen videos representing asymmetric gait patterns were chosen and they are shown in Table 6.1 and the gait parameter data can be viewed in Appendix C. The visualization of the human model is the same in all videos shown. This was done so no prosthetic or other alterations were present that could bias the subject's decision. This visualization allowed the subjects to view only the effect of these asymmetric changes on the gait patterns.

6.1.3 Gait Perception Metric

This metric is a qualitative assessment of perception bias that people have when visually evaluating an individual's gait. A 7-point Likert scale was used in a previous study conducted by Handzic et al. [32, 33] to quantify the gait from normal to extremely impaired or uncanny. In this study the subjects were asked to rate the gait patterns based on either they agreed or disagreed if the gait pattern looks normal. The responses seen in Figure 6.2 show the options from strongly agree (Likert rating = 7) to strongly disagree (Likert rating = 1) if the gait pattern in the video is normal. A potential metric that can be implemented for this research might be allowing user's to assign a range of values for each parameter's symmetry. This will help in evaluating the change in perception of gait when multiple physical changes are added. Unless there is a correlation between the CGAM and the perception of an individuals gait pattern, CGAM could incorporate the perception as an underlying feature. This would help to include visual appearance of a gait pattern as part of the metric. This might require a large database of individual's perceptions or a good predictive model, but this could help balance all aspects of a gait pattern.

6.2 Results

A total of 31 individuals took part in the study of which 7 were female and the rest were male. Out of this 22 individual's data, 5 female and rest male, was selected based on them rating at least three videos. The cumulative means of all Likert scale ratings for each video for individuals are shown in Table 6.1. These gait patterns are from the motion capture data collected in the experiments presented in Chapters 4 and 5. The Likert scale ratings are used along side the 11 gait parameter asymmetries that were calculated for these experiments to find the relationship between people's perception and individual gait parameter asymmetries. Figure 6.3 shows the Kruskal-Wallis analysis that tests for the null hypothesis and shows the statistically significant difference

