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KINEMATIC ANALYSIS OF SPINAL CORD INJURY ANIMALS TREATED WITH A NEUROTROPHIN-INFUSED SCAFFOLD AND BODY WEIGHT SUPPORTED TREADMILL TRAINING

by

Alexander Herman

A Thesis

Submitted to the
Department of Mechanical Engineering
Henry M. Rowan College of Engineering
In Partial Fulfillment of the Requirement
For the Degree of
Master of Science in Mechanical Engineering
at
Rowan University
March 28th 2018

Thesis Chair: Dr. Jennifer Kadlowec

2018 Alexander Herman

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Dedications

To my parents Lori and Andy for helping me (and in some cases begrudgingly) getting to where I am today by seeing the potential in me and guiding me to utilize it.

To my sister Rachel for being my biggest inspiration for overcoming whatever comes your way whether it be a task that needs to be completed, to peer pressure saying you couldn't do, or your body saying you can't do it.

Acknowledgments

I would like to thank my thesis advisors and committee Dr. Jennifer Kadlowec, Dr. Anita Singh and Dr. Eric Constans for guiding and helping me in getting to this point in my academic career. I would also like to thank my colleagues and lab partners, Jacklyn Witko and Brittany King for helping out with the animals and setup and assistance and all of the students who worked under Dr. Singh's mentorship that helped me with the data analysis. The Rowan School of Osteopathic Medicine Vivarium for their help and caretaking of the animals and also those who helped review this paper.

This study was supported by the New Jersey Commission on Spinal Cord Research – Exploratory Research Grant # CSCR14ERG001

Abstract

Alexander Herman
KINEMATIC ANALYSIS OF SPINAL CORD INJURY ANIMALS TREATED WITH A NEUROTROPHIN-INFUSED SCAFFOLD AND BODY WEIGHT SUPPORTED TREADMILL TRAINING
2017-2018
Dr. Anita Singh
Master of Science in Mechanical Engineering

Spinal Cord Injury (SCI) is a condition that affects around 250,000 Americans with no cure. Existing treatments rely on physical therapies such as body weight support treadmill training (BWSTT). Treatments currently being researched include the use of implantable cells and biomaterials. Our study investigated the changes in locomotive gait and range of motion via a combinational treatment using a bioengineered scaffold [poly (N-isopropyl acrylamide) polyethylene glycol (PNIPAAm-g-PEG) with BDNF and NT-3] and rehabilitation training using BWSTT in a clinically relevant contusion SCI animal model. Five different groups of animals (Sham, Injury, BWSTT, Implant, and Combinational) were tested on a treadmill with BWSTT at three different BWS (75%, 65%, and 55%) and two different speeds (7 cm/s and 10 cm/s). Using three motion capture cameras, kinematic data were acquired and analyzed to study functional recovery in these groups. Our results show some kinematic recovery in the Combination therapy and BWSTT animals. Step height, length, and number of steps were significantly higher in these groups of animals. The obtained data warrant further studies that aim to investigate the efficacy of different biomaterial implants and combinational therapies.

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Chapter 1

Introduction

1.1 Background

Spinal Cord Injury (SCI) is a significant cause of morbidity and mortality in the United States. According to the National Institute of Neurological Disorders and Stroke, around 12,000 SCIs occur each year, which costs the health care system approximately $3 billion dollars annually [1]. SCI typically occurs when either a piece of spinal vertebrae breaks or dislocates in a way that puts enough pressure on the spinal cord to cause some damage. Any damage that does occur can have an effect at or below the level of injury [1]. The majority of SCIs are caused by motor vehicle accidents, with other major causes being falls, and acts of violence. More about the epidemiology of SCI is discussed in Chapter 3.1.

Currently, there is no known cure for SCI. The options available only reduce the symptoms of SCI [2]. These symptoms can be very debilitating and include decreased motor function, and secondary complications such as circulation, breathing problems, lower bone density, and increased muscular atrophy [1], [3]. One of the most widely used current treatments for SCI is body weight-support treadmill training (BWSTT). While it is one of the most widely used treatments, BWSTT may not be superior to other methods, yet it is the treatment that deals with the limited activity involved in SCI patients. It is only effective when there is a partial SCI. The majority of SCIs that occur are partial SCIs that allow some commutation below the injury location [3]–[5]. What has been studied in the past has been the use of cell therapies. Cell transplants alone are not sufficient for

regeneration and can pose problems with immune rejection, tumor generation, and an ineffective environment for regeneration [2], [6]. Additionally, to supplement these treatments, growth factors called neurotrophins are added to these transplants such as neurotrophin 3 (NT-3) and brain-derived neurotrophic factor (BDNF). In terms of advancing the treatment of SCI, research has been focused in fields such as regeneration of partially damaged SC tissue and the use of biomaterials to aid in neuron or axonal regeneration, with an additional focus on a combination of biomaterial and cell transplants. This combinational approach helps alleviate the concerns of cell transplants alone by providing stability to the site and a suitable environment for delivering new cells to the point of injury [2]. The aim of our study is to help overcome the problems of cell transplants alone by using a specially designed biomaterial scaffold made from poly (N-isopropyl acrylamide) with poly (ethylene glycol) (PNIPAAM-g-PEG) infused with NT-3 and BDNF neurotrophin growth factors.

While there has been a great deal of research on highlighting the effects of neuroregeneration of the axons, there have been few studies showing what these therapies have on the kinematic aspect of gait analysis and how these therapies specifically compare to existing physical therapy techniques. The main focus of this study was to investigate the combinational effects of this bioengineered scaffold with neurotrophins along with existing rehabilitation therapies such a BWSTT. A full list of the abbreviations used in this paper can be found in Appendix A: Definitions and Aberrations.

1.2 Problem Statement

To study changes in locomotive gait and range of motion after combinational treatment using a PNIPAAM-g-PEG bioengineered scaffold loaded with NT-3 and BDNF neurotrophins and rehabilitation training using body weight support treadmill training (BWSTT) in a clinically relevant contusion spinal cord injury (SCI) animal model.

1.2.1 Hypothesis. The neurotrophin secreting scaffold will help promote neuroprotection and regeneration that will help improve the locomotion and range of motion of the animals when employed in conjunction with body weight support treadmill training compared to the scaffold and body weight support treadmill training treatment alone.

Chapter 2

Anatomy

2.1 Spine

In vertebrate animals, the spine is a bony structure that consists of a series of bones called vertebrae and cartilage disks between each vertebra called intervertebral disks. Its main function is to protect the spinal cord. Additionally, it serves to support the skull and provides support to the ribs, pelvis, and back muscles. The spine functions as a flexible rod that provides some flexion and extension in the frontal and sagittal plane while also providing some rotation at the torso and head [7]. A picture describing the type of motion of the spine is shown in Figure 1.

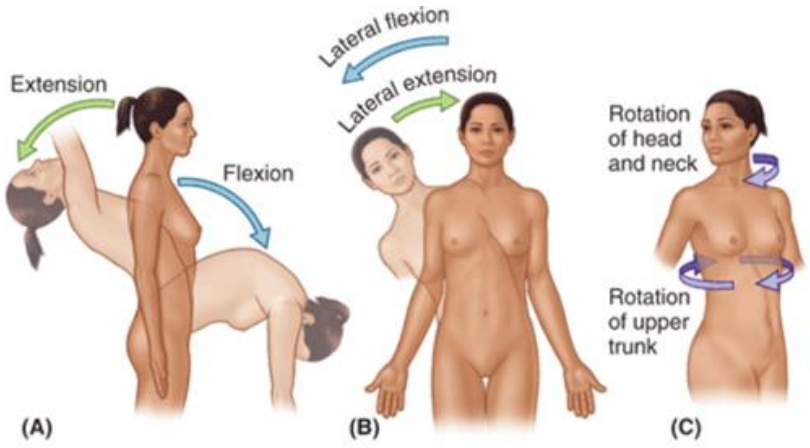


Figure 1. Diagram showing the different movements of the spinal column. From the sagittal plane there is extension and flexion; in the frontal plane, there is lateral extension and extension; and in transverse plane there is rotation in the trunk and neck. A total of 3 degrees of freedom is present [8]

The spine itself is divided into five different sections that correspond to the type of vertebrae, specifically the cervical, thoracic, lumbar, sacrum, and coccyx. At birth, a newborn starts out with 33 vertebrae (7 cervical, 12 thoracic, 5 lumbar, 5 sacral, 4 coccygeal) but as the child grows, the sacral and coccygeal vertebrae fuse together and form 1 sacrum and 1 coccyx vertebrae bringing, the total vertebrae count in an adult to 26 [7]. In an adult, each section of vertebrae appears to have some curve when viewed from the sagittal plane. The cervical and lumbar sections have a convex shape, while the thoracic, sacral, and coccyx sections have a concave curve with respect to the anterior side of the body. From a mechanical perspective, the curves of the spinal column act to improve its strength, and serve as natural dampers or shock absorbers when performing locomotion and helping to maintain an upright balance [7]. A diagram of the spinal column showing the different sections of the spine from the frontal and sagittal planes is shown in Figure 2.

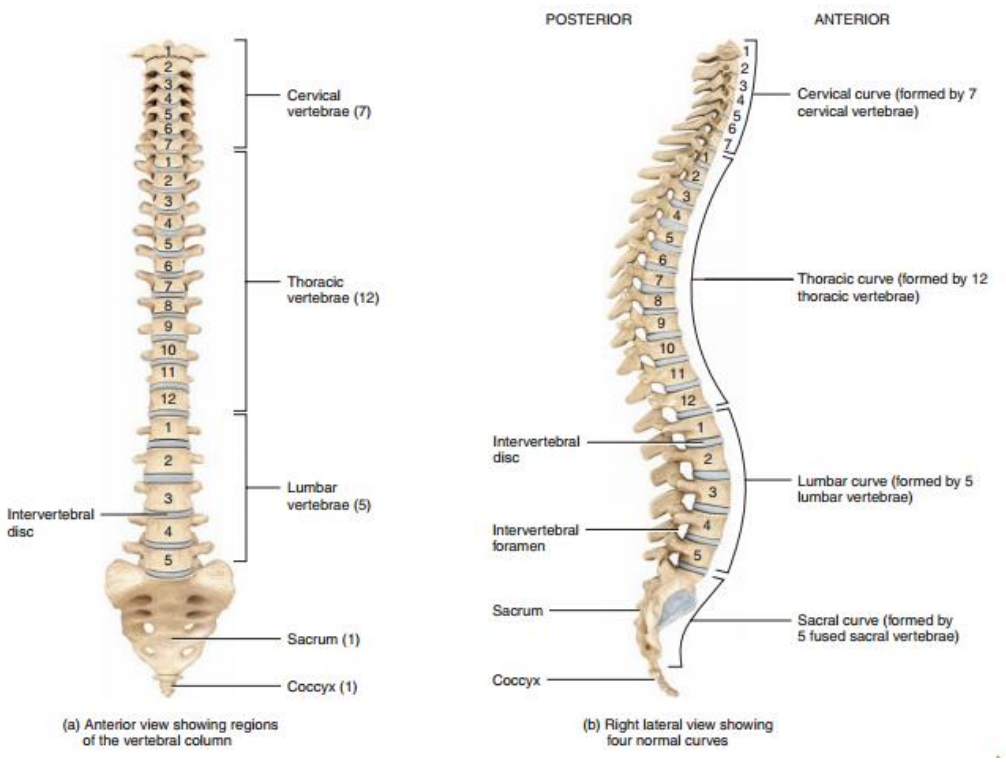


Figure 2. Frontal and sagittal views of the adult spinal column. The spine in the anterior view does not show any curves whereas the lateral view shows the different curvatures of the different sections of the spinal column [7].

2.2 Nervous System

The nervous system is a network of connected cells called neurons and support cells called neuroglia. A neuron is a special type of cell that allows electro-chemical signals to be transmitted throughout the body. This network of neurons is responsible for regulating a person's bodily actions. These actions include controlling sensory functions for input, integrative functions for sensory for processing, and motor functions for output [7]. The nervous system itself can be broken down into two main systems: the central nervous system (CNS) and the peripheral nervous system (PNS), which are discussed in detail in Chapter 2.2.1 and 2.2.2.

2.2.1 Central nervous system (CNS). The central nervous system (CNS) is the part of the nervous system that encompasses the brain and the spinal cord. It is commonly referred to as the control center of the body and controls vital bodily functions. The CNS itself contains about 100 billion neurons and is the source of signals that trigger the endocrine system to secrete a specific chemical or hormone, and trigger muscular systems to contract a specific motion. It is also on the receiving end of sensory inputs from different systems across the human body processes [7].

2.2.2 Peripheral nervous system (PNS). The peripheral nervous system is every other piece of nervous tissue outside of the central nervous system, including sensory glands/receptors and nerves that branch from the spinal cord throughout the body [7]. Nerves are defined as bundles of axons and connective tissue that originates from the CNS and serves a specific set of regions within the body. At the point where the nerves meet the CNS, there are small lumps of nervous tissue called

ganglia that serve as the transition point between the CNS and PNS. A sensory gland that is part of the PNS is simply referred to as a structure that monitors external changes in the environment. PNS is broken down into three different systems: somatic nervous system (SNS), autonomic nervous system (ANS), and an enteric nervous system (ENS). The SNS contains sensory receptors and motor neurons from different parts of the body that are responsible for controlling skeletal muscle. The ANS controls sensory receptors and motor neurons that control autonomous functions of the body like heart rate and breathing. The majority of the ANS is located in visceral organs. The ANS itself has two separate divisions: the sympathetic and parasympathetic divisions. These typically increase and decrease organ activity, respectively. Finally, the ENS is the part of the PNS that controls the digestive tract. Although the ENS technically shares some sympathetic and parasympathetic nerves with the ANS, it mostly operates independently [7]. A block diagram that identifies the CNS and the three separate systems of the PNS is shown in Figure 3.

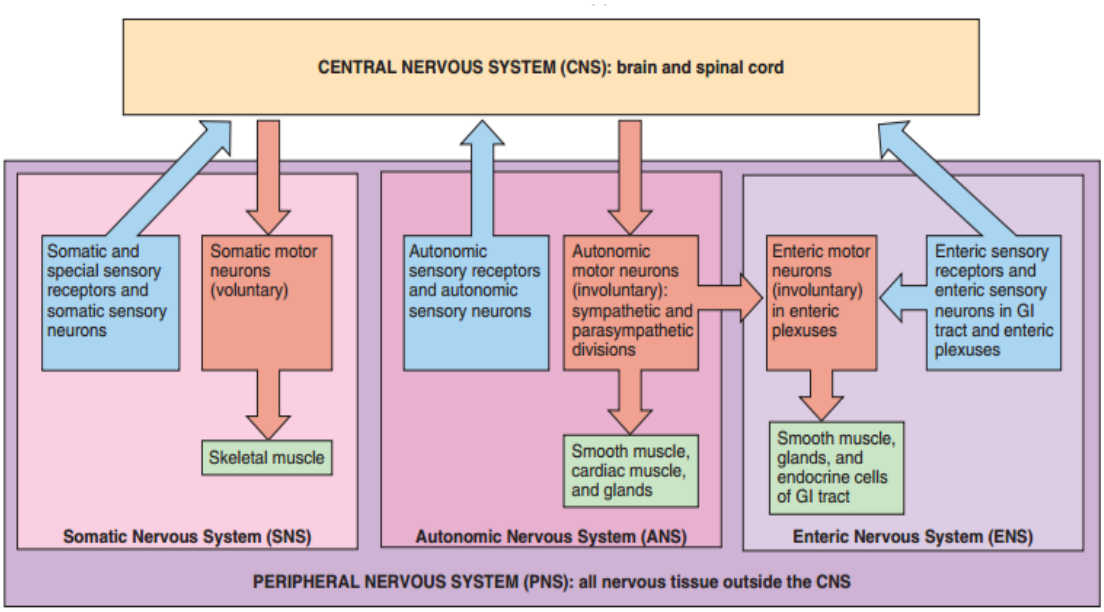


Figure 3. A block diagram of the interactions between the central nervous system and the peripheral nervous system. The diagram highlights the different receptors and motor neurons in the three different systems in the peripheral nervous system.

Chapter 3

Spinal Cord Injury

3.1 Epidemiology

According to the National Institute of Health's Institute of Neurological Disorders and Stroke, there are about 250,000 Americans living with SCI. This figure grows by 12,000 a year in the United States alone. SCI appears mostly in men (about 80%) [1]. According to the National Spinal Cord Injury Statistical Center (NSCISC), about 40% of all spinal cord injuries are caused from vehicular accidents, about 30% from falls, and the rest from violence, sports or other means [9]. A chart with a more detailed breakdown is shown in Figure 4.

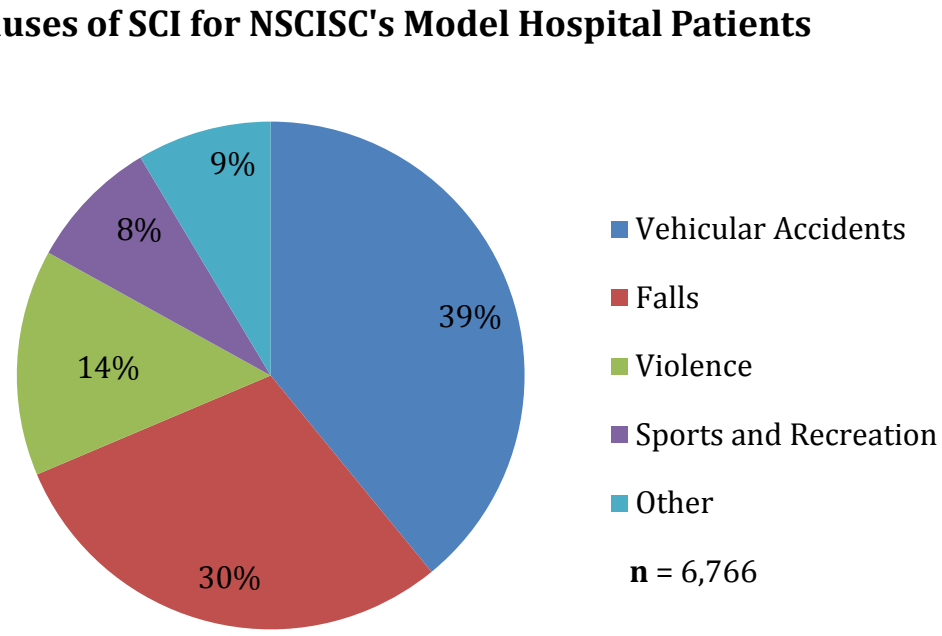


Figure 4. Causes of Spinal Cord Injury for patients admitted with SCI in 28 hospitals enrolled in the NSCISC's SCI Model System from September 2005 to March 2015. The total number of patients admitted is 6,766 [9].

In addition to the primary injury of SCI, many serious secondary complications can ensue. Some of these secondary effects include a form of paralysis caused by inflammation of the spinal cord and excessive neurotransmitter release. Patients can also experience complications resulting from the injury, such as difficulty breathing, muscle spasms, pneumonia, and circulation problems [1]. Over the course of time the complications can cause great burdens for the patient and caregivers [10].

3.2 Types of SCI

Generally, there are two broad types of SCI: complete and incomplete. A complete SCI is defined as the absence of nerve activity below the point of injury, and an incomplete SCI is defined as in the presence of some nervous activity preserved below the point of injury. The determination of whether the SCI is one of those two types is based on the use of the American Spinal Injury Association (ASIA) Impairment Scale [1], [2]. The scale is broken down into five levels ranging from A to E, where A is a complete injury and E is normal function in terms of motor and sensory function. A table describing the different levels of the AISA scale is shown in Table 1.

Table 1

Table of the Classifications of the American Spinal Injury Association Impairment Scale. Each classification defines a different level of SCI ranging from classification A, describing a complete SCI, to classification E, describing no SCI and normal motor and sensory function. Source: NIH Institute of Neurological Disorders and Stroke [1].

American Spinal Injury Association (ASIA) Impairment Scale	
Classification	**Description**
A	Complete: no motor or sensory function is preserved below the level of injury, including the sacral segments S4-S5
B	Incomplete: sensory, but not motor, function is preserved below the neurologic level and some sensation in the sacral segments S4-S5
C	Incomplete: motor function is preserved below the neurologic level, however, more than half of key muscles below the neurologic level have a muscle grade less than 3 (i.e., not strong enough to move against gravity)
D	Incomplete: motor function is preserved below the neurologic level, and at least half of key muscles below the neurologic level have a muscle grade of 3 or more (i.e., joints can be moved against gravity)
E	Normal: motor and sensory functions are normal

3.3 Current Treatments for SCI

There are no current marketable devices or clinical procedures to completely cure either complete or incomplete SCI. The only points of care are to treat the symptoms of SCI using physical therapy, or to try methods to restore neural function, with little success [2], [11], [12]. Types of treatment that are available for treating SCI are pharmaceuticals, implants, and physical therapy methods. Pharmaceutical methods such as corticosteroids are used to reduce the body's inflammatory response after SCI. Implants, while still being investigated and

improved on, are based on biocompatible materials that allow cells to grow or that can be implanted beforehand and are discussed in detail in Chapter 3.6. Physical therapies such as BWSTT and Functional Electrical Stimulation (FES) that allow increasing nervous activity through locomotion or external stimulation that can aid in regaining nervous function to damaged areas are discussed in detail in Chapter 3.4.

3.3.1 Pharmaceutical methods. Pharmaceutical methods involve the delivery of a pharmaceutical substance within a short amount of time of the primary injury; typically, corticosteroids such methylprednisolone [12]. Corticosteroids act to suppress the immune system response that occurs from the result of an injury such as an SCI.

3.4 Physical Therapy

3.4.1 Body weight support treadmill training (BWSTT). BWSTT is a type of physical therapy that involves the use of a treadmill mechanism that uses an adjustable shoulder harness to support patients by taking the weight off their leg [13]. This system can be adapted for use with manual assistance or with the use of robotic gait trainers that allow the user to increase intensity, reduce therapist fatigue, and monitor different aspects of the gait cycle, such as joint position and forces applied, potentially increasing efficiency of the treatment [14]–[18]. Examples of the setup that are used to perform BWSTT are shown in *Figure 5*. This therapy has been investigated numerous times in animal models and has made it to clinical studies, along with a different type of system that achieves similar results

[19]. Recent studies, however, have found that the success of the treatments in animal studies might not transfer over to human clinical studies; nevertheless, the treatment itself provides potential for improvement through the use of biomaterials, which are discussed in Chapter 4.2 [4], [19].

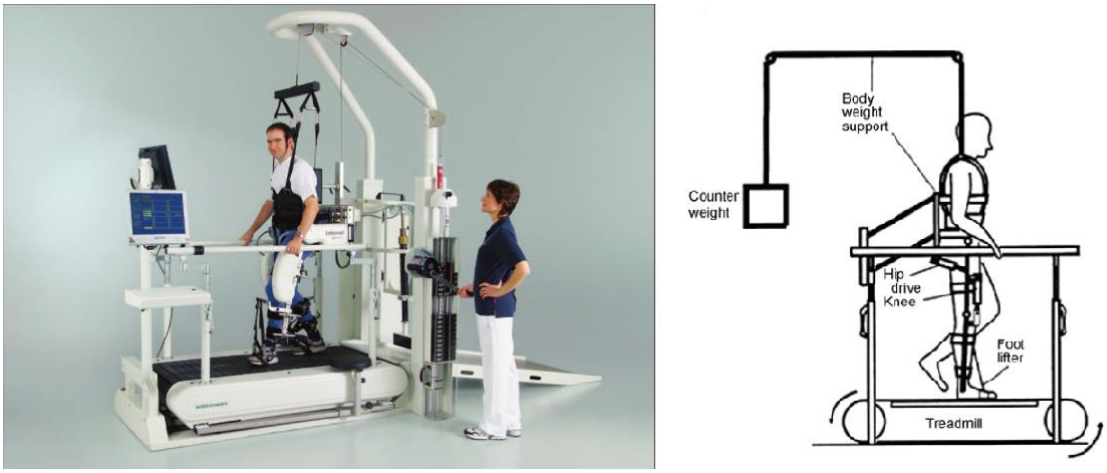


Figure 5. BWSTT systems that are used to help treat SCI in humans. Left is from Hornby et al., 2005 and Right is from Dietz, 2008 [20], [21].

3.4.2 Functional electrical stimulation (FES). Functional electrical stimulation (FES) is a type of therapy that involves the use of electrical signals sent to different muscle groups that help in activation during an activity or exercise. Several studies have shown that temporary use of FES after a SCI can help restore some voluntary muscle control. It is hypothesized that FES can help stimulate the CNS to become more functional after an injury [22], [23]. Normally, this therapy is not used by itself but as a supplement to other methods of physical therapy, such as cycling and treadmill training [23]. While our studies do not include the use of FES, this method of physical therapy holds promise for our future work.

3.5 Cell Based Transplants

A growing type of treatment that has been researched is a neuroregeneration of neural tissue through the use of stem cells. Several types of stem cells are currently being explored in research such as neural (NSC), mesenchymal (MSC), embryonic (ESC), and induced pluripotent stem cells (iPSC) in addition non stem cells such as glial cells [2], [24]. Each of the different types of cell-based therapies has their advantages and disadvantages. For instance, NSCs have can provide supportive substrate for axonal regrowth and can help with remyelination of axons, MSCs are easy to extract and have low immunogenicity, ESC can easily differentiate to other types of cells and, iPSC have low immune responses and low ethical constraints [24]. However, each of these treatments still present issues that prevent them from being used for patients with SCIs. Some of those issues include ethical concerns with ESCs and NSCs, preventing immune responses and tumor generation along with the ability to differentiate to the desired cells. Several things that can be used to address some of these issues such as the implementation of neurotropic factors to help promote regeneration of nervous tissue and the implementation of biomaterial scaffolds to provide chemical, and mechanical properties, aid in differentiation, and help with cell survival are discussed in Chapter 3.6 [24]. A table highlighting the different advantages and disadvantages for each cell based treatment for SCI is shown in Table 2.

Table 2

A table comparing the advantages and disadvantages of different cell based therapies for SCI. Sourced from Shi et al. 2017 [24].

Types of stem cells	Therapeutic mechanisms and advantages	Disadvantages
NSCs	Neuronal replacement therapy	Undifferentiation or differentiation along
	Remyelinate the demyelinated axons	the glial lineage after transplantation
	Secrete neurotrophic factors	Ethical constraints
	Ameliorate T-cell receptor-mediated T-cell activation and inhibit signaling of inflammatory cytokines in immune cells	
MSCs	Immunomodulation	Tumorigenicity
	Anti-apoptotic effects	
	Secrete neurotropic factors and cytokines	
	Permissive cellular substrate for promotion of host axonal growth	
	Easily extracted and cultivated in large numbers	
	No ethical constraints	
ESCs	Can be repeatedly passaged in culture	Immunogenicity
	Differentiate into neuronal or glial cells	Ethical constraints
	Secrete trophic factors	
iPSCs	Avoid immune rejection	Tumorigenicity
	No ethical constraints and tissue donation	Genetic and epigenetic abnormalities

3.6 Biomaterial Transplants

In addition to Cell-Based transplants, a treatment that has also been used in a few animal studies is hydrogel-based biomaterial that helps promote the regeneration of axons after an injury. Hydrogels are simply materials that are water based gels that have the ability to closely mimic the tissues present in the CNS [2], [25]. These hydrogels typically develop into a scaffold, a temporary support structure that facilitates the growth of cells. Earlier types of regenerative therapies involved the use of stem cells alone. To address some of the issues with cell based transplants, current research is turning towards the use of combination treatment of biomaterial that are infused with stem cells or other growth factors such as neurotrophin 3 (NT-3) and brain-derived neurotrophic factor (BDNF) to help with neuroprotection and neuroregeneration. These growth factors are simply substances that help promote nerve growth and offer neuroprotection [2], [6], [24].

3.6.1 Types of biomaterials. The biomaterials that have been used in previous literature are either natural or synthetic. Some of the naturally occurring materials are Matrigel, Collagen, Hyaluronic Acid, Alginate, and Dextran [6]. Some of the advantages of naturally occurring biomaterials are that they are easy to make, are biodegradable, and have properties that are recognized by the cells that allow for integration. However while they are natural, they can potentially increase an immune response, can biodegrade too rapidly, have low reproducibility, and can be difficult to sterilize [2], [6]. That last point is especially a concern when transitioning to clinical studies as lack of sterilization can lead to an immune response, which is one of the secondary effects resulting from a SCI.

Consequently, synthetic biomaterials have been increasing in their use due to their customization and adaptability by combining different materials. Some of these materials can even be implemented minimally-invasively via injection, which can reduce the number of complications experienced in traditional surgery [6]. However, one problem with synthetic materials is that they have poor biocompatibility. This can present a problem when being used in a clinical setting as they must meet FDA guidelines before they can be marketed (e.g. meeting biocompatibility in ISO 10993) [26]. Their adaptability in being customized can help alleviate this issue [6]. Some of the synthetic materials that have been featured in some studies are derived poly(lactic acid) based or poly(lactic-co-glycolic acid), methacrylate-based materials such as poly[N-2-(hydroxypropyl) methacrylamide] (PHPMA) or poly (2-hydroxyethyl methacrylate) (PHEMA), and poly (N-isopropyl acrylamide) or PNIPAAm [2], [6], [27].

These biomaterials, in order to improve their effectiveness, have been combined with stem cells such as a neural, mesenchymal, as well as growth factors such as NT-3, BDNF [2], [6], [27]. From Tsintou et al.'s review , the majority of studies used these combinational materials in transection and hemisection injury models and reported positive results with axonal regeneration [6]. For the use of our study, we used poly (N-isopropylacrylamide)-poly (ethylene glycol) (PNIPAAm-g-PEG) that secreted NT-3 and BDNF neurotrophins. PNIPAAm-g-PEG has the ability to deal with the biocompatibility problem of other synthetic biomaterial along with providing mechanical support and match the properties of tissue present in CNS. Another advantage is that it can be injected at room temperature and solidifies at body temperature [27]–[29]. Additionally, several studies focus on the direct effect of neuronal growth by itself but do not focus on the combined effect of physical therapy. The use of combinational therapy with hydrogel-based scaffolds seems to be the direction in which the treatment of SCI is heading, but more research is still needed in this field before clinical trials can be performed [2], [6]. Our study fills in the gap of what happens when the use of a novel biomaterial such as PNIPAAm-g-PEG loaded with NT-3 and BDNF neurotrophins is provided and identifying any synergetic benefit with treadmill training. More about the kinematics aspect of the study is discussed in Chapter 4.

Chapter 4

Kinematics

4.1 Overview

Kinematics is simply the study of the motion of objects or segments without considering the forces involved in producing the motion [30]–[32]. Kinematics is typically studied in biomechanics when the objective is to study how parts of the body move when other factors involved, such as the forces required, are not relevant. A kinematic study serves as a good starting point in the studies we are performing as it is relatively easy to measure and does not require an overly complicated setup.

4.1.1 Gait analysis. Gait is a term that refers to bipedal locomotion, which requires coordination of several joints and muscles. The analysis of gait itself has been a major aspect of physical therapy and rehabilitation in a clinical setting and with technological advances. The practice of gait analysis itself is becoming easier, more accessible than ever, and allows more people to understand it [31]. Some aspects that are looked at as a part of gait analysis are range of motion in all three anatomical planes, joint angles, swing-stance durations, and forces imparted. Gait analysis can be achieved in several different ways, including the use of stopwatches[13], [33], [34]; switches and writing instruments for distance and time measurement; accelerometers[35], electrogoniometers [36][37], and motion capture systems for angle measurements [16], [34], [38]–[40]; force and pressure

plates[37], and electromyography (EMG) [5], [12], [36], [41]. We focused mainly on a motion capture system to study gait in our experiments.

4.2 Available Kinematic Studies

4.2.1 Human studies. Efforts to help improve human kinematics have typically been performed with robotic gait training systems and BWSTT as a form of physical therapy (PT) [3], [4], [14], [42]. Both treatments are related to each other; robotic gait training is based on BWSTT [14]. Some of the studies in question focus on using robotic training alone such as the Fleerkotte et al. study; but BWSTT studies in combination with EMG and other methods for evaluating locomotion are more abundant and are easier to set up.

4.2.1.1 Effect of BWSTT on kinematics in humans. The determination of the efficacy of BWSTT systems is still at an early stage, despite the fact that several systems have been on the market for some time [14]. For the referenced robotic gait training study by Fleerkotte et al., out of the 10 study participants that completed the study in 8 weeks, between 89% and 100% of participants experienced improved kinematics such as step length (average increase of 0.03 m), hip range of motion (ROM) (increase of 2 degrees), with a 22% participant increase in symmetrical use of both legs. On average, walking speeds increased for their 6 and 10 meter walking tests to a speed of 0.06 m/s with 9/10 subjects experiencing improvements. The experiments of Fleerkotte et al. also indicated increase in total walking distance throughout the total rehabilitation durations that were not fixed distances (184 m to 216 m), with 100% participant improvement. They concluded that robotic gait train

is a feasible method of improving the walking ability for people with an incomplete SCI. While this treatment uses a form of BWSTT, the use of a robotic system helps to reduce the amount of labor and discomfort from the trainers [14]. Unlike the robotic system however, BWSTT has established literature to show its beneficial effects on locomotion and kinematics [43]–[47]. While there are several studies that demonstrate that BWSTT can improve locomotion, some other studies that used BWSTT such as Dobkin et al. included patients who, after BWSTT, underwent improvements that were not significant compared to other therapies. The Dobkin et al. study involved BWSTT and a more basic over-ground mobility training over the course of 12 weeks with follow-up at 6 months. The participants all had an SCI within 8 weeks at the start of the study, and were classified as a C and D on the ASIA scale (see Table 1). In both groups, the participants who were able to walk at the end of 6 months had improved kinematics such as speed and distance walked, and increased Walking Index for SCI scores, but the study did not produce different results between the two therapies. The study does highlight however that "BWSTT may be a valuable training adjunct in future trials of biologic interventions that promote axonal regeneration [42]."

4.2.2 Animal studies. Compared to human studies, animal studies involving SCI are more abundant. A great deal of kinematic studies involve rats [5], [19], [40], [48]–[51] but there are some studies where other animals such as rabbits or cats were used [52], [53]. As with the human studies, there is a focus on BWSTT; but in addition, there are also studies on the use of biomaterial scaffolds and

combinational treatments that aim to help axonal regeneration that can lead to regained motor function [2], [22], [51], [54].

4.2.2.1 Effect of BWSTT on kinematics in animals.

Before BWSTT was implemented in human studies, it was first developed from SCI animal models. While it has been studied for nearly 30 years and has had success in animal models, BWSTT procedures still need additional refining if the ultimate goal of rehabilitation is to regain motor function [19]. Some of the studies that have shown some success with BWSTT are Alluin et al. and Singh et al. [5], [40]. The Alluin et al. study evaluated the recovery of several kinematic parameters in rats, such as the number of consecutive steps walked on the treadmill, paw placement, and cycle alteration. Researchers trained the rats on a treadmill for 6 weeks of treatment after a contusion SCI and then evaluated each of these parameters. These parameters allowed them to classify locomotion into a scale between 0 and 3, where 3 were the best walkers and 0 were the worst, or those that did not walk at all.

The study's kinematic results indicated that hind limb training did increase "swing duration variation during locomotion." They also indicated that locomotion could recover to a certain degree, but that the method of recovery was not limited to only BWSTT or to training before a SCI. These results help establish a baseline in terms of establishing how effective a specific treatment helps at improving locomotion. A figure of their swing and stance durations are shown in *Figure 6* [40].

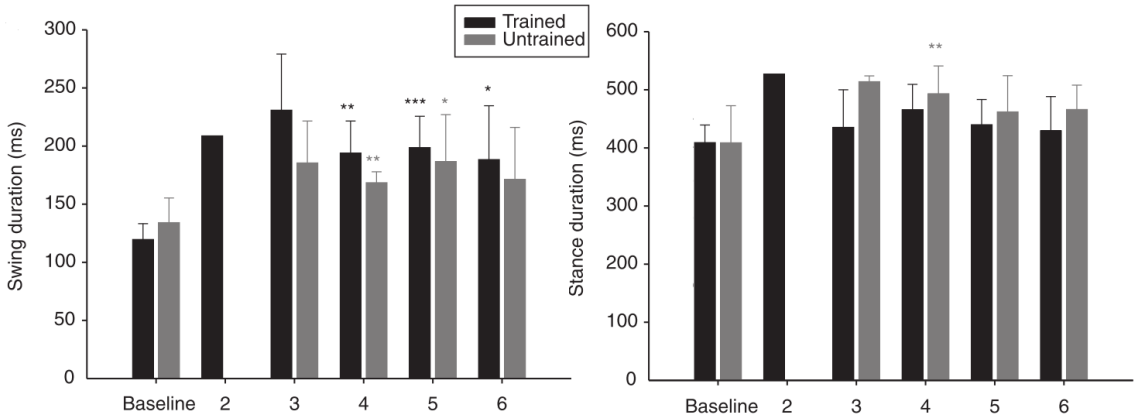


Figure 6. Swing and Stance duration plots from Alluin et al. 's study [40]

Singh et al. study studied how effective locomotive recovery was in animals that received a contusion SCI that underwent BWSTT. The animals in the study had BWSTT after injury for 8 weeks, with a second transection surgery at 9 weeks and an additional 2 weeks of training. The researchers looked at parameters such as the length and height of step, and duration of the swing stance phases. Throughout the training, there was significant difference between the groups with BWSTT and no BWSTT at Week 5, but not at Week 9 in terms of swing duration, step height, and length. BWSTT for the groups that received the transection surgery at Week 9, the groups did not experience immediate locomotive loss, unlike the untrained groups. This result highlights that BWSTT may be required for maintenance of locomotive recovery and that it can help accelerate locomotive recovery, although it might not produce a better outcome. A figure of their step height and duration is shown in *Figure 7* [5].

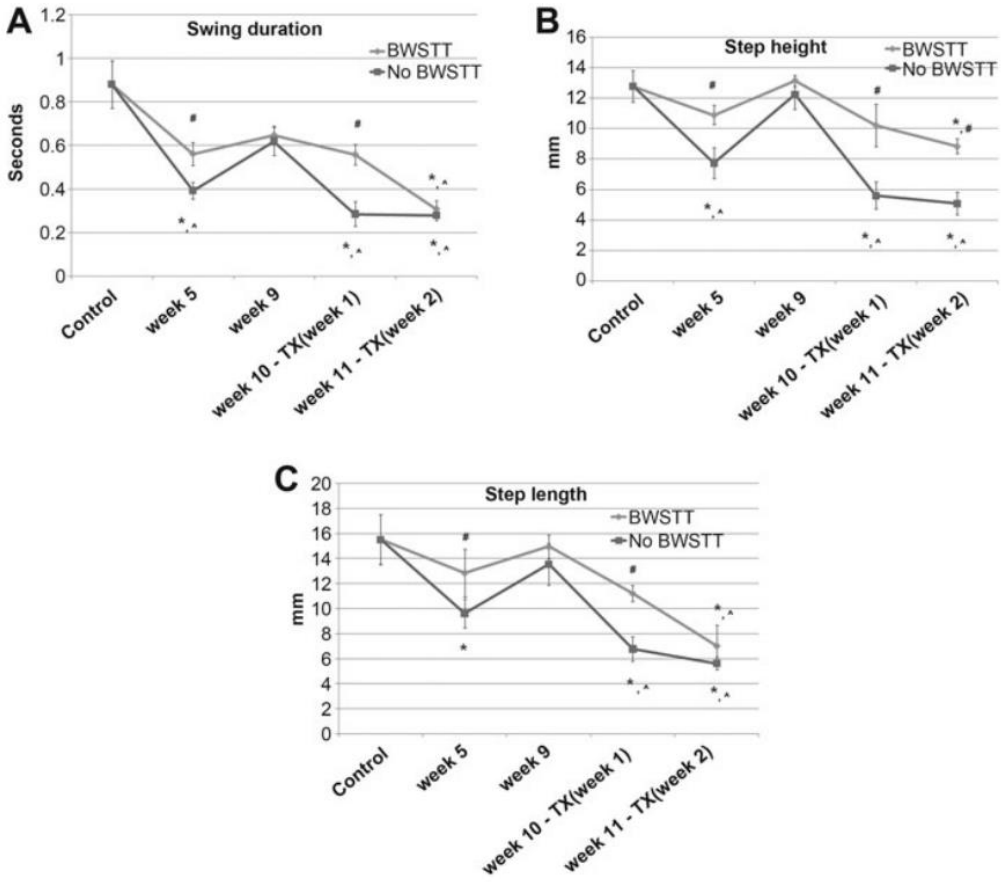


Figure 7. Step height, length, and swing duration result plots in Singh et al. [5].

