The Effects of Visual-Spatial Distractor Task Paired Stability Training on Ankle Stability Following a Single Leg Lateral Ankle Inversion Sprain

by

Simon Chan

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Science

in

Biology

Carleton University
Ottawa, Ontario

Abstract

Ankle sprains are a common injury with high rates of recurrence, even after discharge from rehabilitative therapy, likely the result of chronic ankle joint instability. Current rehabilitative training primarily consists of cognizant stabilization, where participants are instructed to specifically focus on stabilization of the ankle. This approach primarily utilizes the motor cortex and requires attentional resources. However, ankle joint stability is innately maintained by the cerebellum. We hypothesized that stability training paired with a visuospatial distractor task, leads to greater improvements in ankle stability. All participants were diagnosed with a single leg ankle inversion sprain and performed the same 4-week stability training, except the experimental group training was paired visuospatial distractor. Average muscle activity required to maintain ankle joint stability decreased 59% in the experimental group, compared to 4% in the control. This suggests a benefit in utilizing a paired distractor to improve ankle stability following an acute inversion sprain.

Acknowledgements

This research would not have been successful without the unwavering support of Dr. Iain McKinnell and Dr. Jeff Dawson, who have both contributed a significant amount of time, energy, enthusiasm, and guidance. Immense appreciation and gratitude needs to be given to Dr. Jayne Yack and Dr. Emily Standen for dedicating their time and expertise in their irreplaceable role on the thesis advisory committee for this project. Additionally, thanks to Dr. Taryn Taylor, the team at Carleton Sports Medicine Clinic, and the team of physicians and clinicians at Pro Physio Sports Medicine Clinics. Lastly, special thanks to Dr. Sue Bertram, Dr. Andy Adler, Danny Lemay and Kong Chiv for so graciously offering their technical expertise, lab and research resources.

This research would not have been possible without the financial support provided by the Canadian Institutes of Health Research (CIHR).

Table of Contents

List of Tables

List of Illustrations

List of Abbreviations

AT, Anterior Tibialis

ATFL, Anterior Talofibular Ligament

ATTL, Anterior Tibiotalar Ligament

ANOVA, Analysis of Variance

CLF, Calcaneofibular Ligament

DF, Degrees of Freedom

EMG, Electromyography

GLMM, Generalized Linear Mixed Model

iEMG, Integrated Electromyography

LMER, Linear Mixed Effects Regression

LSM, Least Squares Mean

MVIC, Maximal Voluntary Isometric Contraction

PL, Peroneus Longus

PTFL, Posterior Talofibular Ligament

PTTL, Posterior Tibiotalar Ligament

PRICE, Protect Rest Ice Compression Elevation

REML, Restricted Maximum Likelihood

sEMG, Surface Electromyography

TCL, Tibiocalcaneal Ligament

TNL, Tibionavicular Ligament

List of Appendices

1.0 Introduction

Ankle sprains are statistically the most common musculoskeletal injuries in North America, occurring at an estimated rate of 1 in 10,000 individuals per day. Ankle sprains make up over 30% of all sports medicine clinic visits each year (Waterman et al., 2010; Yeung et al., 1994). After discharge from clinical rehabilitation for an ankle sprain, it has been observed that the rate of recurrence, classified by a repeated sprain of the same ankle and type of sprain, was 73%. Additionally, 59% of individuals reported residual symptoms after discharge (Hubbard & Cordova, 2009 and Sefton et al., 2009). Considering the goal of rehabilitative physical therapy is to treat patients with musculoskeletal injuries and return them to a pre-injury state, these findings and re-injury rates suggests that there are areas to improve the preexisting clinical rehabilitative treatment protocol for ankle sprains.

Currently, traditional rehabilitative therapy for ankle sprains addresses connective tissue laxity and muscular weakness with limited emphasis on postural and ankle stability exercises. Clinicians rehabilitating a sprained ankle will typically utilize several balance and coordination exercises involving single leg stances, whereby the individual is able to and encouraged to actively and willfully utilize cognitive resources to concentrate on their balance (Mattacola & Dwyer, 2002). This form of stability training places emphasis on the individual actively controlling and stabilizing the ankle. However, ankle stability is a largely autonomic process and evidence suggests that these ankle injuries mostly occur when the individual is not considering or utilizing any deliberate effort in stabilizing the ankle (Jones, 1994 and Proske & Gandevia, 2012).

1.2 Hypothesis and Objectives

Participants that perform rehabilitative ankle stability training with a paired visuospatial distractor task will have a greater rates of improvement in ankle joint stability than those performing the same stability training without the paired distractor task

- H_0 = There is no significant difference in ankle stability improvements between experimental and traditional sprain treatment groups. The experimental group would show no significant reduction in mean muscle activity over the 4 weeks.
- H_a = There is a significant difference in ankle stability improvements between experimental and traditional sprain treatment groups. The experimental group would show a significant reduction in mean muscle activity over the 4 weeks.

The objective of this study was to evaluate the effect of introducing a distractor task during the stability training component of ankle sprain rehabilitation. The addition of a distractor task to the rehabilitative stability training protocol, was predicted to result in an improvement in ankle stability, compared to rehabilitation without the distractor task. Meaning, experimental sprain treatment group's mean level of muscle activity over the four weeks, in the anterior tibialis (AT) and peroneus longus (PL) of the sprained ankle, would be significantly lower than the mean level of muscle activity in the AT and PL of the sprained ankle in the traditional sprain treatment group.