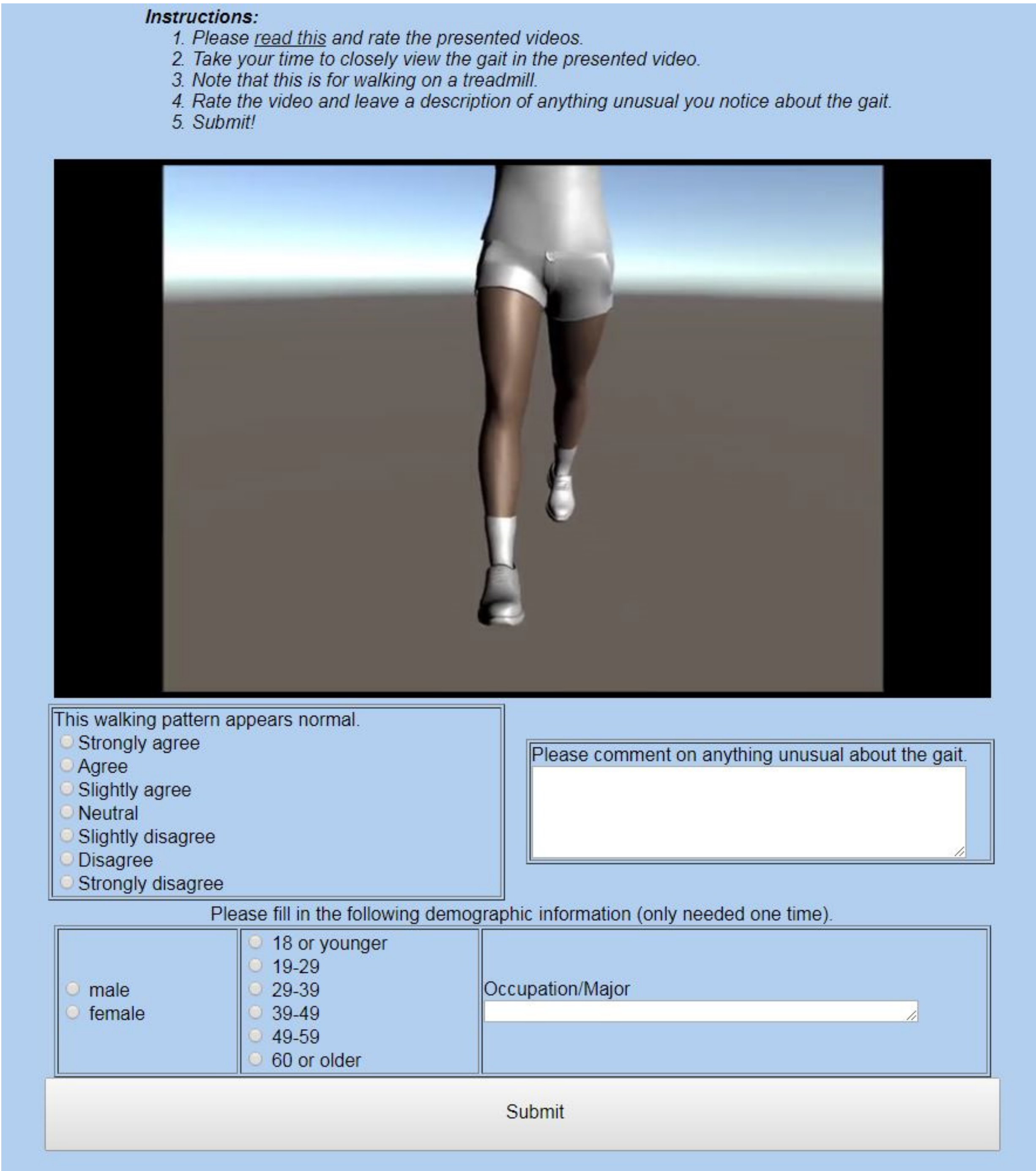

Figure 6.2: User Interface of Walking Videos.

Table 6.1: CGAM Scores vs Likert Scale.

Video No.	Gait Pattern	CGAM	Likert Scale
1	Subject 3-Leg Length-Normal-Weight-Small	10.70	3.1
2	Subject 3-Leg Length-Big-Weight-Small	11.81	3.8
3	Subject 3-Normal-Tread Velocity 0.9m/s	9.79	3.8
4	Subject 4-Leg Length-Small-Weight-Small	14.31	3.6
5	Subject 4-Leg Length-Normal-Weight-Big	12.87	3.6
6	Subject 4-Normal-Tread Velocity 0.5m/s	9.88	3.7
7	Subject 5-Leg Length-Normal-Weight-Big	14.00	2.4
8	Subject 7-Leg Length-Small-Weight-Big	11.95	4.1
9	Subject 7-With Stroke Simulator	9.78	4.9
10	Subject 8-Leg Length-Big-Weight-Big	20.12	4.7
11	Subject 9-Leg Length-Normal-Self selected 1.1m/s	10.42	5.7
12	Subject 10-Leg Length-Big-Weight-Big	17.96	2.9
13	Subject 10-Leg Length-Normal-Weight-Big	11.50	3.5
14	Subject 10-With Stroke Simulator	12.60	4.1
15	Amputee-Normal	21.30	4.1
16	Amputee-9 cm Knee Asymmetry-Weight	14.50	3.0

between the different gait patterns [$H_{(6,277)}$ =7.4, $p < 0.001$]. The Chi-squared goodness of fit analysis showed that the data did not follow a normal distribution [$\chi^2_{(6,N=22)}$= 45.24, $p < 0.001$]. Gait pattern 11, which is Normal walking without any perturbation, is statistically significantly different from gait patterns 1, 5, 7, 11, 12, 13, and 16. Gait pattern 7 is statistically significantly different from gait patterns 9, 10, and 11. Gait patterns 9 and 10 are not significantly different than 11. Gait patterns 2, 3, 4, 6, 8, 14, and 15 show no statistically significant differences with any other gait parameters with CGAM.

The individuals were able to distinguish between normal and abnormal gait patterns. There were three able-body gait patterns without any perturbations presented to the subjects. Two of these gait patterns are 3 and 6 were not at the individual's normal gait velocity. Normal gait velocity of an individual was determined by 10 meter walk test. The gait patterns of these two subjects were rated lower than 4. However, gait pattern 11, which was an able-body gait pattern with no perturbation and at the individual's self selected speed, was perceived to be closest to normal. It was interesting to see that subjects did not find gait pattern 8, 9, 10, and 14 as abnormal