It is important to note that some of these results, although beneficial in animal studies, did not translate as well to human studies. This warrants animal studies to better understand human outcomes studies with BWSTT therapy, such as the use of body weight support apparatuses that are not limited to just a treadmill [19]. Some of the ideas that have been present in literature are therapies that include the use of biomaterials aid in the formation of new axonal pathways, are discussed in the next chapter.

4.2.2.2 Effect of biomaterials on kinematics.

Newer studies utilize biomaterial scaffolds that aid in neural regrowth [2], [6], [12], [23], [25], but there are few studies comparing the effect of the use of biomaterial scaffolds after SCI to gait analysis. One study that reviews the existing literature on biomaterial for use with neural regeneration is Tsintou et al. This study found that many researchers are turning to therapies that involve the use of a scaffold combined with the use of cell or neurotrophic factors and have shown that there is some success in neural regeneration *in vitro* and *in vivo* with a few animal models. However, the technology is still in its infancy, and it is too early to determine its effectiveness [6]. Our experiments aimed to provide more clarity from a kinematic perspective through gait analysis when a biomaterial scaffold infused with neurotrophins was combined with BWSTT in a partial SCI animal model.

Chapter 5

Experimental Setup

In order to simulate a small treadmill for our animal experiments, a custom treadmill was designed from a modified belt sander hooked up to a stepper motor. A body weight support (BWS) arm mechanism was also developed as a part of the treadmill. The arm had a plate attached to it on one end to allow the animal to be connected to it via a vest and velcro straps. A load cell was attached on the other side of the arm. This load cell was designed to read the weight the animal was exerting on the BWS arm while it was walking on the treadmill. There was an additional stepper motor to control the amount of weight the arm needed to support, by applying a load on the other side of the arm. A picture of this treadmill setup is shown in *Figure 8*. It is similar to that of those setups used in Singh et al., Kruse et al., Nessler et al., and De Leon et al. just without the robotics arms [5], [16], [55], [56]. All of the components of the treadmill and BWS arm were controlled through a data acquisition unit or myDAQ® that is controlled with a custom LabVIEW® program (National Instruments, Austin, TX).

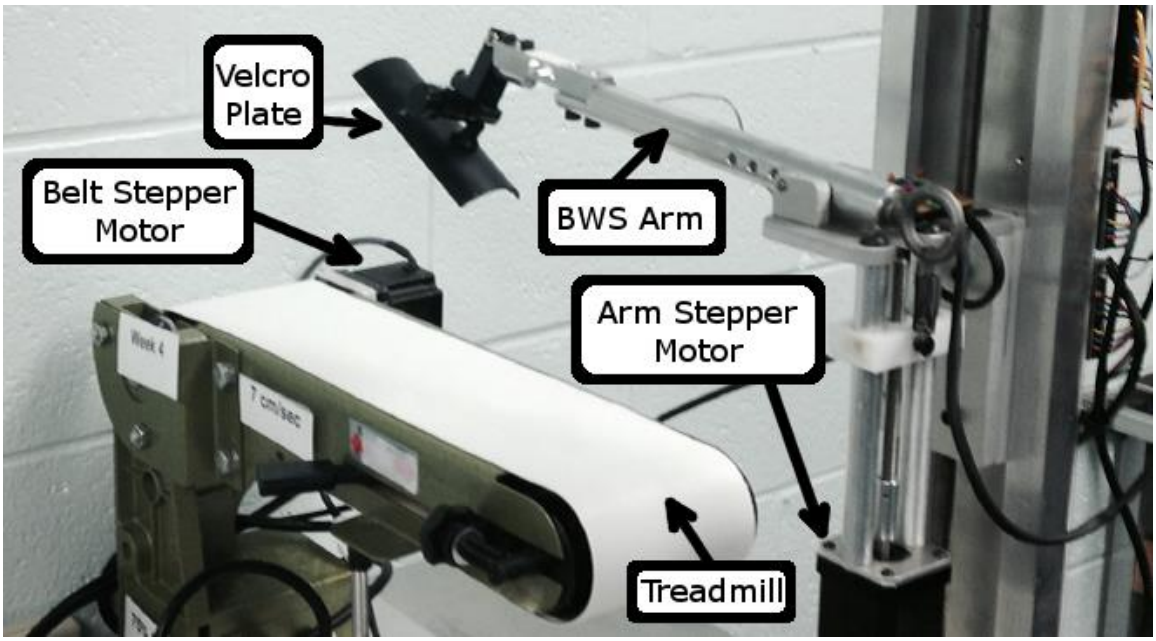


Figure 8. A Figure of the Treadmill used for BWSTT. The Treadmill belt was controlled by a stepper motor. The animal was attached to the velcro plate on BWS arm and secured with velcro straps. The weight that the animal displaced was controlled by the arm stepper motor by applying a load to it.

This custom treadmill was placed on a steel table about 48" high. Before the animal was placed on the treadmill, its back left leg was shaved and the motion capture marker placements were marked on the skin before placing the adhesive markers on the leg joints of the animal. Markers were placed on the following five spots: the iliac bone, hip joint, knee joint, ankle joint, and the metatarsal. More details on the markers and motion capturing aspects are discussed in Chapter 5.1. The animal was then carefully placed in a vest that allows its head and sometimes its arms to peek through the vest. The positioning of the animal with labeled markers is shown in *Figure 9*.

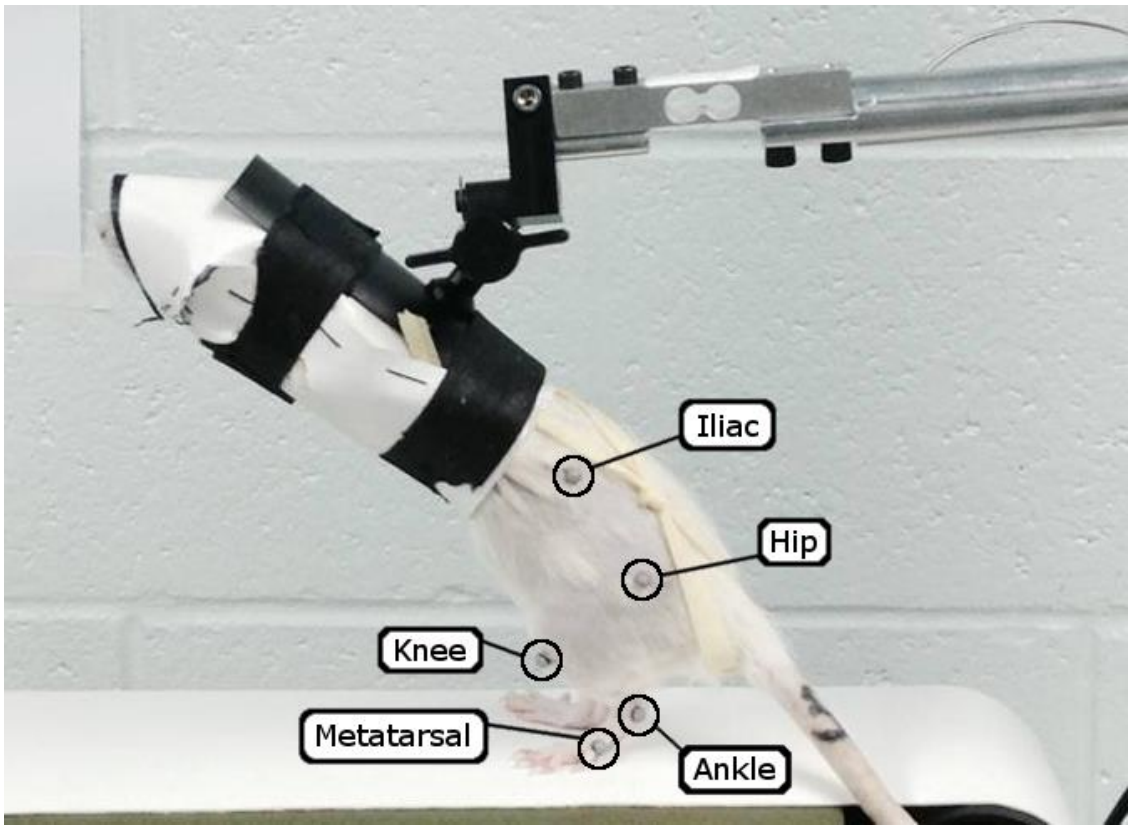


Figure 9. The positioning of the animal on the treadmill. Before it was placed on the treadmill, the left hind leg is shaved, and then the marker placements are marked and then overlaid with reflective markers. The animal is then secured to BWS arm to the velcro plate with velcro straps. The five markers that are placed on the animal are labeled as such.

In order to get the motion capture data necessary for the overall experiment, an OptiTrack (Natural Point Inc., Corvallis, OR) infrared motion capture system was implemented. This system was chosen based on its cost to frame rate ratio and resolution ratio compared to other commensurate systems. More details discussing the specifics of the camera system and how it was configured are discussed in Chapter 5.1.

To properly evaluate the performance of the PNIPAAM-g-PEG scaffold with NT-3 and BDNF neurotrophins, each set of animals was split into five different

experimental groups: Baseline, Injury, BWSTT, Implant, and Combination groups. Each of these groups gave a comparison point of different treatment options from which effectiveness of the biomaterial by itself or combined with existing therapies could be measured. Each of the animals walked on the treadmill at three different body weight supports (75%, 65%, 55%) and at two different speeds (7 cm/s and 10 cm/s). The number of animals that performed each of these speeds and BWS varied depending on the animals' ability. The groups themselves are discussed in more detail in Chapter 5.2.

5.1 Motion Capture System

Motion Capture is a way of recording a target within a capture volume with multiple cameras synced together from which 3D motion is extracted [57]. The specific system used is known as a passive reflective marker system. This system works by taking infrared light from markers placed in specific spots on a target and reflecting the light back to the camera [57]. Our motion capture system was capable of tracking markers with sub-millimeter accuracy with ideal capture volume size, lighting, and camera configuration [57]. By utilizing motion capture technology, we were able to obtain a more in depth look at the animals' gait, such as measuring joint angles, ranges, and excursions, for each animal. Then, we compared that data to the different animals in each set. Our motion capture setup consisted of three motion capture cameras: 2 Flex 3s and 1 Flex 13, both from OptiTrack. When synced together, all three cameras could record at 100 frames per second (FPS) (100 FPS for the Flex 3 and 120 FPS for the Flex 13 by themselves). The Flex 3s produced an image resolution of 640x480 and the Flex 13 had a resolution of 1280x1024. Both

cameras were capable of sub-millimeter precision and were powered and synchronized through a standard USB 2.0 connection [58], [59]. The cameras are further discussed in Chapter 5.1.1. In addition to the cameras, some of the additional equipment needed for the motion capture setup includes the motion capture software Motive (Natural Point Inc., Corvallis, OR), a hardware key for the software, a computer, tripods, a USB hub to power the cameras, calibration wand, adhesive markers, USB cables, and a ground plane square (or three reflective markers).

5.1.1 Camera layout. To accurately and properly capture the motion of the animal walking on the treadmill, the motion capture cameras were placed in a certain way such that 3D tracking data could be captured from any camera location. Since we were interested only in the left hind leg of the animal, the camera was positioned such that it was able to determine the location of each marker on the one hind leg. This allowed us to keep the cameras in close confinement with limited space. One issue that arose from limited space is the increased chance of inaccurate marker position data. This problem can be mitigated and is entirely dependent on the position of the cameras. Since the process of optical motion capturing works by comparing at least two different 2D images at the same point in time to generate position in a 3D capture volume, the cameras have to be at opposing angles so that there is overlap in each of the 2D images. The more overlapping images in the camera system, the more accurate the motion capture data. Since the animal was only going to be walking on the treadmill, the size of the capture volume was relativity small. For the setup, we had the Flex 13 orthogonal to where the hind leg would be on the treadmill. From there, our two Flex 3s would be approximately two

feet away from the Flex 13 and would each be turned to face the treadmill with an angle of around 37.5 degrees. A diagram of the camera setup from the top view is shown in Figure 10 with a labeled picture of the setup in Figure 11. The cameras also had a downward facing angle of 10 degrees to give the cameras a better view of the hind leg when it splays outward from the walking plane. The Flex 13, having the highest resolution and being in the center, allowed the capture of any marker data that might have been missed from the Flex 3s, which were at nearly opposing angles to maximize their ability to capture the position of each of the markers. All of the cameras were supported on standard camera tripods with the height being around 54" high. Any loose cabling that went from the camera to the computer was wrapped around the tripod and secured with velcro straps to prevent accidents. The cables were then connected to a high-powered USB hub, which was then connected to the computer that ran the motion capturing software. The software procedure is discussed in Chapter 5.1.3.

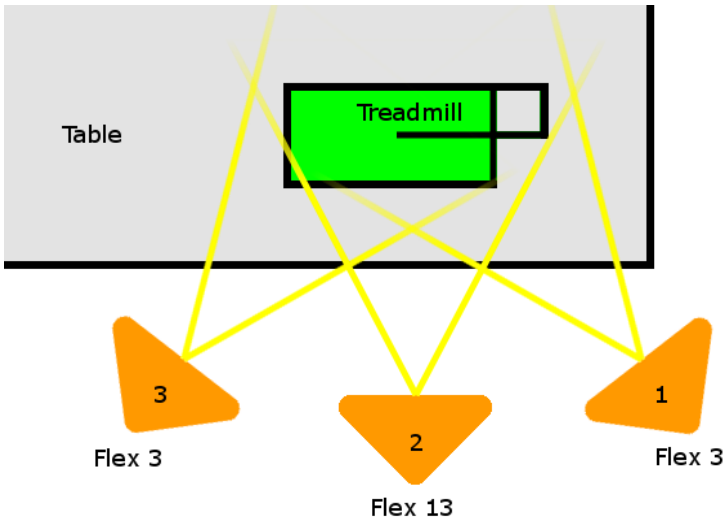


Figure 10. A Diagram of the Camera Positions with respect to the treadmill when viewed from the top. Each of the camera's field of view is indicated by each of the yellow lines, highlighting the overlapping nature of each camera view. Each camera is labeled and numbered according to the motion capture software. There is a space at the end of the table that allows the technician to manipulate the animal on and off the treadmill.

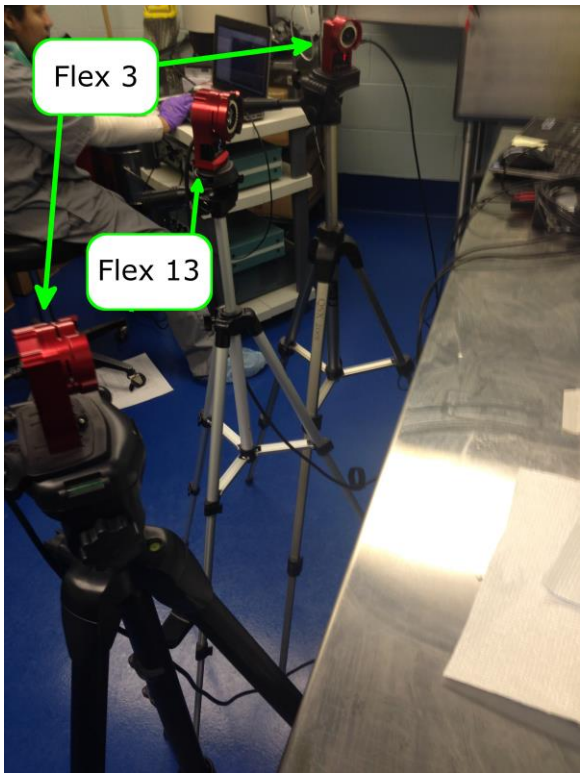


Figure 11. A labeled picture of the Camera layout when viewed from the end of the table. All three cameras are angled to the point where the animal is expected to walk on the treadmill (not shown in the picture). The Flex 3s being on the sides while the Flex 13 being in center.

5.1.2 Software and tools. The software used for recording the motion of the animal on the treadmill was Motive (Natural Point Inc., Corvallis, OR) which was designed to work with the OptiTrack cameras. Using the cameras over USB made it essentially plug and play, but camera specific settings such as camera threshold and exposure settings, needed to be configured before calibration. Exposure was how much light reached the camera and the threshold was the minimum brightness that allowed a pixel to be recognized as a marker [60]. The specifics on how these setting were changed are discussed in Chapter 5.1.3. To properly calibrate the camera system, a calibration wand and three individual markers or calibration squares

were needed. The calibration wand was just three markers on a ridged arm spaced 100mm between the first and second marker and 150mm between the second and third one. Since the wand was a set length with all three markers on the same plane, and with each camera stationary, distance and position were able to be calculated, as long as the wand was waved over the area where the motion capture was expected. The procedure for performing this is discussed in Chapter 5.1.3. When the calibration itself was completed, the software needed to know where the origin is with respect to the cameras, which was accomplished with a triangle or just three markers that formed a right angle on the same plane. The markers that were to be used on the animals themselves were simple 5mm facial markers with an adhesive backing.

5.1.3 Motion capture procedure. Since the process behind motion capturing was software-based in Motive, a specific procedure was needed to reliably capture the animals' repeated performances on the treadmill. The process was broken down into three different phases: setup, calibration, and capture.

Setup involved placing the treadmill in the center or to the front of center of the table for easy access. The placement was marked with tape as the treadmill was moved during the calibration procedure. Then each of the cameras were attached to its respective tripod, connecting a USB cord to the computer running Motive. The camera's placement is shown in Figure 10 and Figure 11. The excess cables were gathered together and secured so that the animal handlers did not trip over the cords. Once the cameras were plugged in and attached to the hub, it was necessary to fine-tune the position of the camera using the camera views in Motive. Once

Motive was open, the calibration pane was then selected, and the cameras positioned to focus on the animal as it walked on the treadmill, as highlighted in Figure 10. The exposure and threshold settings were then set up; they were dependent on the lighting in the room, and they helped ensure that only the reflective markers showed up in Motive without any false positives. For the most part, the settings were consistent as the lighting stayed constant, with slight variations from day to day. A table of the default values for exposure and threshold for each camera is shown in Table 3. Camera views in the calibration panes looked like the views in Figure 12. The camera was positioned while the cameras were in reference mode, while the proper exposure and threshold setting were set in tracking mode (default). Tracking or reference mode were triggered by clicking the camera icon (current mode: reference mode) or target icon (current mode: tracking mode) to change between the two modes. If necessary, a masking tool was used to identify an area as false, but it was used with caution, as markers were then prevented from showing up in that mask.

Table 3

Default Values for Threshold and Exposure for the Flex 13 and Flex 3 Camera for the normal lighting environment in the vivarium that produced the most ideal results between marker sensitivity and no false positive markers.

Default Values	**Flex 3**	**Flex 13**
Threshold	231	231
Exposure	5	55

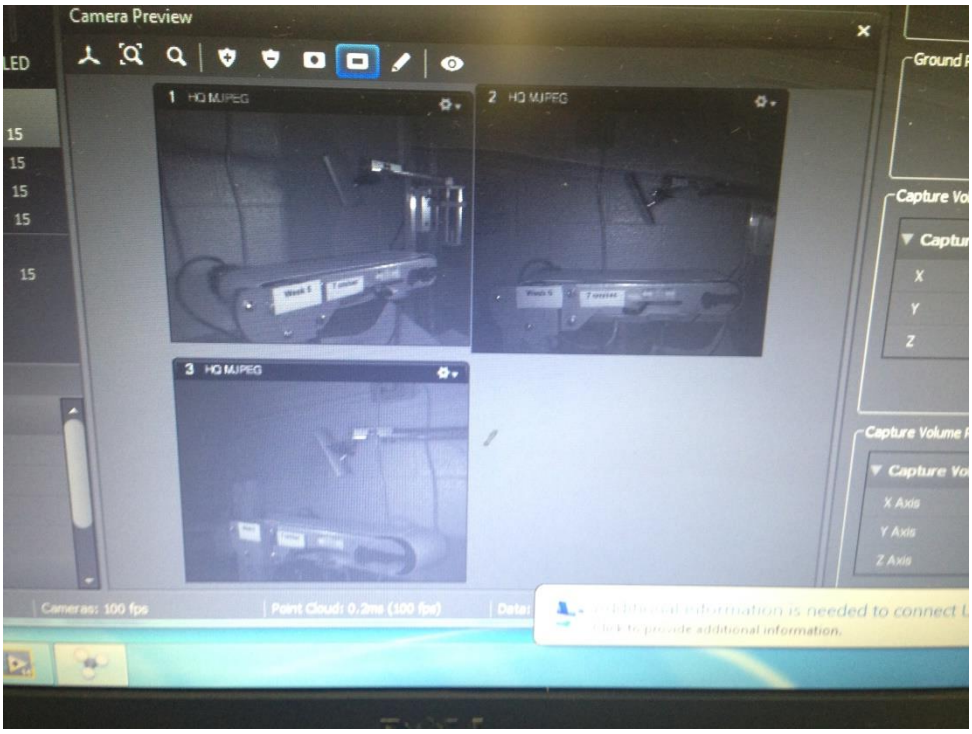


Figure 12. A picture of the camera views as shown in the Motive Calibration Pane, in reference mode. All camera views are centered on the animal walking on the treadmill.

Once all of the cameras were set up in the correct position and the proper values were set, the cameras were placed into tracking mode; the calibration was then able to begin, while making sure the wand size was set to small or 250mm. The treadmill first needed to be pushed aside so that there was room to wand the control volume. Calibration began by clicking the “start wanding” button. It starts to record and take samples once the cameras recognize the wand. For proper calibration, it was important that the wand be waved in the largest area possible while being concentrated on areas of greatest movement. Motive indicated when it had a sufficient number of samples to calibrate the system, but the more samples recorded, the better the calibration results were. Since our capture volume was on

the small side, we increased the number of samples slightly beyond Motive's recommendations. From our experience and as part of the procedure, calibration only stopped when each camera recorded over 1,000 sample points. Anything lower resulted in less than ideal calibration calculation results.

After the cameras were calibrated, the cameras could not be disturbed. If the cameras were accidentally bumped, the entire system had to be recalibrated. However, Motive made recalibration easier by offering a recalibration option. This option required fewer samples to recalibrate (in our case, 500) by utilizing its initial position as an initial condition. After calibration, the capture phase procedure for each animal began. Before the first animal was placed on the treadmill, a Marker Set was created in the Edit Pane. This allowed a marker set or marker label to be added to every take, as opposed to one at a time for every take. The markers were then labeled according to their respective placement on the animal: "Iliac," "Hip," "Knee," "Ankle," and "Metatarsal." Then the animal was then prepped to be placed on the treadmill. This involved shaving the animal's left hind leg, marking the marker placement with a permanent marker, placing the animal in a vest to secure its upper arms, and placing the marker. Five markers were necessary because, at least three markers were needed in order to calculate an angle; then there needed to be two additional markers, from which an angle was not measured, for joint position. The additional markers were also used as anchor points for determining the joint angle distal or proximal to the marker. To make sure the position of the markers was as accurate as possible; they were placed on top of a bony structure, which reduced the amount of movement of the skin when the animal was walking. The iliac marker was

placed on the superior end of the iliac crest; the hip marker was on top of the greater trochanter; the knee marker was placed on the axis of rotation itself; the ankle marker was placed on top of the lateral malleolus; and the metatarsal marker was placed on the fifth metatarsal head (most lateral metatarsal). A diagram showing the marker positions with respect to the bones and joints themselves is shown in Figure 13.

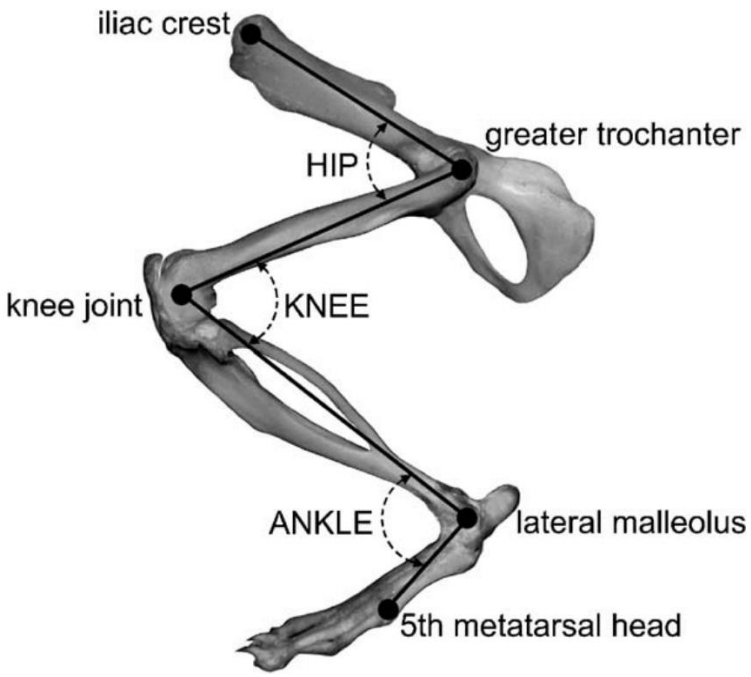


Figure 13. A diagram of the animal's left hind leg highlighting the bone locations where the markers were placed from above the skin showing the three angles that can be calculated from these five marker locations. From J. Pereira et al. [61]

Once the markers were placed on the animal, they needed to be secured into the velcro plate on the BWS arm with straps. Once it was set, the animal was in a position illustrated in *Figure 9*. Motive was then set up to record the motion capture and the treadmill controls were started. Load cell data were logged. After completion of the motion capture, the project folder viewer was renamed to the

desired nomenclature. The nomenclature we used was: *AnimalNumber-WeekNumber-TakeNumber-Speed-%BWS-Notes.* Animal Number was the number that the animal it was given, the week number was the time, which it was tested on (i.e. Baseline, week 4, and week 8), the speed was the speed of the treadmill, and the %BWS was the BWS of the animal that was tested on the treadmill. Any additional notes were added to the end of the take file name. This nomenclature was translated to later aspects of the project for files names. The take was then quickly examined in Motive to confirm it was suitable for future data analysis. If so, then the process was repeated with different treadmill speeds (7cm/s and 10 cm/s), different BWS (75%, 65%, 55%) and different animals.

5.2 Experimental Groups

The different groups were necessary to evaluate efficacy of the PNIPAAM-g-PEG implant with NT-3 and BDNF neurotrophins and its effect on improved gait after. To properly determine the treatments effectiveness, it needed to be compared to several aspects. Those aspects include how it compares to standard treatment of a normal and injured animal by itself, and how does it compare when supplemented with current treatment options. Five different factors need to be considered, each labeled: Baseline, Injury, BWSTT, Implant, and Combination. Each of the groups was trained to walk on the treadmill under passive assistance for one week before receiving an injury. The animals received a moderate 25 mm spinal cord contusion injury with an NYU device at the T9/T10 vertebra location. The group that received an implant received it two weeks after injury. A timeline of the different treatment options and when each of them were performed are shown in *Figure 14*.

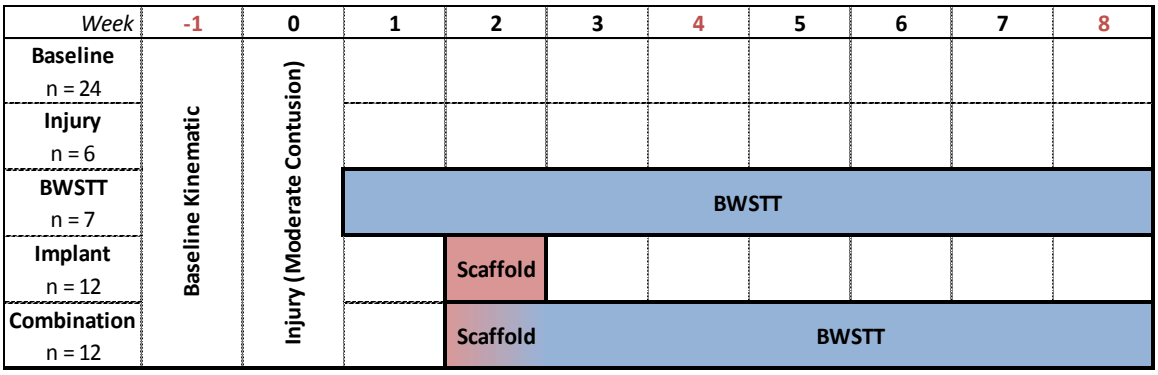


Figure 14. Timeline of the Kinematics and Treatments in the study. All Baseline kinematic readings were captured a week before injury; the remaining kinematic readings were taken at Week 4 and 8. N values are the number of animals that were placed into each group but it does not reflect the number of animals that completed the kinematic study. The Baseline n is the number animals to complete a baseline reading.

5.2.1 Baseline. The Baseline group was simply a group of normal animals that had been trained to walk on the treadmill with no treatments or injuries applied to it. Thus, this group was considered the best case scenario in terms of recovery. In our experiments, we set every animal with a baseline reading into a Baseline group; after they received an injury, they were then split up into the remaining four groups.

5.2.2 Injury. The Injury group was a group of animals that had been trained to walk on the treadmill but received an SCI after getting a baseline reading on the treadmill. This effectively was the opposite of the Baseline in that it served as the worst case scenario in terms of recovery, as there was no treatment options performed.

5.2.3 BWSTT. The BWSTT group was a group of animals that had been trained to walk on the treadmill, received a SCI, and, after the injury, that had

undergone rehabilitation using body weight support treadmill training or BWSTT for 8 weeks. For our study, this group was trained immediately after surgery for about 1000 steps a day, 5 days a week, for 8 weeks.

5.2.4 Implant The Implant group was a group of animals that had been trained to walk on the treadmill, received a SCI, and, 2 weeks after the injury, and had a PNIPAAM-g-PEG scaffold with NT-3 and BDNF neurotrophins implanted at the injury site. No further rehabilitation was implemented.

5.2.5 Combination. The Combination group was a group of animals that had been trained to walk on the treadmill, received a SCI, and 2 weeks after the Injury had a PNIPAAM-g-PEG scaffold with NT-3 and BDNF neurotrophins implanted at the injury site and received BWSTT for 8 weeks after implant surgery.

Chapter 6

Data Analysis

6.1 Motive Processing

Once all of the motion capture data were recorded and completed, the motion capture data had to be preprocessed to prepare it and obtain the required data. It should be noted that not all of the takes met our classification of analyzable data. For a take to be considered analyzable, the take had to contain greater than three continuous strides on the treadmill with minimal take imperfections. Approximately 75% of the takes contained data that could be processed using MATLAB code (further details in Chapter 6.4), while the rest of the takes either underwent manual evaluation that involved counting the number of steps on the treadmill and describing how the animal walked, or could not receive either MATLAB or manual evaluation. A chart breaking down the number of takes is shown in *Figure 15*.

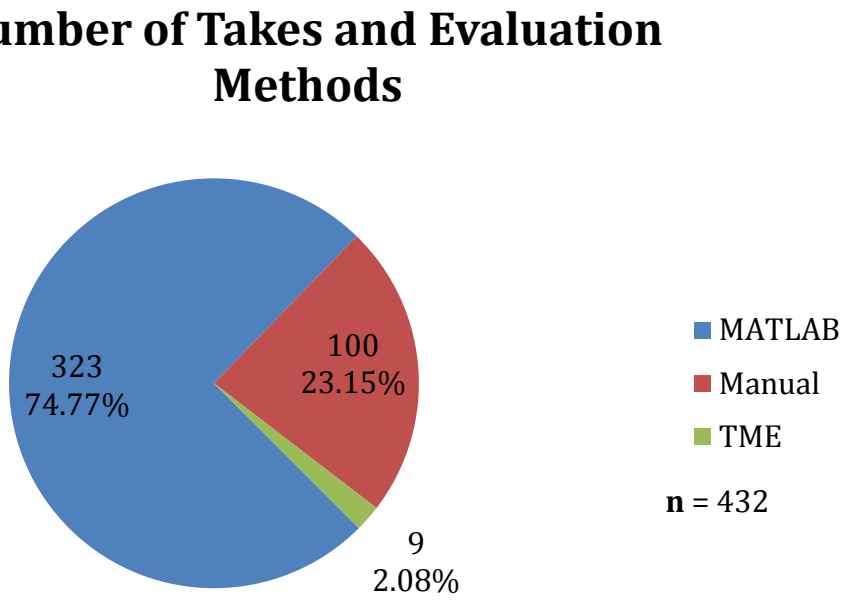


Figure 15. Chart of the total number of takes and whether they could be analyzed through MATLAB, manually or could not be analyzed due to too much error (TME), n = 432.

6.1.1 Noise removal. Because of the nature of marker based motion capturing, there are some unavoidable errors in the motion capturing data, even with all of the proper precautions [62]. These include noisy, extra, missing, or merged markers that affect the results. This can happen for a variety of reasons, including but not limited to sudden changes in movement, dropped frames, occlusions from view of the camera, and random noise that appears in the motion capture data [32]. Motive itself has tools built-in that allowed us to properly handle these issues. These include tools to remove the ends of markers with gaps, to fill in gaps in markers with different interpolation methods, to smooth out markers with noise, and to swap and merge marker labels. While Motive does provide the tools available to fix gaps and erroneous markers, they could not be excessively used [62].

Since each edit added unavoidable additional error, each take had to be investigated and evaluated as to whether it was suitable for analysis. Takes that were too noisy and or of poor quality, such as those containing lots of "jumping" and discontinuous markers, were not analyzed. Out of 332 motion capture takes that met the criteria for MATLAB or manual analyzing, nine takes (2.71%) were not used due to having excessive noise and jumpy markers. If the error correction tool were used for these nine takes, it would not be a realistic representation of the actual motion of the marker due to inability to differentiate noise from actual markers.

There were several types of noise profiles in all different spots in the take. Some of the easiest noises to manage were with no movements present, as shown in *Figure 16*. By looking at the entire take and surrounding frames, it could be concluded that there was no movement, especially considering the magnitude of the noise profile was the same for all of the spikes. It could also be classified as noise because both the *y* coordinate and *z* coordinate jumped position in similar ways, which would not be typical of normal gait movement. This noise profile was not exclusive to nonmoving markers, as seen in *Figure 17* and could be handled as though there were no movement. Any small residual jumps were smoothed out using the smooth tool when there was not much change in marker movements. In terms of the settings for frequency, the more marker movement, the higher the frequencies were used (approximately 10 Hz compared to 6 Hz for no movement; with 8 Hz being the default). These frequencies were chosen based on the recommendation from the Motive documentation and experimentation from test takes.

Figure 16. Stages involved to manually removing noise from a marker that is not moving. Note the noise spikes are all increased at the same magnitude and can easily be removed by selecting and moving them all. This noise profile was seen multiple times even when there was movement present.

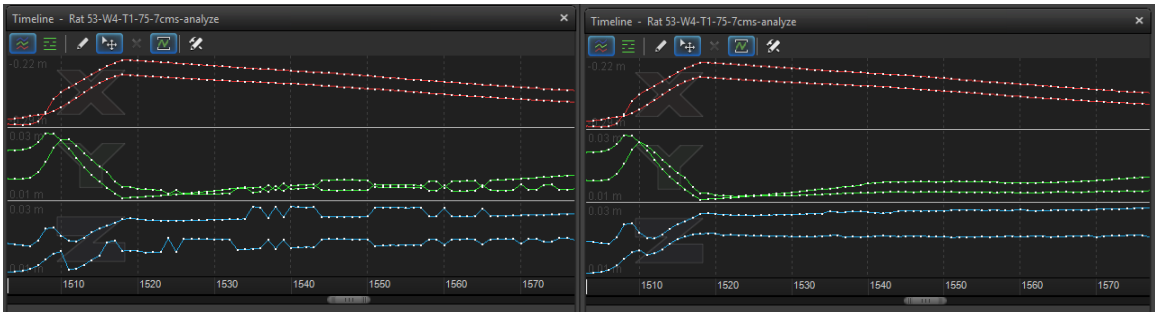


Figure 17. A noise profile similar to that of the profile shown in *Figure 16* except with marker movement. The left panel shows the marker path with noise and noise removed utilizing the same techniques as in Figure 16. After the noise was manually removed, the stance portion of the tracking (the linear region) was smoothed with a frequency of approximately 8 Hz.

In some circumstances, there were instances where two markers are so close together, as with the metatarsal and ankle marker, that Motive either classified it as one marker, or confused the trajectories of one marker with the other. These examples can be seen in *Figure 18*. To help fix this error, normal noise-removing techniques could help properly identify where the marker belonged. However, this was not always enough. In these cases, the gap-filling tool was used to fill in missing marker data, based on extrapolations of position data to a reference marker. For example, if the ankle marker needed to have gaps filled, the metatarsal, and knee marker would be used as reference markers. If noise was not removed to a

reasonable level, a section of the take could be re-trajectorized, to recalculate where the marker position would be. Re-trajectorizing parts of the take undoes everything selected; thus it was done only when the noise-remove procedure was performed poorly or did not remove enough noise. *Figure 19* shows how re-trajectorizing a take could affect noise profiles.

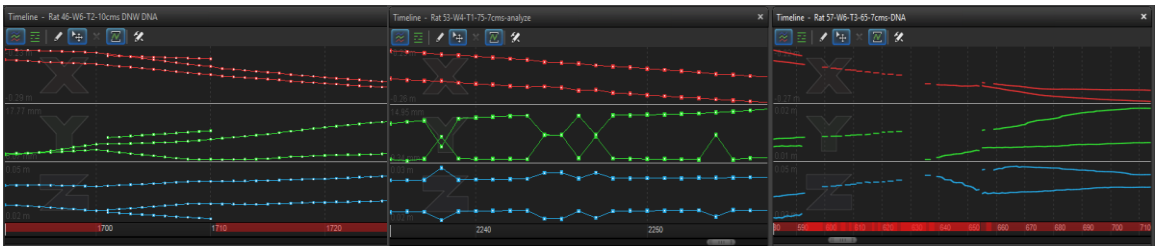


Figure 18. Example of marker trajectories combining to erroneously create a marker (left). Existing markers jump to meet in the middle to effectively "merge together" (center). One trajectory of a marker combines with different components of another marker (right).

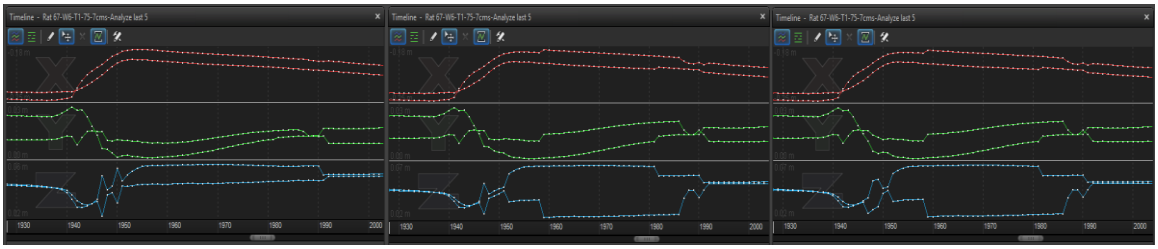


Figure 19. Examples of Noise Profiles and how they change from before being trajectorized (left), trajectorizing once (middle) and a second time (right). This tool helped in differentiating noise versus actual marker movement based on movement changes after trajectorizing.

After the take was processed and take noise removed for three to five consecutive strides, the desired stride range was then marked and the heel strike and toe off frame was labeled and recorded in a spreadsheet for additional processing. Once

these points were labeled, the take range was exported as a CSV file to prepare for MATLAB processing.

6.2 Excel CSV Processing

After a take was post-processed in Motive, it then needed to be exported as a CSV file, which was then processed in MATLAB. To help with that import process, only the desired range of the take was analyzed and exported from Motive to a CSV file. It was saved in the following nomenclature: *AnimalNumber-WeekNumber-Speed-%BWS.* After the file was exported, it was then run through a custom Excel Visual Basic for Applications (VBA) script to clean up all of the unnecessary information from the CSV file and make it easier to import into MATLAB. The CSV file contained the raw coordinates of each marker for every frame, including the frame number and time data. This means that there were 17 columns of data for the take (3 columns per marker, 5 markers). The *x*, *y*, and *z* coordinates were based on the origin, defined at the commencement of the take, from the three markers placed on the treadmill.