1.3 Ankle Sprain Classification, Anatomy, and Pathophysiology

1.3.1 Ankle Sprain Classification

Ankle sprains can be classified by type and severity. The type of sprain is dependent on the motion the ankle undergoes during injury (Figure 1). Inversion sprains, which make up approximately 85% of all ankle sprains, occur when forceful lateral supination occurs in the foot, resulting in an outward rolling motion (Garrick, 1977 and Waterman et al., 2010). Eversion sprains occur when excessive or abrupt medial pronation occurs in the foot, causing an inward rolling motion (Garrick, 1977 and Waterman et al., 2010). High ankle sprains are the result of incongruity in rate of rotation in the lower leg, ankle, and foot (Garrick, 1977 and Waterman et al., 2010).

The severity of a sprain can be classified under 3 grades (Figure 2). The grading system assesses the level of damage to the ligaments, as well as, the magnitude in the loss of function of the ankle. Grade I sprains are the least severe and can be characterized by pain and swelling, but the individual is still able to walk with mild discomfort. Grade I sprains involve only stretching of the ligaments, tendons and muscles (Lynch, 2002). Grade II sprains are more severe, characterized by significant swelling, bruising and pain. An individual with a Grade II sprain typically can still walk but with a greater level of pain. Grade II sprains typically involve more severe stretching of the ligaments, tendons and muscles with the possibility of minor or partial tearing of the ligament. Grade III sprains are the most severe and is characterized by heavy swelling, bruising and pain. Someone suffering from a grade III sprain will be unable to walk or utilize the ankle. Grade III sprains involve a complete tear in the ligament (Lynch, 2002).

Due to the limited mobility of the ankle in eversion movements, eversion sprains are rare and often times result in complete tearing in the medial ligaments or breakages in the tibia or talus. High ankle sprains involve uncontrolled rotational force on the lower leg and often is combined with rotational force in the upper leg. This rotational force between the lower and upper leg often leads to damage to the knee's cruciate ligaments, in addition to the high ankle sprain. Eversion and high ankle sprains are relatively uncommon, occurring in about 15% of all sprains, with the majority of sprains being grade I and II inversion sprains (Waterman et al., 2010). Additionally, the typical level of severity of eversion and high ankle sprains often means that these sprains will present with other injuries.

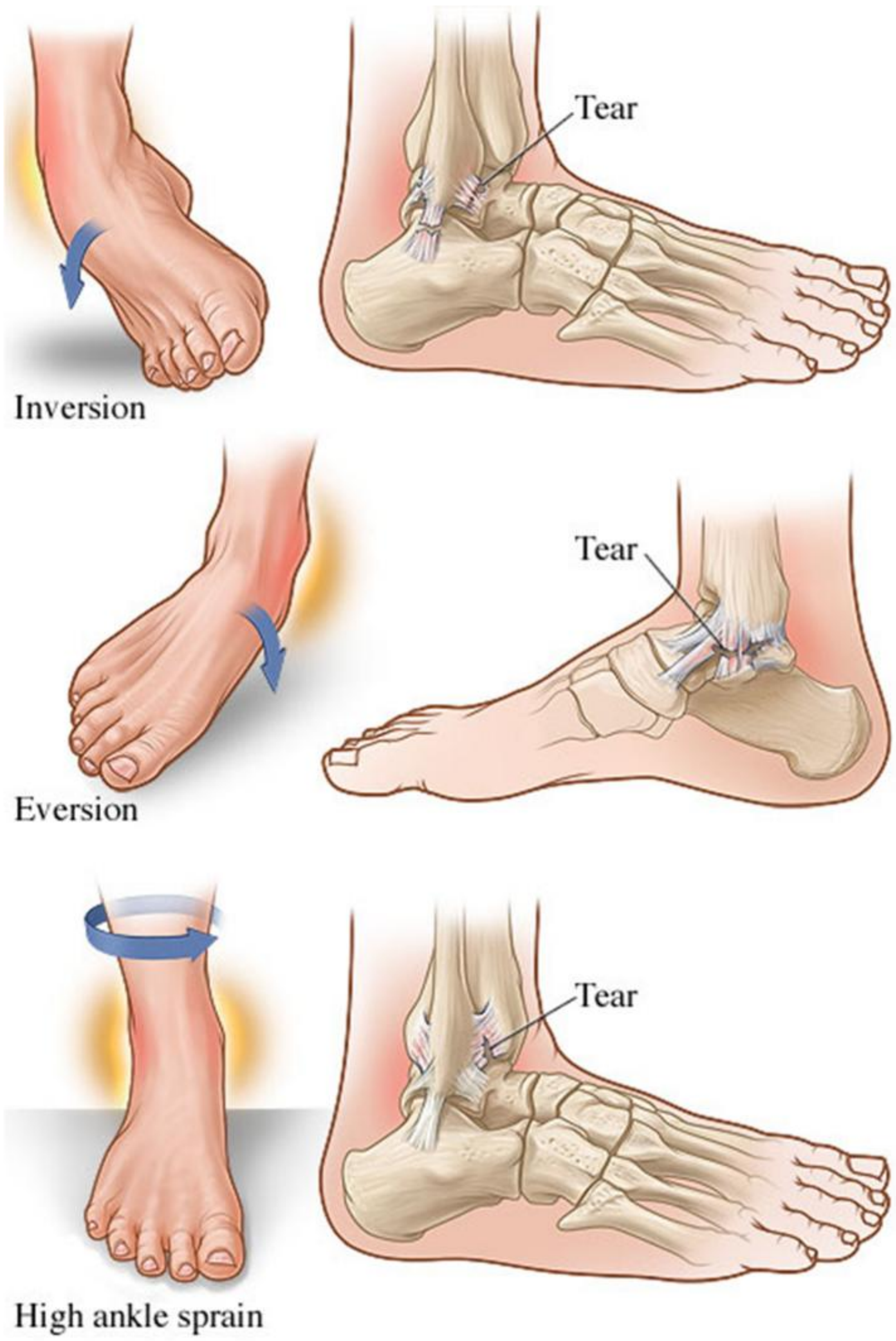

Figure 1: Diagram of movements associated with each type of ankle sprain and the injuries to ligaments associated with each type of sprain. (Getty Images, Stock Image)