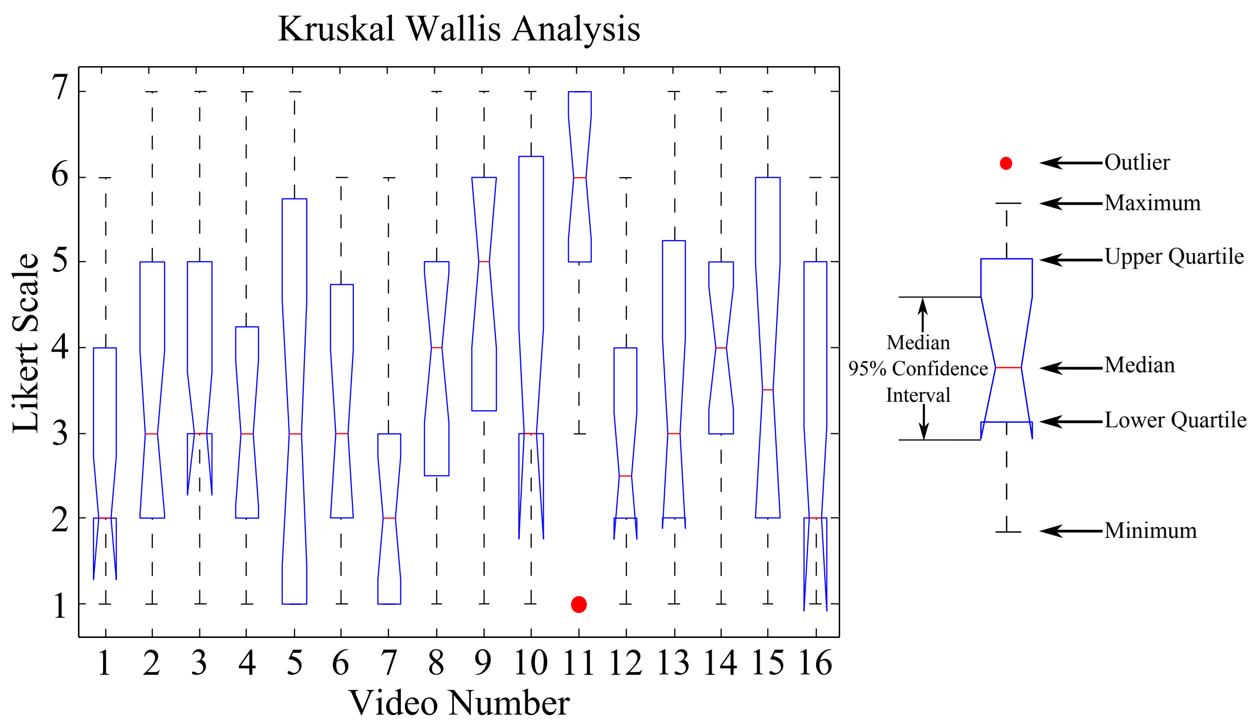

Figure 6.3: Kruskal Wallis Analysis Performed on CGAM vs Likert Scale. Video numbers correspond to Table 6.1.

as they had the largest perturbations applied to them. Particularly the combination of large/small LLD and large distal mass was rated more normal which may be explained by the cancellation effect related to the asymmetric perturbations.

There were two amputee gait patterns presented to the subjects. The subjects rated the prosthetic gait with normal knee height more normal than asymmetric knee height. It is worth noting that the human graphic model was not changed for any of these perturbations; only the motions were changed. The subjects were able to identify the subtle asymmetries in motion caused by a prosthesis. The most noticeable factor would be the consistent return of the prosthesis which is more machine like than human like. This machine like motion is further exaggerated at a lower knee height with distal mass as the subject is still adapting to the change. Other gait patterns with similar ratings as amputees were a combination of small LLD and mass and a combination of big LLD and mass.

The most abnormal gait pattern was gait pattern 7 with a large distal mass and the smallest Likert rating of 2.4. This was interesting as gait patterns 5 and 13 in the same condition were rated

Figure 6.4: Word Bubble from User Comments. The Size of the Words Correspond to the Number of Times a Specific Word has been used. (created at www.wordclouds.com)

slightly more normal. Gait pattern 1 with a small distal mass was also rated as abnormal. Now, looking at all the mean ratings, it seems that a combination of leg length and distal mass seems to appear more normal than just the distal mass. It also seems that applying the stroke simulator to limit knee flexion does not make the subject seem abnormal. In fact gait pattern 9 with stroke simulator was rated it to be 4.95 which is slightly above neutral.

Linear regression analysis was performed on the 16 different gait patterns and their corresponding Likert ratings (16*1 vector). The p-value for the data with (16 rows of videos *12 columns containing gait parameters and CGAM matrix) and without (16 rows of videos *11 gait parameters matrix) the CGAM scores included are shown in Table 6.2. The rationale behind performing two seperate analyses is that CGAM is inherently different from the gait parameter

Table 6.2: p-Value from Linear Regression of Likert Scale vs Gait Parameters with and without CGAM. (Bold indicates significance and Negative sign of coefficient indicated negative slope)