6.3 MATLAB

MATLAB or Matrix Laboratory (MathWorks, Inc., Natick, MA) is mathematical computational software that was the basis of the data analysis of this project and was used to compute key values such as angles and ranges while also providing visual plots of the data. It is run off script files and functions that are in its own language. The data from the exported CSVs needed to be converted to a MAT file for the code that was used for this study to work. A MAT file is simply a data file that

makes it easier to read in MATLAB. The CSV files were imported and then saved as a MAT file so it could be easily referenced later for processing.

6.4 Code

The code that was used in for the MATLAB processing was a 570 line piece of code that was essentially designed to do three types of mathematical operations, and export three tables and seven plots. This code was designed to process five consecutive strides in a take. There were two derivatives of this code that process three and four strides in a take, and produced less data and plots. The three different calculations in all of the codes were dot product, range and excursion calculations, and mapping functions. The dot product was used to calculate the joint angle between three markers to produce hip, knee, and ankle angles. This calculation could be considered the most important calculation in the entire code. The range and excursion aspect was essentially just subtraction and finding the maximum and minimum joint angle per stride. The mapping function was an interpolation of the individual stride angles and samples so that there were 101 readings. This process normalized all of the stride angles so that they were all the same length and could properly be compared to each other. The mapped data for this round of experiments were only for plotting, group comparison purposes, but exported in one of the three tables so that future data analysis could be performed. Although the code could do all of the calculations, the entry of the data (e.g., telling it which take analysis and when the strides started) had to be manually imported. The process of importing the necessary data, was simply typing in a few strings, such as the MAT file name, and the elements of the MAT file name, such as the animal

number, week number, speed, %BWS, and the group number. Additionally, it involved inputting the frame numbers of heel location, as that was how the code broke up the individual strides. This input section of the code is shown in *Figure 20*. The individual heel strikes for each take were recorded in a spreadsheet; it was also indicated whether that take was analyzed or not. That sheet can be found in Appendix B: Stride Table

```
17  load('56-Week4-10cms-75%'); % Loads Data From Pre-created MAT File
18
19  ratset = 'Set 3';
20  rat = '56';
21  test = 'Week 4';
22  speed = '10';
23  bws = '75';
24  group = '3';
25  int = 'spline';   % Interpolation method
26
27  s(1) = Frame(1);    % frame for splitting data to individual strides
28  s(2) = 452;
29  s(3) = 565;
30  s(4) = 709;
31  s(5) = 851;
32  s(6) = Frame(end);
33
34  lps = 0;   % Number of Stick Figure Lines to Plot (Set 0 for full sample)
```

Figure 20. The first few line of the MATLAB code which required user input. The code required the input of the MAT file name, properties of take, and the heel strike frame number of the desired take. In this case it was Animal 56, Week 4, 10 cm/s, 75% BWS, and it was in BWSTT group. The heel strikes were present in frame numbers 452, 565, 709, 851 in addition to the first and last frame of the take.

The breakdown of the code was as follows:

- Import the data from the pre-created MAT file
- Split the take into individual strides

- Perform the Dot Product on the Coordinates of each marker at each frame to produce joint angles throughout the entire take
- Calculate the angle ranges and joint excursions for each joint and stride
- Map each stride joint angle to 101 points
- Plot stick figure plots for each stride
- Plot joint angles plot throughout the entire take and a mapped stride plot.
- Export mapped stride data, take average data, and individual stride data in CSV files.

The main MATLAB code can be found in Appendix C: Main MATLAB Code.

6.4.1 Angles and excursions. The main aspect of this code was the ability to calculate the joint angles from the raw position data. This was made possible through the use of the dot product as shown in equation 1 below

$$\boldsymbol{a} \cdot \boldsymbol{b} = \|\boldsymbol{a}\|\|\boldsymbol{b}\| \cos\theta = \boldsymbol{a}_x\boldsymbol{b}_x + \boldsymbol{a}_y\boldsymbol{b}_y + \boldsymbol{a}_z\boldsymbol{b}_z \quad (1)$$

with **a** and **b** being vectors, ‖**a**‖ being the magnitude of vector **a**, and *x*, *y*, and *z* being the individual coordinates of vectors **a** and **b**. Rearranging the vector and magnitude terms in term of a vector between two points we arrived at:

$$\boldsymbol{a}_x = x_2 - x_1$$

$$\boldsymbol{a}_y = y_2 - y_1 \quad (2)$$

$$\boldsymbol{a}_z = z_2 - z_1$$

$$\|\boldsymbol{a}\| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (3)$$

with *x*, *y*, and *z* being the individual coordinates of points 1 and 2. Additionally, equation 4 was rearranged to solve for θ as follows:

$$\theta = \cos^{-1} \frac{\boldsymbol{a}_x \boldsymbol{b}_x + \boldsymbol{a}_y \boldsymbol{b}_y + \boldsymbol{a}_z \boldsymbol{b}_z}{\|\boldsymbol{a}\| \|\boldsymbol{b}\|} \quad (4)$$

Since the raw data that were exported from Motive were individual points in a Cartesian coordinate system, those points could be converted to vectors, which then could be converted to angles.

In terms of ranges and excursions, they are simply a calculation between the largest and smallest angle and determined the excursion of each joint for each stride, and the ranges were just actual maximum and minimum angles.

6.5 Plots and Data

The MATLAB code, as highlighted in Chapter 6.4, was responsible for processing the kinematic data that were outputted from Motive. Three types of plots were generated: stick figure plots, angle plots of the entire take for all three joints, mapped angle plots for each of the joints, and averaged mapped angle plots per group, with an average angle chart for each joint based on the strides analyzed for that take. Plots for a selected animal in each group are shown in *Figure 21* thru *Figure 23*. Plots were additionally calculated outside of MATLAB that used some of the exported data, such as the average ranges and stride lengths. There were also plots of the number of steps that were not reliant on the use of MATLAB but rather on just the video and Motive takes. Some takes were only analyzed in Excel due to the fact that they did not meet the minimum criteria for evaluation in MATLAB but still held relevant data that allowed us to gain more insight as to why they could not be analyzed in that manner. The specific takes that were analyzed in MATLAB, Excel, both or not at all can be found in the stride table in Appendix B: Stride Table. The

use of plots in this chapter mostly highlight the use the 10cm/s treadmill speed and 75% BWS, with the exception of the number of steps taken plots. The reason for this was because this speed and BWS combinations had a reasonable number of animals in all five groups that walked at Week 4 and Week 8 to allow for statistics to be run. The rest of the speed and BWS combinations, at least one group in Week 4 or Week 8, there were not enough animals that walked to allow statistics to be run. The plots that were generated for all speed and BWS combinations and that weren't utilized in the number of step plots can be found in Appendix D: Plots from Remaining Speed and BWS Combinations.

6.5.1 Stick figure plots. Stick figure plots are plots that show the trajectory of an animal's stride in 2D space. This provides a good visualization of how a specific animal is performing as it creates a visual of each joint position at every frame throughout the stride. Strides in this case started at the heel strike and the position stick started as a cool color. As the animal moved through the stride, the different sticks become a "warmer" color, and provided an indication as to stick location during stride. Several stick figure plots for a different animal in each group are shown in Figure 21. Since the stick figures were produced from animals that had been analyzed and in the Injury group, there was no one animal that was analyzed during Week 4 and Week 8 at 10 cm/s. As a result, two different animals from the same group were used.

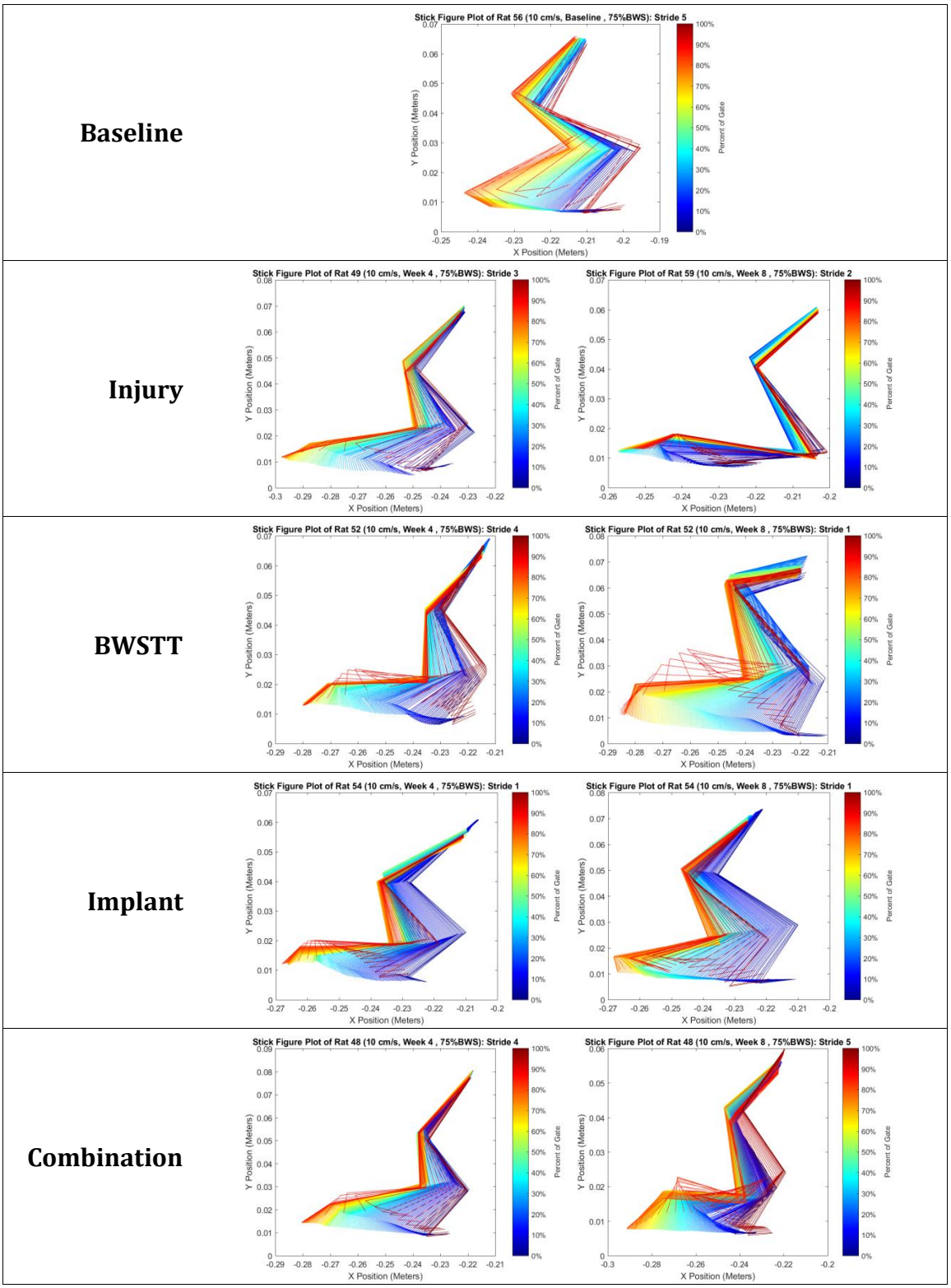


Figure 21. Stick Figure Plots for one animal in each group that walked at 10 cm/s with 75% BWS. The Injury group however had no animal, with analyzable takes that walked at both Week 4 (Left Plots) and Week 8 (Right Plots). Animals Used: 56 (Baseline), 49 and 59 (Injury), 52 (BWSTT), 54 (Implant), 48 (Combination).

6.5.2 Full angle plots. The full angle plots were simply a plot angle of all three joints throughout the entire take. The X-axis in these plots was frames, which run at a frequency of 100 Hz, so that 100 frames were one second in real time. These plots were useful in providing a better and more quantifiable visualization of the joint movements for the entire take for a specific animal. Just as with the stick figure plots, these full angle plots were generated only from animals that were analyzed in MATLAB. The animal numbers from stick figure plots in Figure 21 were the same as the Full Angle plots in *Figure 22*.

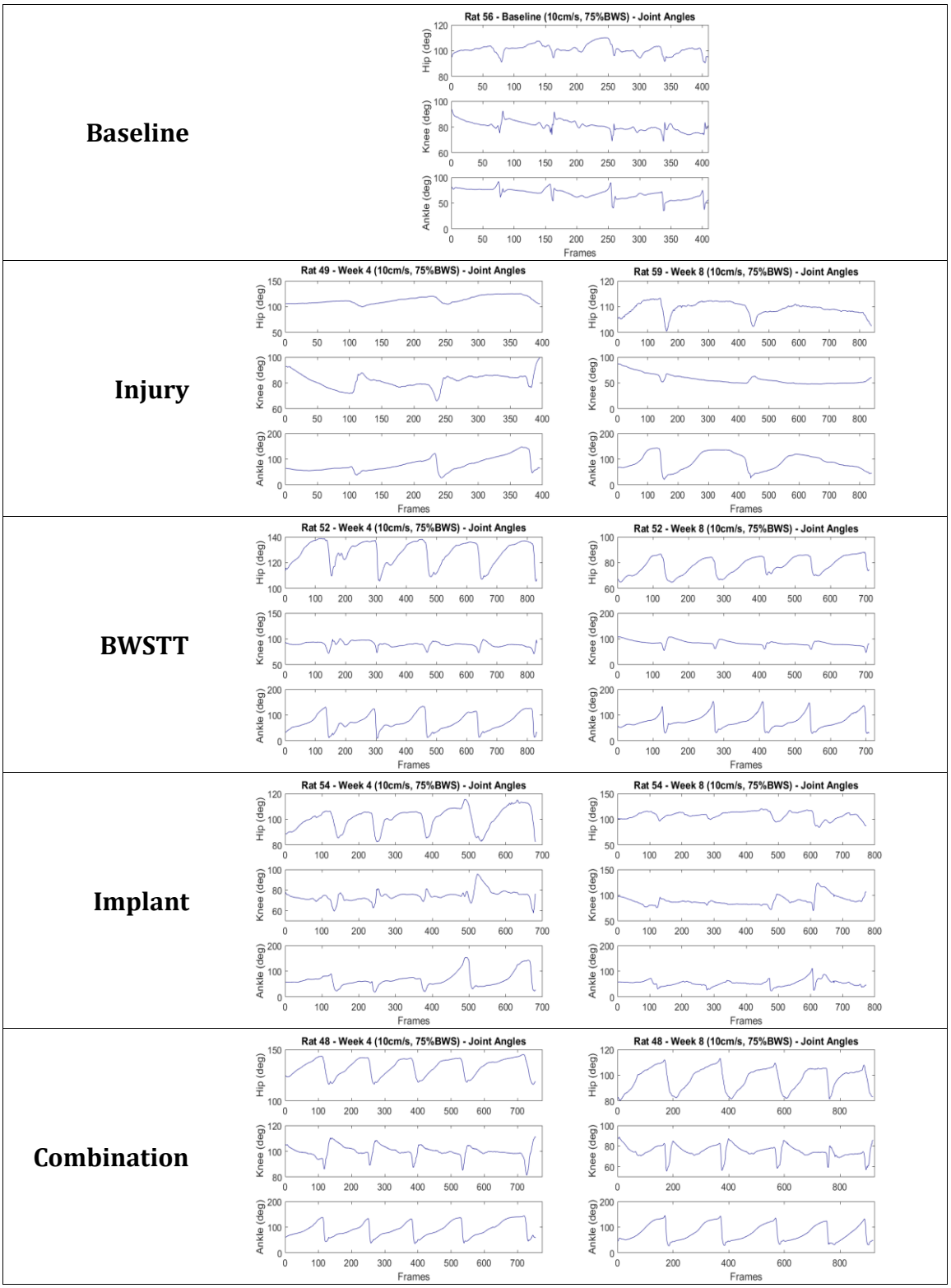


Figure 22. Full Angle Plots for one animal in each group that walked at 10 cm/s with 75% BWS. The Injury group however had no animal, with analyzable takes that walked at both Week 4 (Left Plots) and Week 8 (Right Plots). Animals Used: 56 (Baseline), 49 and 59 (Injury), 52 (BWSTT), 54 (Implant), 48 (Combination).

6.5.3 Mapped angle plots. Mapped angle plots were like the full angle plots in that the only data used were the joint angles. However, mapped angle plots split the joint angles for each stride, and then the data were resampled so that there were 101 points for each stride. This allowed the angle data to be more easily compared with another animal as they all had same number of data points per stride. Data for these mapped data plots was exported from the code as well so that future analysis could be performed. In addition to splitting and remapping, an average angle was taken for each of those remapped angles to create an average angle profile per stride. The black lines in the plot indicated the individual stride, whereas the blue lines indicated the average stride. Just as with the stick figure and full angle plots, these plots were generated only from animals that had been analyzed in MATLAB. The animal numbers from plots in *Figure 21* and *Figure 22* were the same as the mapped angle plots in *Figure 23*.

Since the dataset for these plots allow for the comparison of the stride angles of different animals within the same group to be compared together, additional plots that provide the averaged mapped angle for all three joints for every animal in each of the five groups for Week 4 and Week 8 are shown in *Figure 24* and *Figure 25*, respectively. These plots provide a picture of average joint angles throughout the gait cycle of an average animal in a specific group and help to show the changes in which part of the gait cycle were changed with the different treatments. The MATLAB code that was used to generate these plots is a different code that generated the plots in Figure 23 but is dependent on it. This code can be found in Appendix E: Average Mapped Plots MATLAB Code.

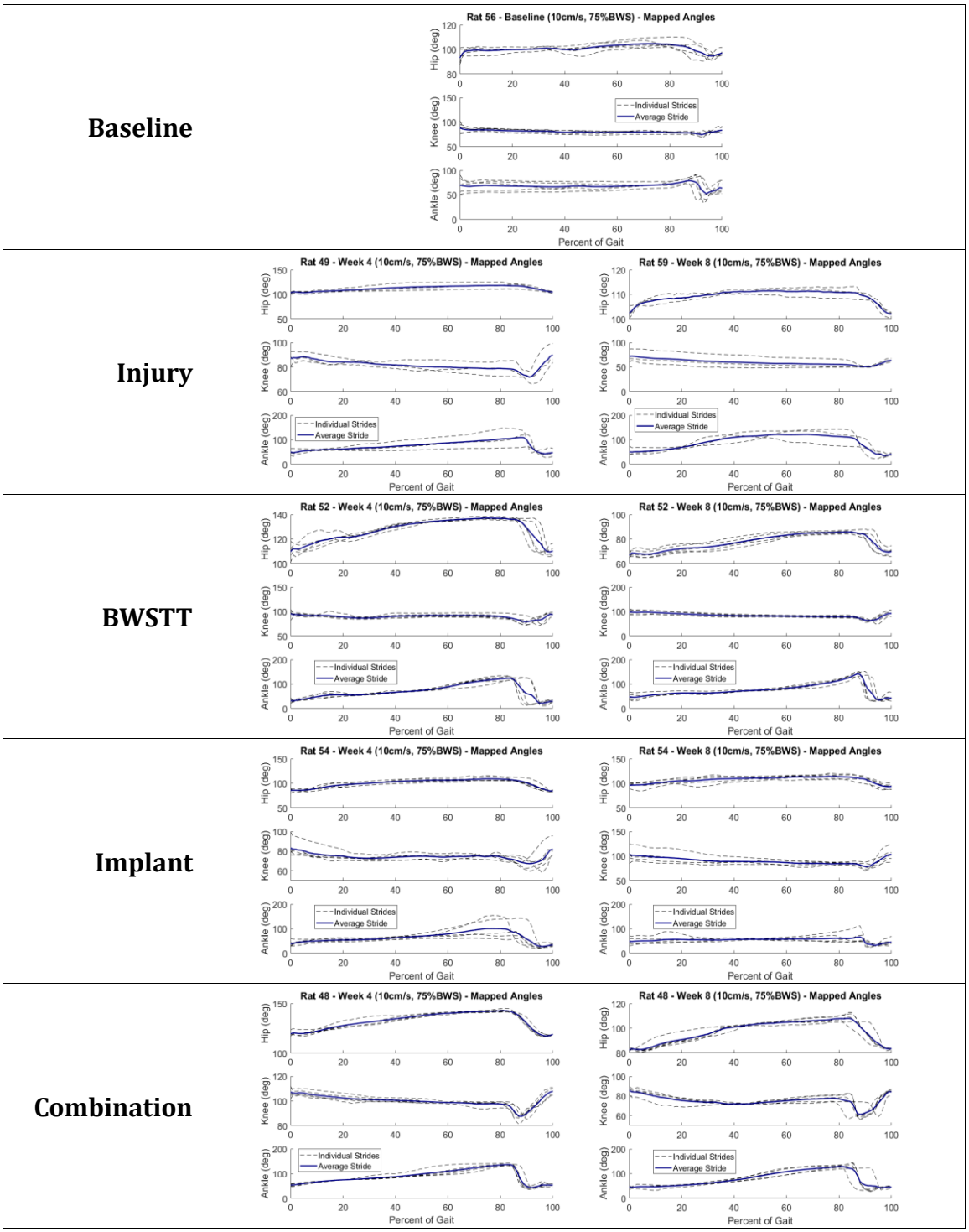


Figure 23. Mapped Angle plots for one animal in each group that walked at 10 cm/s with 75% BWS. The Injury group however had no animal, with analyzable takes that walked at both Week 4 (Left Plots) and Week 8 (Right Plots). The black dotted line represents the individual strides while the blue lines represent the average stride. Animals Used: 56 (Baseline), 49 and 59 (Injury), 52 (BWSTT), 54 (Implant), 48 (Combination).

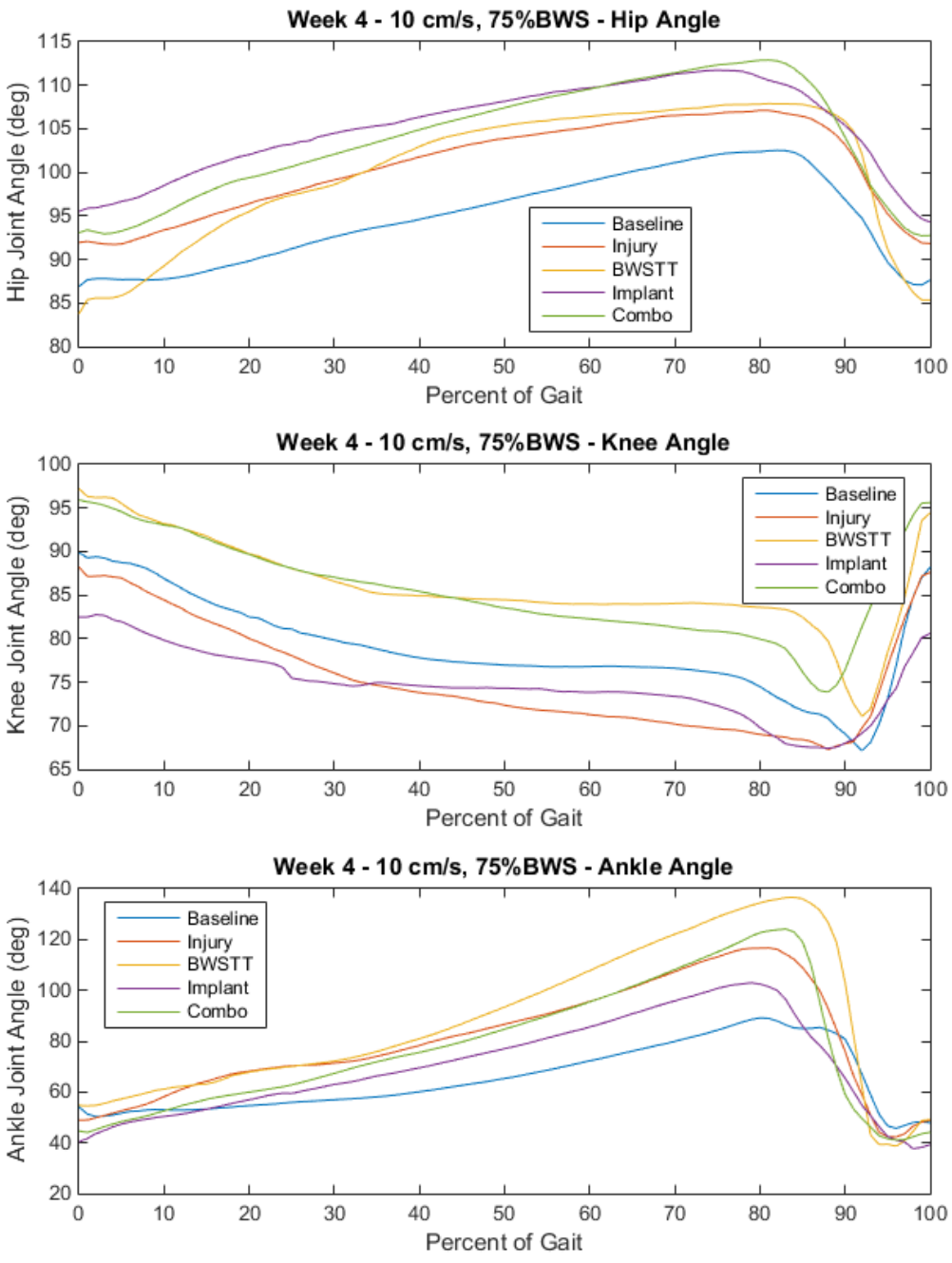


Figure 24. Average Mapped Angle Plots for all the Hip (top), Knee (middle), and Ankle (bottom) for all five groups for Week 4 for animals that walked at 10 cm/s and 75% BWS.

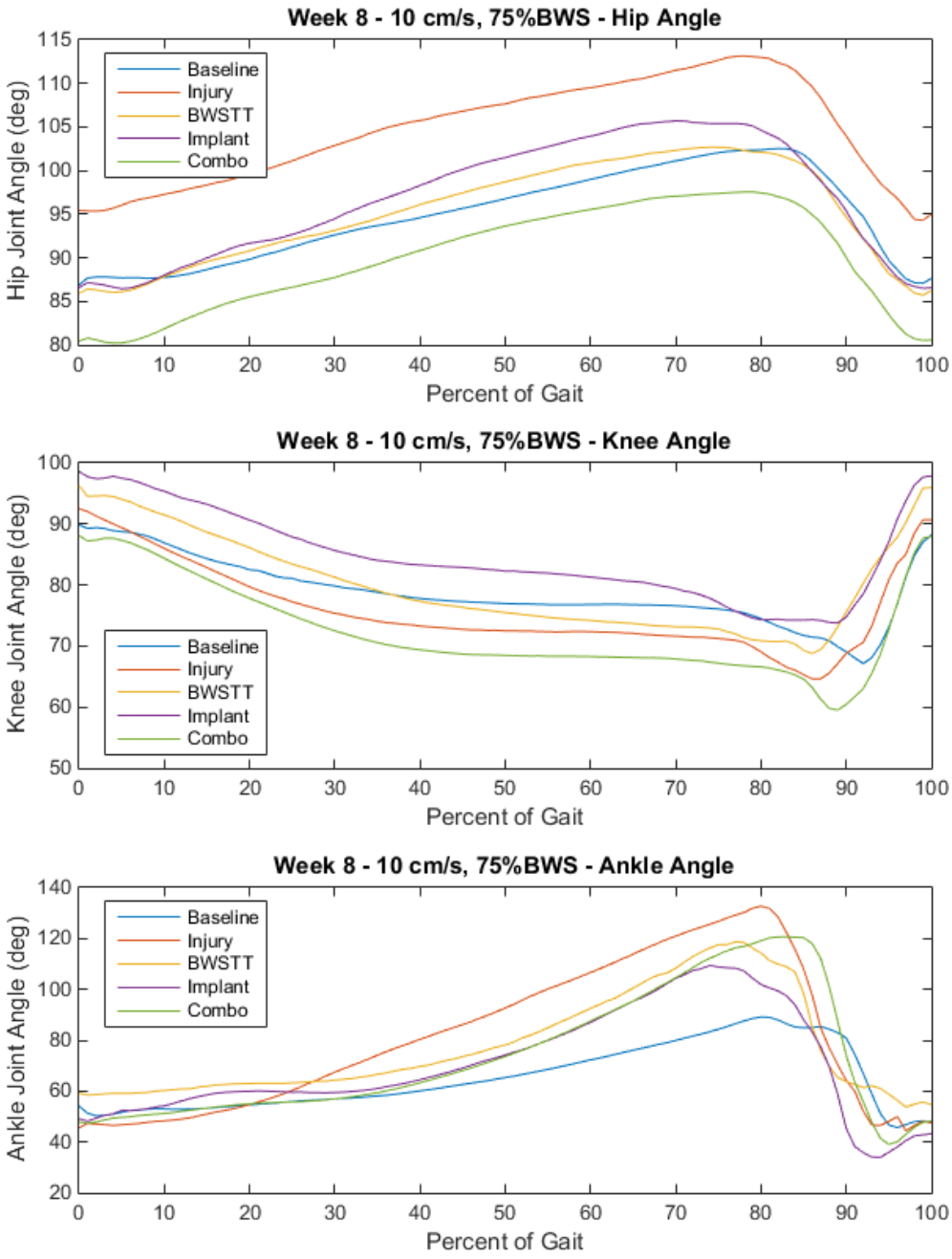
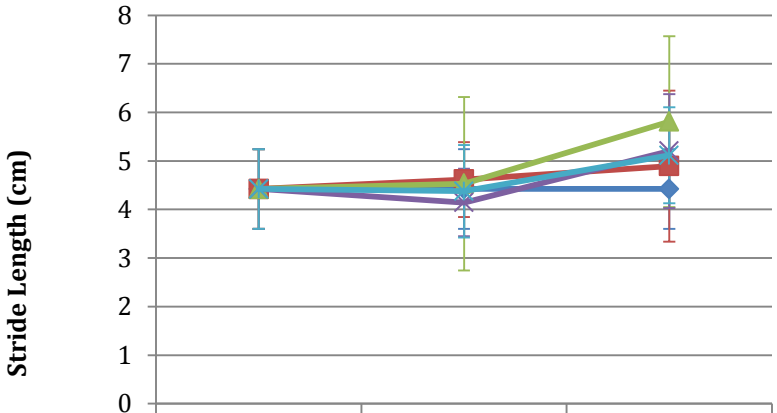


Figure 25. Average Mapped Angle Plots for all the Hip (top), Knee (middle), and Ankle (bottom) for all five groups for Week 8 for animals that walked at 10 cm/s and 75% BWS.

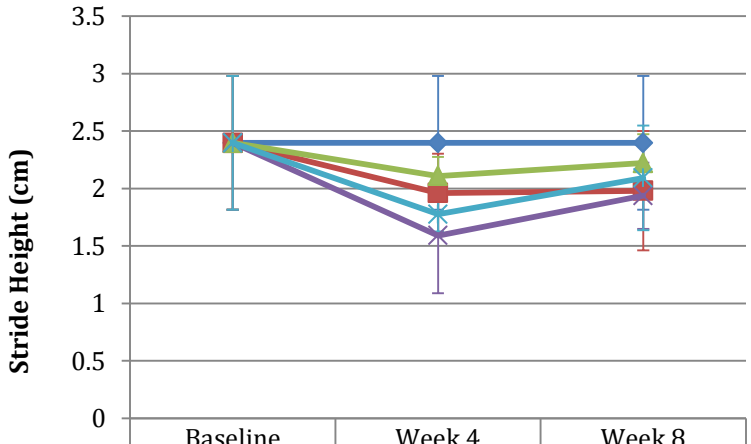
6.5.4 Excel plots. While the majority of data analysis was performed in MATLAB, some of the final processing was done in Microsoft Excel (Microsoft Inc., Redmond, WA). These plots were either generated from exported CSVs from MATLAB, which was then put into a pivot table to plot the results or was manually entered into Excel and then put into a pivot table. The data that were additionally processed from MATLAB in Excel were average stride lengths and heights for each marker, and angles for each joint. Data that were manually entered into Excel without any MATLAB processing were the duration of swing, stance phases, and the number steps walked in a take.

6.5.4.1 Stride distance plots. The stride length and height plots were produced from data that MATLAB calculated and exported to CSV files. The data for each take include the average stride length or stride height for each stride. It was measured from the ankle marker and involved subtracting the distance from the toe off to the heel strike. The average stride length over the course of time for each group is shown in *Figure 26*, and the average stride height is shown in *Figure 27*.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

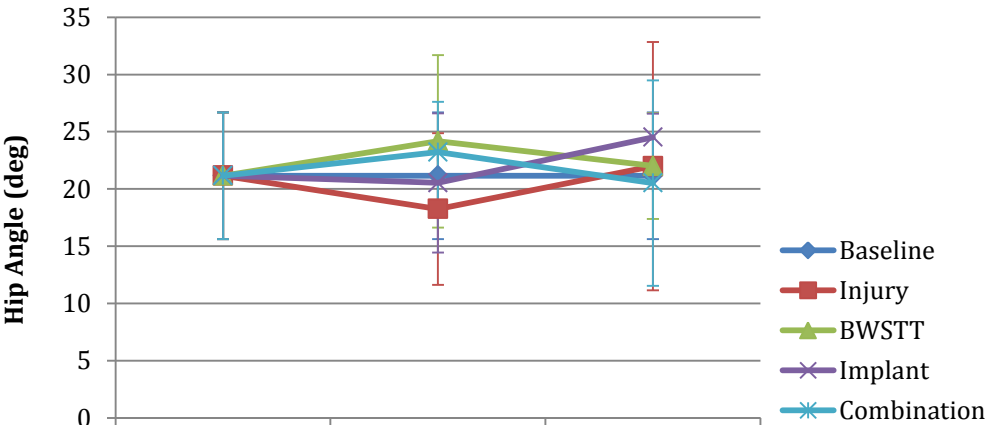
Figure 26. Line plot of the average stride length for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Table shows the number animals that were calculated for each group and each week and was dependent on how many animals had MATLAB analyzable takes. The error bars are one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

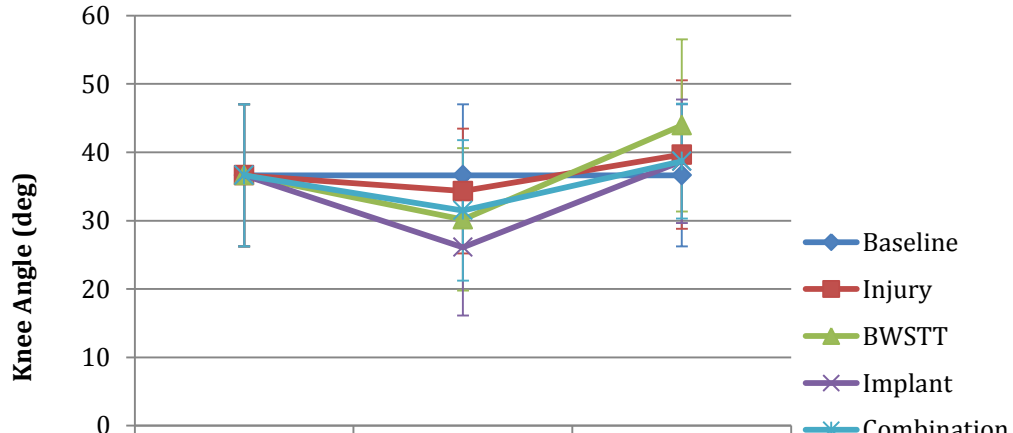
Figure 27. Line plot of the average stride height for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Table shows the number animals that were calculated for each group and each week and was dependent on how many animals had MATLAB analyzable takes. The error bars are one standard deviation.

6.5.4.2 Joint angle plots. The joint angle plots for the hip, knee, and ankle were produced from data that MATLAB calculated and exported to CSV files. The data for each take are the average joint excursion for each stride and was measured for each of the three joints subtracting the max joint angle from the minimum joint angle for each group. The plots are based over the course of time from Baseline to Week 4 to Week 8. The average hip, knee, and ankle angle plots are found in Figure 28, Figure 29, and Figure 30, respectively.



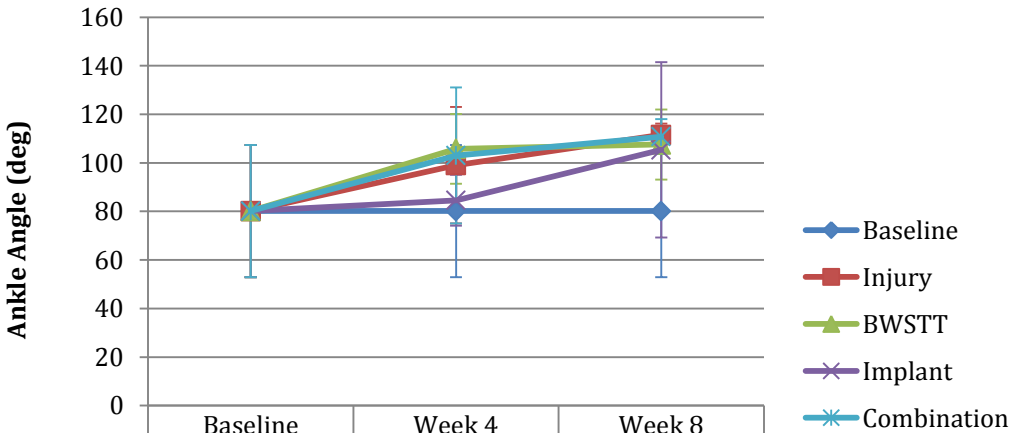
	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

Figure 28. Line plot of the average hip angle for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Table shows the number animals that were calculated for each group and each week and was dependent on how many animals had MATLAB analyzable takes. The error bars are one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

Figure 29. Line plot of the average knee angle for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Table shows the number animals that were calculated for each group and each week and was dependent on how many animals had MATLAB analyzable takes. The error bars are one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

Figure 30. Line plot of the average ankle angle for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Table shows the number animals that were calculated for each group and each week and was dependent on how many animals had MATLAB analyzable takes. The error bars are one standard deviation.

In addition to line plots these of the joint angles, bar plots were also created to show a specific week with all of the joints and groups. Another difference between the bar and line plots is that this produces an average angle excursion throughout the entire take instead of an average between the individual strides. This helps in providing an overall picture with the joint excursion throughout the entire take without looking at it from an individual stride perspective. These bar joint angle plots for Week 4 and Week 8 are shown in *Figure 31* and *Figure 32*, respectively.

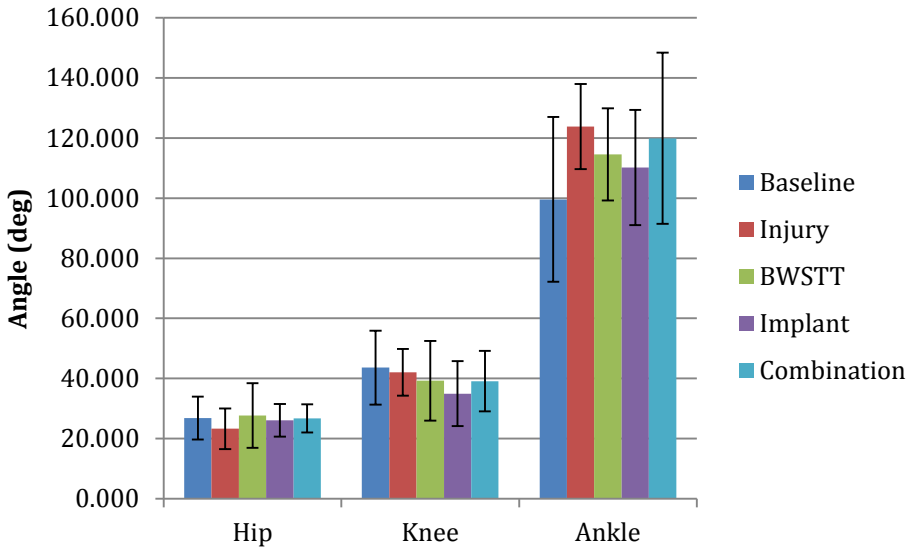


Figure 31. Total angle excursions bar plot for Week 4 animals at 10 cm/s at 75% BWS. Baseline n = 10, Injury n = 6, BWSTT n = 2, Implant n = 6, Combination n = 6. Error bars represent one standard deviation.