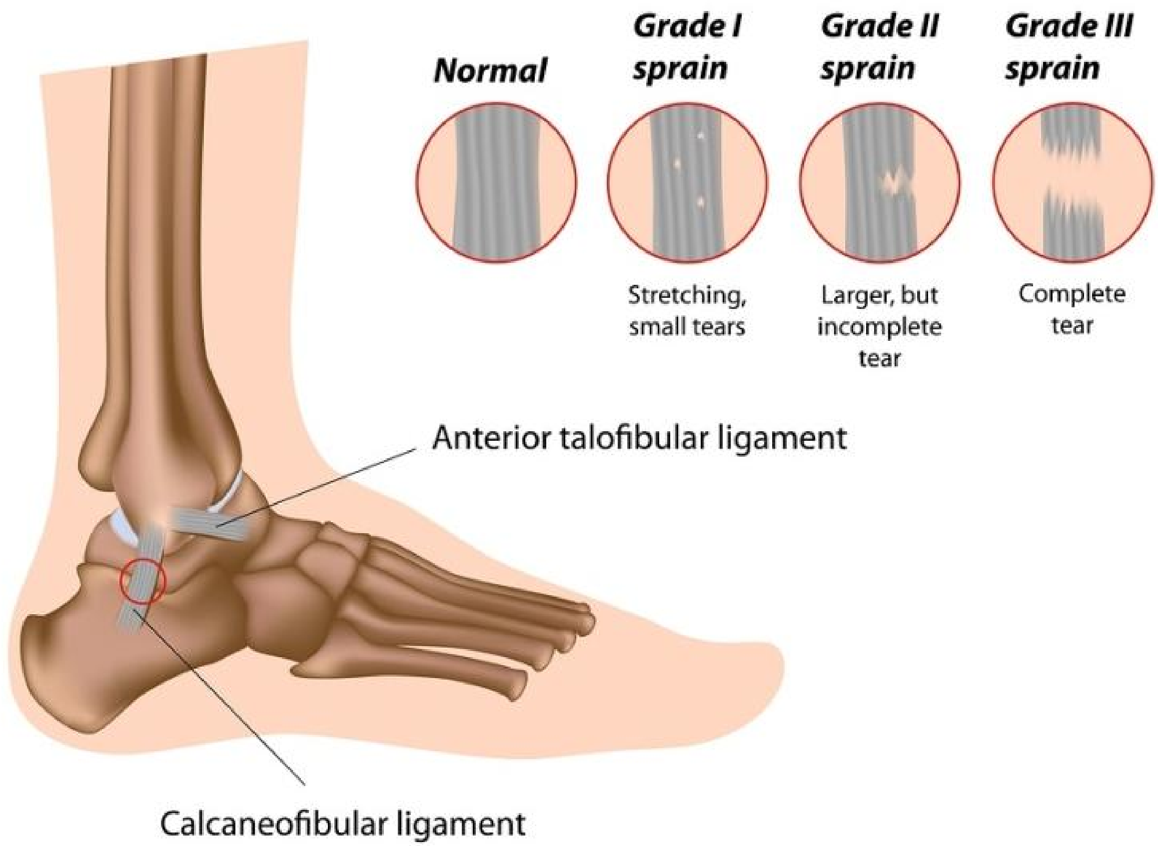

Figure 2: Diagram of lateral ankle sprain severity gradation based upon level of cellular damage to ligamentous connective tissue. (Getty Images, Stock Image)

1.3.2 Ankle Anatomy

The “ankle joint” is a complex amalgamation of 3 joints (Figure 3); the talocrural joint, the subtalar joint, and the distal tibiofibular joint (McMinn et al., 1996). The ankle joint is capable of movements in all three planes of motion; sagittal, frontal, and transverse. Each joint, in the foot and ankle, can be separated by the movement it is primarily responsible for (Figure 3). The talocrural joint is responsible primarily for sagittal plane movements, such as, plantar flexion and dorsiflexion of the foot. It is structurally comprised of three bones; the tibia, fibula and the talus. The subtalar joint is responsible for transverse or lateral plane movements, such as, inversion and eversion of the foot and is the junction between the talus and calcaneus. Lastly, the distal tibiofibular joint is responsible for internal and external rotation of the foot and other frontal plant movements. It is the distal most point of the tibia and fibula, proximal to the talus (McMinn et al., 1996). These 3 joints and movements are often not performed in isolation, meaning the planes of movement produced by each joint is often combined with the other movements in a coordinated fashion.

Lateral and medial ligaments connecting the ankle bones provide stability to the ankle (Figure 4). The lateral ligaments of the ankle are the anterior and posterior talofibular ligament (ATFL and PTFL), which connects the talus to the fibula, and the calcaneofibular ligament (CFL), which connects the calcaneus to the fibula (Burks & Morgan, 1994). The medial ankle ligaments are often simply referred to as the medial deltoid ligaments and is comprised of the anterior and posterior tibiotalar ligaments (ATTL and PTTL), which connect the tibia to the talus, the tibiocalcaneal ligament (TCL), connects the tibia to the calcaneus, and the tibionavicular ligament (TNL), connects the tibia to the navicular (Burks & Morgan, 1994). The talocalcaneal ligaments connect the talus to the calcaneus in the subtalar joint, while the distal tibiofibular joint is secured by the lateral malleolus ligaments (Burks & Morgan, 1994).