Gait Parameter	p-value CGAM	Coefficients	p-value no CGAM	Coefficients
Step Length	0.9	-0.002	0.93	0.001
Step Time	0.11	-0.033	0.14	-0.023
Vertical Force	**0.02**	-0.073	**0.02**	-0.069
Propulsive Force	**0.02**	-0.026	**0.01**	-0.028
Braking Force	**0.01**	0.032	**0.01**	0.028
Knee Angle	0.95	-0.002	0.81	-0.0067
Ankle Angle	**0.02**	0.067	**0.01**	0.078
Hip Angle	**0.01**	-0.016	**0.01**	-0.014
Ankle Moment	0.29	0.014	0.41	0.001
Knee Moment	0.78	0.005	0.70	0.007
Hip Moment	0.85	0.002	0.47	0.006
CGAM	0.44	0.060		

asymmetry data. A p-value below 0.05 shows significance. Linear regression analysis finds the relationship between Likert scale and the gait parameters and represents it in a form of a linear equation. The coefficients of the gait parameters with a p-value greater than 0.05 can be set to zero because they do not possess enough significance to represent the complete dataset. Ankle and hip angle, vertical, propulsive, and braking forces show significance when the data with and without the CGAM values were tested. However, it is interesting to note that kinetic gait parameters showed significance consistently because they are not directly perceived visually. Ankle and hip angle are visually perceived and this relevant because the majority of the perturbations, such as LLD and distal mass, were added near the ankle joint. On the flip side I expected knee angles to show significance because there were perturbations with the stroke simulator and prosthetic knee at two different asymmetric knee heights. There was no significance in the perception of knee angle asymmetry, this may be because subjects do not perceive knee angle asymmetries as abnormal compared to ankle and hip angle asymmetries.

Some individuals also left comments of the different gait patterns. Figure 6.4 shows the word cloud that was made using the comments from all the subjects, the size of the word is directly proportional to the frequency of use. The word "left", "foot/feet", and "right" are the most frequent in all the comments. There is also some indication by viewing the word cloud after removing the generic words that ankle/feet/foot (68 times) and hip/waist/torso (18 times) is mentioned more times than knee (8 times). This may show some indication about the visual asymmetries the subjects picked up on and the results seem to reflect this. Analyzing these words also helps understand the terminology that regular individuals use when describing gait. In the case presented here the subjects were able to communicate the differences they viewed using simple words. It is expected that this word cloud will be filled with more specific terminology when more data from trained clinicians is obtained in future studies.

6.3 Discussion

Visual perception plays a large role in the evaluation of an individual's gait pattern in rehabilitation. Therapists are trained to look for different aspects of an individual's gait. This works well for the aspects of gait that can be visually perceived. I would like to understand the biases that drive the expectation of individuals in regards to gait patterns. Quantifying this would help understand fundamental aspects of human perception of gait patterns. Further, by using asymmetric gait patterns that have been quantified with known gait parameter asymmetries helps in a methodical approach to draw relationships between visually perceived parameters and invisible parameters such as kinetics. The videos demonstrating the gait asymmetries were generated to represent the largest range of gait asymmetries as possible. Additionally, CGAM for each of the gait parameters was also used to select videos to draw relationships between visual perception and CGAM.

The results suggest that the subjects were receptive to asymmetric gait and consistently rated it to be more abnormal. Interesting behavior was seen with cases of gait patterns when only distal mass was seen as more abnormal than gait patterns with a combination of mass and LLD. This may be due to the changes in step length and step time. The opposite leg to the mass takes longer steps while the leg with the mass takes longer step time. This may have exaggerated the asymmetry leading users to pick up on the asymmetry. In the case of a combination of LLD and mass, this effect is reduced as discussed in Chapter 4 which leads to a higher rating. The subjects did rate the gait pattern without perturbation at a self selected speed higher than gait patterns at speeds slower than self selected speeds. It is also important to note that the subjects did not notice asymmetry in knee angles in the case of gait with stroke simulator to be abnormal, albeit they also did not notice it to be normal. This is further reinforced by analyzing the p-values which showed that ankle and hip angle and forces were significant but not knee angles.