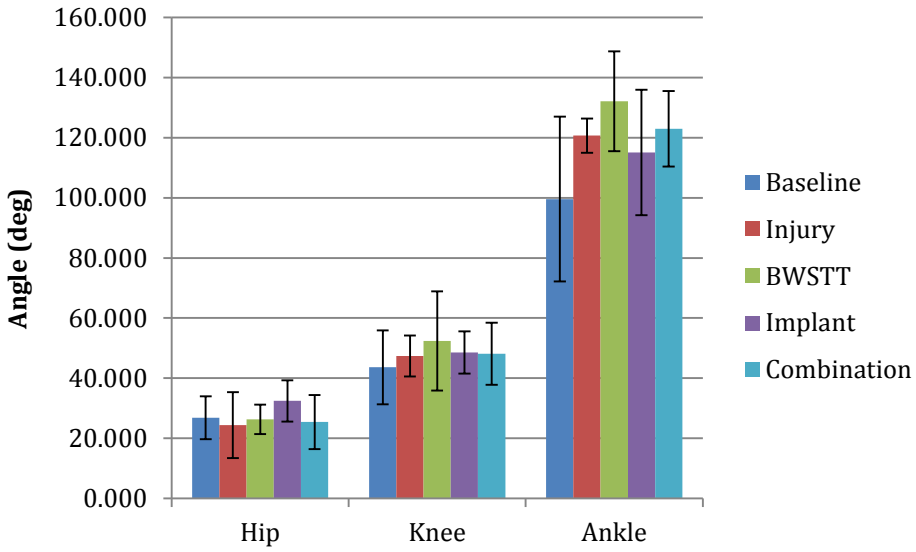
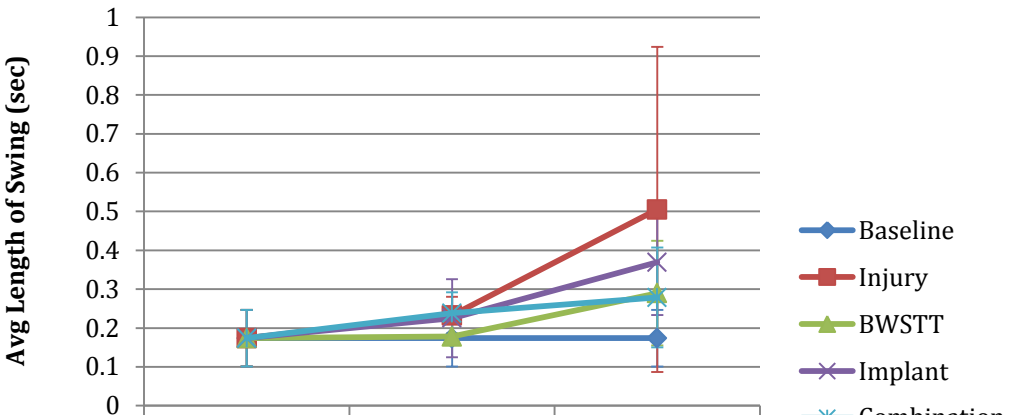


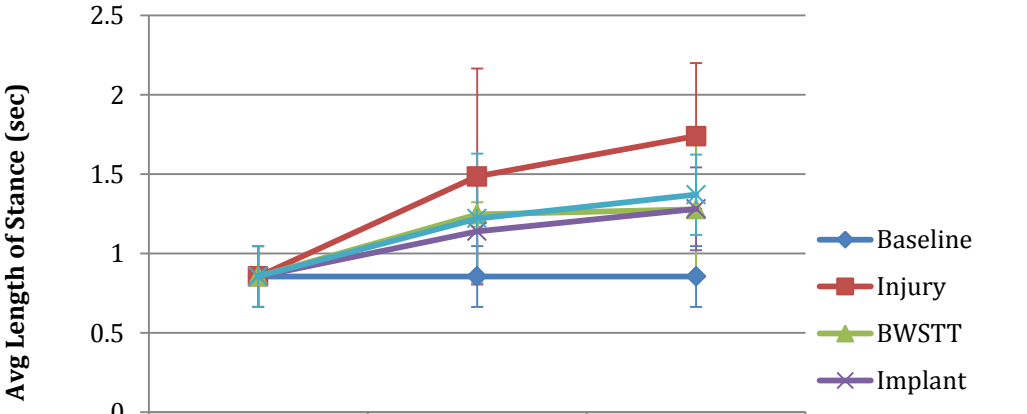
Figure 32. Total angle excursions bar plot for Week 8 animals at 10 cm/s and 75% BWS. Baseline n = 10, Injury n = 5, BWSTT n = 6, Implant n = 5, Combination n = 11. Error bars represent one standard deviation.

6.5.4.3 Duration plots. The duration plots for the swing and stance were produced from data that were manually evaluated by looking at the Motive takes to determine when the swing starts from toe off to heel strike and when stance starts from heel strike to toe off. The data for each take are the average duration of the swing or stance for each group. The plots are based over the course of time from Baseline to Week 4 to Week 8. The swing and stance plots are shown in *Figure 33* and *Figure 34*, respectively.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

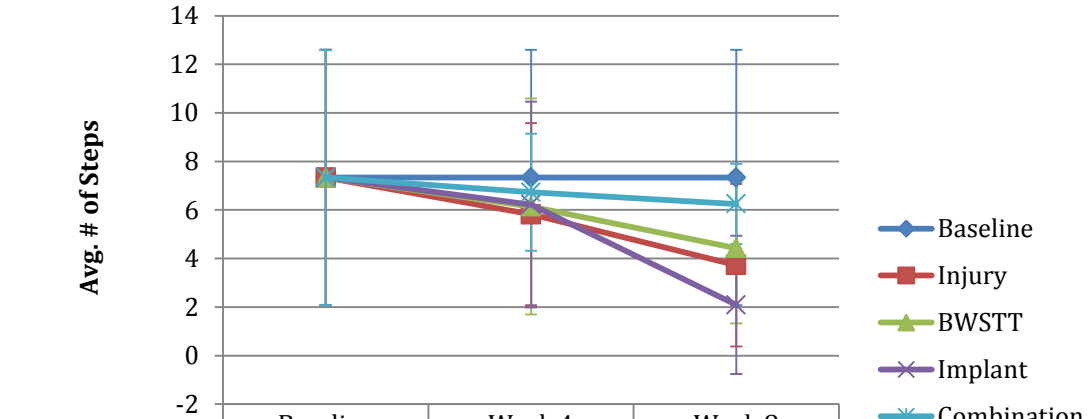
Figure 33. Average duration of an animal's swing for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Error bars represent one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 6	n = 5
BWSTT	n = 10	n = 2	n = 6
Implant	n = 10	n = 6	n = 4
Combination	n = 10	n = 6	n = 11

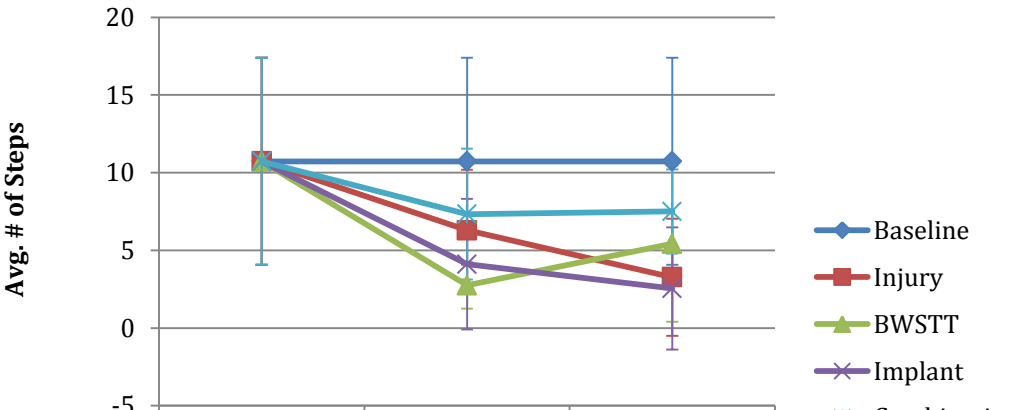
Figure 34. Average duration of an animal's stance for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Error bars represent one standard deviation.

6.5.4.4 Number of steps plots. The number of step plots for the step counts were produced from data that were manually evaluated from looking at the Motive takes to determine the number of steps that an animal walked on a treadmill. These data were not dependent on MATLAB processing and included animals that just walked on the treadmill to help fill in the gaps that the MATLAB evaluation was not able to identify. The data for each take are simply the number of steps that the animal successfully performed on the treadmill throughout the entire take. The line plot version of the step count averages over the course of time from Baseline to Week 4 to Week 8 for both treadmill speeds, and all three BWS are shown in *Figure 35* thru *Figure 40*. The step counts are also presented in a histogram form for Week 4 and Week 8 are shown in *Figure 41* and *Figure 42*, respectively.



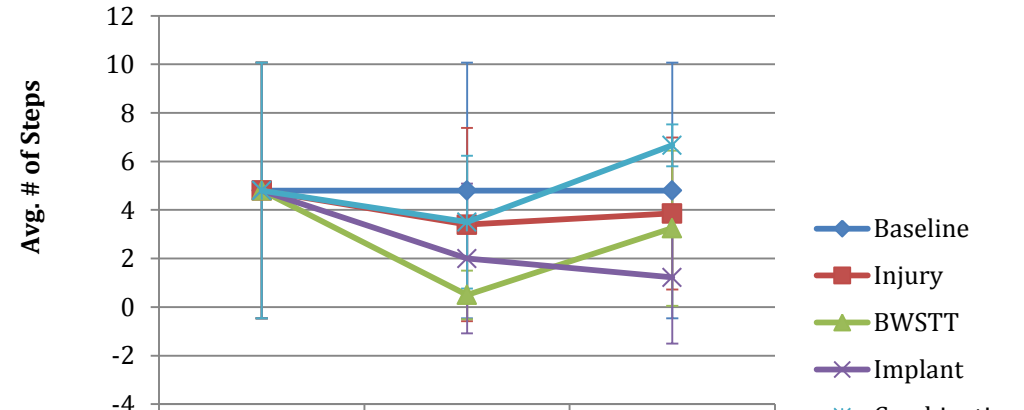
	Baseline	Week 4	Week 8
Baseline	n = 15	n = 15	n = 15
Injury	n = 15	n = 11	n = 11
BWSTT	n = 15	n = 7	n = 7
Implant	n = 15	n = 9	n = 11
Combination	n = 15	n = 11	n = 12

Figure 35. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 7 cm/s and 75% BWS. Error bars represent one standard deviation.



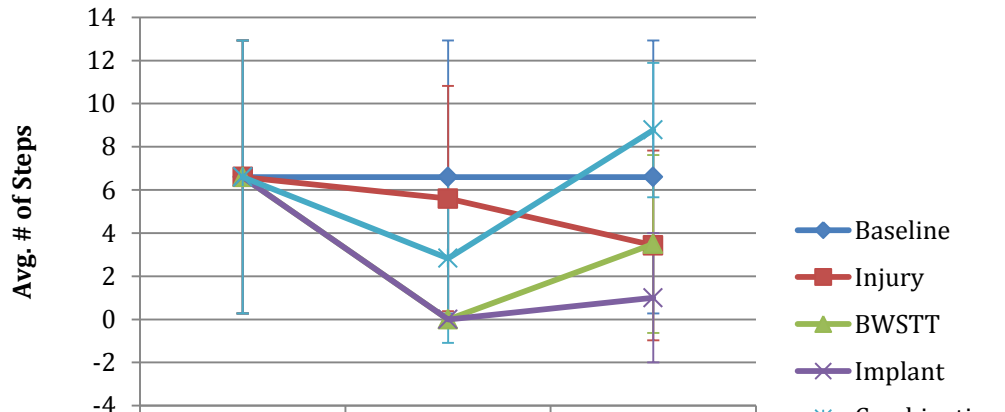
	Baseline	Week 4	Week 8
Baseline	n = 15	n = 15	n = 15
Injury	n = 15	n = 7	n = 11
BWSTT	n = 15	n = 4	n = 7
Implant	n = 15	n = 9	n = 11
Combination	n = 15	n = 9	n = 12

Figure 36. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 75% BWS. Error bars represent one standard deviation.



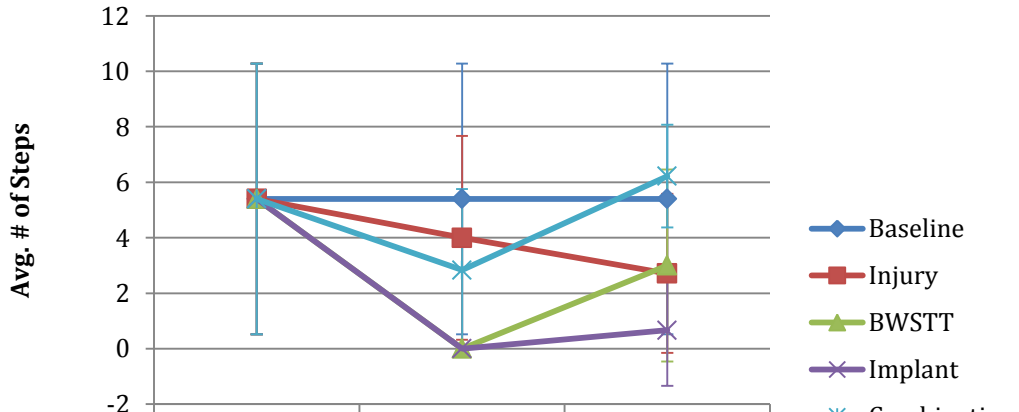
	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 5	n = 7
BWSTT	n = 10	n = 4	n = 4
Implant	n = 10	n = 5	n = 9
Combination	n = 10	n = 6	n = 9

Figure 37. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 7 cm/s and 65% BWS. Error bars represent one standard deviation.



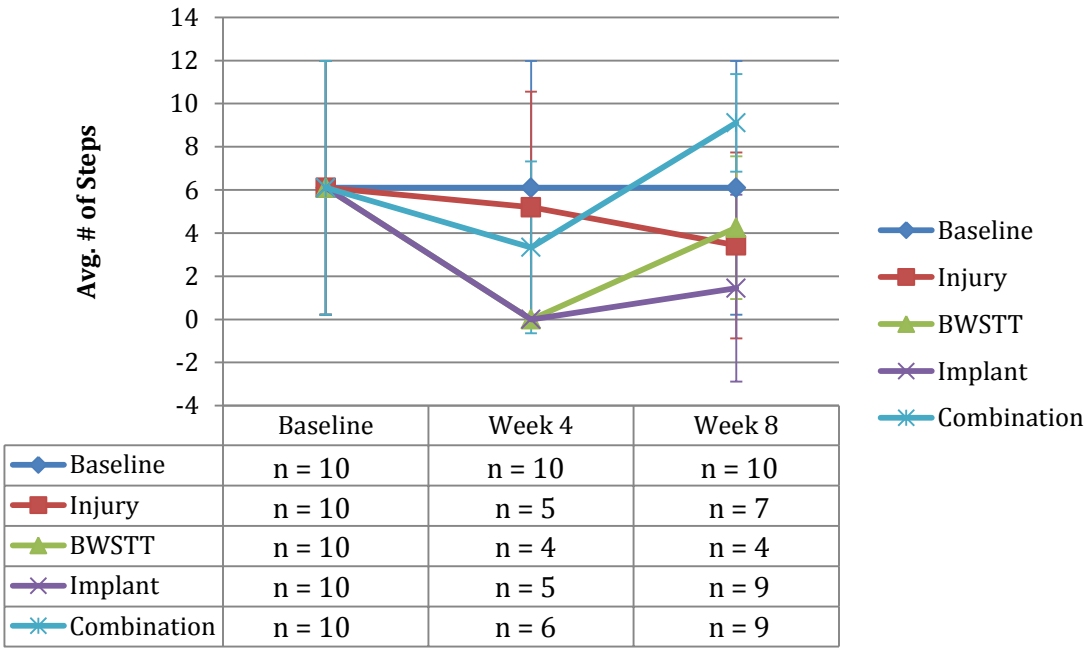
	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 5	n = 7
BWSTT	n = 10	n = 4	n = 4
Implant	n = 10	n = 5	n = 9
Combination	n = 10	n = 6	n = 9

Figure 38. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 65% BWS. Error bars represent one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 5	n = 7
BWSTT	n = 10	n = 4	n = 4
Implant	n = 10	n = 5	n = 9
Combination	n = 10	n = 6	n = 9

Figure 39. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 7 cm/s and 55% BWS. Error bars represent one standard deviation.



	Baseline	Week 4	Week 8
Baseline	n = 10	n = 10	n = 10
Injury	n = 10	n = 5	n = 7
BWSTT	n = 10	n = 4	n = 4
Implant	n = 10	n = 5	n = 9
Combination	n = 10	n = 6	n = 9

Figure 40. A line plots showing the average number of steps for all 5 groups from Baseline to Week 4 to Week 8 at 10 cm/s and 55% BWS. Error bars represent one standard deviation.

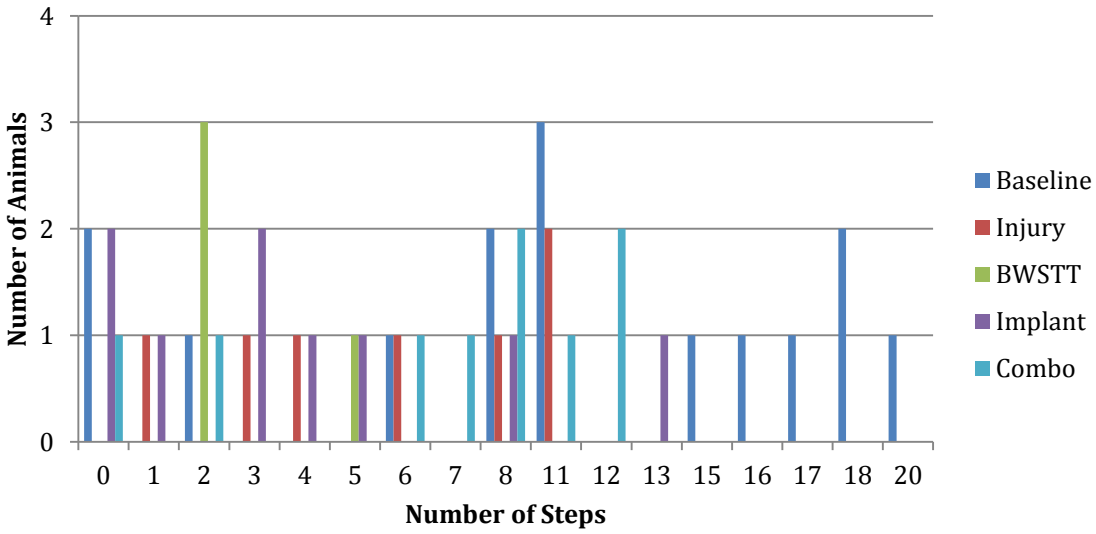


Figure 41. Histogram Plot of the Number of Steps Performed by Every Animal during Week 4 at 10 cm/s at 75% BWS.

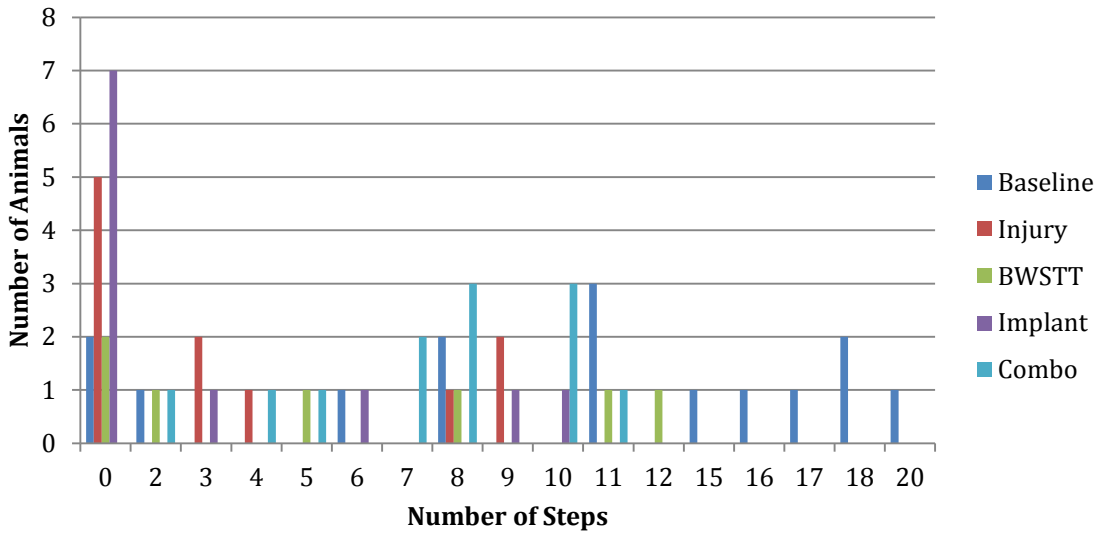


Figure 42. Histogram Plot of the Number of Steps Performed by Every Animal during Week 8 at 10 cm/s at 75% BWS.

Chapter 7

Discussion

7.1 Distances and Height Ranges

As previously discussed, the distances and height ranges were obtained from the processing of the motion capture data in MATLAB and in Excel. The ranges and distances of the animals from each of the five groups are shown in *Figure 26* and *Figure 27* measured from the ankle at a speed of 10 cm/s and a BWS of 75%. A higher value in either distances or height equates to greater range of motion. For our Baseline group there was an average stride distance of 4.423 cm and a standard deviation of 0.82 cm, with an average height of 2.397 cm and a standard deviation of 0.582 cm. All groups had increased stride distances by 0.47 cm at the end of 8 weeks but all groups had a decrease in stride height by 0.416 cm. The Injury group however experienced the second greatest variation in performance in stride distance length and height behind the BWSTT group. The Injury group had a 25% higher standard deviation in distance and height for Week 8 than the average standard deviation of every other group for week 8. There was a lack of animals that were able to perform on the treadmill for the BWSTT group for week 4 where only two animals walked, which explains the higher variation in the distances. A table of the ranges and standard deviations, which were used to create *Figure 26* and *Figure 27*, are shown in Table 4. Overall, compared to the Baseline, the distance between all groups tended to increase as time went on with BWSTT having the greatest improvement in stride length. Other data sets such as the number of steps

(discussed in Chapter 7.3) highlight how, in a more reliable manner, how that group performed.

Table 4

Table of the Stride Lengths and Heights as shown in Figure 26 and Figure 27 with the standard deviations. Treadmill speed of 10 cm/s

Stride Length	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	4.423	0.820	4.423	0.820	4.423	0.820	4.423	0.820	4.423	0.820
Week 4	4.423	0.820	4.619	0.772	4.531	1.785	4.144	0.694	4.377	0.951
Week 8	4.423	0.820	4.893	1.556	5.810	1.761	5.205	1.174	5.117	0.989
Stride Height	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	2.397	0.582	2.397	0.582	2.397	0.582	2.397	0.582	2.397	0.582
Week 4	2.397	0.582	1.961	0.310	2.109	0.166	1.591	0.503	1.775	0.150
Week 8	2.397	0.582	1.981	0.521	2.221	0.252	1.937	0.288	2.092	0.456

After 8 weeks of training the BWSTT, Implant, and Combination groups, the average strides became more extended with lower heights achieved during the swing phase compared to the Baseline. For these three groups, the magnitude of increase for the length was greater than the decrease in height during the swing phase. In addition, for the stride height, the data highlight that the BWSTT group had a faster recovery compared to the Injury and Implant groups. The Combination group was better than the Implant group and Injury group alone but a bit less than the BWSTT group. This indicates that there was an improvement in the range of motion, however combined with the variances between the different groups, it hard to tell whether the treatment stood out from one another.

Compared to previous literature, the trend of increasing stride length over a BWS training regimen is seen in prior literature such as the Alluin et al. study from 2011. In this study, there was an increase in step length partially in the Injury and BWSTT group thru with recovery after six weeks for their study. The trend in the time between Week 4 and Week 8 is similar to Singh et al. from 2011 where there was a faster increase in step length in BWSTT group compared to the injured group. In regards to the step height trends, they are very similar to both the Alluin et al. from 2015 and Singh et al. from 2011. In our study and in both Alluin's and Singh's studies, there was a decrease in step height after injury with some recovery in step heights being closer to the Baseline by Week 8. The trained groups improved at a faster rate compared to the Injury group [5], [40], [63].

7.2 Angles Ranges and Excursions

From the motion capture data and processing of the data in MATLAB and in Excel, the Angle ranges and excursions of the animals from each of the five groups for each joint in week 4 and week 8 are shown in *Figure 31* and *Figure 32*, respectively. The same data in different line plots over time for each joint are found in *Figure 28* thru *Figure 30*. Similar to the stride length and heights, the higher value in angles for the ankle, knee, and hip equates to greater range of motion of the joint. However in the case of the ankle joint for all the groups beside the Baseline, the range increased after injury and had little variations to week 8 with a slight increase to 108° between the four groups. For the other joints, there was a decrease in range of motion in week 4 for both the hip and knee compared to the Baseline. After week 8, however range of motion seemed to improve for both the hip and knee for all

groups. This trend indicates that the animals are more likely to drag their foot on the treadmill and with more training; the drag is more likely to decrease with the increase in hip and knee angles. The knee joint however is a joint that can be problematic to properly motion capture due to the increased amount of movable skin on top of the joint itself. By week 8, the three different treatment groups are all seeing improvement in angular motion compared to the Injury group but the changes between the groups themselves are relatively small. A table of the ranges and standard deviations, that were used to create *Figure 28* thru *Figure 32*, are shown in Table 5.

A review of our data finds similarities in trends in several studies regarding an Ankle, Knee and Hip excursion in our trained groups verses our untrained groups. These similarities were found in Alluin et al. 2011, and Goldshmit et al. 2008 In both Alluin's and Goldshmit's studies, there was an increased range in the ankle angle after injury with ranges starting to plateau after a few weeks. In terms of the Knee joint, in the Alluin study and our data, the injured group compared to the trained group exhibit similar trends. The injured and trained groups have reduced ranges after injury, which slowly increased as training progressed. For the hip angle, our data follows aspects of both Alluin's and Goldshmit's studies. We had a decrease in hip ranges for our injured groups as in Goldshmit's study and increased hip angles for our trained groups like the Alluin study. By the end of the training period after eight weeks, our trained groups have less range (but closer to Baseline) compared to the untrained groups, which is similar to both Alluin and Goldshmit studies [40], [64].

Table 5

Table of the Joint Angle Ranges of motion in degrees as shown in Figure 28 thru Figure 32 with the standard deviations. Treadmill speed of 10 cm/s

Ankle	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	80.15	27.21	80.15	27.21	80.15	27.21	80.15	27.21	80.15	27.21
Week 4	80.15	27.21	99.06	24.04	105.8	14.40	84.57	10.48	103.0	28.03
Week 8	80.15	27.21	111.5	4.720	107.6	14.47	105.4	36.17	110.8	7.202
Knee	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	36.65	10.39	36.65	10.39	36.65	10.39	36.65	10.39	36.65	10.39
Week 4	36.65	10.39	34.31	9.13	30.19	10.41	26.11	9.97	31.5	10.29
Week 8	36.65	10.39	39.67	10.85	43.94	12.58	38.67	9.04	38.7	8.4
Hip	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	21.17	5.54	21.17	5.54	21.17	5.54	21.17	5.54	21.17	5.54
Week 4	21.17	5.54	18.26	6.62	24.17	7.54	20.53	6.08	23.21	4.41
Week 8	21.17	5.54	21.98	10.85	22.01	4.63	24.52	2.06	20.52	8.96

In addition to the data range of motion data, it was observed from the mapped joint angle plots exported from MATLAB that the Combination group and BWSTT groups are more consistent in their strides in terms of joint angles. As shown in Figure 21 through Figure 23 the joint angles and the points at where they transition from stance to swing, is more defined and consistent between strides. This was determined due to the compactness of the black dotted line in *Figure 23*. While the joint angles for all of the groups do improve from week 4 to week 8 compared to the Injury group, the variances between the different groups are still close enough. Therefore, it is hard to tell whether the different treatments stood out from one another.

This was further supplemented by the averaged mapped angles plots shown in Figure 24 and Figure 25 for week 4 and week 8, respectively. These plots differ from Figure 23 because they show the average for the entire group's mapped joint angles instead of being from just one animal in each group. These plots highlight that there is a difference between the trained groups and non-trained group in terms of how they walk. The trained groups are more able to make more rapid changes in their joint angles and tended to deviate closer to the Baseline faster than the non-trained group if the non-trained groups changed at all. When compared to each other, there were little differences between the BWSTT and Combo groups in terms of joint angle profiles, changes in angles with an increase in the gait cycle, and similar recovery patterns toward the Baseline. Additionally, the Implant group showed some form of joint motion recovery more than the Injury group on its own by week 8, but not as significant between that and the BWSTT group.

7.3 Number of Steps and Duration of Swing Stance Phases

From the motion capture data and processing of the data in MATLAB in Excel, the duration of the swing and stance phase for the animals from each of the five groups for each joint in week 4 and week 8 are shown in *Figure 33* and *Figure 34*, respectively. Additionally data from the number of steps the animals walked, whether or not they met the threshold for MATLAB analysis or not, are shown in *Figure 35* thru *Figure 42*. The higher the number of steps indicates a specific animal's ability to walk. They were classified into each of their individual groups and provided more insight into the animals that could not be analyzed thru the MATLAB code. On average, for 10 cm/s and 75% BWS, a Baseline animal was able to walk

10.7 steps with a standard deviation of 6.6. The Injury group had an average of 6.3 steps with a standard deviation of 3.9 for Week 4. On week 8, this average was 3.8 steps with a standard deviation of 3.77. For all other speeds and BWS, the injury and Implant group had a steady decrease in the average number of steps taken. The BWSTT and Combination groups had decrease in the number of step until Week 4 and then either steady or increased average number of steps at Week 8. There were some cases, in some of the BWS and speeds, where the Combination group had an average step count higher than the Baseline and in other cases where the Injury group had an average step count higher than the BWSTT group. In both of those cases the variability between the different animals in the same group as relatively high compared to each other. These results help explain why there were few injury animals able to be analyzed thru MATLAB or able to be motion captured. All groups had fewer steps than the Baseline, but there were increases in the number of steps being performed for the BWSTT group. This was followed by the Combination group, with the Implant group having a smaller average than the injury but with a similarly high deviation. A data table that was used to plot the data in *Figure 36* is shown in Table 6. The data in *Figure 41* and *Figure 42* are from the same data set as *Figure 36* but in histogram form. This shows the number of animals that performed a certain number of steps per group. This data indicated that by itself, the biomaterial implant is not as effective as BWSTT alone and is more similar to the Injury group. However, when combined with BWSTT, it can show slight improvement in its number of steps.

Table 6

Table of the Number of steps walked for each group of animal as shown in Figure 36 and Figure 41 thru Figure 42 with the standard deviations. Treadmill speed of 10 cm/s and a BWS of 75% was used for this data set.

Avg. Steps	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	10.73	6.66	10.73	6.66	10.73	6.66	10.73	6.66	10.73	6.66
Week 4	10.73	6.66	6.29	3.90	2.75	1.50	4.11	4.20	7.33	4.21
Week 8	10.73	6.66	3.27	3.77	5.43	5.03	2.55	3.93	7.50	2.71

For the Swing Stance Durations, it is ideal when the differences between the measured duration and the Baseline duration are minimal. This data however, unlike the step counts, were only available from the animals that were able to walk on the treadmill. For the Injury group by Week 8, the swing times increased nearly 200% and for nearly 100% the stance time. This further supplements the Injury group's inability to walk on the treadmill from the number of steps data. In the groups that received treatment after SCI, there was an improvement in duration for swing and stance and these were close to the Baseline reading of 0.174 seconds. The standard deviation was 0.073 seconds for swing phase and 0.855 seconds with a standard deviation of 0.192 seconds. This compared to the Injury group in Week 8, which was 0.505 seconds with a standard deviation of 0.419 for the swing phase and 1.739 seconds with a standard deviation of 0.46 seconds for the stance phase. The BWSTT, Implant and Combination time for swing and stance were similar from one another for both Week 4 and Week 8 and did not show a significant different between the therapies. Compared to existing studies, our data draws similarities to both of the Alluin et al. studies from 2011 and 2015 where there was a net increase

in swing and stance durations throughout the course of training. There were similar circumstances where our trained animals had more noticeable longer steps, which resulted in more time for each of the swing and stance phases. The numerical data that were used to generate the plots in *Figure 33* and *Figure 34* are shown in Table 7 [40], [63].

Table 7

Table of the times of the swing and stance phase for each group of animal as shown in Figure 33 and Figure 34 with the standard deviations. Treadmill speed of 10 cm/s and BWS of 75% was used for this data set.

Swing	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	0.174	0.073	0.174	0.073	0.174	0.073	0.174	0.073	0.174	0.073
Week 4	0.174	0.073	0.232	0.048	0.178	0.008	0.225	0.101	0.238	0.054
Week 8	0.174	0.073	0.505	0.419	0.290	0.135	0.369	0.136	0.279	0.128
Stance	**Baseline**		**Injury**		**BWSTT**		**Implant**		**Combination**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Baseline	0.855	0.192	0.855	0.192	0.855	0.192	0.855	0.192	0.855	0.192
Week 4	0.855	0.192	1.485	0.680	1.246	0.076	1.140	0.309	1.220	0.409
Week 8	0.855	0.192	1.739	0.460	1.279	0.411	1.281	0.262	1.370	0.253

7.4 Limitations of Our Study

While the attempts to mitigate any limitations in our study were taken, there were still some issues that remained. As discussed in Chapters 5.1 and 6.1.1, there are issues with noise present in the motion capture system. In our system, our three camera setup, while suitable increased the occurrence of noise. This increase in noise made it harder to completely analyze incomplete motion capture take. Our setup would have benefited from the use of an additional camera to help curbed the

amount of noise present and with the addition of at least two more camera would have help with more accurate reference camera data as well.

Additionally with our animals themselves, their ability to walk our treadmill was also a limiting factor in our study. There was only one data set of animals (10 cm/s and 75% BWS) where at least 4 animals from each group were able walk on the treadmill for Week 4 and Week 8 of the motion capture session. This only allowed us to run a statistical analysis of the one set where there was only significance ($p<0.05$) in the number of steps taken for the Combination and Injury group compared to Baseline. While the ability to coerce an animal to walk on a treadmill can be issue, future studies should take this factor into account when designing similar experiments to allow for extra animals to be utilized.

7.5 Future Studies

All of these data sets indicate that this biomaterial scaffold implant made with PNIPAAM-g-PEG with NT-3 and BDNF neurotrophins has a positive impact on the recovery of kinematics for animals that have had a partial spinal cord injury. From this study, the effects of this specific treatment from a kinematic perspective by itself, is not as effective as BWSTT. However, it can potentially possess synergetic benefits when used with BWSTT. The effect of this synergic behavior for this particular scaffold combination is not conclusive from our data and needs to be determined by future research.

Studies that investigate this phenomenon should consider an advanced motion capture system, as the movements are smaller compared to normal motion capture systems. Regular high-speed cameras should also be used. Additionally, behaviors

involving the use of force plates would allow more insight to total effect of kinematics with the use of these treatments. Along with identifying, researching, and developing new biomaterials to develop the scaffolds, testing the use of different biomaterials to overcome the difficulties in oxygen delivery and promoting cell growth would also be needed. Potential for looking into different type of exercise therapies to treat SCI should also be considered as part a study. Future research looking into different types of therapies to treat SCI should also be considered.

Chapter 8

Conclusion

The use of biomaterial scaffolds is increasing in use and seems to be where the treatment of SCI is leading in the future [2], [6]. BWSTT success in animal studies has not translated to human studies as ideally as initially hoped but it does serve as a vital building block for future work. In our study, we determined that there is kinematic recovery for the BWSTT and Combination group but the overall effect of the Combination therapy and BWSTT should be explored more, to give a better understanding of its efficacy. In terms of the Implant itself, it did not improve kinematics compared to the BWSTT and Combination groups but it did however perform better than the Injury group. Considering the potential for the use of biomaterials to treat SCI, many questions about its efficacy still need to be answered. This therapy can help provide more insight into how effective a biomaterial scaffold for treating SCI can be.