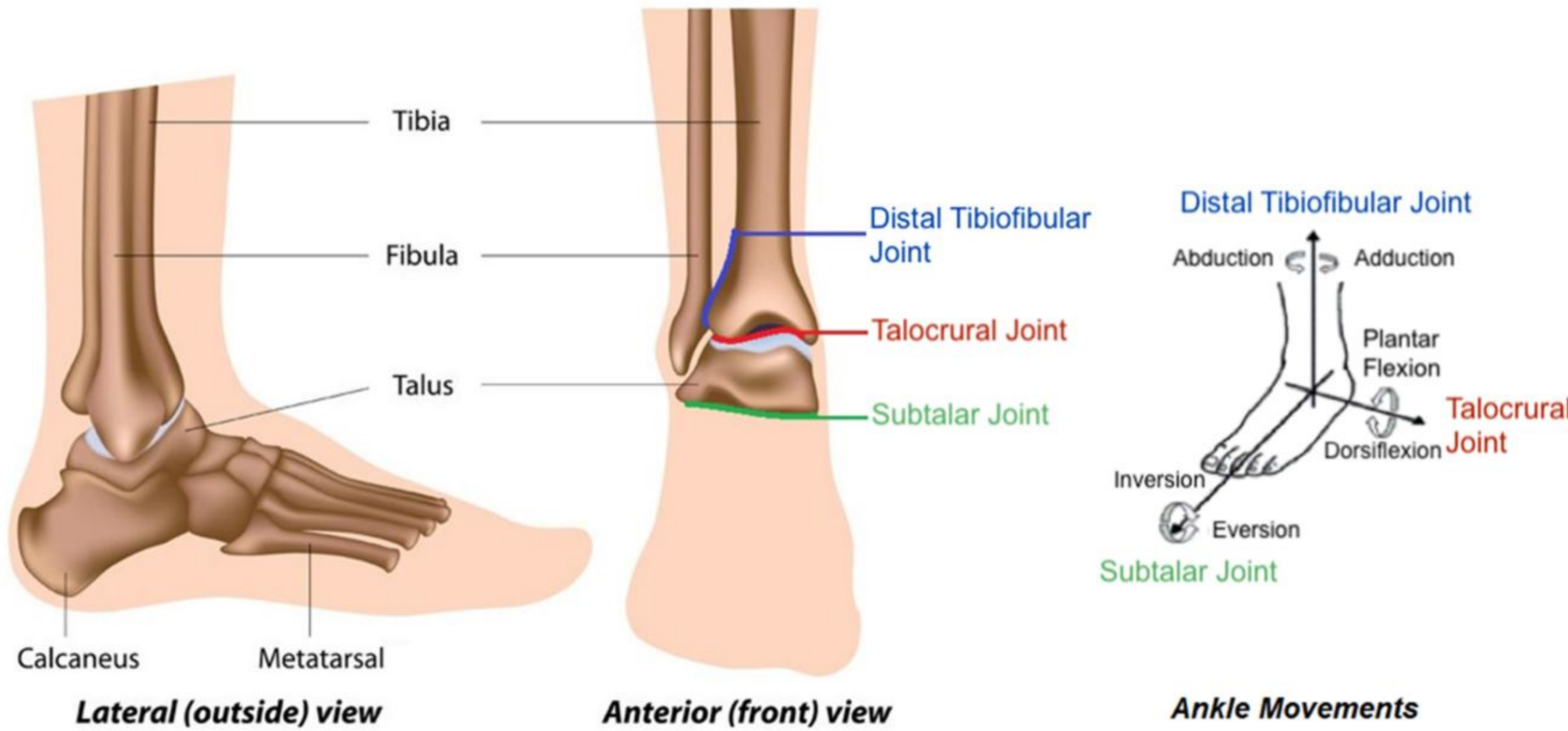

Figure 3: Lateral and anterior view of the ankle joint complex, showing the 3 main joints of the ankle; distal tibiofibular joint, talocrural joint, and the subtalar joint, and the associated axes and movements. (Getty Images, Stock Image)

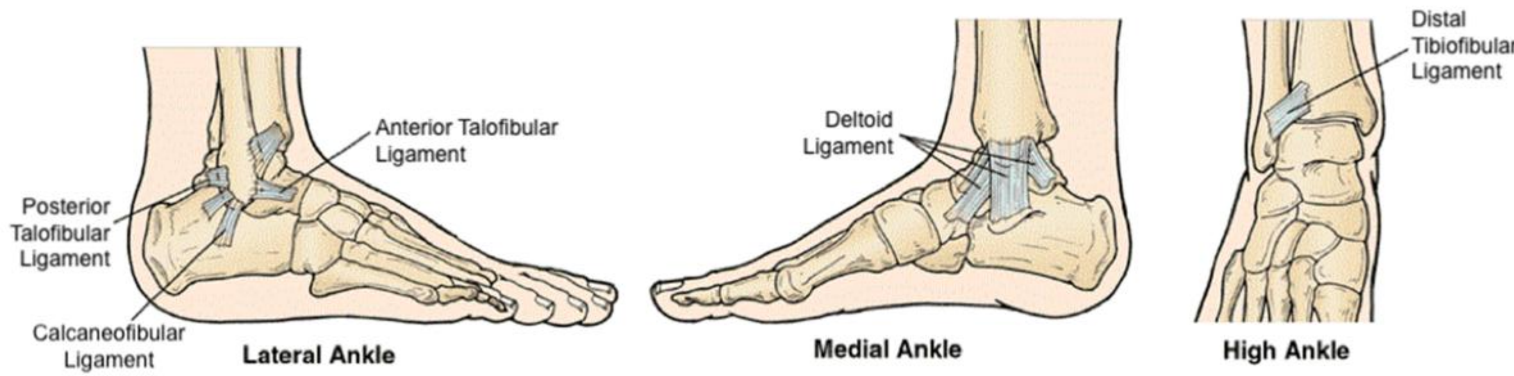

Figure 4: Diagram of the ligaments of the lateral, medial, and high ankle. (Getty Images, Stock Image)