CHAPTER 7: DISCUSSION AND CONCLUSIONS

The series of experiments conducted in regards to Aims 1 - 4 have shown results that give clues into the behavior of asymmetric gait when asymmetric devices or techniques are applied. Figure 7.1 shows the flowchart that illustrates the execution of this research study based on the Aims. Aim 1 seeks to prove the existence of a combination of gait parameters that are asymmetric but provide a balanced overall gait pattern that is beneficial. Gait symmetry is often used as a measure of gait quality more than gait function. Hence, it is important to correlate the benefits of overall symmetry to the improvement in actual gait function. To aid with determining overall asymmetry of a gait pattern, Aim 2 formulates CGAM that can combine multiple gait parameter asymmetries to yield a single number index. Scaling the asymmetries using weighted inverse covariances allows for consistent index values given the same number of gait parameters for comparison. Another important aspect to determining the role of symmetry in function is to estimate visual perception of individuals. The rationale for studying perception is that physical therapists evaluate gait patterns visually. By assessing the level of abnormality in asymmetric gait patterns, Aim 3 seeks to add another dimension to overall gait asymmetry function. Finally, Aim 4 seeks to establish the relationship between gait quality and function. This is to show that an asymmetric gait could affect the functional gait of an individual. This is a natural follow up to Aim 1 - 3 where the results show evidence of correlation of gait asymmetry and functional outcomes of multiple gait parameters. It also seeks to offer evidence that asymmetric rehabilitation devices and techniques have the potential to offer low cost subjective remedies to people with asymmetric gait patterns.

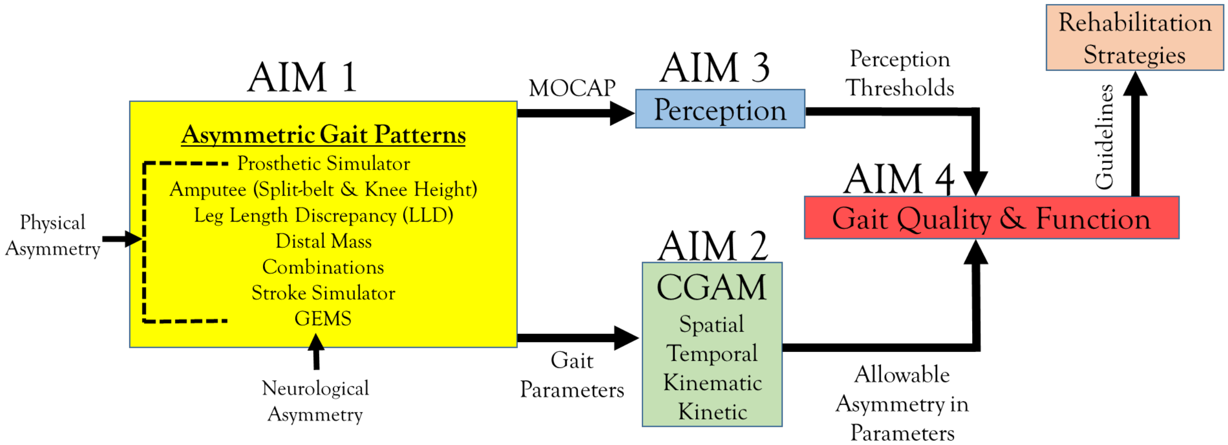

Figure 7.1: Flowchart of the Research Aims.

7.1 Discussion

The fundamental hypothesis for this research is an individual with an asymmetric impairment cannot portray symmetric gait. The approach to answer this question involved performing experiments that systematically applied perturbations of the gait patterns of able-body, transfemoral amputee, and individuals with stroke. The experiments showed that changes such as LLD and adding distal mass affect the able-body subject's spatial, temporal, and kinetic gait parameter asymmetries. This experiment showed a few important results. It showed that when a gait parameter such as step length or step time move towards symmetry, the kinetic parameters become more asymmetric. This shows that pushing one gait parameter to symmetry may drive other gait parameters to become more asymmetric. The experiments with prosthetics with asymmetric knee heights also showed that lower knee heights as it improved spatial and temporal symmetry but increased the knee angle asymmetry. Similarly, individuals with stroke who trained on the GEMS to improve their spatial and temporal symmetry showed large variations in their GRF asymmetry. Combination of LLD and distal mass led some gait parameters to have smaller gait asymmetry than individual effects of LLD and distal mass. This similar effect was also observed with a combination of distal mass and asymmetric knee height on the transfemoral amputee where the combination showed better symmetry than cases without distal mass. This shows evidence that a balance between gait parameter asymmetries can be found by applying small asymmetric changes.

These two broad effects provide part of the evidence necessary to show that an individual with inherent gait asymmetry cannot have a completely symmetric gait.