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Appendix A

Definitions and Aberrations

ANS – Autonomic Nervous System

ASIA – American Spinal Injury Association

BDNF – Brain Derived Neurotrophic Factor

BWS – Body Weight Support

BWSTT – Body Weight Supported Treadmill Training

CNS – Central Nervous System

CSV – Comma Separated Values

EMG – Electromyography

ENS – Enteric Nervous System

FDA – Food and Drug Administration

FES – Functional Electrical Stimulation

FPS – Frames per Second

MATLAB – Matrix Laboratory

NIH – National Institute of Health

NSCISC – National Spinal Cord Injury Statistical Center

NT – Neurotrophin

NT-3 – Neurotrophin-3

PHEMA – poly (2-hydroxyethyl methacrylate)

PHPMA – poly[N-2-(hydroxypropyl) methacrylamide]

PNIPAAm – poly (N-isopropyl acrylamide)

PNIPAAm-g-PEG – poly (N-isopropyl acrylamide) with poly (ethylene glycol)

PNS – Peripheral Nervous System

PT – Physical Therapy

ROM – Range of Motion

SC – Spinal Cord

SCI – Spinal Cord Injury

SNS – Somatic Nervous System

TME – Too Much Error

VBA – Visual Basic

Appendix B

Stride Table

Strides Table | Set 1 | 1/7

Baseline	3	4	5	6	7	8	10	11	12	13	14	16	18	19
1		1930				2430		646		585		763	479	
2		2100				2594		803		659		871	587	
3		2260				2759		907		749		983	717	
4		2414				2923		995		832		1098	829	
5		2588				3100		1093		923		1227	951	
End		2755				3273		1238		1025		1359	1076	
Best Stride		3				5		4		3		4	2	

Week 4/(5)	3	4	5(5)	6(5)	7	8	10	11(5)	12	13	14	16	18	19
1	557	1108			1167	921	911	418		1106				690
2	736	1234			1275	1056	1027	626		1200				802
3	891	1372			1424	1163	1141	843		1312				938
4	1050	1515			1523	1308	1258	1110		1396				1079
5	1206	1675			1652	1419	1377	1247		1476				1216
End	---	1863			1820	1544	1494	1347		1560				1413
Best Stride	---				2	4	2	5		2				4

Week 6	3	4	5	6	7	8	10	11	12	13	14	16	18	19
1	433	774	308		1178	470	459			450				417
2	639	979	512		1333	578	616			586				632
3	1010	1179	803		1470	724	871			730				792
4	1334	1397	1211		1614	896	1050			878				998
5	1770	1626	1845		1761	1093	1287			1026				1160
End	2308	1845	2522		1908	---	1587			1187				1553
Best Stride	1	2	1		4		2			4				2

3 (10cms)	4 (10cms)	5 (10cms)
343	1191	1554
467	1340	1805
632	1484	2107
757	1656	2323
953	1796	2666
1401	1947	3136
1	1	2

Week 8 (7)	3	4	5	6	7	8	10	11	12	13	14	16	18	19
1	750	1642	824		682	1534	439	1548						
2	888	1894	1002		834	1620	562	1779						
3	1075	2150	1178		991	1782	727	1989						
4	1248	2396	1354		1193	1940	889	2199						
5	1456	2621	1567		1338	2079	1065	2399						
End	1642	2857	1790		1563	2237	1281	2603						
Best Stride	5	4	5		1	1	3	4						

Week 8 (10)	3	4	5	6	7	8	10	11	12	13	14	16	18	19
1	1026	627	847			1103	1379	490						
2	1174	742	972			1269	1501	625						
3	1324	827	1095			1388	1613	781						
4	1550	930	1217			1524	1729	907						
5	1826	1090	1338			1676	1848	1036						
End	2038	1215	1457			1746	1975	1168						
Best Stride	4	4	5			2	3	3						

Wasn't Tested
Innsufient Data
Needs Processing

Numbers are Frame Numbers | Frame Rate: 100 FPS | Alex Herman

Baseline	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1									2444			957	2000			1682			1021			
2									2558			1062	2153			1788			1153			
3									2675			1180	2300			1907			1300			
4									2785			1283	2446			2009			1444			
5									2905			1400	2588			2092			1596			
End									3003			1514	2715			2212			1747			
Best Stride									1			5	5			4			3			

Week 4	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				1986		695	1595				880	2903	704				1217	658	573	1340		
2				2124		869	1724				982	3073	857				1374	839	726	1553		
3				2241		1045	1974				1081	3256	1017				1542	1024	880	1742		
4				2368		1220	2186				1191	3443	1189				1716	1163	1020	1934		
5				2526		1394	2369				1285	3625	1344				1900	1395	1191	2125		
End				2636		1596	2578				1385	3811	1515				2064	1498	1365	2328		

Week 6	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1						385	2504			1848		1218	1480				1473		572	426		
2						557	2615			2014		1361	1636				1778		716	641		
3						687	2715			2195		1508	1786				2007		912	921		
4						821	2815			2356		1669	1936				2591		1084	1125		
5						---	2915			2500		1850	2086				2784		1247	1348		
End						---	2992			2690		2021	2250				2884		1408	---		

Week 8 - 75%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				457						934		2631	1193				1021		588	736		
2				628						1171		2815	1366				1212		790	873		
3				762						1406		2957	1534				1400		1002	1007		
4				916						1608		3111	1703				1520		1177	1143		
5				1046						1792		3275	1869				1710		1541	1285		
End				1214						1980		3429	2026				1932		1723	1438		
Week 8 - 65%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				649						682		890	628				2725		575	431		
2				745						799		1069	793				2964		756	598		
3				856						939		1241	947				3142		896	741		
4				993						1187		1464	1122				3320		1126	883		
5				1090						1566		1663	1335				3494		1374	---		
End				1246						1718		1856	1466				3675		1572	---		
Week 8 - 55%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				351						559		2892	1135						538			
2				518						672		3121	1303						758			
3				653						795		3376	1459						963			
4				848						937		3753	1611						1204			
5				1078						1157		4089	1748						1435			
End				---						1309		4542	1916						1671			

Wasn't Tested
Innsufient Data
Needs Processing

Numbers are Frame Numbers Frame Rate: 100 FPS Alex Herman

Baseline	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1									1597			1609	3485			1312			1289			
2									1686			1708	3608			1400			1357			
3									1773			1784	3718			1488			1446			
4									1859			1884	3832			1599			1548			
5									1941			1985	3952			1684			1615			
End									2028			2092	4059			1792			1730			

Week 4	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				2504		1244	352			555	664	976	625					619	617	479		
2				2598		1474	456			668	753	1102	744					784	717	586		
3				2703		1736	533			786	856	1228	862					903	827	702		
4				2780		2114	841			894	952	1383	990					1061	937	753		
5				2881		2466	---			1014	1052	1537	1147					1148	1042	---		
End				2965		2796	---			1144	1151	1675	1361					1330	1145	---		

Week 6	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1						1700	408			2063		580	656				438	523	324	702		
2						1783	467			2195		699	775				547	672	465	820		
3						1871	538			2315		827	888				666	703	574	1118		
4						1951	583			2455		965	1004				785	743	913	1336		
5						2032	693			2595		1105	1119				909	---	---	1690		
End						2135	785			2743		1235	1236				977	---	---	---		

Week 8 - 75%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1										1161		903	1000				1675		460	444		
2										1335		1020	1116				1815		591	579		
3										1520		1152	1239				1953		691	681		
4										1707		1287	1370				2092		805	802		
5										1875		1440	1490				2234		955	---		
End										2087		1610	1598				2410		1293	---		
Week 8 - 65%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				683						811		565	2131				1808		326			
2				781						931		694	2237				1956		467			
3				865						1043		859	2346				2081		646			
4				972						1167		999	2478				2219		880			
5				1081						1284		1137	2602				2370		---			
End				1183						1405		1270	2710				2518		---			
Week 8 - 55%	24	26	28	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1				720						661		537	975						545			
2				847						763		682	1092						653			
3				983						884		809	1212						742			
4				1111						998		1038	1332						837			
5				1215						1132		1222	1452						943			
End				1395						1308		1462	1592						1217			

Wasn't Tested
Innsufient Data
Needs Processing

Baseline-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	779	1283							1102	1313					917								
2	940	1423							1222	1456					1067								
3	1073	1576							1325	1597					1192								
4	1170	1740							1443	1748					1323								
5	1328	1887							1568	1906					1494								
End	1448	2048							1708	2050					1734								
Baseline-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	429	996							3073						2000							1100	
2	550	1191							3203						2148							1250	
3	705	1386							3343						2248							1409	
4	853	1541							3480						2378							1568	
5	1013	1720							3605						2489							1726	
End	1218	1921							3728						2612							1890	
Baseline-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	528	717							683	479					509							1097	
2	702	843							820	606					623							1257	
3	937	972							950	737					738							1440	
4	1164	1096							1086	875					885							1595	
5	1437	1222							1238	1018					1022							1773	
End	1911	1345							1396	1140					1157							1929	

Week 4-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	1050	591	942	684	527	802	959	1133		499					930		464		528	664		833	
2	1233	685	1100	919	783	972	1160	1370		719					1095		685		630	835		993	
3	1427	867	1307	1099	1010	1160	1362	1587		879					1411		896		749	1041		1137	
4	1617	1054	1533	1231	1274	1359	1579	1770		1089					1890		1135		876	1258		1300	
5	1891	1427	1712	---	1514	1519	1809	1967		---					---		1356		---	1479		1452	
End	2126	1860	1981	---	1776	1682	2156	2184		---					---		1824		---	1670		1622	
Week 4-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	698		399	353	577	937														522		296	
2	877		576	562	812	1076														743		421	
3	1061		694	721	1071	1236														971		647	
4	1243		922	905	1337	1418														1175		1003	
5	1425		---	1003	1581	1572														1394		---	
End	1646		---	1158	1843	1739														1633		---	
Week 4-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	609				982	454					628									1035			
2	791				1213	655					870									1235			
3	1093				1443	875					1103									1425			
4	1426				1696	1078					1337									1613			
5	1748				1898	1222					1574									1821			
End	1946				2099	1433					1812									2040			

Week 6-75%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	1336		491	937		2007	330	2617		386	1398		372		1151		309		321	1756		852	
2	1541		670	1438		2200	533	2856		609	1685		511		1484		532		566	1955		1060	
3	1754		855	1515		2406	746	3093		768	1938		766		1927		782		797	2135		1277	
4	1964		1110	2050		2614	1341	3341		932	2228		1096		2374		1044		1032	2368		1518	
5	2183		1461	---		2819	---	3584		---	2476		---		2866		---		1289	2586		1775	
End	2400		1672	---		3012	---	3797		---	2752		---		3218		---		1706	2829		2060	
Week 6-65%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	919		302			798		2101		548	1870									1464		2789	
2	1114		538			1011		2317		933	2255									1693		2976	
3	1312		722			1231		2533		1523	2451									1925		3198	
4	1520		932			1413		2745		2017	2706									2141		3488	
5	1729		1119			1626		2984		---	2988									2358		3630	
End	1935		1356			1815		3251		---	3253									2584		3873	
Week 6-55%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	492					2409		582			1690								994	2130		2100	
2	710					2598		774			1878								1107	2354		2275	
3	937					2800		1015			2050								1224	2570		2576	
4	1217					2997		1233			2226								1365	2799		2784	
5	1443					3200		1441			2424								1505	3065		3065	
End	1720					3399		1681			2596								1660	3313		3331	

Week 8-75%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	545		474		538	1601		1341	710	313	7494	372	459		609				616	603		1083	
2	769		647		739	1860		1554	950	490	7840	649	667		798				799	805		1302	
3	978		847		932	2143		1750	1183	684	8113	881	893		989				988	1028		1534	
4	1253		1076		1133	2417		1938	1435	874	8345	1142	1123		1199				1186	1223		1733	
5	1524		1269		1337	2713		2129	1652	1100	8628	1540	1797		1405				1393	1445		1961	
End	1787		1495		1572	2996		2319	1924	---	8888	1752	2176		1620				1604	1702		2195	
Week 8-65%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	740		1164		632	2993		909	517		1625		623		527				524	1643		899	
2	921		1348		853	3227		1106	716		1906		865		742				695	1824		1072	
3	1113		1544		1114	3484		1284	917		2202		1103		948				893	2013		1258	
4	1299		1741		1420	3749		1495	1100		2484		1388		1186				1106	2214		1423	
5	1481		1920		1669	4000		1691	1292		2780		1569		1439				1312	2404		1643	
End	1669		2130		1999	4255		1869	1500		3056		1813		1683				1497	2622		1883	
Week 8-55%	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	494		491		520	1283		826	1629				475		2884				2492	1711		4235	
2	689		628		713	1526		1004	1880				687		3159				2708	2017		4426	
3	873		799		944	1761		1194	2123				925		3349				2788	2305		4602	
4	1047		962		1156	1995		1397	2351				1185		3627				2993	2653		4804	
5	1216		1147		1375	2266		1596	2566				1427		3840				3213	2912		4996	
End	1384		1296		1688	2561		1793	2778				1644		4080				3499	3200		5193	

Wasn't Tested
Innsufient Data
Needs Processing

Numbers are Frame Numbers Frame Rate: 100 FPS Alex Herman

Baseline-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	1441	875							376	1281					503								
2	1543	1011							458	1415					566								
3	1649	1135							539	1549					633								
4	1752	1258							639	1711					735								
5	1852	1398							719	1851					841								
End	1947	1528							784	1957					996								
Baseline-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	527	563								721					1447								
2	623	666								840					1553								
3	757	790								972					1670								
4	879	918								1103					1768								
5	1015	1046								1226					1885								
End	1152	1180								1347					1997								
Baseline-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	832	1337							4248	440					494								
2	959	1460							4377	617					558								
3	1101	1606							4478	745					626								
4	1245	1752							4589	882					704								
5	1411	1911							4705	1065					788								
End	1597	2052							4824	1330					867								

Week 4-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	509	400		477	870	659	317	555	319		591									3602			
2	644	513		604	1029	821	462	717	452		743									3738			
3	779	645		795	1178	962	566	953	565		931									3905			
4	911	795		1044	1359	1072	702	1143	709		1108									4056			
5	1057	---		---	1524	1213	840	1343	851		1248									4194			
End	1262	---		---	1700	1364	997	1659	1007		1492									4349			
Week 4-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	1060				2917	721					469									715			
2	1210				3082	861					566									885			
3	1365				3273	998					751									1036			
4	1530				3465	1141					931									1187			
5	1685				3698	1271					1115									1338			
End	1841				4204	1381					1300									1520			
Week 4-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	596				590	714					485									2822			
2	724				838	847					633									2991			
3	857				1019	947					753									3169			
4	985				1272	1094					913									3300			
5	1151				1461	1233					1076									3555			
End	1308				1644	1359					1256									3745			

Numbers are Frame Numbers Frame Rate: 100 FPS Alex Herman

Week 6-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	1283		1274			744		670		2377	870								4172	1311		4470	
2	1436		1429			889		825		2640	1053								4414	1468		4671	
3	1577		1619			1020		992		3008	1237								4673	1662		4859	
4	1730		1794			1158		1162		3332	1404								4890	1814		5040	
5	1880		1976			1292		1325		3643	1570								5111	1958		5194	
End	2027		2094			1404		1492		3976	1753								5322	2117		5368	
Week 6-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	671					1234		555			2437								326	1022		975	
2	796					1383		685			2581								476	1176		1138	
3	914					1543		823			2740								643	1349		1309	
4	1040					1700		976			2870								798	1524		1507	
5	1169					1843		1131			3020								947	1680		1722	
End	1301					1987		1293			3171								1124	1826		1872	
Week 6-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	3753					2456		530			1140								1479	1190		466	
2	3920					2617		676			1276								1642	1348		616	
3	4091					2736		849			1397								1786	1515		767	
4	4269					2848		1030			1540								1921	1688		904	
5	4439					2983		1219			1670								2054	1862		1069	
End	4609					3144		1392			1799								2216	2010		1230	

Week 8-75%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	421		1931		532	1111	353	493	6717	273	1214	714	544		479				394	2158		1052	
2	620		2107		676	1306	485	637	6953	383	1385	877	700		618				531	2500		1201	
3	820		2289		819	1509	639	765	7175	537	1582	1162	940		787				676	2725		1354	
4	1019		2458		954	1705	848	914	7436	718	1753	1552	1125		970				830	2929		1495	
5	1185		2625		1088	1908	973	1052	7680	---	1926	---	1315		1152				979	3237		1648	
End	1338		2808		1239	2112	1125	1206	7878	---	2106	---	1517		1342				1123	3554		1798	
Week 8-65%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	580		1046		502	423		1010	2610				451		1307				429	293		753	
2	711		1207		655	573		1167	2798				604		1483				587	438		902	
3	841		1322		801	716		1324	2989				764		1670				760	594		1065	
4	974		1470		937	863		1467	3170				959		1864				905	743		1193	
5	1114		1612		1070	1006		1626	3348				1148		2043				1061	1221		1335	
End	1245		1780		1212	1171		1767	3558				1338		2242				1254	---		1482	
Week 8-55%	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
1	453		1802		654			1169	1004				279		1416		558		1050	457		3480	
2	597		1952		804			1308	1160				425		1601		713		1209	604		3610	
3	736		2073		944			1447	1334				583		1808		1029		1348	773		3747	
4	869		2197		1082			1597	1509				761		1995		1282		1492	947		3884	
5	1007		2326		1224			1736	1678				947		2164		---		1629	1107		4020	
End	1145		2436		1368			1868	1853				1117		2358		---		1784	1271		4172	

Wasn't Tested
Innsufient Data
Needs Processing

Appendix C

Main MATLAB Code

C:\Users\Research\Documents\Data Analysis\Codes\Final Codes\Full_Angles_Analysis.m

```
% Full_Angle_Analysis.m
% Alex Herman
% Masters Thesis
% Description: Plots the Angle of the Hip, Knee and Angle of a Joint of a
% step cycle and created an average using interp1 function also takes one
% stride and creates a stick figure plot for all five strides and output a
% CSV of angle and point distance ranges
% 10/1/2015

clear all; %#ok<CLALL>
close all;
clc;
addpath(genpath('H:\School Work\Masters Research\Data Analysis\Set 1\MAT Files'))
addpath(genpath('H:\School Work\Masters Research\Data Analysis\Set 2\MAT Files'))
addpath(genpath('H:\School Work\Masters Research\Data Analysis\Set 3\MAT Files'))

load('56-Week4-10cms-75%'); % Loads Data From Pre-created MAT File

ratset = 'Set 3';
rat = '56';
test = 'Week 4';
speed = '10';
bws = '75';
group = '3';
int = 'spline';   % Interpolation method

s(1) = Frame(1);    % frame for splitting data to individual strides
s(2) = 452;
s(3) = 565;
s(4) = 709;
s(5) = 851;
s(6) = Frame(end);

lps = 0;   % Number of Stick Figure Lines to Plot (Set 0 for full sample)

saveto = ['H:\School Work\Masters Research\Data Analysis\' ratset '\Plots\' test];

% ------------------------------Transpose Data-------------------------------

% Iliac

X_Iliac = X_Iliac';
Y_Iliac = Y_Iliac';
Z_Iliac = Z_Iliac';

% Hip

X_Hip = X_Hip';
Y_Hip = Y_Hip';
Z_Hip = Z_Hip';

% Knee
```

```
X_Knee = X_Knee';
Y_Knee = Y_Knee';
Z_Knee = Z_Knee';

% Ankle

X_Ankle = X_Ankle';
Y_Ankle = Y_Ankle';
Z_Ankle = Z_Ankle';

% Metatarsal

X_Metatarsal = X_Metatarsal';
Y_Metatarsal = Y_Metatarsal';
Z_Metatarsal = Z_Metatarsal';

%-------------------Initialization of Vectors and Arrays-------------------

X_pelvis = zeros(1,numel(Frame)); % Initializes the X Coordinates of Vectors
X_thigh = zeros(1,numel(Frame));
X_lowerleg = zeros(1,numel(Frame));
X_foot = zeros(1,numel(Frame));

Y_pelvis = zeros(1,numel(Frame)); % Initializes the Y Coordinates of Vectors
Y_thigh = zeros(1,numel(Frame));
Y_lowerleg = zeros(1,numel(Frame));
Y_foot = zeros(1,numel(Frame));

Z_pelvis = zeros(1,numel(Frame)); % Initializes the Z Coordinates of Vectors
Z_thigh = zeros(1,numel(Frame));
Z_lowerleg = zeros(1,numel(Frame));
Z_foot = zeros(1,numel(Frame));

dot_hip = zeros(1,numel(Frame)); % Initializes Dot Product Arrays
dot_knee = zeros(1,numel(Frame));
dot_ankle = zeros(1,numel(Frame));

mag_pelvis = zeros(1,numel(Frame)); % Initializes the Magnitude Arrays
mag_thigh = zeros(1,numel(Frame));
mag_lowerleg = zeros(1,numel(Frame));
mag_foot = zeros(1,numel(Frame));

angle_hip = zeros(1,numel(Frame)); % Initializes the Angle Arrays
angle_ankle = zeros(1,numel(Frame));
angle_knee = zeros(1,numel(Frame));

for i = 1:numel(Frame) % Create the Vectors and Arrays at each Time Interval

%------Create Upper and Lower Extremity Vectors at each Time Interval------

X_pelvis(i) = X_Iliac(i) - X_Hip(i); % X coordinate of the Vectors
X_thigh(i) = X_Knee(i) - X_Hip(i);
X_lowerleg(i) = X_Knee(i) - X_Ankle(i);
```

```
X_foot(i) = X_Metatarsal(i) - X_Ankle(i);

Y_pelvis(i) = Y_Iliac(i) - Y_Hip(i); % Y coordinate of the Vectors
Y_thigh(i) = Y_Knee(i) - Y_Hip(i);
Y_lowerleg(i) = Y_Knee(i) - Y_Ankle(i);
Y_foot(i) =  Y_Metatarsal(i) - Y_Ankle(i);

Z_pelvis(i) = Z_Iliac(i) - Z_Hip(i); % Z coordinate of the Vectors
Z_thigh(i) = Z_Knee(i) - Z_Hip(i);
Z_lowerleg(i) = Z_Knee(i) - Z_Ankle(i);
Z_foot(i) = Z_Metatarsal(i) - Z_Ankle(i);


%-----Solves for the Dot Product of each Vector for each Time Interval-----

dot_hip(i) = X_pelvis(i) * X_thigh(i) + Y_pelvis(i) * Y_thigh(i) + Z_pelvis(i) * Z_thigh(i);
dot_ankle(i) = X_lowerleg(i) * X_foot(i) + Y_lowerleg(i) * Y_foot(i) + Z_lowerleg(i) * Z_foot(i);
dot_knee(i) = X_thigh(i) * X_lowerleg(i) + Y_thigh(i) * Y_lowerleg(i) + Z_thigh(i) *
Z_lowerleg(i);

%------Solves for the Magnitude of each Vector for each Time Interval------

mag_pelvis(i) = sqrt( X_pelvis(i)^2 + Y_pelvis(i)^2 + Z_pelvis(i)^2 );
mag_thigh(i) = sqrt( X_thigh(i)^2 + Y_thigh(i)^2 + Z_thigh(i)^2 );
mag_lowerleg(i) = sqrt( X_lowerleg(i)^2 + Y_lowerleg(i)^2 + Z_lowerleg(i)^2 );
mag_foot(i) = sqrt( X_foot(i)^2 + Y_foot(i)^2 + Z_foot(i)^2 );

%--------Solves for the Angle of the Vectors for each Time Interval--------

angle_hip(i) = acosd( dot_hip(i) / (mag_pelvis(i) * mag_thigh(i)));
angle_ankle(i) = acosd( dot_ankle(i) / (mag_lowerleg(i) * mag_foot(i)));
angle_knee(i) = acosd( dot_knee(i) / (mag_thigh(i) * mag_lowerleg(i)));

end
%-----------------Split the angles into individual strides-----------------

s_length(1) = s(2)-s(1)+1; % Length of each stride
s_length(2) = s(3)-s(2)+1;
s_length(3) = s(4)-s(3)+1;
s_length(4) = s(5)-s(4)+1;
s_length(5) = s(6)-s(5)+1;

s = s - Frame(1) + 1; % Indexes for splitting the strides

% subarrays for stride distances for each point & coord. (Exported Data)

x_iliac_rng(1) = range(X_Iliac(s(1):s(2)));
x_hip_rng(1) = range(X_Hip(s(1):s(2)));
x_knee_rng(1) = range(X_Knee(s(1):s(2)));
x_ankle_rng(1) = range(X_Ankle(s(1):s(2)));
x_meta_rng(1) = range(X_Metatarsal(s(1):s(2)));

y_iliac_rng(1) = range(Y_Iliac(s(1):s(2)));
```

```
y_hip_rng(1) = range(Y_Hip(s(1):s(2)));
y_knee_rng(1) = range(Y_Knee(s(1):s(2)));
y_ankle_rng(1) = range(Y_Ankle(s(1):s(2)));
y_meta_rng(1) = range(Y_Metatarsal(s(1):s(2)));

z_iliac_rng(1) = range(Z_Iliac(s(1):s(2)));
z_hip_rng(1) = range(Z_Hip(s(1):s(2)));
z_knee_rng(1) = range(Z_Knee(s(1):s(2)));
z_ankle_rng(1) = range(Z_Ankle(s(1):s(2)));
z_meta_rng(1) = range(Z_Metatarsal(s(1):s(2)));

x_iliac_rng(2) = range(X_Iliac(s(2):s(3)));
x_hip_rng(2) = range(X_Hip(s(2):s(3)));
x_knee_rng(2) = range(X_Knee(s(2):s(3)));
x_ankle_rng(2) = range(X_Ankle(s(2):s(3)));
x_meta_rng(2) = range(X_Metatarsal(s(2):s(3)));

y_iliac_rng(2) = range(Y_Iliac(s(2):s(3)));
y_hip_rng(2) = range(Y_Hip(s(2):s(3)));
y_knee_rng(2) = range(Y_Knee(s(2):s(3)));
y_ankle_rng(2) = range(Y_Ankle(s(2):s(3)));
y_meta_rng(2) = range(Y_Metatarsal(s(2):s(3)));

z_iliac_rng(2) = range(Z_Iliac(s(2):s(3)));
z_hip_rng(2) = range(Z_Hip(s(2):s(3)));
z_knee_rng(2) = range(Z_Knee(s(2):s(3)));
z_ankle_rng(2) = range(Z_Ankle(s(2):s(3)));
z_meta_rng(2) = range(Z_Metatarsal(s(2):s(3)));


x_iliac_rng(3) = range(X_Iliac(s(3):s(4)));
x_hip_rng(3) = range(X_Hip(s(3):s(4)));
x_knee_rng(3) = range(X_Knee(s(3):s(4)));
x_ankle_rng(3) = range(X_Ankle(s(3):s(4)));
x_meta_rng(3) = range(X_Metatarsal(s(3):s(4)));

y_iliac_rng(3) = range(Y_Iliac(s(3):s(4)));
y_hip_rng(3) = range(Y_Hip(s(3):s(4)));
y_knee_rng(3) = range(Y_Knee(s(3):s(4)));
y_ankle_rng(3) = range(Y_Ankle(s(3):s(4)));
y_meta_rng(3) = range(Y_Metatarsal(s(3):s(4)));

z_iliac_rng(3) = range(Z_Iliac(s(3):s(4)));
z_hip_rng(3) = range(Z_Hip(s(3):s(4)));
z_knee_rng(3) = range(Z_Knee(s(3):s(4)));
z_ankle_rng(3) = range(Z_Ankle(s(3):s(4)));
z_meta_rng(3) = range(Z_Metatarsal(s(3):s(4)));

x_iliac_rng(4) = range(X_Iliac(s(4):s(5)));
x_hip_rng(4) = range(X_Hip(s(4):s(5)));
x_knee_rng(4) = range(X_Knee(s(4):s(5)));
x_ankle_rng(4) = range(X_Ankle(s(4):s(5)));
x_meta_rng(4) = range(X_Metatarsal(s(4):s(5)));
```

```
y_iliac_rng(4) = range(Y_Iliac(s(4):s(5)));
y_hip_rng(4) = range(Y_Hip(s(4):s(5)));
y_knee_rng(4) = range(Y_Knee(s(4):s(5)));
y_ankle_rng(4) = range(Y_Ankle(s(4):s(5)));
y_meta_rng(4) = range(Y_Metatarsal(s(4):s(5)));

z_iliac_rng(4) = range(Z_Iliac(s(4):s(5)));
z_hip_rng(4) = range(Z_Hip(s(4):s(5)));
z_knee_rng(4) = range(Z_Knee(s(4):s(5)));
z_ankle_rng(4) = range(Z_Ankle(s(4):s(5)));
z_meta_rng(4) = range(Z_Metatarsal(s(4):s(5)));

x_iliac_rng(5) = range(X_Iliac(s(5):s(6)));
x_hip_rng(5) = range(X_Hip(s(5):s(6)));
x_knee_rng(5) = range(X_Knee(s(5):s(6)));
x_ankle_rng(5) = range(X_Ankle(s(5):s(6)));
x_meta_rng(5) = range(X_Metatarsal(s(5):s(6)));

y_iliac_rng(5) = range(Y_Iliac(s(5):s(6)));
y_hip_rng(5) = range(Y_Hip(s(5):s(6)));
y_knee_rng(5) = range(Y_Knee(s(5):s(6)));
y_ankle_rng(5) = range(Y_Ankle(s(5):s(6)));
y_meta_rng(5) = range(Y_Metatarsal(s(5):s(6)));

z_iliac_rng(5) = range(Z_Iliac(s(5):s(6)));
z_hip_rng(5) = range(Z_Hip(s(5):s(6)));
z_knee_rng(5) = range(Z_Knee(s(5):s(6)));
z_ankle_rng(5) = range(Z_Ankle(s(5):s(6)));
z_meta_rng(5) = range(Z_Metatarsal(s(5):s(6)));


x_iliac_rng_avg = mean(x_iliac_rng,2)*100;
x_hip_rng_avg = mean(x_hip_rng,2)*100;
x_knee_rng_avg = mean(x_knee_rng,2)*100;
x_ankle_rng_avg = mean(x_ankle_rng,2)*100;
x_meta_rng_avg = mean(x_meta_rng,2)*100;

y_iliac_rng_avg = mean(y_iliac_rng,2)*100;
y_hip_rng_avg = mean(y_hip_rng,2)*100;
y_knee_rng_avg = mean(y_knee_rng,2)*100;
y_ankle_rng_avg = mean(y_ankle_rng,2)*100;
y_meta_rng_avg = mean(y_meta_rng,2)*100;

z_iliac_rng_avg = mean(z_iliac_rng,2)*100;
z_hip_rng_avg = mean(z_hip_rng,2)*100;
z_knee_rng_avg = mean(z_knee_rng,2)*100;
z_ankle_rng_avg = mean(z_ankle_rng,2)*100;
z_meta_rng_avg = mean(z_meta_rng,2)*100;

% subarrays for frame number corresponding to stride number (angles)
% (Ranges Exported)
```

```
angle_hip_s{1} = angle_hip(s(1):s(2));
angle_ankle_s{1} = angle_ankle(s(1):s(2));
angle_knee_s{1} = angle_knee(s(1):s(2));
angle_hip_rng(1) = range(angle_hip_s{1});
angle_hip_max(1) = max(angle_hip_s{1});
angle_hip_min(1) = min(angle_hip_s{1});
angle_ankle_rng(1) = range(angle_ankle_s{1});
angle_ankle_max(1) = max(angle_ankle_s{1});
angle_ankle_min(1) = min(angle_ankle_s{1});
angle_knee_rng(1) = range(angle_knee_s{1});
angle_knee_max(1) = max(angle_knee_s{1});
angle_knee_min(1) = min(angle_knee_s{1});

angle_hip_s{2} = angle_hip(s{2}:s{3});
angle_ankle_s{2} = angle_ankle(s(2):s(3));
angle_knee_s{2} = angle_knee(s(2):s(3));
angle_hip_rng(2)= range(angle_hip_s{2});
angle_hip_max(2) = max(angle_hip_s{2});
angle_hip_min(2) = min(angle_hip_s{2});
angle_ankle_rng(2) = range(angle_ankle_s{2});
angle_ankle_max(2) = max(angle_ankle_s{2});
angle_ankle_min(2) = min(angle_ankle_s{2});
angle_knee_rng(2) = range(angle_knee_s{2});
angle_knee_max(2) = max(angle_knee_s{2});
angle_knee_min(2) = min(angle_knee_s{2});

angle_hip_s{3} = angle_hip(s(3):s(4));
angle_ankle_s{3} = angle_ankle(s(3):s(4));
angle_knee_s{3} = angle_knee(s(3):s(4));
angle_hip_rng(3)= range(angle_hip_s{3});
angle_hip_max(3) = max(angle_hip_s{3});
angle_hip_min(3) = min(angle_hip_s{3});
angle_ankle_rng(3) = range(angle_ankle_s{3});
angle_ankle_max(3) = max(angle_ankle_s{3});
angle_ankle_min(3) = min(angle_ankle_s{3});
angle_knee_rng(3) = range(angle_knee_s{3});
angle_knee_max(3) = max(angle_knee_s{3});
angle_knee_min(3) = min(angle_knee_s{3});

angle_hip_s{4} = angle_hip(s{4}:s{5});
angle_ankle_s{4} = angle_ankle(s{4}:s{5});
angle_knee_s{4} = angle_knee(s(4):s(5));
angle_hip_rng(4)= range(angle_hip_s{4});
angle_hip_max(4) = max(angle_hip_s{4});
angle_hip_min(4) = min(angle_hip_s{4});
angle_ankle_rng(4) = range(angle_ankle_s{4});
angle_ankle_max(4) = max(angle_ankle_s{4});
angle_ankle_min(4) = min(angle_ankle_s{4});
angle_knee_rng(4) = range(angle_knee_s{4});
angle_knee_max(4) = max(angle_knee_s{4});
angle_knee_min(4) = min(angle_knee_s{4});

angle_hip_s{5} = angle_hip(s(5):s(6));
```

```
angle_ankle_s{5} = angle_ankle(s(5):s(6));
angle_knee_s{5} = angle_knee(s(5):s(6));
angle_hip_rng(5)= range(angle_hip_s{5});
angle_hip_max(5) = max(angle_hip_s{5});
angle_hip_min(5) = min(angle_hip_s{5});
angle_ankle_rng(5) = range(angle_ankle_s{5});
angle_ankle_max(5) = max(angle_ankle_s{5});
angle_ankle_min(5) = min(angle_ankle_s{5});
angle_knee_rng(5) = range(angle_knee_s{5});
angle_knee_max(5) = max(angle_knee_s{5});
angle_knee_min(5) = min(angle_knee_s{5});

hip_avg_strd_ang_rng = mean(angle_hip_rng,2); % Average Stride Angle Range
knee_avg_strd_ang_rng = mean(angle_knee_rng,2);
ankle_avg_strd_ang_rng = mean(angle_ankle_rng,2);

hip_ang_rng = range(angle_hip); % Total Take Angle Range
knee_ang_rng = range(angle_knee);
ankle_ang_rng = range(angle_ankle);

% Initialize mapped angle matrices
hip_map_angle = zeros(5,101);
knee_map_angle = zeros(5,101);
ankle_map_angle = zeros(5,101);

%------------------Maps joint angles to percent of stride------------------

for i = 1:5 % Iterates each stride

    % Interpolates strides angles to percentage of gate
    hip_map_angle(i,:)=interp1(1:s_length(i),angle_hip_s{i},0:s_length(i)/100:s_length(i),int);
    knee_map_angle(i,:)=interp1(1:s_length(i),angle_knee_s{i},0:s_length(i)/100:s_length(i),int);

    ankle_map_angle(i,:)=interp1(1:s_length(i),angle_ankle_s{i},0:s_length(i)/100:s_length(i),int
    );

end

% Creates average angle for each joint, and its range, max and min angle

hip_avg_ang = mean(hip_map_angle);
hip_avg_ang_rng = range(hip_avg_ang);
hip_avg_ang_max = max(hip_avg_ang);
hip_avg_ang_min = min(hip_avg_ang);
knee_avg_ang = mean(knee_map_angle);
knee_avg_ang_rng = range(knee_avg_ang);
knee_avg_ang_max = max(knee_avg_ang);
knee_avg_ang_min = min(knee_avg_ang);
ankle_avg_ang = mean(ankle_map_angle);
ankle_avg_ang_rng = range(ankle_avg_ang);
ankle_avg_ang_max = max(ankle_avg_ang);
ankle_avg_ang_min = min(ankle_avg_ang);
```

```
%------------------------Stick Figure Line Creation------------------------

for sfs = 1:5

if lps == 0
   lps = s_length(sfs);
end

X_Iliac_sf = X_Iliac(s(sfs):s(sfs+1));
X_Iliac_sfm = interp1(1:numel(X_Iliac_sf),X_Iliac_sf,...
    1:numel(X_Iliac_sf)/lps:numel(X_Iliac_sf),int)';
Y_Iliac_sf = Y_Iliac(s(sfs):s(sfs+1));
Y_Iliac_sfm = interp1(1:numel(Y_Iliac_sf),Y_Iliac_sf,...
    1:numel(Y_Iliac_sf)/lps:numel(Y_Iliac_sf),int)';
Z_Iliac_sf = Z_Iliac(s(sfs):s(sfs+1));
Z_Iliac_sfm = interp1(1:numel(Z_Iliac_sf),Z_Iliac_sf,...
    1:numel(Z_Iliac_sf)/lps:numel(Z_Iliac_sf),int)';

X_Hip_sf = X_Hip(s(sfs):s(sfs+1));
X_Hip_sfm = interp1(1:numel(X_Hip_sf),X_Hip_sf,...
    1:numel(X_Hip_sf)/lps:numel(X_Hip_sf),int)';
Y_Hip_sf = Y_Hip(s(sfs):s(sfs+1));
Y_Hip_sfm = interp1(1:numel(Y_Hip_sf),Y_Hip_sf,...
    1:numel(Y_Hip_sf)/lps:numel(Y_Hip_sf),int)';
Z_Hip_sf = Z_Hip(s(sfs):s(sfs+1));
Z_Hip_sfm = interp1(1:numel(Z_Hip_sf),Z_Hip_sf,...
    1:numel(Z_Hip_sf)/lps:numel(Z_Hip_sf),int)';

X_Knee_sf = X_Knee(s(sfs):s(sfs+1));
X_Knee_sfm = interp1(1:numel(X_Knee_sf),X_Knee_sf,...
    1:numel(X_Knee_sf)/lps:numel(X_Knee_sf),int)';
Y_Knee_sf = Y_Knee(s(sfs):s(sfs+1));
Y_Knee_sfm = interp1(1:numel(Y_Knee_sf),Y_Knee_sf,...
    1:numel(Y_Knee_sf)/lps:numel(Y_Knee_sf),int)';
Z_Knee_sf = Z_Knee(s(sfs):s(sfs+1));
Z_Knee_sfm = interp1(1:numel(Z_Knee_sf),Z_Knee_sf,...
    1:numel(Z_Knee_sf)/lps:numel(Z_Knee_sf),int)';

X_Ankle_sf = X_Ankle(s(sfs):s(sfs+1));
X_Ankle_sfm = interp1(1:numel(X_Ankle_sf),X_Ankle_sf,...
    1:numel(X_Ankle_sf)/lps:numel(X_Ankle_sf),int)';
Y_Ankle_sf = Y_Ankle(s(sfs):s(sfs+1));
Y_Ankle_sfm = interp1(1:numel(Y_Ankle_sf),Y_Ankle_sf,...
    1:numel(Y_Ankle_sf)/lps:numel(Y_Ankle_sf),int)';
Z_Ankle_sf = Z_Ankle(s(sfs):s(sfs+1));
Z_Ankle_sfm = interp1(1:numel(Z_Ankle_sf),Z_Ankle_sf,...
    1:numel(Z_Ankle_sf)/lps:numel(Z_Ankle_sf),int)';

X_Metatarsal_sf = X_Metatarsal(s(sfs):s(sfs+1));
X_Metatarsal_sfm = interp1(1:numel(X_Metatarsal_sf),X_Metatarsal_sf,...
    1:numel(X_Metatarsal_sf)/lps:numel(X_Metatarsal_sf),int)';
Y_Metatarsal_sf = Y_Metatarsal(s(sfs):s(sfs+1));
```