1.3.3 Mechanisms and Biomechanics of an Acute Lateral Ankle Inversion Sprain

1.3.3A Material Properties of Ligaments

Ligaments have contrasting roles and functions within the body. Ligaments connect two bones together, provide stability to the joint, disperse excess energy, and also must allow for mobility in the joint to enable proper function. To meet these competing demands, ligaments need to have viscoelastic characteristics. Viscoelasticity is the property of a material to exhibit both viscous and elastic properties. Polymers are materials that are comprised of various other materials. Ligaments and most organic biomaterials are a polymer of many other components, about 60-70% fluids, 20-30% collagen fibres and small amounts of proteoglycans (Korhonen & Saarakkala, 2011). It is primarily the mixture of collagen fibres, which also have viscoelastic properties, and the fluids that give ligaments this viscoelastic property that allows ligaments around a joint to withstand a reasonable degree of stress without permanent deformation or damage (Korhonen & Saarakkala, 2011). The individual fibres within the ligament are organized in a unidirectional fashion providing a basal level of tension and stiffness but still have a significant amount of laxity. Individual fibres are then clustered into bundles, these bundles have crimps, forming a wave-like pattern. The structural arrangement of the fibres is a very large contributing factor to the elasticity of ligaments. As stress is applied to the ligament, its elastic property allows it to strain and deform without permanent damage, this is known as elastic deformation (Figure 5). After the stress is removed, the ligament disperses energy as it returns to its original conformation (Figure 6). The stress point just prior to irreversible deformation is known as its yield point (Figure 5). Plastic deformation occurs after the yield point, further deformation in the ligament will result in irreversible damage, meaning the ligament will not return to its original shape (Figure 5 and Figure 6). If a significant amount of stress is placed on the ligament past the yield point, the ligament could rupture resulting in catastrophic failure (Figure 5). Ligaments, like every viscoelastic material, has a specific yield point and failure point (Korhonen & Saarakkala, 2011).

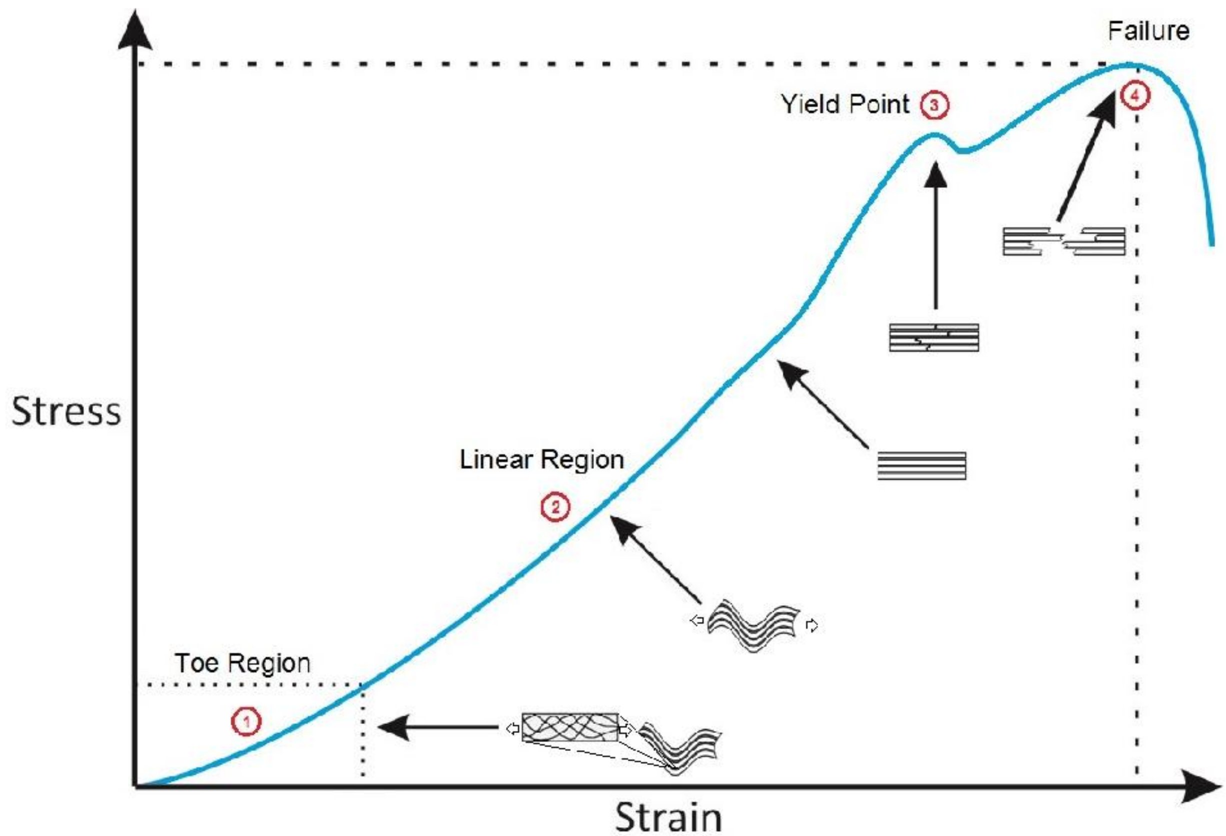

Figure 5: Generalized stress-strain curve of ligamentous connective tissue, showing the toe region ①, linear region ②, yield point ③, and failure point ④ (Modified from Wheaton & Jensen, 2010)