To further study the effect of gait asymmetry across all gait parameters, it was necessary to develop data driven methodologies. The result of this was the combined gait asymmetry metric which serves as an index to use quantitative multidimensional data and represent it in a single number. CGAM as a measure helps track overall changes from one gait pattern to another. CGAM is not designed to find the right balance in gait parameter asymmetries that would lead to a better overall gait. Rather, it offers a simple method to combine multiple gait parameter asymmetries. This research can be extended to incorporate the CGAM in the search for the balance and in turn develop more devices and techniques that can help impaired individuals achieve their desired gait pattern. CGAM allowed a further investigation into the relationship between the gait parameters and potentially find this balance between the different gait asymmetries. CGAM provides the index for overall asymmetry of a given gait pattern with gait parameters that can be spatial, temporal, kinematic, or kinetic in nature. A smaller CGAM indicates a smaller overall asymmetry among parameters and a larger CGAM indicates the opposite. CGAM uses the inverse covariance of the given dataset to scale the parameters with larger values to even the playing field. All the data collected for this dissertation was analyzed using CGAM. As seen in Chapters 4 and 5 CGAM scores follow a similar behavior to that of the majority of gait parameters. CGAM scores for able-body gait with no perturbation is always lower than gait with a stroke simulator which is designed to alter the gait pattern. Gait of an amputee is also shown to be more asymmetric than able-body gait. The maximum number of parameters used to analyze CGAM score is 11 in this dissertation, but CGAM is designed to study a much larger number of gait parameters as long as they are represented as a percentage of symmetry for each step. To validate CGAM as an Index, clinical measures such as TUG, 6MWT, and gait velocity were correlated for trials involving individuals with stroke trained on GEMS and transfemoral amputees trained on split-belt treadmill. The mild to moderate correlation shows that CGAM is promising as a clinical index using gait parameter asymmetries. CGAM serves as a quantitative metric for defining overall asymmetry of an individual. It must be validated on more studies involving multiple gait impairments to show evidence of its robustness. The metric can be used along side other indexes simply as a quantitative measure for overall asymmetry.

Perception plays a part in the equation in evaluating gait asymmetry. This is because in social conditions humans are able to pick up on subtle changes in an individual's gait. Visual evaluation of gait is also common practice in clinical assessments. Handzic et al. [32, 33] carefully chose single parameter changes in PDW gait and evaluated people's perception on each individual change. I have extended this by including gait patterns that have changes in asymmetries across 11 different gait parameters. A similar Likert scale was used in the evaluation of subject's perception of gait from normal (7) to abnormal 1 (1). The data was selected from a range of data that had the LLD and distal mass on the same leg, stroke simulator, and transfemoral amputee with asymmetric knee height. CGAM was used as one of the parameters for selection in the hopes of establishing correlation between visual perception and overall asymmetry. This was not the case from the results presented in Chapter 6. r^2 correlation showed a mild correlation with knee moments but there was no correlation to CGAM. This was also the case with linear regression analysis, but it was interesting to see that forces showed significance in representing this data. Another interesting aspect that emerged from the analysis is that the subjects found gait patterns with perturbations at the ankle more abnormal than perturbations at the knee. This is also reflected in the linear regression analysis that ankle and hip angles have some significance in representing the data. This definitely warrants further investigation.

Finally, to complete the investigation to find the balance of gait parameter asymmetries to set as a goal for rehabilitation it is important to understand the relationship between gait quality and function. Symmetry represents the quality of human gait while clinical assessments such as TUG, 6MWT, and gait velocity measure gait function. Asymmetric knee heights showed an interesting side to this relationship where a knee height lower than 7% of normal knee height was considered uncomfortable by the transfemoral amputee. Additionally adding a distal mass makes this worse. Although overall symmetry improved, since, 6MWT and gait velocity were not measured like in the other study, it is not possible to comment on improvement in functionality. However, it does show that a slightly lower knee height is acceptable and may be with a prosthesis which is slightly heavier with a uniform weight distribution it may be possible to bring about better gait function and asymmetry by leveraging the dynamic change. The clinical measures did show that there is definitely a moderate relationship with overall asymmetry and functional improvement. The CGAM scores were able to show similar behaviors with the clinical measures. These results are encouraging but there needs to be more thorough evaluation of CGAM on studies with larger subject populations.

7.2 Limitations

Although this research demonstrates the ability to describe overall asymmetry in gait patterns, it is limited by the amount of information necessary to determine the outcomes for an individual's gait. For example, CGAM can show the differences in overall asymmetries in gait patterns but it is not possible at the moment to define clinical significance. The CGAM has to be tested on multiple gait patterns analyzing the same variables in order to determine the clinically significant values. The other aspect that the CGAM cannot determine is the social and quality of life variables. These are subjective variables widely used to estimate people's perception and their sense of well being. These variables may need to be looked at in addition to the objective CGAM scores in order to determine the outcomes of rehabilitation strategies. Another limitation to CGAM is that it relies on percentage asymmetries and hence details such as acceleration of the foot or other deviations in gait patterns may be excluded from the analysis. This research study did not analyze methods to identify significant parameters. Although the CGAM can combine multiple levels of gait parameters it is not designed to identify the minimum gait parameters required to represent the overall gait pattern. This is important because in most clinical environments it is hard to obtain large versatile datasets.