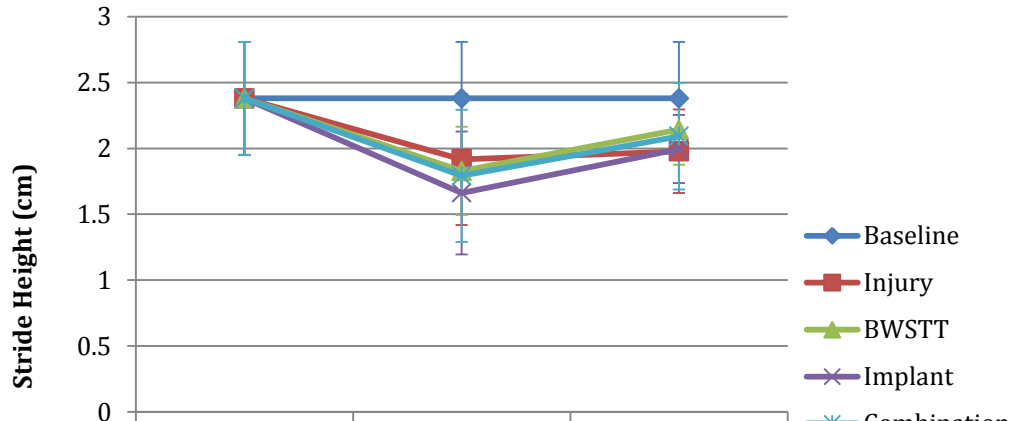
```
Y_Metatarsal_sfm = interp1(1:numel(Y_Metatarsal_sf),Y_Metatarsal_sf,...
    1:numel(Y_Metatarsal_sf)/lps:numel(Y_Metatarsal_sf),int)';
Z_Metatarsal_sf = Z_Metatarsal(s(sfs):s(sfs+1));
Z_Metatarsal_sfm = interp1(1:numel(Z_Metatarsal_sf),Z_Metatarsal_sf,...
    1:numel(Z_Metatarsal_sf)/lps:numel(Z_Metatarsal_sf),int)';

sf_x = [X_Iliac_sfm,X_Hip_sfm,X_Knee_sfm,X_Ankle_sfm,X_Metatarsal_sfm]';
sf_z = [Y_Iliac_sfm,Y_Hip_sfm,Y_Knee_sfm,Y_Ankle_sfm,Y_Metatarsal_sfm]';
sf_y = [Z_Iliac_sfm,Z_Hip_sfm,Z_Knee_sfm,Z_Ankle_sfm,Z_Metatarsal_sfm]';


% Plots Stick Figure Plot for Each Stride
figure
co=colormap(jet(lps));
set(groot,'defaultAxesColorOrder',co)
% plot3(sf_x,sf_y,sf_z)
plot(sf_x,sf_z)
colormap jet
title(['Stick Figure Plot of Rat ' rat ...
    ' (' speed ' cm/s, ' test ' , ' bws '%BWS): Stride ' num2str(sfs)])
xlabel('X Position (Meters)')
ylabel('Y Position (Meters)')
zlabel('Z Position (Meters)')
cb = colorbar('Ticks',0:0.1:1,...
         'TickLabels',{'0%','10%','20%','30%','40%','50%',...
         '60%','70%','80%','90%','100%'});
cb.Label.String = 'Percent of Gate'; % For R2014b and newer
%set(get(cb,'Title'),'String','% of Gate');
print([saveto '\' rat '-' test '-' speed 'cms-' bws '-S' num2str(sfs)],'-dpng')

end

%----------------------Exporting Numerical Results-------------------------

data1 = {rat,test,speed,bws,group,x_iliac_rng_avg,x_hip_rng_avg,...
    x_knee_rng_avg,x_ankle_rng_avg,x_meta_rng_avg,y_iliac_rng_avg,...
    y_hip_rng_avg,y_knee_rng_avg,y_ankle_rng_avg,y_meta_rng_avg,...
    hip_ang_rng,hip_avg_strd_ang_rng,knee_ang_rng,knee_avg_strd_ang_rng,...
    ankle_ang_rng,ankle_avg_strd_ang_rng};

exTable1 = cell2table(data1,'VariableNames',{'Rat','Week','Speed','BWS',...

    'Group','Avg_X_Iliac_Stride_Range_cm','Avg_X_Hip_Stride_Range_cm','Avg_X_Knee_Stride_Range_cm
    ',...

    'Avg_X_Ankle_Stride_Range_cm','Avg_X_Metatarsal_Stride_Range_cm','Avg_Y_Iliac_Stride_Range_cm
    ',...
    'Avg_Y_Hip_Stride_Range_cm','Avg_Y_Knee_Stride_Range_cm','Avg_Y_Ankle_Stride_Range_cm',...
    'Avg_Y_Metatarsal_Stride_Range_cm','Total_Hip_Angle_Range_deg',...
    'Hip_Avg_Stride_Angle_Range_deg','Total_Knee_Angle_Range_deg',...
    'Knee_Avg_Stride_Angle_Range_deg','Total_Ankle_Angle_Range_deg',...
    'Ankle_Avg_Stride_Angle_Range_deg'});
```

```
writetable(exTable1,[saveto '\' rat '-' test '-' speed 'cms-' bws '-AvgData.csv'])

THip = array2table(hip_map_angle','VariableNames',{'Hip1', 'Hip2', 'Hip3', 'Hip4', 'Hip5'});
THipAvg = array2table(hip_avg_ang','VariableNames',{'Hip_Avg'});
TKnee = array2table(knee_map_angle','VariableNames',{'Knee1', 'Knee2', 'Knee3', 'Knee4',
'Knee5'});
TKneeAvg = array2table(knee_avg_ang','VariableNames',{'Knee_Avg'});
TAnkle = array2table(ankle_map_angle','VariableNames',{'Ankle', 'Ankle2', 'Ankle3', 'Ankle4',
'Ankle5'});
TAnkleAvg = array2table(ankle_avg_ang','VariableNames',{'Ankle_Avg'});

exTable2 = [THip THipAvg TKnee TKneeAvg TAnkle TAnkleAvg];

writetable(exTable2,[saveto '\' rat '-' test '-' speed 'cms-' bws '-MapData.csv'])

data =
[s_length/100;x_iliac_rng*100;x_hip_rng*100;x_knee_rng*100;x_ankle_rng*100;x_meta_rng*100;...
    y_iliac_rng*100;y_hip_rng*100;y_knee_rng*100;y_ankle_rng*100;y_meta_rng*100;...
    z_iliac_rng*100;z_hip_rng*100;z_knee_rng*100;z_ankle_rng*100;z_meta_rng*100;...
    angle_hip_rng;angle_knee_rng;angle_ankle_rng;angle_hip_max;angle_knee_max;...
    angle_ankle_max;angle_hip_min;angle_knee_min;angle_ankle_min];

rns =  {'Stride_Length_(sec)','X_Iliac_Range_(cm)','X_Hip_Range_(cm)','X_Knee_Range_(cm)'...
    ,'X_Ankle_Range_(cm)','X_Meta_Range_(cm)','Y_Iliac_Range_(cm)','Y_Hip_Range_(cm)'...
    ,'Y_Knee_Range_(cm)','Y_Ankle_Range_(cm)','Y_Meta_Range_(cm)','Z_Iliac_Range_(cm)'...
    ,'Z_Hip_Range_(cm)','Z_Knee_Range_(cm)','Z_Ankle_Range_(cm)','Z_Meta_Range_(cm)'...
    ,'Hip_Angle_Range_(deg)','Knee_Angle_Range_(deg)','Ankle_Angle_Range_(deg)'...
    ,'Hip_Angle_Max_(deg)','Knee_Angle_Max_(deg)','Ankle_Angle_Max_(deg)'...
    ,'Hip_Angle_Min_(deg)','Knee_Angle_Min_(deg)','Ankle_Angle_Min_(deg)'};

exTable3 = array2table(data,'VariableNames',{'S1','S2','S3','S4','S5'},'RowNames',rns);
exTable3.Avg_Stride = mean(exTable3{:,1:end},2);

writetable(exTable3,[saveto '\' rat '-' test '-' speed 'cms-' bws
'-Data.csv'],'WriteRowNames',true)

%-------------------------Plotting the Results----------------------------

% Figure with all 3 angle over course of take
figure('Position',[20 20 700 700])

subplot(3,1,1);                 % Hip Angle
plot(s(1):s(6),angle_hip)
xlabel('Frames')
ylabel('Hip Joint Angle(deg)')
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Hip Angle - Entire Take'])

subplot(3,1,2);                 % Knee Angle
plot(s(1):s(6),angle_knee)
xlabel('Frames')
ylabel('Knee Joint Angle (deg)')
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Knee Angle - Entire Take'])
```

```
subplot(3,1,3);                % Ankle Ankle
plot(s(1):s(6), angle_ankle)
xlabel('Frames')
ylabel('Ankle Joint Angle(deg)')
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Ankle Angle - Entire Take'])
print([saveto '\' rat '-' test '-' speed 'cms-' bws '-Take'],'-dpng')

% Figure for percent of stride with average or each
figure('Position',[20 20 700 700])

subplot(3,1,1);             % Hip Angle for each stride and average
hold on
p(1) = plot(0:100, hip_map_angle(1,:),'k--','linewidth',0.25); %#
plot(0:100, hip_map_angle(2,:),'k--',0:100,hip_map_angle(3,:),'k--',...
    0:100, hip_map_angle(4,:),'k--',0:100, hip_map_angle(5,:),'k--',...
    'linewidth',0.25)
p(2) = plot(0:100,hip_avg_ang,'linewidth',2); %#
xlabel('Percent of Stride')
ylabel('Hip Joint Angle (deg)')
legend( p([1 2]),'Individual Strides','Average Stride','Location','Best');
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Hip Angle'])

subplot(3,1,2);             % Knee Angle for each stride and average
hold on
p(1) = plot(0:100, knee_map_angle(1,:),'k--','linewidth',0.25); %#
plot(0:100, knee_map_angle(2,:),'k--',0:100,knee_map_angle(3,:),'k--',...
    0:100, knee_map_angle(4,:),'k--',0:100, knee_map_angle(5,:),'k--',...
    'linewidth',0.25)
p(2) = plot(0:100,knee_avg_ang,'linewidth',2); %#
xlabel('Percent of Stride')
ylabel('Knee Joint Angle (deg)')
legend(p([1 2]),'Individual Strides','Average Stride','Location','Best');
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Knee Angle'])
hold off

subplot(3,1,3);             % Ankle Angle for each stride and average
hold on
p(1) = plot(0:100, ankle_map_angle(1,:),'k--','linewidth',0.25); %#
plot(0:100, ankle_map_angle(2,:),'k--',0:100,ankle_map_angle(3,:),'k--',...
    0:100, ankle_map_angle(4,:),'k--',0:100, ankle_map_angle(5,:),'k--',...
    'linewidth',0.25)
p(2) = plot(0:100,ankle_avg_ang,'linewidth',2); %#
xlabel('Percent of Stride')
ylabel('Ankle Joint Angle (deg)')
legend(p([1 2]),'Individual Strides','Average Stride','Location','Best');
title(['Rat ' rat ' - ' test ' (' speed 'cm/s, ' bws '%BWS) - Ankle Angle'])
print([saveto '\' rat '-' test '-' speed 'cms-' bws '-Strides'],'-dpng')
```

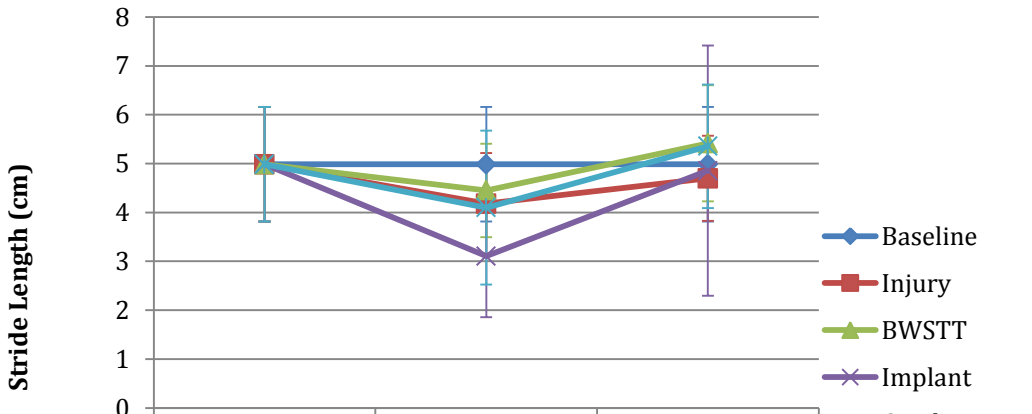
Appendix D

Plots from Remaining Speed and BWS Combinations7 cm/s – 75% BWS



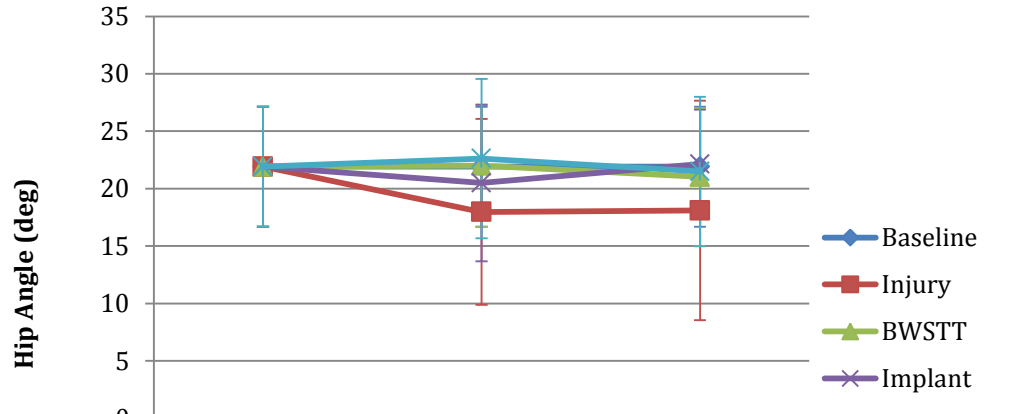
	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 5
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

Appendix Figure 1. Stride Height Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 75% BWS



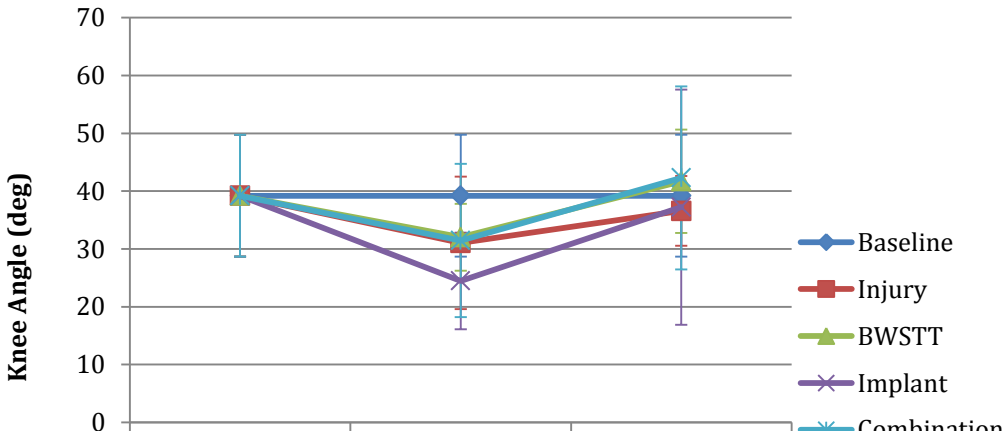
	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 5
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

Appendix Figure 2. Stride Length Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 75% BWS



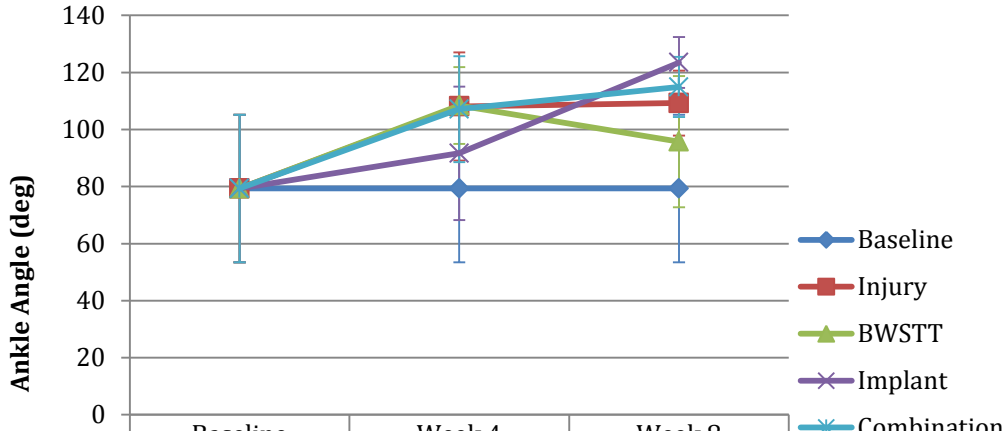
	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 5
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

Appendix Figure 3. Hip Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 75% BWS



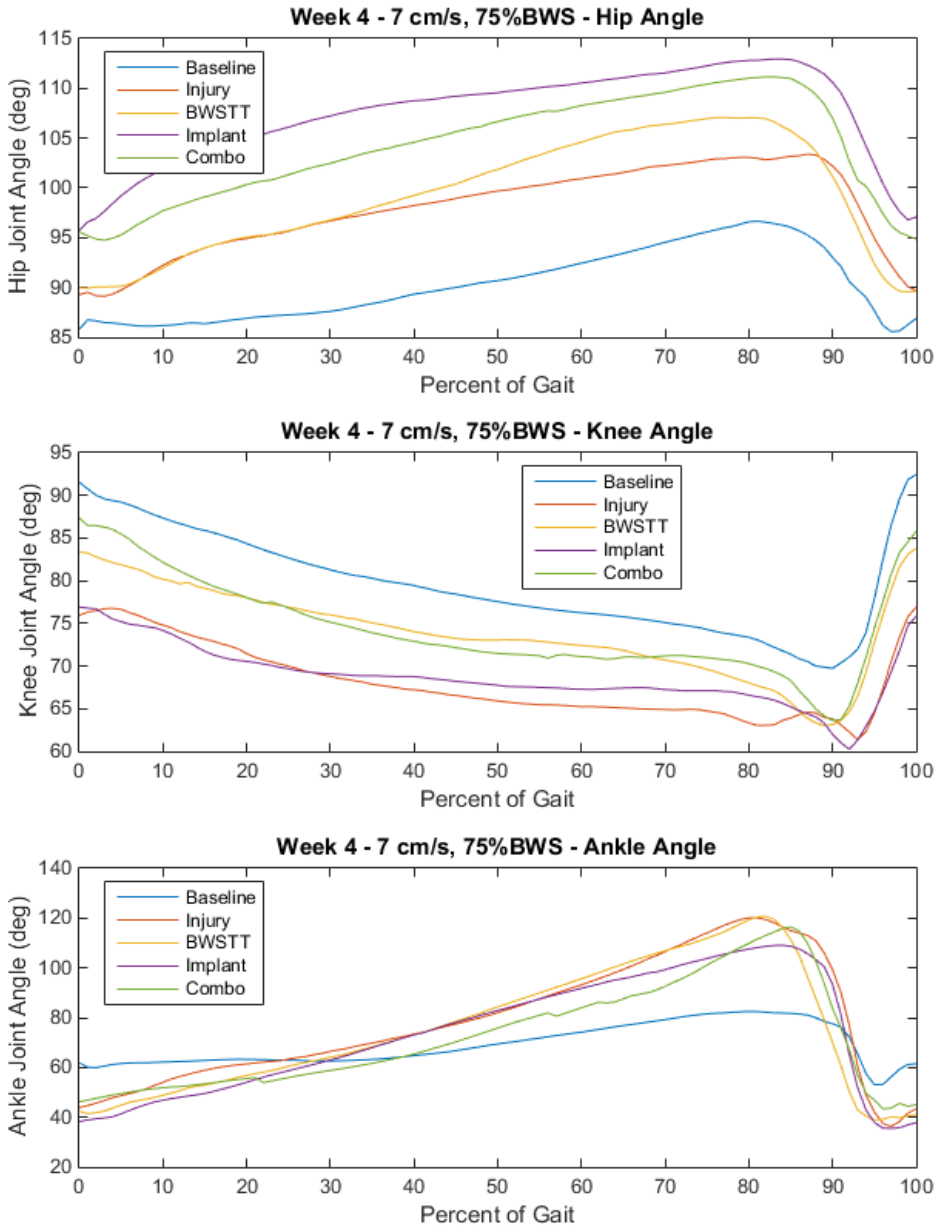
	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 5
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

Appendix Figure 4. Knee Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 75% BWS

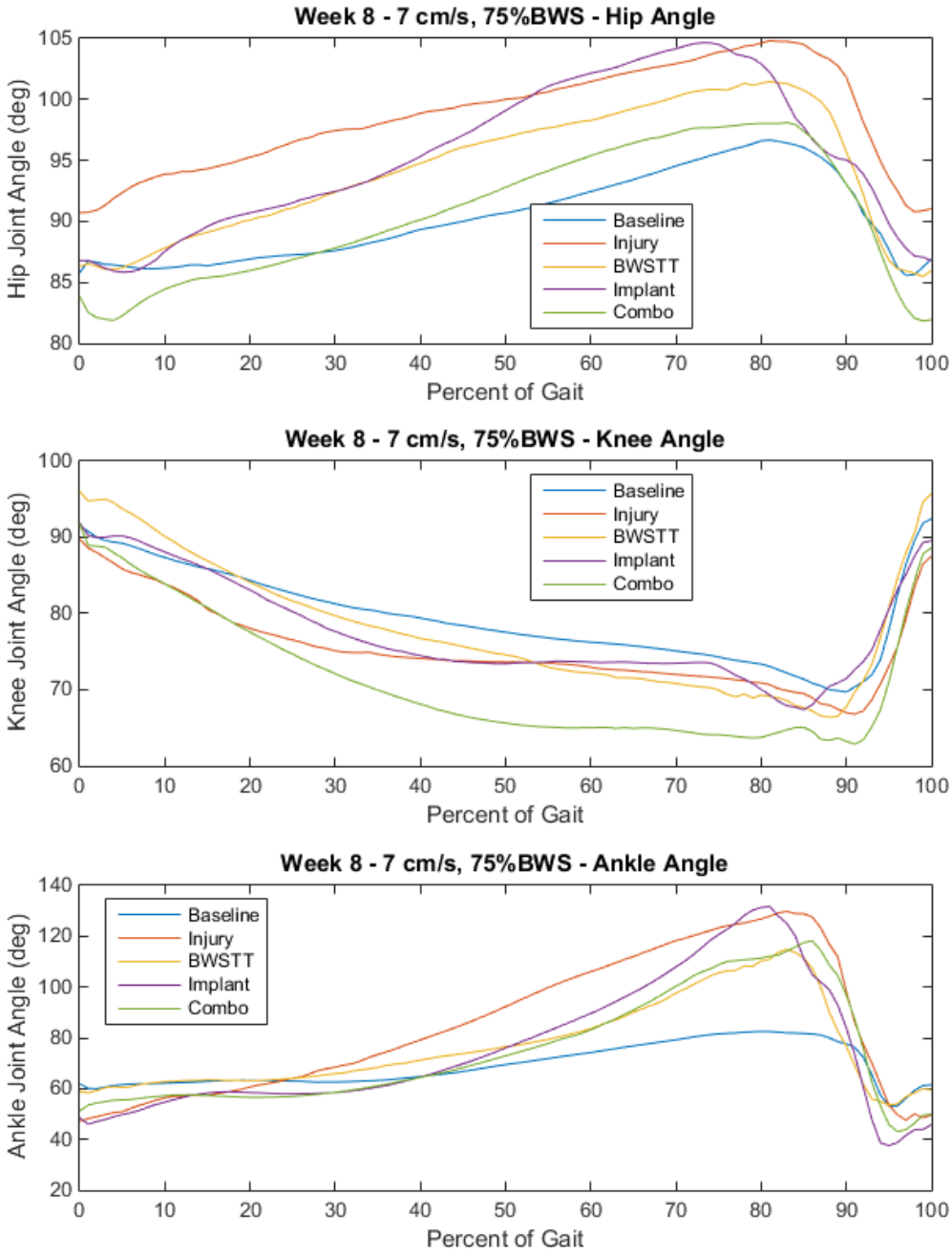


	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 5
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

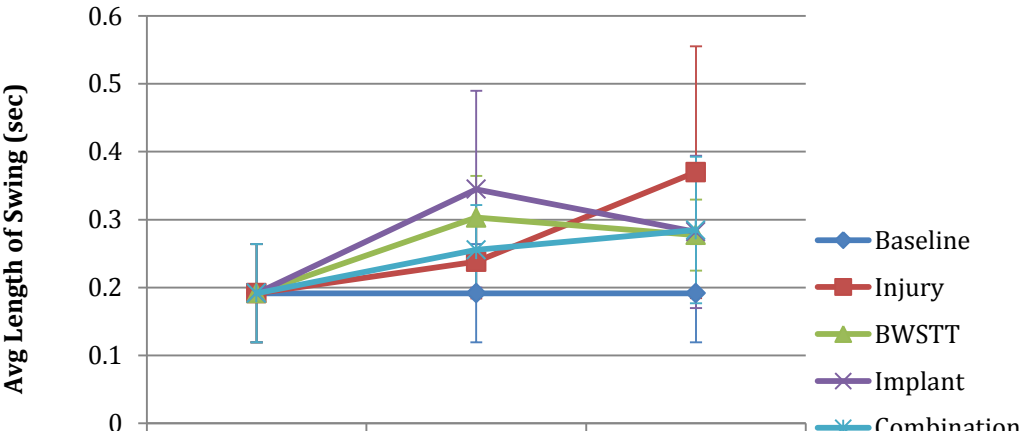
Appendix Figure 5. Ankle Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 75% BWS



Appendix Figure 6. Averaged Mapped Angle Plots at Week 4 for the 5 groups throughout an average gait cycle for 7 cm/s and 75% BWS

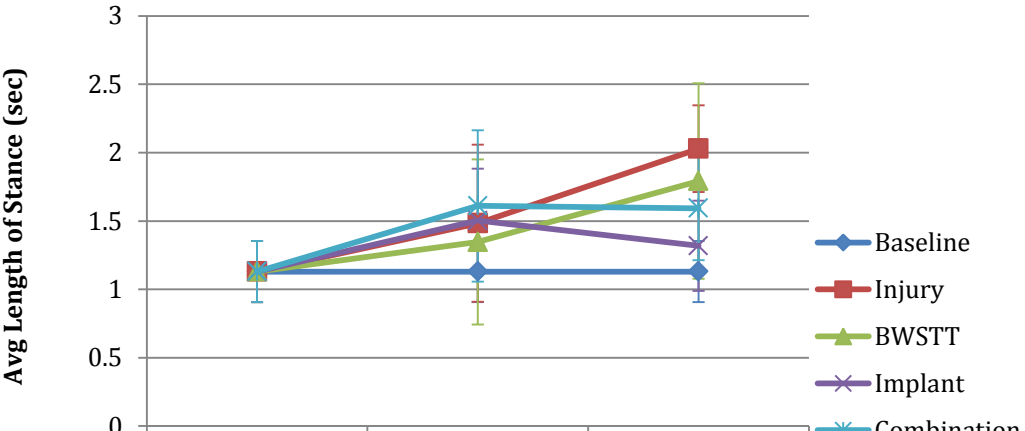


Appendix Figure 7. Averaged Mapped Angle Plots at Week 8 for the 5 groups throughout an average gait cycle for 7 cm/s and 75% BWS



	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 6
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

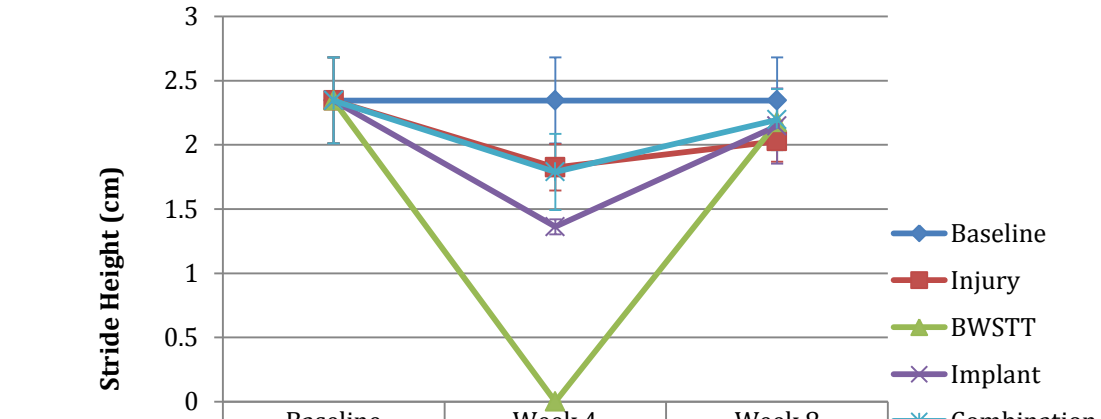
Appendix Figure 8. Swing Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 75% BWS



	Baseline	Week 4	Week 8
Baseline	n = 16	n = 16	n = 16
Injury	n = 16	n = 6	n = 6
BWSTT	n = 16	n = 6	n = 6
Implant	n = 16	n = 8	n = 3
Combination	n = 16	n = 11	n = 12

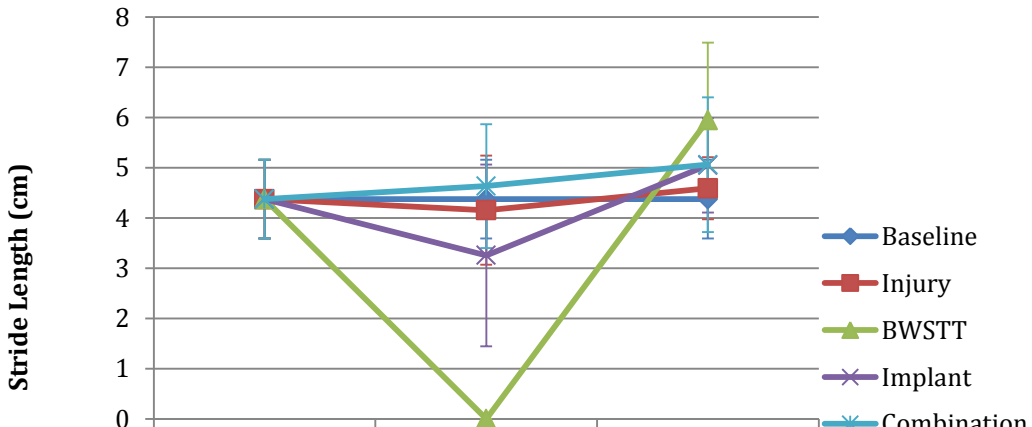
Appendix Figure 9. Stance Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 75% BWS

7 cm/s – 65% BWS



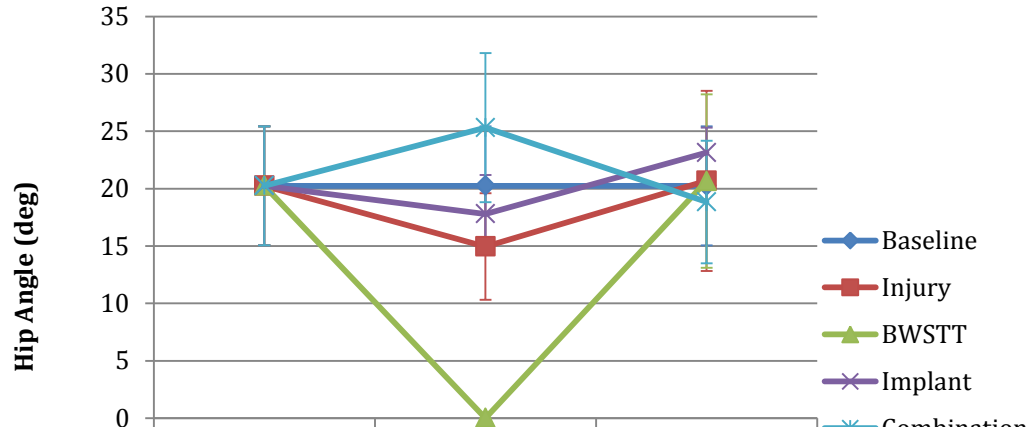
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 2	n = 4
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 2	n = 2
Combination	n = 5	n = 3	n = 9

Appendix Figure 10. Stride Height Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 65% BWS



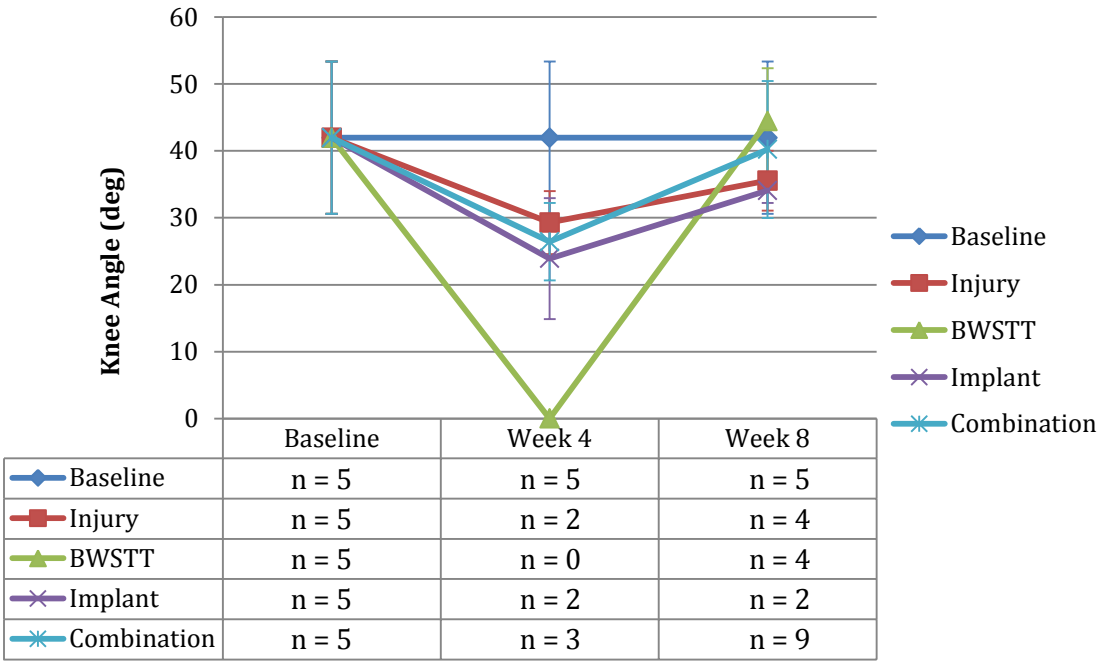
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 2	n = 4
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 2	n = 2
Combination	n = 5	n = 3	n = 9

Appendix Figure 11. Stride Length Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 65% BWS



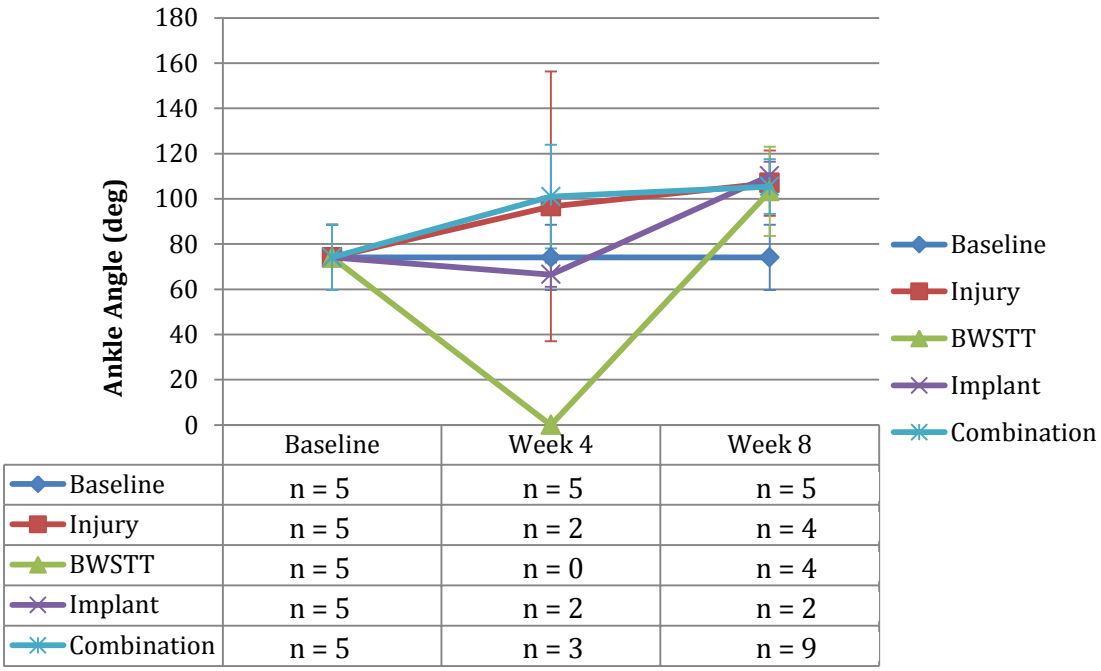
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 2	n = 4
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 2	n = 2
Combination	n = 5	n = 3	n = 9

Appendix Figure 12. Hip Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 65% BWS



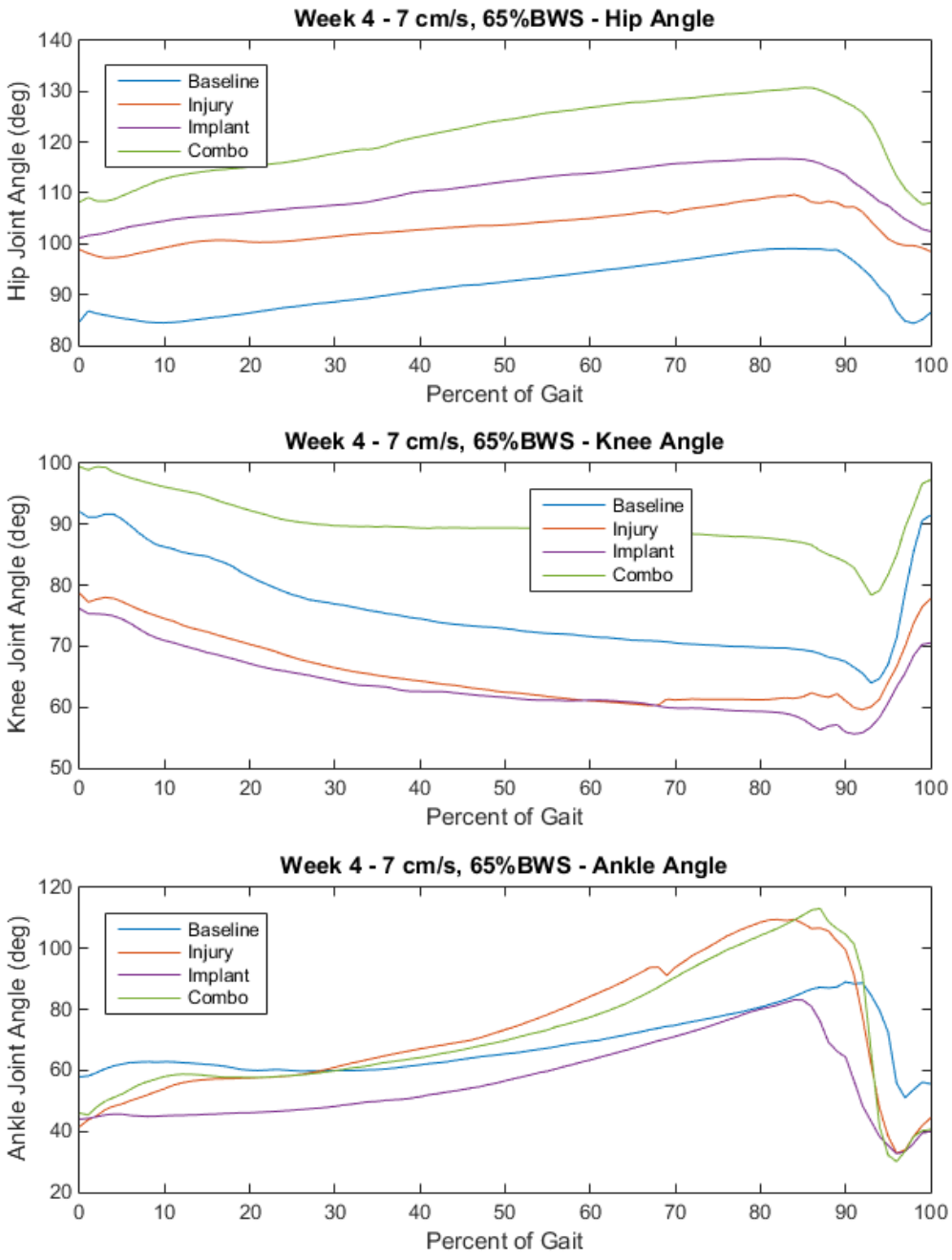
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 2	n = 4
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 2	n = 2
Combination	n = 5	n = 3	n = 9

Appendix Figure 13. Knee Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 65% BWS

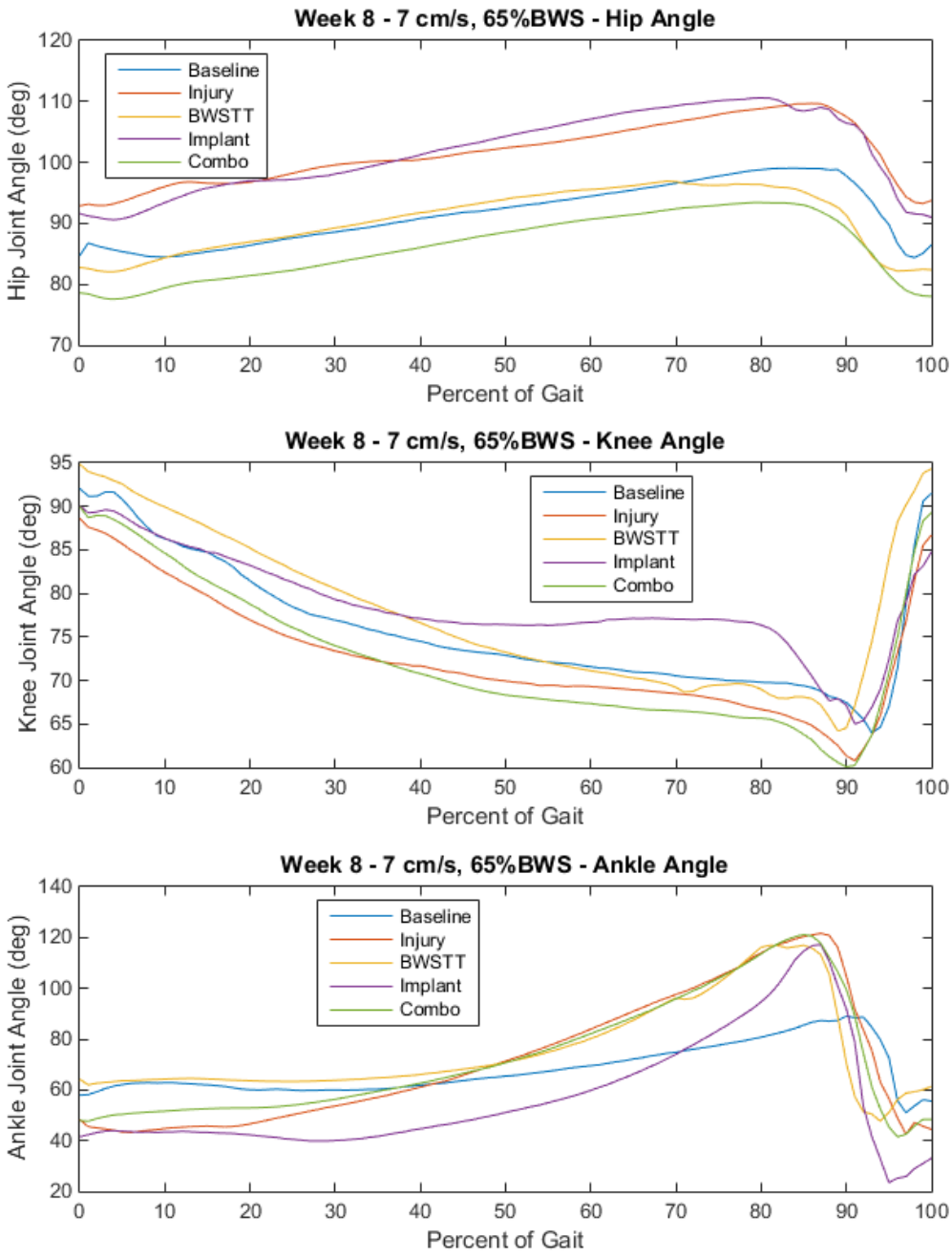


	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 2	n = 4
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 2	n = 2
Combination	n = 5	n = 3	n = 9