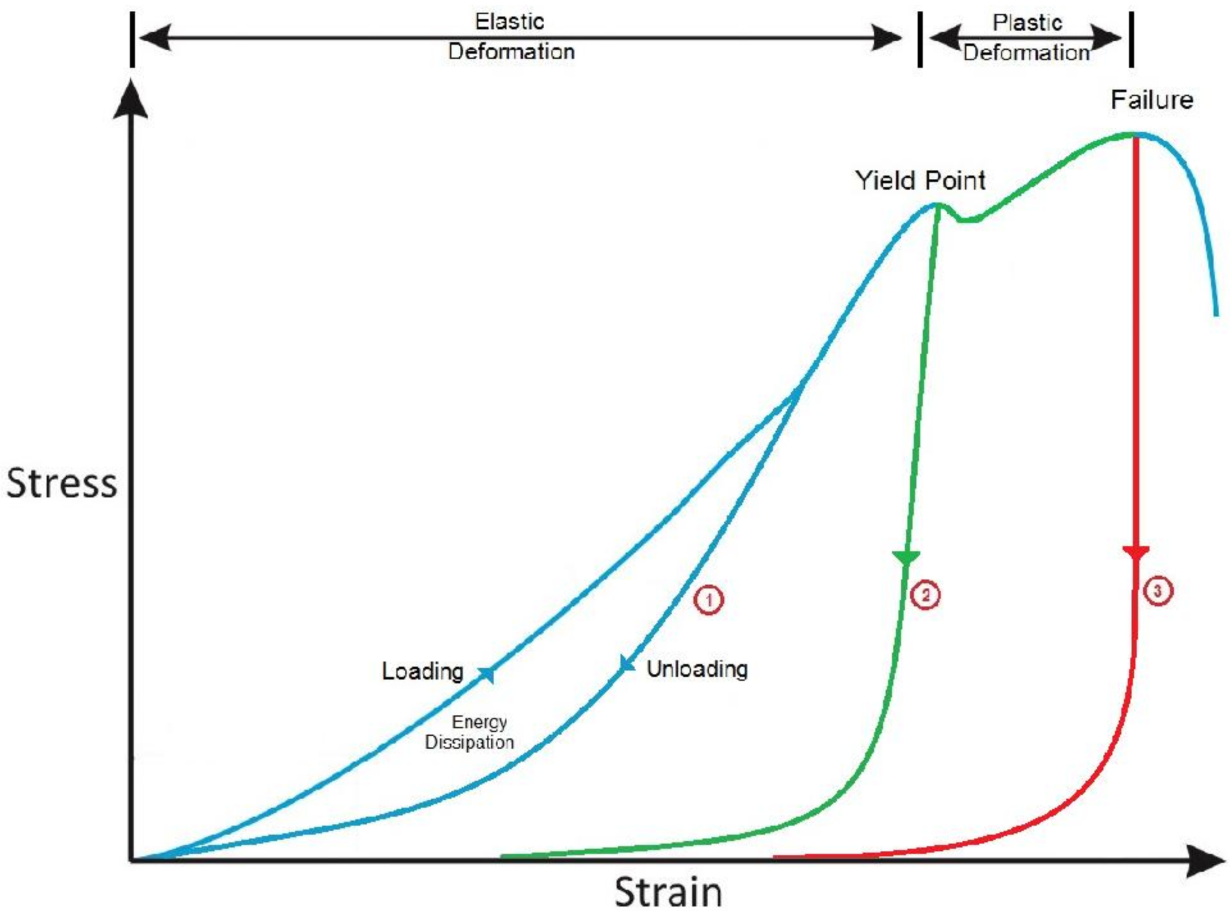

Figure 6: Combined hysteresis and stress-strain curve of ligamentous connective tissue, showing; energy dissipation, loading/unloading phases, elastic deformation ①, plastic deformation ② & ③, yield point and failure point. (Modified from Wheaton & Jensen, 2010)

Figure 5 represents a generalized stress-strain curve for ligamentous connective tissue. As stress and strain increase in the ligament, changes to the structural arrangement of the ligament occur, the level of changes and damage dictate the grade of sprain. The toe region is the initial phase of strain, where elongation is the result of the straightening in the individual fibres of collagen (Korhonen & Saarakkala, 2011). As the ligament continues to elongate, the crimps and wave-like pattern of the collagen fibre bundles straighten, this is the linear region (Korhonen & Saarakkala, 2011). After the linear region and the bundled fibres are fully stretched, further elongation progresses into the yield region. Minor damage occurs as the individual fibres are pulled apart, it is at this degree of strain that grade I sprains are likely to occur. At the yield point, significant damage has been done to the ligament and tears in the collagen fibre bundles occur, grade II sprains occur at the plastic deformation region (Korhonen & Saarakkala, 2011). At the failure point, rupture of the ligament, grade III sprain, occurs and all the fibre bundles have been torn.