7.3 Main Contribution

I started this research project to create an objective metric that can evaluate gait pattern using gait asymmetries. By conducting experiments of various asymmetric gait patterns I have shown evidence that improving certain aspects of gait is not the correct approach. For example, when an individual with asymmetric gait is trained to correct their spatial asymmetry, it may at the cost of their kinetic asymmetry. My evaluation of the gait parameters spanning four different types using CGAM has shown that an overall holistic approach is required while rehabilitating an asymmetric gait. The goal should be to find the correct balance between all gait parameters that contribute to an individual's gait pattern. Further, with clinical trials I was also able to validate the use of CGAM as a potential metric in evaluating different impaired asymmetric gait patterns. I also found that in addition to the quantitative metric like the CGAM it is important to analyze factors such as visual perception of asymmetric gait patterns. Initial evaluation revealed interesting aspects of visual perception that challenges the current thinking. My research has taken a step towards the potential implementation of rehabilitation of asymmetric gait patterns by using asymmetric methods and also train individuals to impact multiple parameters. The research also shows the path to potentially integrate large variety of data both quantitative and qualitative to define beneficial gait patterns for impaired individuals.

7.4 Future Work

The future extension of this research study would be to include more data types of gait patterns. Specifically, indicators of visual perception and subjective scales of quality of life and discomfort. The addition of these measures will help determining clinical relevance faster for CGAM scores. It also helps in establishing the CGAM score thresholds for each type of gait pattern. For example, it will make it easier for clinicians to establish overall beneficial gait patterns if the subject reports lower discomfort, better quality of life, and quantitatively the gait pattern has a lower overall asymmetry. This can be further reinforced by adding visual perception of the asymmetric gait pattern.

The other direction this research might benefit is to study the effect of neuroplasticity in rehabilitation. Quantifying this neurological programming may help understand the underlying physiological changes that are outcomes for gait rehabilitation. Finally, being part of clinical trials especially with GEMS showed that individuals with stroke may benefit from simply training and exercising the correct group of muscles necessary for gait. It may be worth performing a placebo trial with a device that offers resistance to their non-paretic limb and forces them to rely on their paretic limb may not necessarily improve symmetry but may improve their overall gait functionality.

7.5 Conclusion

To summarize, the dissertation shows evidence that rehabilitating gait asymmetries should be an holistic approach. Targeting certain types of asymmetry may not be the correct approach as it may adversely affect other gait parameters that may lead to pervasive long term effects. The experiments conducted to prove the hypothesis showed that simple and inexpensive asymmetric changes may provide relief to asymmetric gait patterns. The CGAM metric showed potential for being used as a quantitative metric for multiple impairments that cause gait asymmetries. Further, the research also suggests that it is important to consider quantitative such as CGAM, social such as perception, and subjective such as pain and quality of life data to evaluate overall improvement of an individual's gait. The different components investigated using able body, transfemoral amputee, and individuals with stroke illustrate that gait asymmetries can cause multiple parameter asymmetries to gait patterns. The simple asymmetric perturbations applied on the gait patterns showed that it is possible to combat the negative effects of asymmetric impairment with asymmetry. To tackle these problems this research has shown that quantitative metrics along with social metrics of visual perception offer a good direction in evaluating and rehabilitating asymmetric gait patterns.

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Total	0.00 USD

APPENDIX B: CGAM FUNCTION

B.1 CGAM Matlab Function

```
function [ Score, StdScore ] = CGAM( D , Par1,Par2)

% CGAM Function

C = cov(D(:,[Par1:Par2])); % Finding Covariance

IC = inv(C);% Inverse Covariance

[r,c] = size(D); % Finding row length

Var = (1/((sum(sum(IC))))); % 1/(sum of inverse covariance)

for j = 1:1:length(r)

d(j) = real((sqrt(D(j,[Par1:Par2])*IC*D(j,[Par1:Par2])'*Var)));

end

Score = mean(d); % Mean of all CGAM distances

StdScore = std(d)/sqrt(length(d)); % Standard Error

end
```

D = n*m data set

Par1 = Beginning column parameter number

Par2 = End column parameter number

Example: We have a dataset with 10 rows but we only want to analyze the columns 2 through 7 then Par1 = 2 and Par2 = 7.