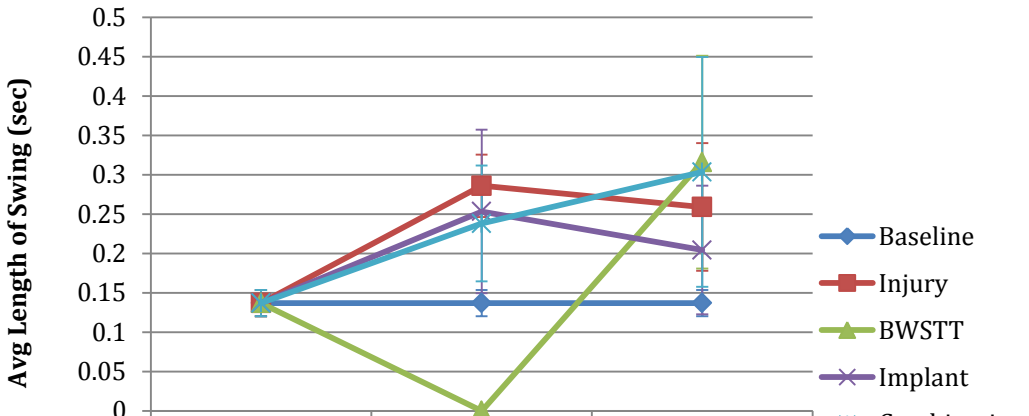
Appendix Figure 14. Ankle Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 65% BWS



Appendix Figure 15. Averaged Mapped Angle Plots at Week 4 for the 5 groups throughout an average gait cycle for 7 cm/s and 65% BWS

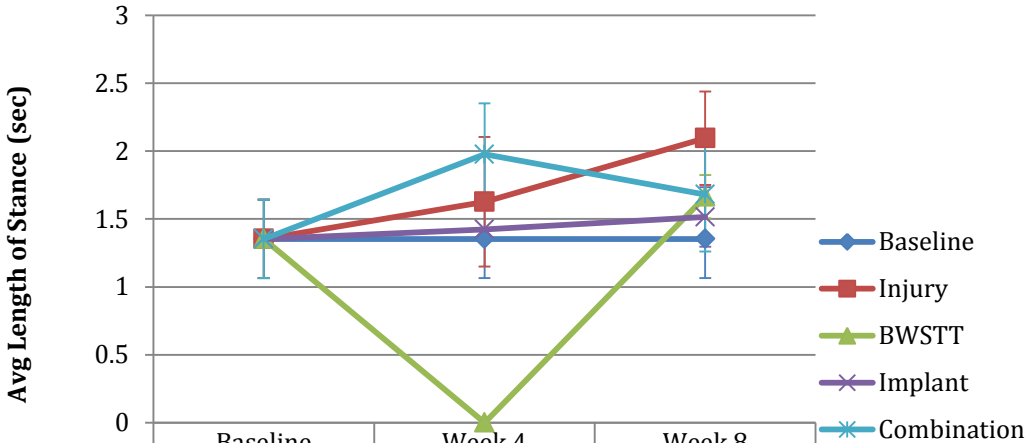


Appendix Figure 16. Averaged Mapped Angle Plots at Week 8 for the 5 groups throughout an average gait cycle for 7 cm/s and 65% BWS



	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 2	n = 4
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 2	n = 2
Combination	n = 4	n = 2	n = 9

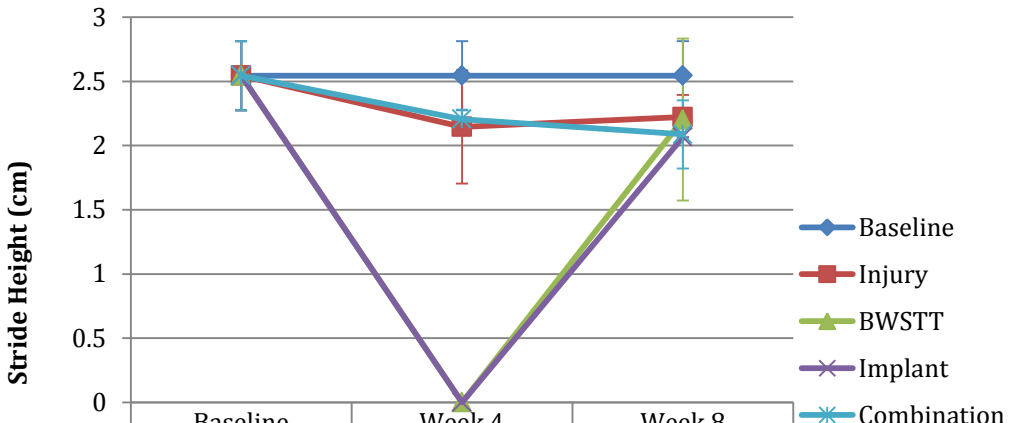
Appendix Figure 17. Swing Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 65% BWS



	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 2	n = 4
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 2	n = 2
Combination	n = 4	n = 2	n = 9

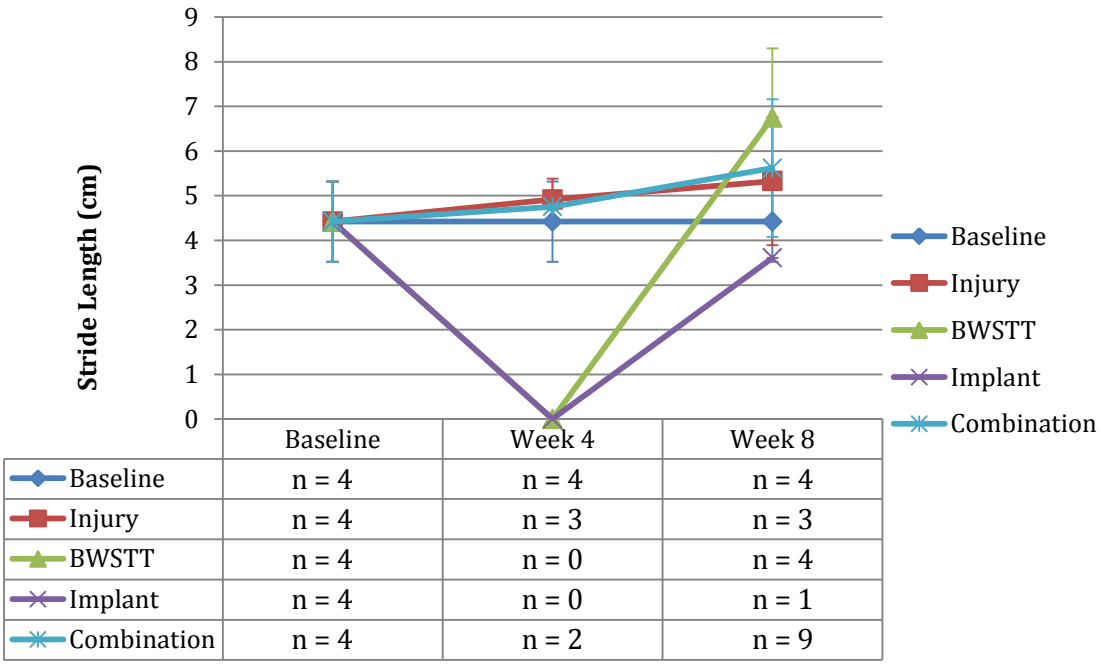
Appendix Figure 18. Stance Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 65% BWS

10 cm/s – 65% BWS



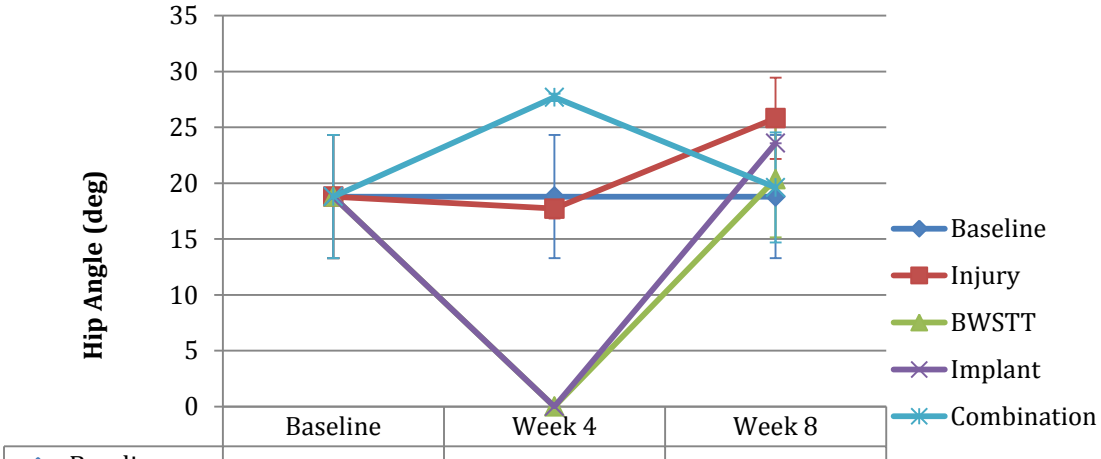
	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

Appendix Figure 19. Stride Height Plot for the 5 groups, throughout all Weeks of the training for 10 cm/s and 65% BWS



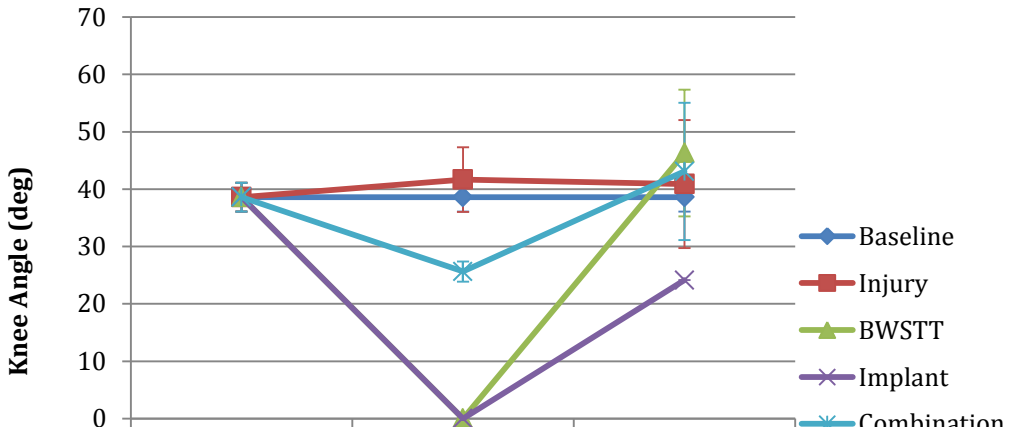
	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

Appendix Figure 20. Stride Length Plot for the 5 groups, throughout all Weeks of the training for 10 cm/s and 65% BWS



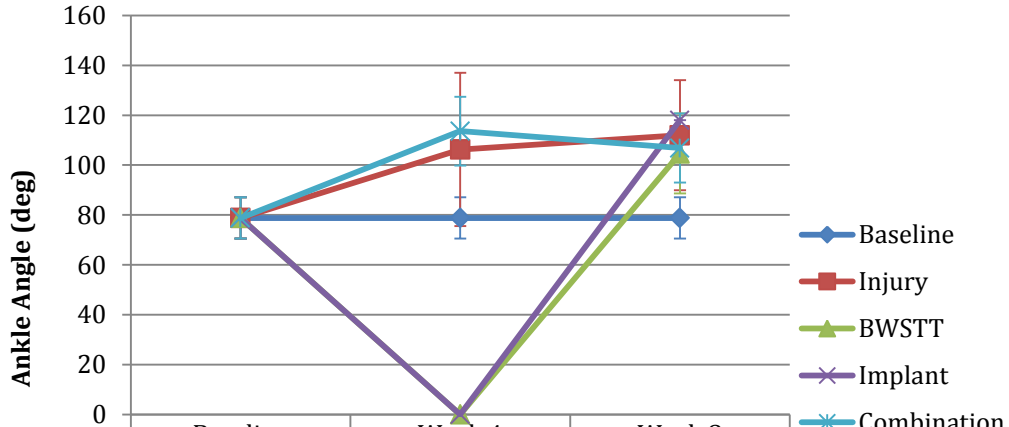
	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

Appendix Figure 21. Hip Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 65% BWS



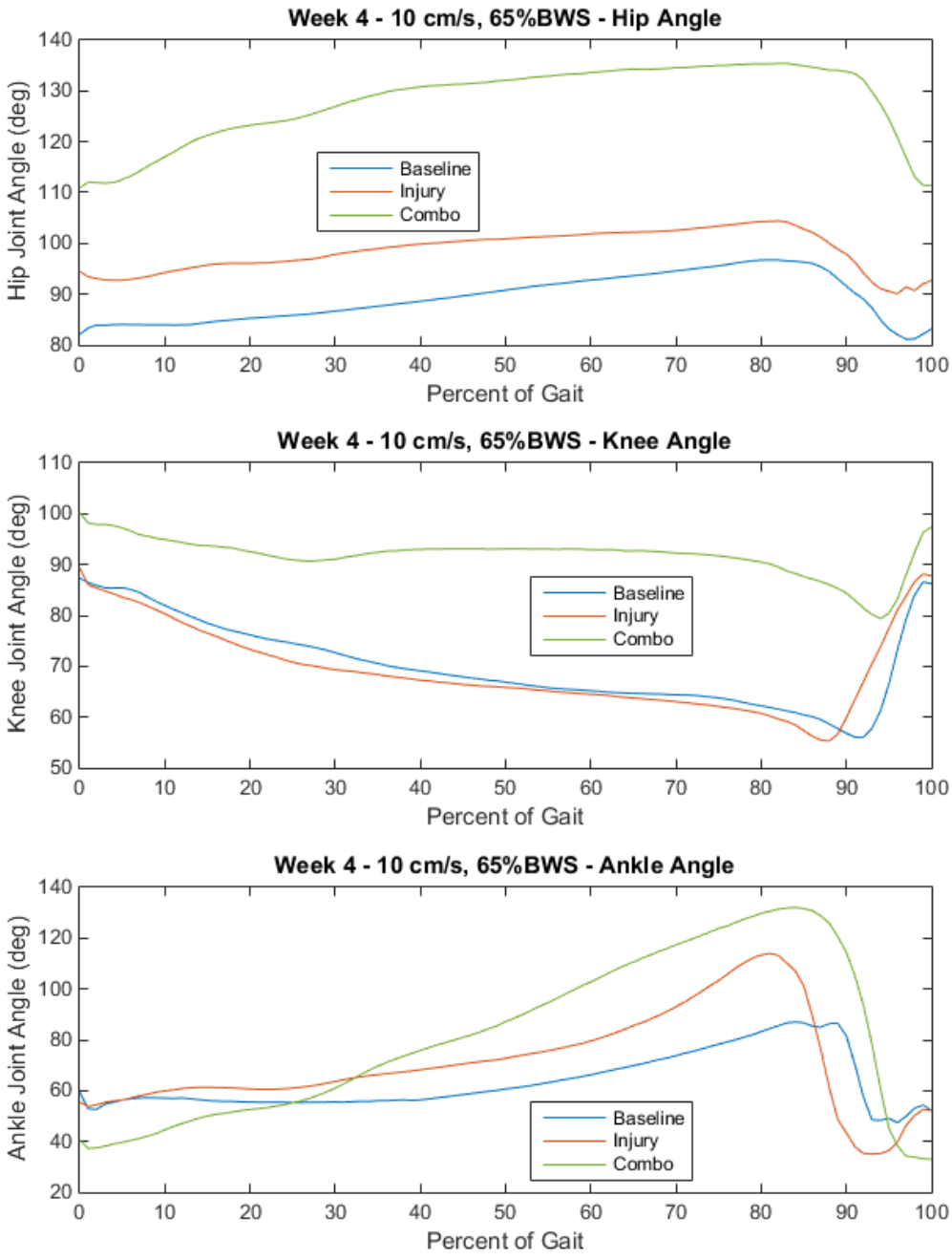
	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

Appendix Figure 22. Knee Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 65% BWS

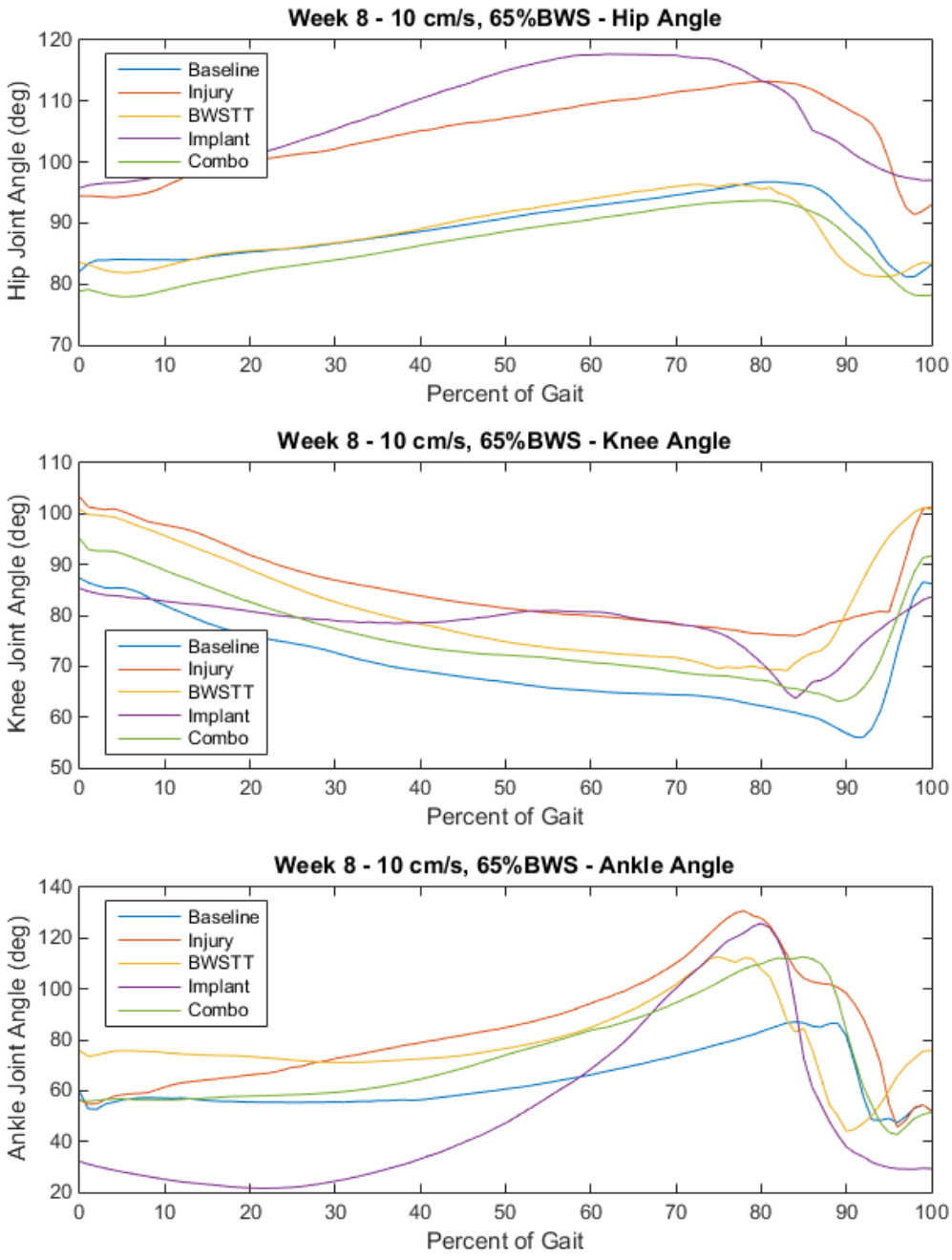


	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

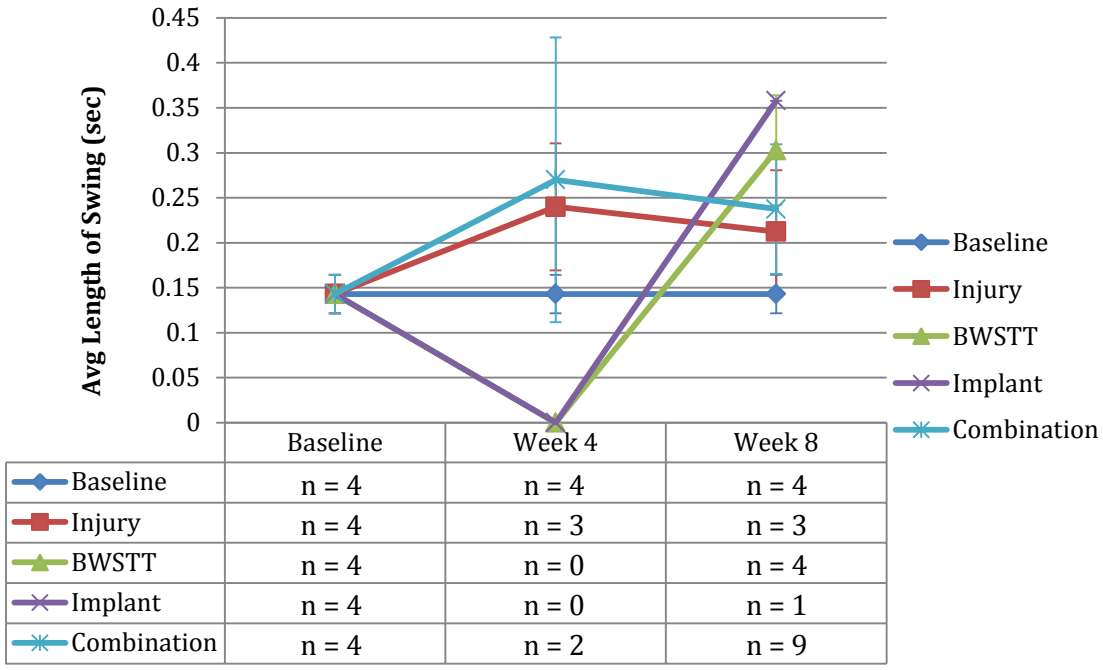
Appendix Figure 23. Ankle Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 65% BWS



Appendix Figure 24. Averaged Mapped Angle Plots at Week 4 for the 5 groups throughout an average gait cycle for 10 cm/s and 65% BWS

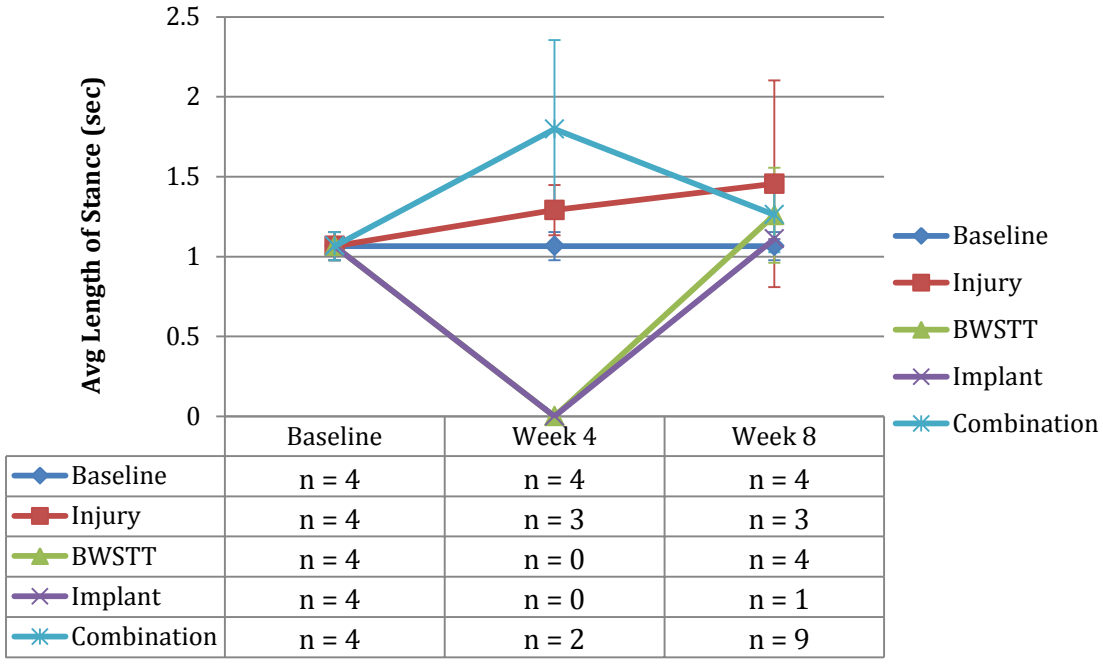


Appendix Figure 25. Averaged Mapped Angle Plots at Week 8 for the 5 groups throughout an average gait cycle for 10 cm/s and 65% BWS



	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

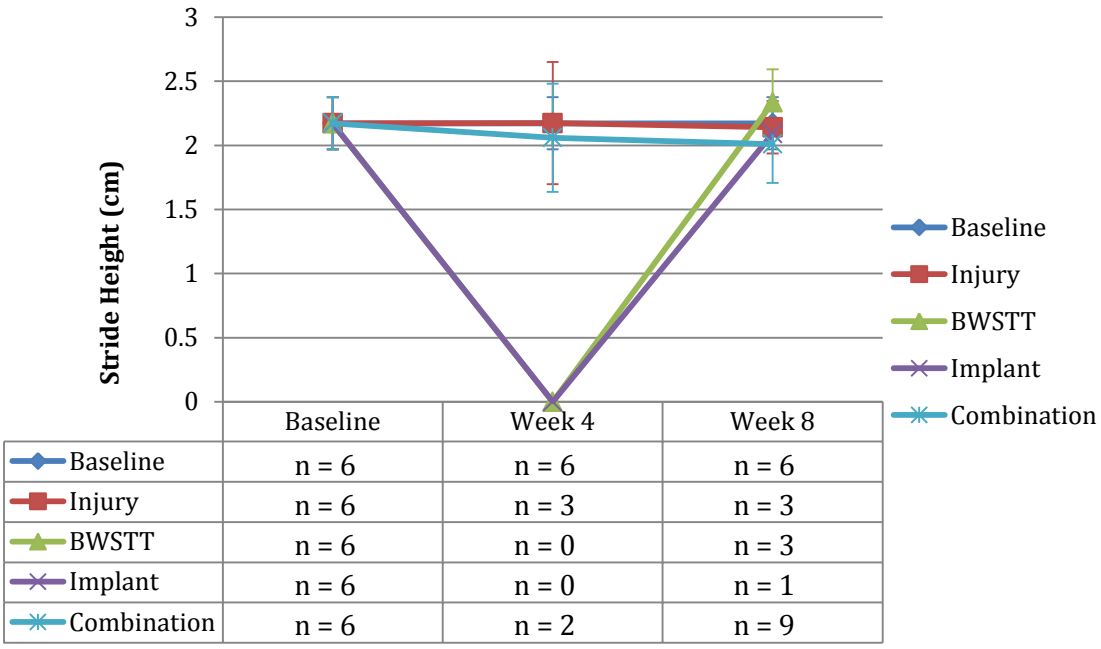
Appendix Figure 26. Swing Duration Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 65% BWS



	Baseline	Week 4	Week 8
Baseline	n = 4	n = 4	n = 4
Injury	n = 4	n = 3	n = 3
BWSTT	n = 4	n = 0	n = 4
Implant	n = 4	n = 0	n = 1
Combination	n = 4	n = 2	n = 9

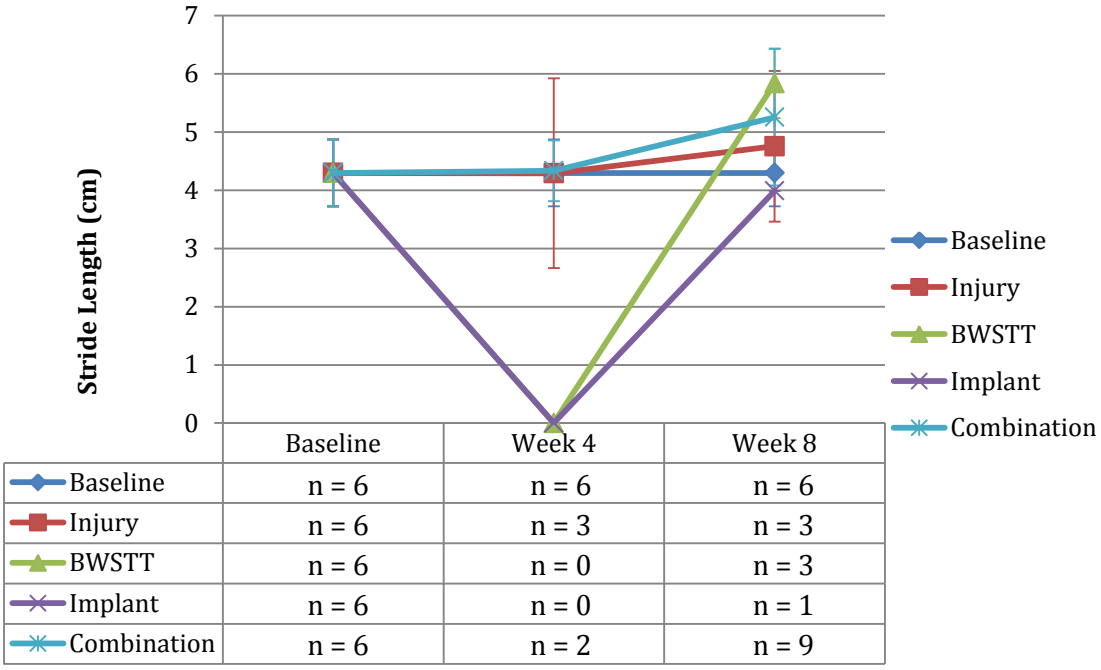
Appendix Figure 27. Stance Duration Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 65% BWS

7 cm/s – 55% BWS



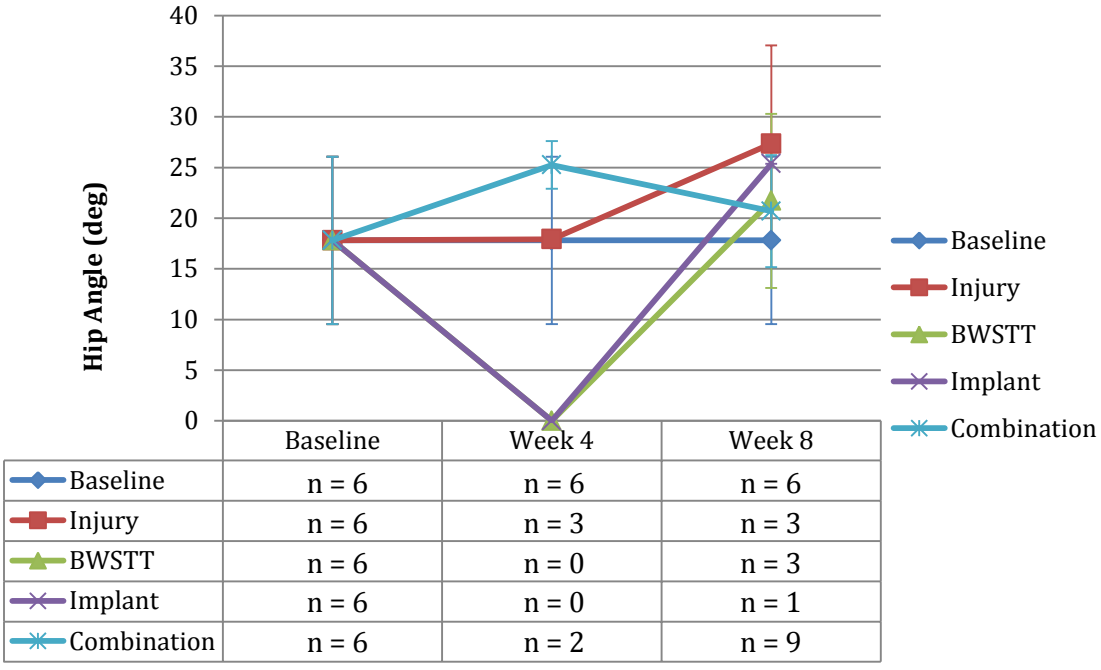
	Baseline	Week 4	Week 8
Baseline	n = 6	n = 6	n = 6
Injury	n = 6	n = 3	n = 3
BWSTT	n = 6	n = 0	n = 3
Implant	n = 6	n = 0	n = 1
Combination	n = 6	n = 2	n = 9

Appendix Figure 28. Stride Height Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 55% BWS



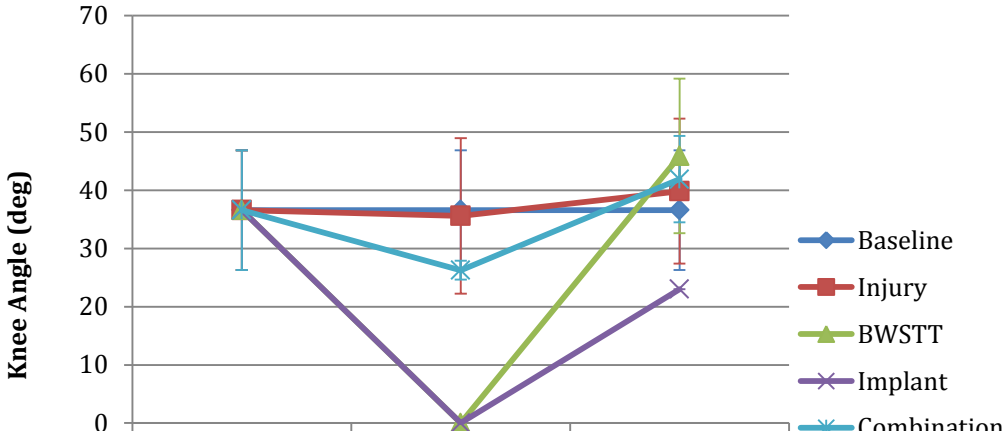
	Baseline	Week 4	Week 8
Baseline	n = 6	n = 6	n = 6
Injury	n = 6	n = 3	n = 3
BWSTT	n = 6	n = 0	n = 3
Implant	n = 6	n = 0	n = 1
Combination	n = 6	n = 2	n = 9

Appendix Figure 29. Stride Length Plot for the 5 groups, throughout all Weeks of the training for 7 cm/s and 55% BWS



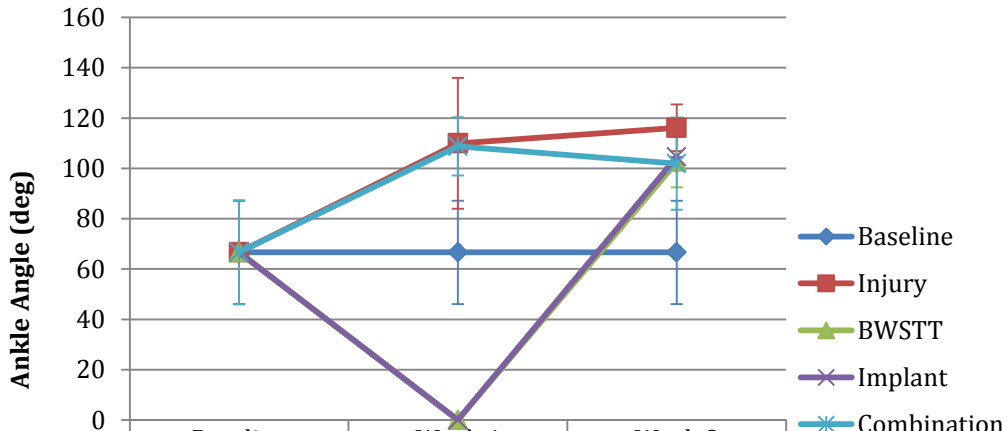
	Baseline	Week 4	Week 8
Baseline	n = 6	n = 6	n = 6
Injury	n = 6	n = 3	n = 3
BWSTT	n = 6	n = 0	n = 3
Implant	n = 6	n = 0	n = 1
Combination	n = 6	n = 2	n = 9

Appendix Figure 30. Hip Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 55% BWS



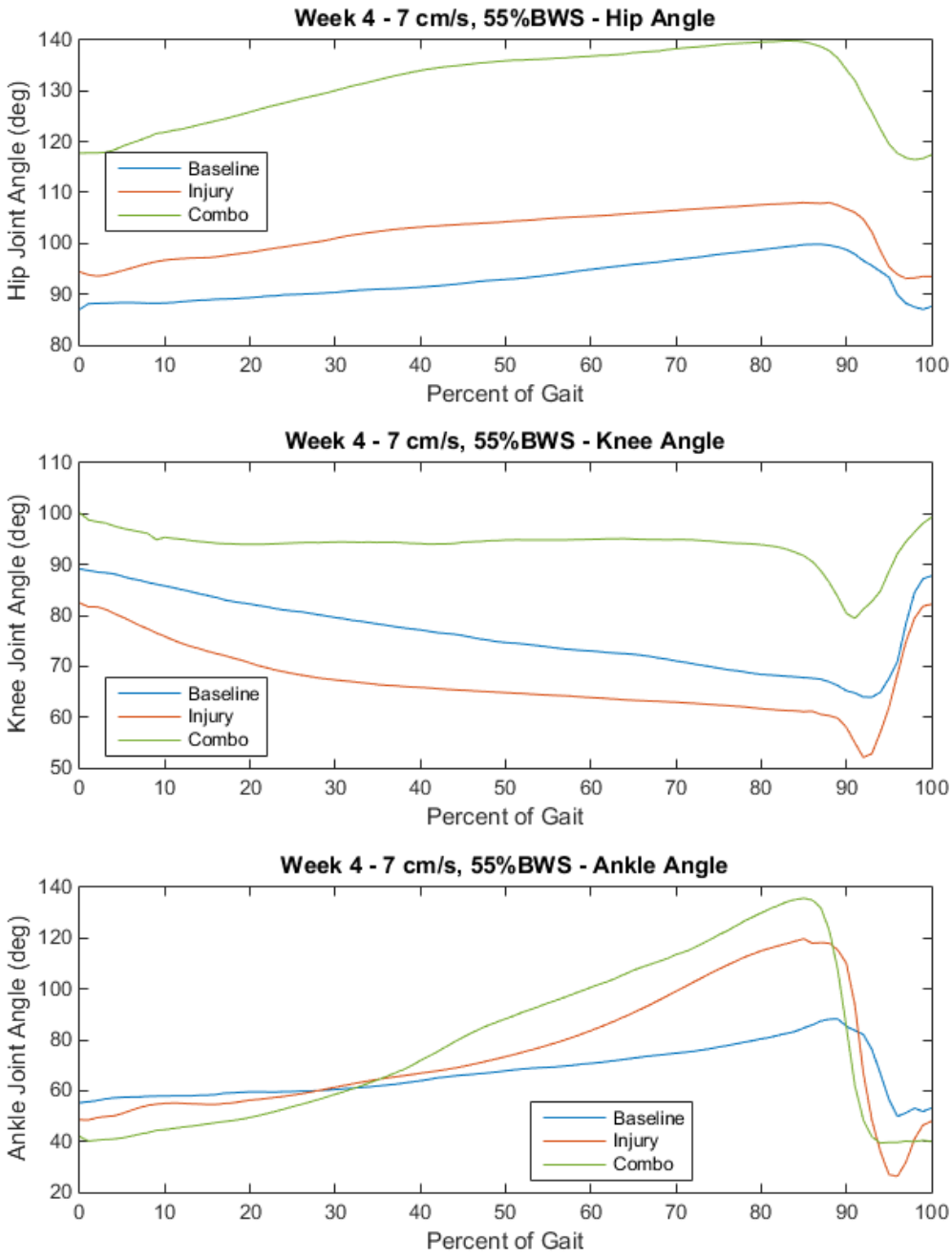
	Baseline	Week 4	Week 8
Baseline	n = 6	n = 6	n = 6
Injury	n = 6	n = 3	n = 3
BWSTT	n = 6	n = 0	n = 3
Implant	n = 6	n = 0	n = 1
Combination	n = 6	n = 2	n = 9