In the combined hysteresis and stress-strain curve, figure 6, shows loading and unloading on a ligament. In viscoelastic materials, like ligaments and connective tissue, loading curves and unloading curves are different, this difference is called hysteresis (Robi et al., 2013). The area between the loading and unloading curve represents the energy that is dissipated. In perfectly elastic materials, the loading and unloading curves are the same, which suggests that there is no energy lost in the process. This ability to dissipate energy allows ligaments and other connective tissue to disperse excess energy, which protects the joints and bones (Korhonen & Saarakkala, 2011). Prior to the yield point, any loading and unloading cycle will result in the ligament returning to the original length and shape, shown by curve ①. Cycles in this region are said to be undergoing elastic deformation (Korhonen & Saarakkala, 2011 and Robi et al., 2013). Past the yield point, plastic deformation occurs. Cycles in this region do not return to their original length and shape, shown by curves ② and ③. As the loading moves further past the yield point, the more damage is done to the ligament and the greater the difference between the new unloaded length and shape and the original (Robi et al., 2013).

1.3.3B Kinetics of an Acute Lateral Ankle Inversion Sprains

Lateral inversion sprains typically occur during a foot strike or landing event, where forceful lateral supination of the foot is combined with plantar flexion and internal rotation (Figure 7) (Garrick, 1977, Waterman et al., 2010 and Yeung et al., 1994). This combination of excessive inversion, plantar flexion and internal rotation in the foot leads to straining of the lateral ankle ligaments (Figure 4) (Garrick, 1977, Yeung et al., 1994, and Waterman et al., 2010). Any resultant damage from a sprain is due to the strain placed on the lateral ankle ligaments exceeding their tensile strength (Kelikian & Sarrafian, 2011). Due to the plantar flexion often associated with lateral inversion sprains, the ATFL is typically the most significantly damaged, as it is strained the most severely. Supination causes damage to the CFL (Garrick, 1977). All three lateral ligaments work together to stabilize the sides of the ankle. As the ATFL is strained beyond its yield point and potentially ruptured, the excess stress is then placed on the CFL. As the CLF fails, the subsequent stress is added to the PTFL (Garrick, 1977). To assess and predict the amount of force needed to cause an acute lateral ankle inversion sprain, the specific yield and failure points need to be evaluated. Yield and failure points were experimentally determined in cadaveric studies conducted by Kelikian and Sarrafian. According to Kelikian and Sarrafian, the yield points of the ATFL, CFL, and PTFL were 222 N, 289 N, and 400 N, respectively. The failure points of the ATFL, CFL, and PTFL were 231 N, 307 N, and 418 N, respectively (Figure 8).

The timeline of recovery from an inversion sprain varies greatly depending on; the severity, prior history of sprains, compliance to rehabilitative protocols, and many of other factors. Rehabilitation protocols are aimed at returning the individual to a pre-injury state but studies have shown that inversion sprains in the ankles have long-term ramifications that increase incidences of recurrence and re-injury (Waterman et al., 2010). Additionally, long-term ankle instability appears to be strongly associated with prior sprains (Hubbard & Cordova, 2009). Based on the structural and material properties of ligamentous connective tissue, injury mechanics, recovery protocol, and the long-term ramifications of an acute lateral ankle inversion sprain, further study is required to identify and create a rehabilitative framework that can address the underlying cause of lasting long-term ankle instability and the increase in sprain recurrence rate.

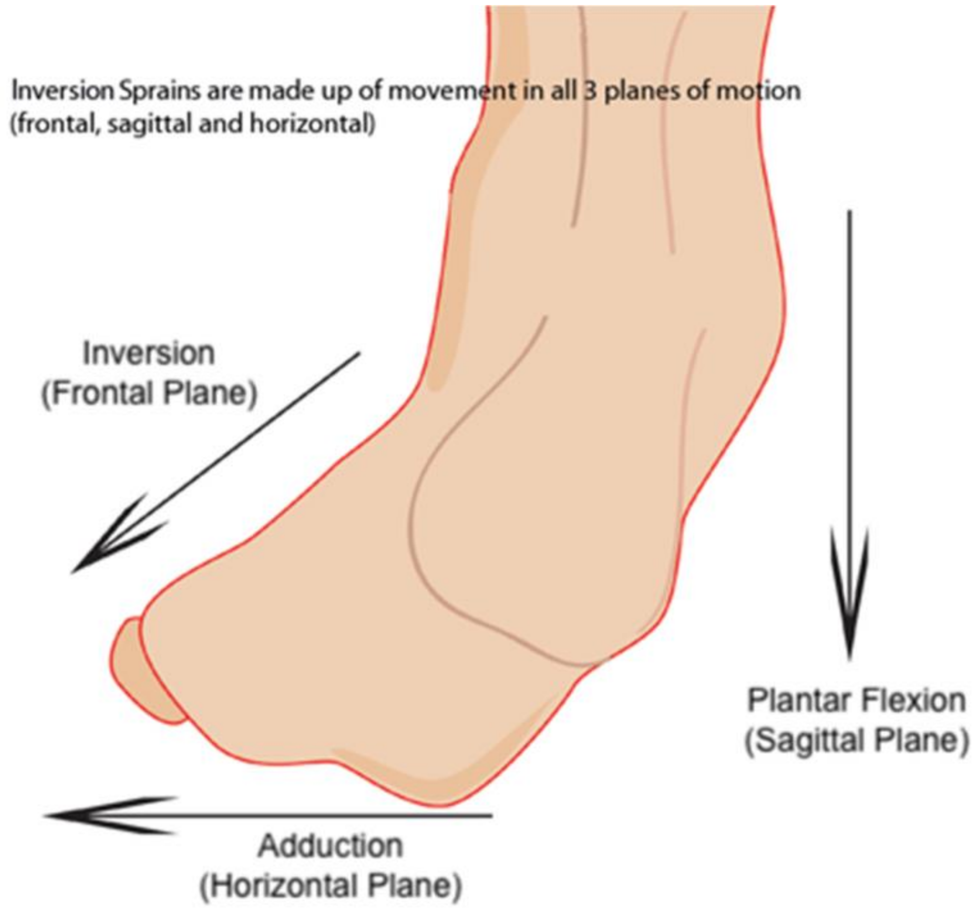

Figure 7: Diagram of the 3 movements typically associated with lateral ankle inversion sprains (Getty Images)