APPENDIX C: PERCEPTION DATA

Table C.1 Gait Parameter Asymmetries for 16 Videos

Video Number	Perturbation	SL	ST	VF	PF	BF	KA	AA	HA	AM	KM	HM	CGAM	Likert Scale
1	S3-LL-N-W-S	-28.332	-5.6442	1.6969	-40.329	-33.555	3.6913	2.0017	4.3669	-34.254	-18.737	-82.469	10.698	3.0952
2	S3-LL-B-W-S	-4.4516	-0.95428	23.565	-7.1271	21.231	-2.4493	6.2701	10.972	-4.9524	-6.0195	-31.186	11.809	3.8148
3	S3-N-0.9	-24.514	-1.6328	1.7273	-17.972	-5.2119	2.2589	1.1699	21.83	-29.704	-14.098	-61.417	9.7941	3.7727
4	S4-LL-S-W-S	13.844	-5.6889	-9.6202	-42.746	-48.224	0.29292	3.4924	60.574	-29.065	-37.927	-81.713	14.309	3.5789
5	S4-LL-N-W-B	4.8962	-10.961	-1.3967	-67.68	-71.534	3.6368	3.2625	31.411	-21.373	-30.646	-85.354	12.87	3.64
6	S4-N-0.5	-13.687	-6.5228	0.73788	-6.9696	-24.351	2.3308	2.2906	11.544	-16.012	-28.102	-53.93	9.8863	3.6667
7	S5-LL-N-W-B	7.45	-17.793	-7.0096	-8.6892	-45.776	-9.1127	1.2129	43.426	-45.031	-41.594	-58.861	14.001	2.4
8	S7-LL-S-W-B	4.9613	-2.092	2.3855	-17.052	-30.402	-2.0765	6.2375	4.8464	-8.4173	-7.0474	-86.279	11.956	4.0909
9	S7-SS-W	2.6029	0.14081	-1.6505	-14.489	-24.368	-19.885	9.7087	-25.555	23.992	-16.587	-49.67	9.7884	4.9524
10	S8-LL-B-W-B	-4.6506	-1.9059	8.5434	-49.182	-40.066	9.7476	21.56	-1.0821	-32.017	-21.19	-58.964	20.115	4.7368
11	S9-LL-N-W-N	-13.53	-24.323	1.5015	-48.054	-14.25	-5.5842	2.6081	-7.5135	-17.837	-14.284	-18.34	10.421	5.7143
12	S10-LL-B-W-B	-4.89	-0.02694	-0.04501	-54.374	-49.23	-8.7965	1.3913	88.156	-9.1694	-3.4652	-54.431	17.958	2.8947
13	S10-LL-N-W-B	-1.4008	-10.087	-1.3707	-72.153	-80.265	10.877	-1.0097	-11.54	-14.95	-11.911	-62.554	11.451	3.5455
14	S10-SS-W	5.5593	3.7201	2.9641	-27.424	-7.3646	-3.0159	-8.1164	-13.754	22.137	-10.646	-26.543	12.55	4.0476
15	Amputee-Normal	-2.8876	14.468	-16.478	-91.89	-74.058	23.095	-10.461	-4.9407	-78.632	-49.805	-23.371	21.233	4.1
16	Amputee-9_W	3.7562	16.14	0.40934	-43.426	-4.8757	26.513	-4.6259	0.80541	-63.763	-38.252	-12.268	14.496	3

ABOUT THE AUTHOR

Tyagi Ramakrishnan is originally from Chennai, Tamil Nadu, India. As an undergraduate in Anna University (2008-12) he realised that the human body is the most complex machine to ever exist. Inspiration struck when he saw Dr. Hugh Herr's talk on his bionic transtibial prostheses in 2008. He started conducting research and built a pneumatic free piston hydraulic pump for his junior design project and found his calling in exoskeletons.

However, his journey into graduate research started with a lesson in reality as exoskeletons are not particularly beneficial in rehabilitation or useful in augmentation. Instead he turned his attention to simple low cost passive solutions under the guidance of Dr. Kyle Reed. Over the last five years he has worked on several research projects testing a variety of devices and techniques geared towards rehabilitation. He has worked in clinical trials with stroke and transfemoral amputees. His research has resulted in five patents pending in the realm of prosthetics, robotics, and orthotics. He also has published in journals and conference proceedings with more to come in the future. In addition to his M.S.M.E (2012-14) he has also completed the graduate certifications in robotics and entrepreneurship. The contents of this dissertation portray his research towards his Doctorate degree in Mechanical Engineering at University of South Florida.

He plans on moving to Los Alamos, New Mexico to be with his wife. He will extend his research in prosthetics, robotics, and human augmentation to build mechanical systems with Artificial Intelligence.