Appendix Figure 31. Knee Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 55% BWS

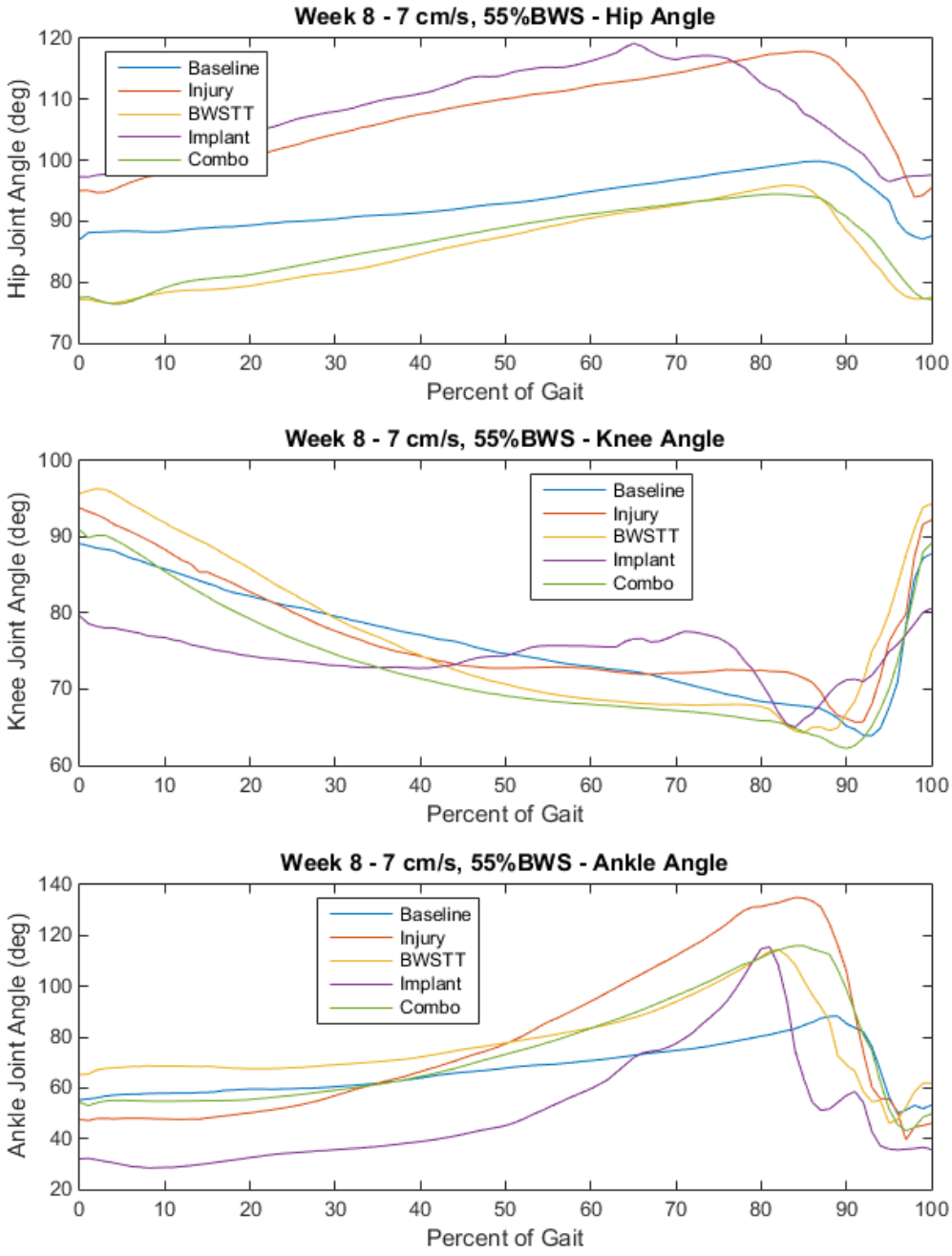


	Baseline	Week 4	Week 8
Baseline	n = 6	n = 6	n = 6
Injury	n = 6	n = 3	n = 3
BWSTT	n = 6	n = 0	n = 3
Implant	n = 6	n = 0	n = 1
Combination	n = 6	n = 2	n = 9

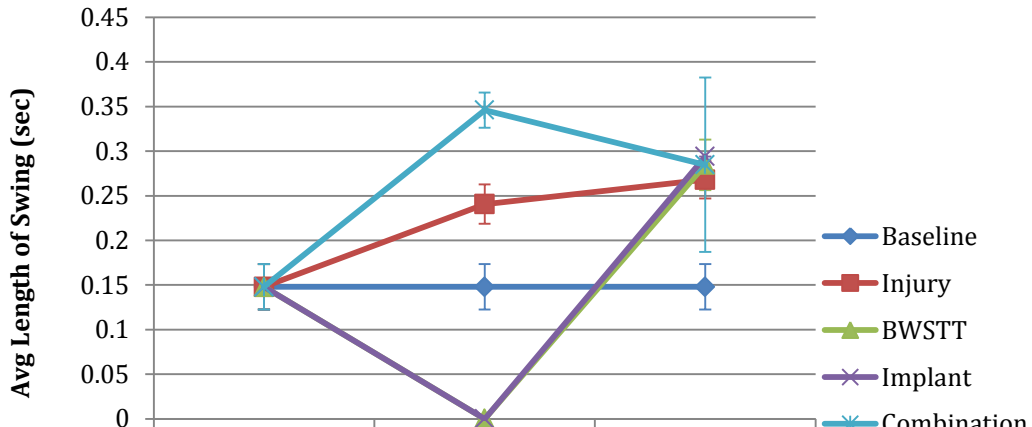
Appendix Figure 32. Ankle Angles Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 55% BWS



Appendix Figure 33. Averaged Mapped Angle Plots at Week 4 for the 5 groups throughout an average gait cycle for 7 cm/s and 55% BWS

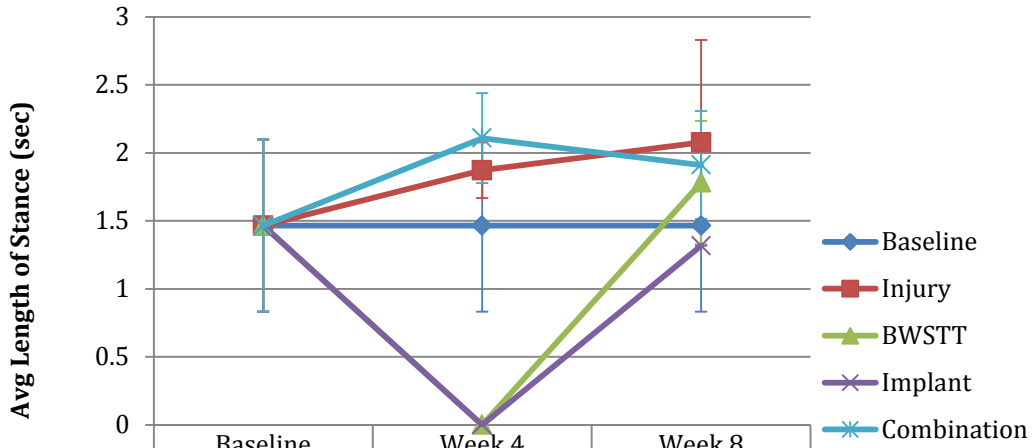


Appendix Figure 34. Averaged Mapped Angle Plots at Week 8 for the 5 groups throughout an average gait cycle for 7 cm/s and 55% BWS



	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 3
BWSTT	n = 5	n = 0	n = 3
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

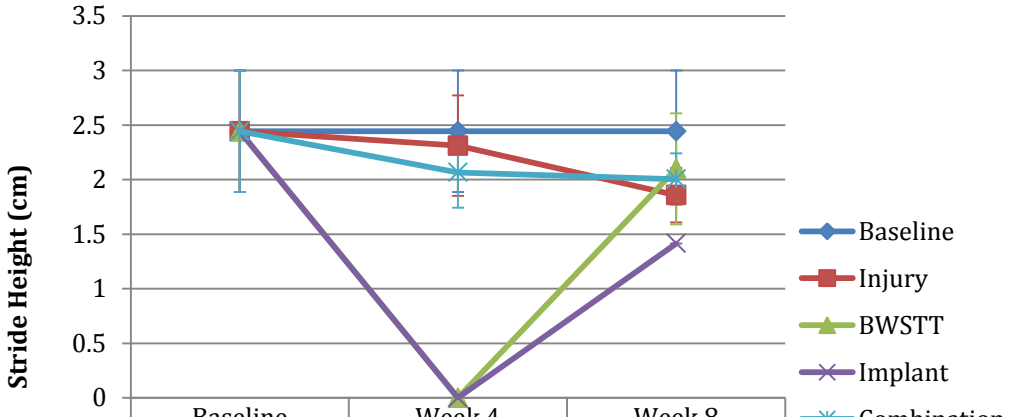
Appendix Figure 35. Swing Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 55% BWS



	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 3
BWSTT	n = 5	n = 0	n = 3
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

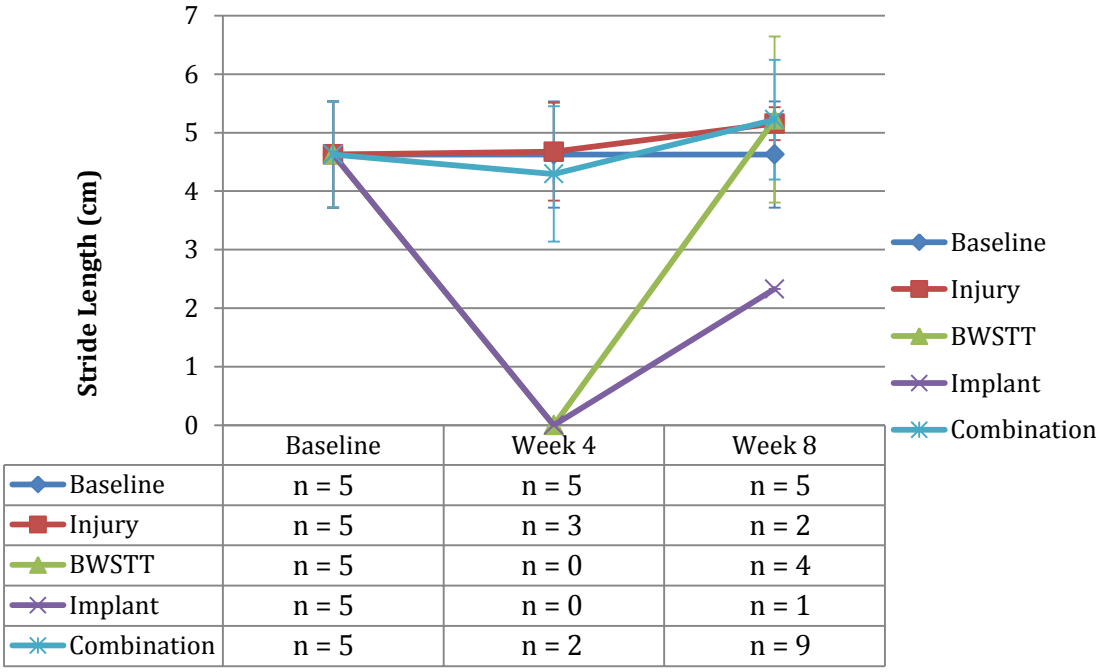
Appendix Figure 36. Stance Duration Plot for the 5 groups throughout all Weeks of the training for 7 cm/s and 55% BWS

10 cm/s – 55% BWS



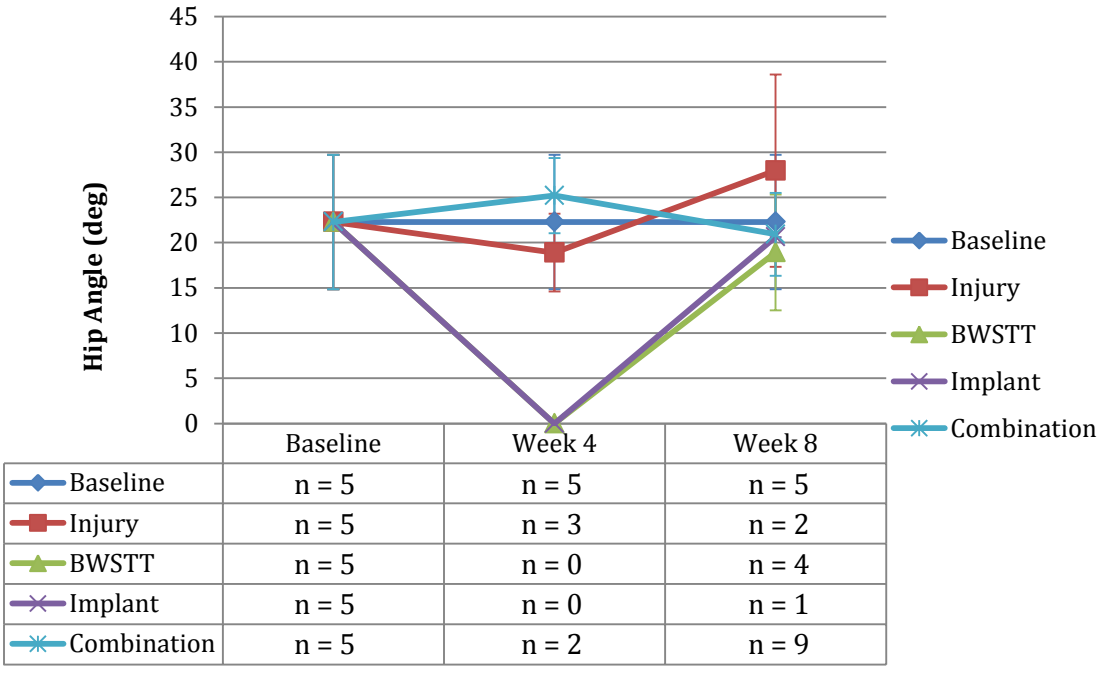
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 37. Stride Height Plot for the 5 groups, throughout all Weeks of the training for 10 cm/s and 55% BWS



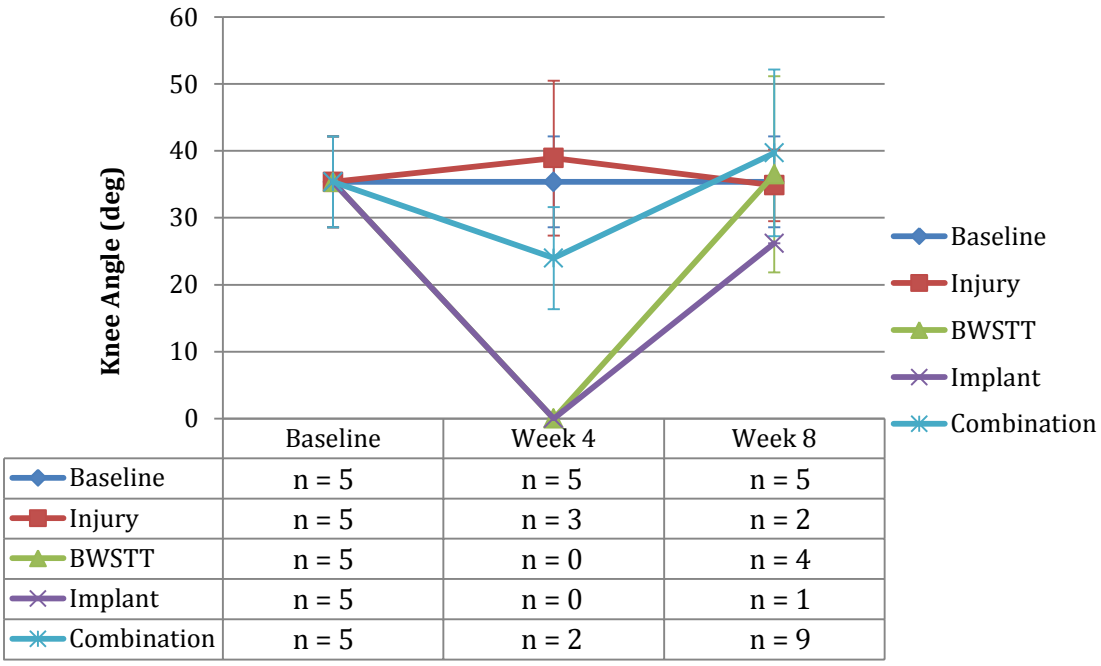
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 38. Stride Length Plot for the 5 groups, throughout all Weeks of the training for 10 cm/s and 55% BWS



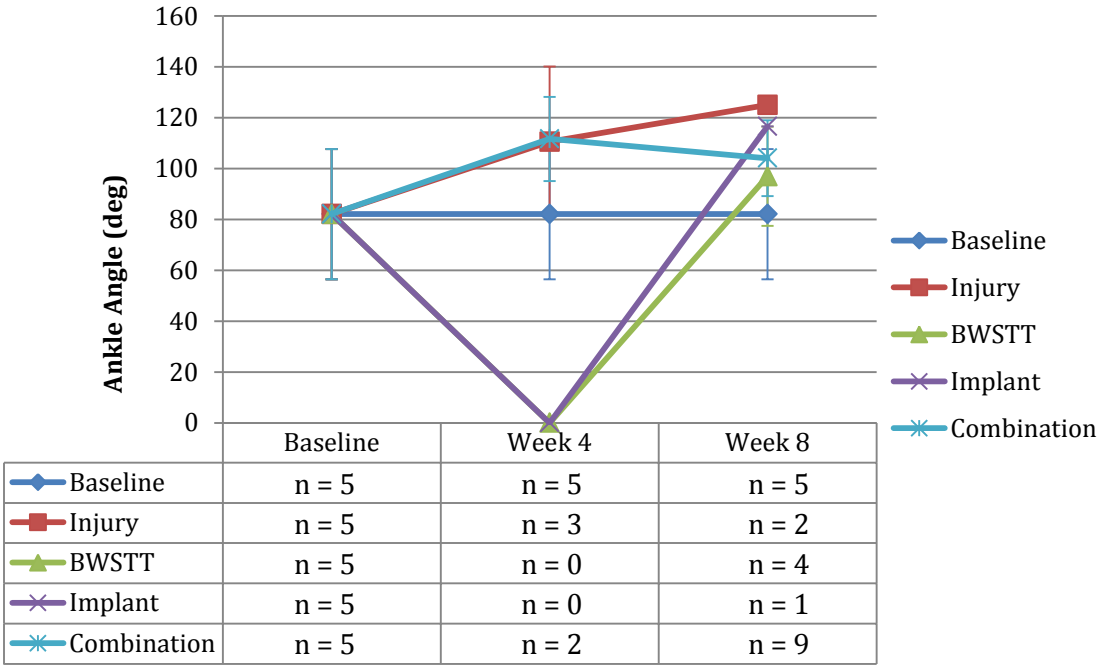
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 39. Hip Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 55% BWS



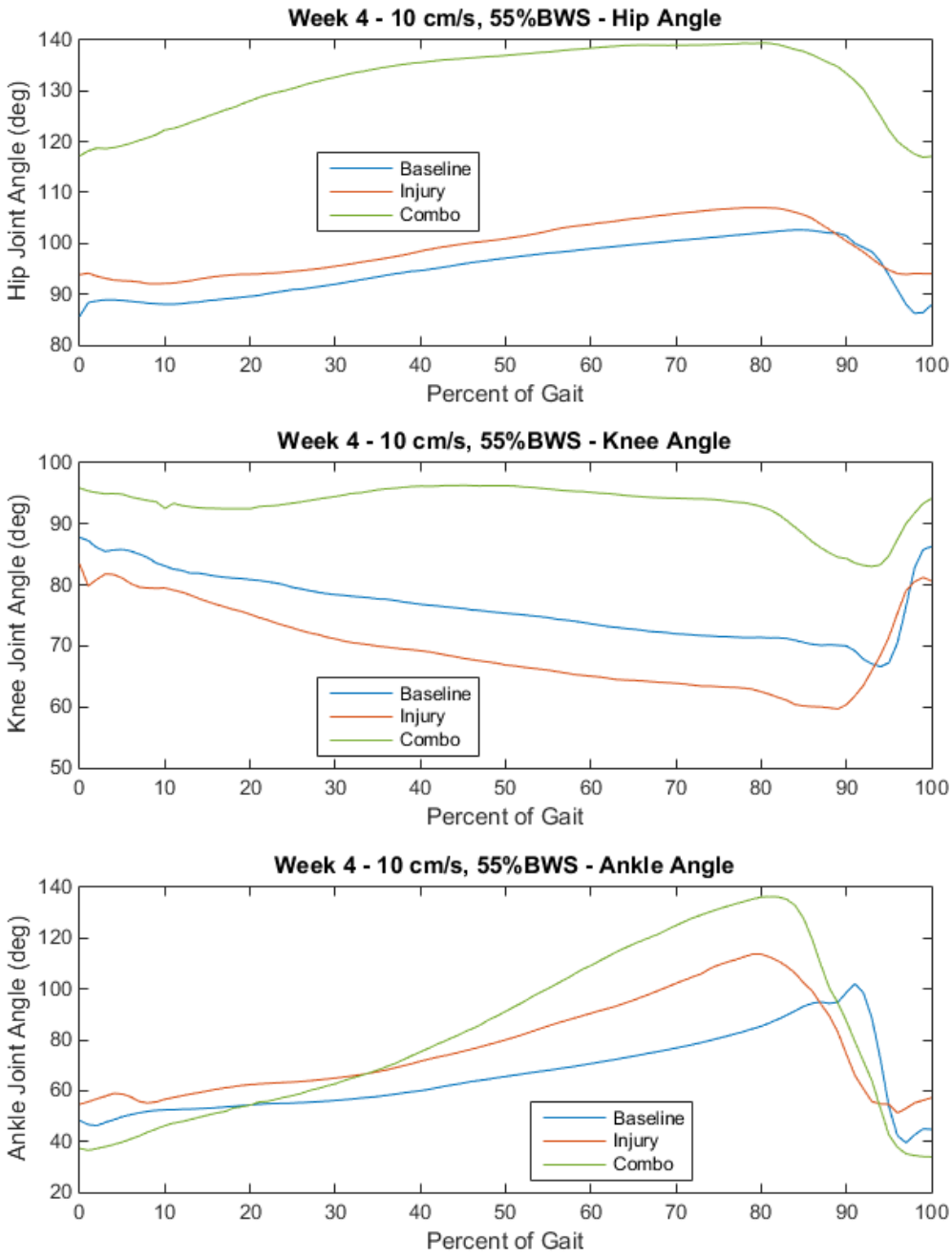
	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 40. Knee Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 55% BWS

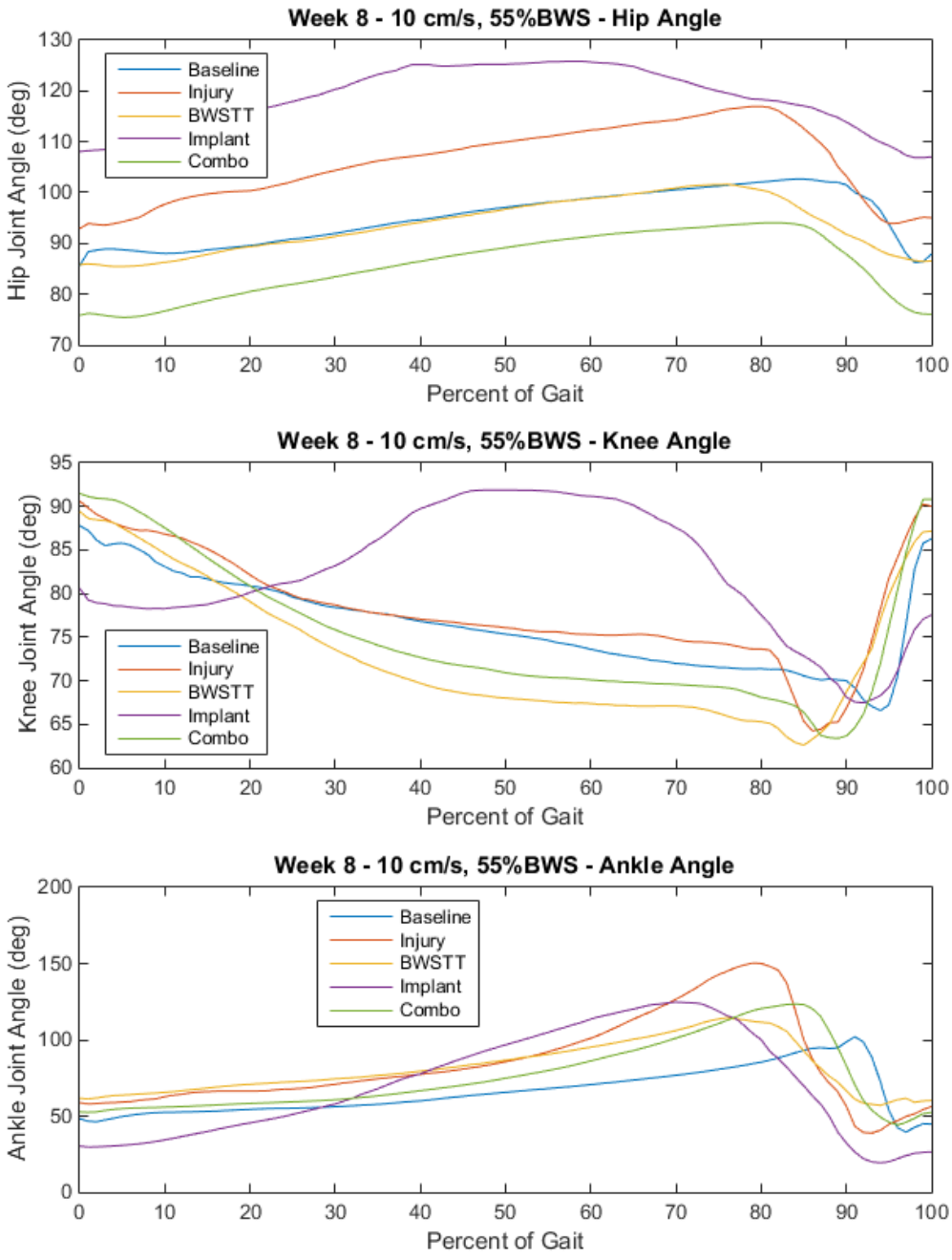


	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

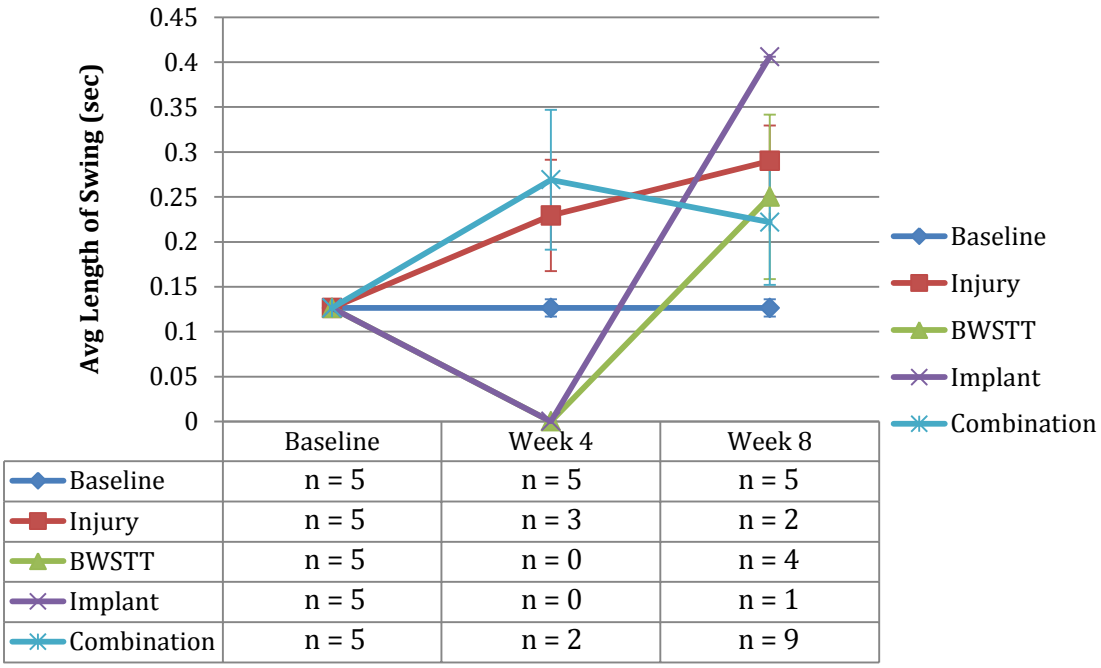
Appendix Figure 41. Ankle Angles Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 55% BWS



Appendix Figure 42. Averaged Mapped Angle Plots at Week 4 for the 5 groups throughout an average gait cycle for 10 cm/s and 55% BWS

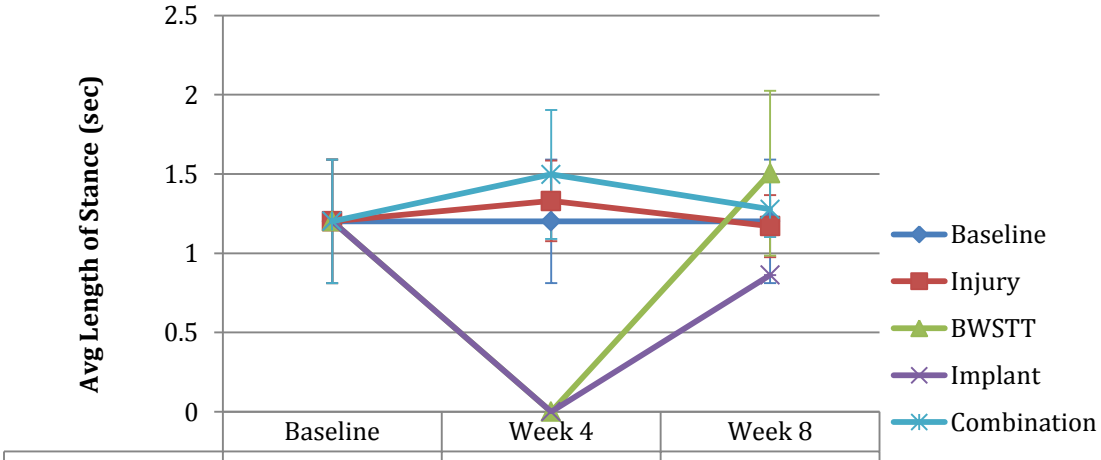


Appendix Figure 43. Averaged Mapped Angle Plots at Week 8 for the 5 groups throughout an average gait cycle for 10 cm/s and 55% BWS



	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 44. Swing Duration Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 55% BWS



	Baseline	Week 4	Week 8
Baseline	n = 5	n = 5	n = 5
Injury	n = 5	n = 3	n = 2
BWSTT	n = 5	n = 0	n = 4
Implant	n = 5	n = 0	n = 1
Combination	n = 5	n = 2	n = 9

Appendix Figure 45. Stance Duration Plot for the 5 groups throughout all Weeks of the training for 10 cm/s and 55% BWS

Appendix E

Average Mapped Plots MATLAB Code

C:\Users\Research\Documents\Data Analysis\MapData Combined Plots\MapAngle Plot Data All Spds&BWS\plot_gen.m

```
clearvars
close all
clc

dir_str = {'7cms-75%','10cms-75%','7cms-65%','10cms-65%','7cms-55%','10cms-55%'}; % Speed & BWS
Folders
wk_str = {'Week 4', 'Week 8'}; % Weeks of plot to generate (4 or 8)
grp_str = {'Baseline', 'Injury', 'BWSTT', 'Implant', 'Combo'}; % Subfolders, Groups, and Legend
grp_lgd = logical(1:numel(grp_str)); % Logical array for legends if no data is available for a
group
f_path = 'C:\Users\Alexander.Herman\Downloads\Thesis Documents\MapAngle Plot Data\'; % Orgin Path

for str_idx = 1:numel(dir_str) % cycles thru the speed and BWS subfolders
    s_path = [f_path dir_str{str_idx} '\' ]; % Save path for plots
    for wk_idx = 1:numel(wk_str) % cycles thru the week subfolders
        [Hip,Knee,Ankle] = deal(zeros(101,numel(grp_str))); % Initlizes avg. mapped angles
        for i = 1:numel(grp_str) % cycles thru the group subfolders
            w_path = [s_path wk_str{wk_idx} '\' grp_str{i} '\']; % Group Subfolder Path
            files = dir([w_path '*.csv']);
            if ~isempty(files)
                j = 1; % counter
                [Hip_Avg, Knee_Avg, Ankle_Avg] = deal(zeros(101,size(files,1)));

                for file = files' % Cycle thru all of the CSV files in the group subfolder
                    % Import the Average Angle Column vectors for all 3 mapped joint angles
                    [Hip_Avg(:,j),Knee_Avg(:,j),Ankle_Avg(:,j)] = plot_import([w_path
                    file.name]);
                    j=j+1;
                end % for

                % Avergages each mapped joint angle
                Hip(:,i) = mean(Hip_Avg,2);
                Knee(:,i) = mean(Knee_Avg,2);
                Ankle(:,i) = mean(Ankle_Avg,2);

                clear('Hip_Avg','Knee_Avg','Ankle_Avg');
            else % If there are no files/data for that group sets NaN for the data
                Hip(:,i) = NaN(101,1);
                Knee(:,i) = NaN(101,1);
                Ankle(:,i) = NaN(101,1);
                grp_lgd(i) = false; % Logical array saying no data in this group
            end %if
        end % for i

        % X axis vector
        x = cat(2,(0:1:100)',(0:1:100)',(0:1:100)',(0:1:100)',(0:1:100)');
        ids = find(grp_lgd); % Index for group subfolders that had data
        spd = dir_str{str_idx}(1:strfind(dir_str{str_idx},'cms')-1);
        bws = dir_str{str_idx}(end-2:end);

        % Subplot
        fig = figure('Position',[50 50 700 900]);
        subplot(3,1,1);
```

```
        ax1 = plot(x,Hip);
        title([wk_str{wk_idx} ' - ' spd ' cm/s, ' bws 'BWS - Hip Angle']) ;
        xlabel('Percent of Gait');
        ylabel('Hip Joint Angle (deg)');
        legend(ax1(ids),grp_str{ids},'Location','best');

        subplot(3,1,2);
        ax2 = plot(x,Knee);
        title([wk_str{wk_idx} ' - ' spd ' cm/s, ' bws 'BWS - Knee Angle']);
        xlabel('Percent of Gait');
        ylabel('Knee Joint Angle (deg)');
        legend(ax2(ids),grp_str{ids},'Location','best');

        subplot(3,1,3);
        ax3 = plot(x,Ankle);
        title([wk_str{wk_idx} ' - ' spd ' cm/s, ' bws 'BWS - Ankle Angle']) ;
        xlabel('Percent of Gait');
        ylabel('Ankle Joint Angle (deg)');
        legend(ax3(ids),grp_str{ids},'Location','best');

        % Save figure as PNG and FIG
        fig.PaperPositionMode = 'auto';
        s_name = [dir_str{str_idx} '-' wk_str{wk_idx} '-Mapped'];
        savefig(fig,[s_path s_name])
        set(fig,'color','w');
        img = getframe(fig);
        imwrite(img.cdata, [s_path s_name '.png']);
        close all

        grp_lgd = logical(1:numel(grp_str)); % resets the logicals

    end % for wk_idx
end % for str_idx
```

```
function [Hip_Avg,Knee_Avg,Ankle_Avg] = plot_import(filename, startRow, endRow)
%IMPORTFILE Import numeric data from a text file as column vectors.
%   [HIP_AVG,KNEE_AVG,ANKLE_AVG] = IMPORTFILE(FILENAME) Reads data from
%   text file FILENAME for the default selection.
%   [HIP_AVG,KNEE_AVG,ANKLE_AVG] = IMPORTFILE(FILENAME, STARTROW, ENDROW)
%   Reads data from rows STARTROW through ENDROW of text file FILENAME.
% Example:
%   [Hip_Avg,Knee_Avg,Ankle_Avg] =
%   importfile('35-Baseline-10cms-75-MapData.csv',1, 102);
%    See also TEXTSCAN.
% Auto-generated by MATLAB on 2018/04/02 12:56:59

%% Initialize variables.
delimiter = ',';
if nargin<=2
    startRow = 2;
    endRow = inf;
end

%% Read columns of data as strings:
% For more information, see the TEXTSCAN documentation.

% Idenfies the right columns to export based from its size due to the
% number of stides in the take
colTest = csvread(filename,1,0);
[~,col_t]=size(colTest);

if col_t <= 12 % 3 Strides
    formatSpec = '%*s%*s%*s%*s%*s%*s%*s%*s%*s%[^\n\r]';
elseif col_t <= 15 % 4 Strides
    formatSpec = '%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%[^\n\r]';
else % Every other size (only 5 really)
    formatSpec = '%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%*s%[^\n\r]';
end
%% Open the text file.
fileID = fopen(filename,'r');

%% Read columns of data according to format string.
% This call is based on the structure of the file used to generate this
% code. If an error occurs for a different file, try regenerating the code
% from the Import Tool.
dataArray = textscan(fileID, formatSpec, endRow(1)-startRow(1)+1, 'Delimiter', delimiter,
'HeaderLines', startRow(1)-1, 'ReturnOnError', false);
for block=2:length(startRow)
    frewind(fileID);
    dataArrayBlock = textscan(fileID, formatSpec, endRow(block)-startRow(block)+1, 'Delimiter',
    delimiter, 'HeaderLines', startRow(block)-1, 'ReturnOnError', false);
    for col=1:length(dataArray)
        dataArray{col} = [dataArray{col};dataArrayBlock{col}];
    end
end

%% Close the text file.
```

```
fclose(fileID);

%% Convert the contents of columns containing numeric strings to numbers.
% Replace non-numeric strings with NaN.
raw = repmat({''},length(dataArray{1}),length(dataArray)-1);
for col=1:length(dataArray)-1
    raw(1:length(dataArray{col}),col) = dataArray{col};
end
numericData = NaN(size(dataArray{1},1),size(dataArray,2));

for col=[1,2,3]
    % Converts strings in the input cell array to numbers. Replaced non-numeric
    % strings with NaN.
    rawData = dataArray{col};
    for row=1:size(rawData, 1);
        % Create a regular expression to detect and remove non-numeric prefixes and
        % suffixes.
        regexstr =
        '(?<prefix>.*?)(?<numbers>([-]*(\d+[\,]*)+[\.]{0,1}\d*[eEdD]{0,1}[-+]*\d*[i]{0,1})|([-]*(
        \d+[\,]*)*[\.]{1,1}\d+[eEdD]{0,1}[-+]*\d*[i]{0,1}))(?<suffix>.*)';
        try
            result = regexp(rawData{row}, regexstr, 'names');
            numbers = result.numbers;

            % Detected commas in non-thousand locations.
            invalidThousandsSeparator = false;
            if any(numbers==',');
                thousandsRegExp = '^\d+?(\,\d{3})*\.{0,1}\d*$';
                if isempty(regexp(thousandsRegExp, ',', 'once'));
                    numbers = NaN;
                    invalidThousandsSeparator = true;
                end
            end
            % Convert numeric strings to numbers.
            if ~invalidThousandsSeparator;
                numbers = textscan(strrep(numbers, ',', ''), '%f');
                numericData(row, col) = numbers{1};
                raw{row, col} = numbers{1};
            end
        catch me
        end
    end
end

%% Replace non-numeric cells with NaN
R = cellfun(@(x) ~isnumeric(x) && ~islogical(x),raw); % Find non-numeric cells
raw(R) = {NaN}; % Replace non-numeric cells

%% Allocate imported array to column variable names
Hip_Avg = cell2mat(raw(:, 1));
Knee_Avg = cell2mat(raw(:, 2));
Ankle_Avg = cell2mat(raw(:, 3));
```