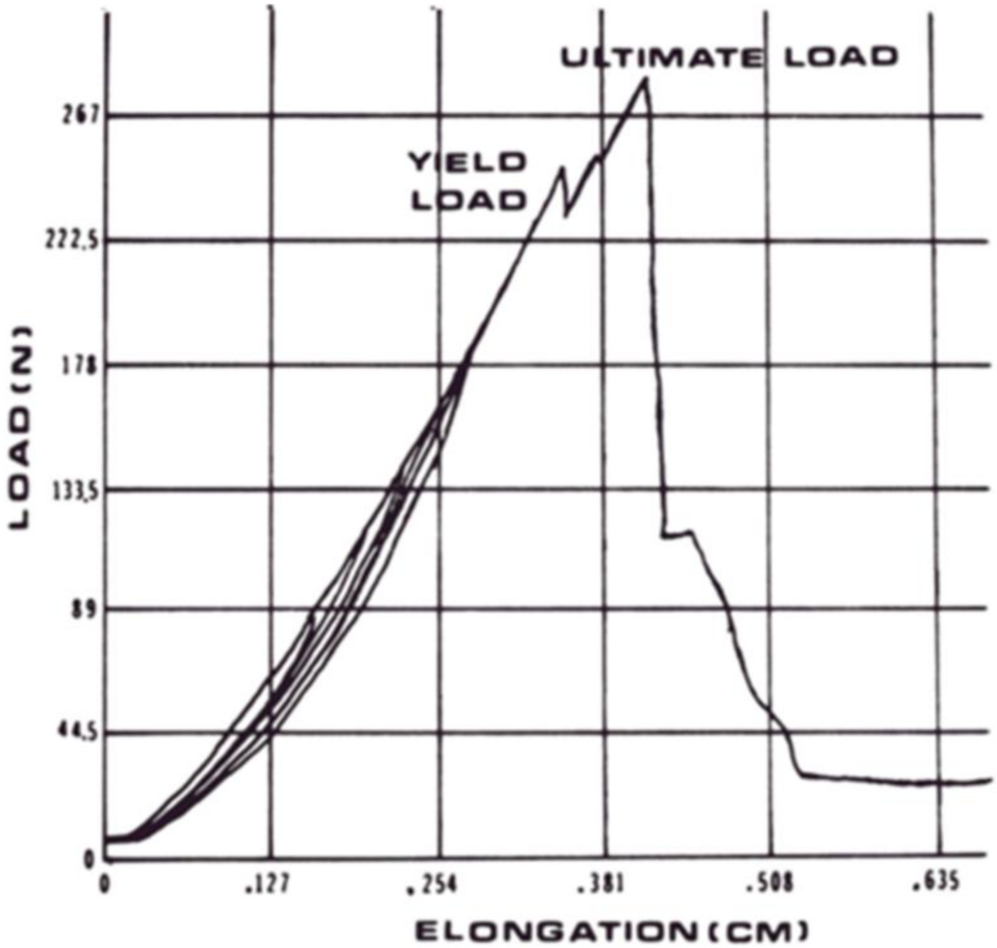

Figure 8: Tensile test results of lateral ankle ligaments, presented in a tension-elongation graph (Kelikian & Sarrafian, 2011).

1.4 Rehabilitative Phases and Current Clinical Treatment Protocol

There are 3 main phases in the rehabilitation protocol for an acute lateral ankle inversion sprain, acute phase, recovery phase, and remodeling phase (Robi et al., 2013).

1.4.1 Acute Phase

The acute phase typically lasts 3 days, with the primary goal of reducing inflammation and pain. During this phase, patients are prescribed standard protect, rest, ice, compression, and elevation (PRICE) protocol. Patients are instructed to use protective and supportive braces to immobilize the sprained ankle, rest and avoid use or loading of the ankle, ice the swollen and inflamed area for 15 minutes three times daily, use compressive bandages to compress the ankle to reduce swelling, and elevate the swollen areas above the level of the heart when possible (Houghton, 2008).

1.4.2 Recovery Phase

Once the majority of the inflammation subsides, patients typically undergo a physical examination of the ankle and foot. The physical examination procedure provides a reasonably accurate and relatively concise method of identifying the nature and severity of the ankle sprain. The physical examination is made on the basis of patient history and a series of physical tests which differentiates an ankle sprain from a fracture, but also allows for the evaluation of the type and grade of the sprain. Patients evaluated with a fracture or grade III sprain will have the fracture set and immobilized into a cast or, if necessary, undergo surgical intervention. Patients with a grade I or II sprain usually enter the recovery phase immediately after the acute phase. The recovery phase typically lasts 7 to 14 days, which aims to eliminate pain symptoms, restore basic function, and load-bearing capacity of the foot and ankle (Robi et al., 2013). Patients within this phase perform exercises aimed at improving range of motion and basic levels of stability, such as, static isometric contractions of the muscles of the lower leg and ankle, isotonic movements of the foot, walking, and stair stepping (Roebroeck et al., 1998).

1.4.3 Remodeling Phase

The remodeling phase can last several weeks to several months, depending on the severity of the sprain and the patient's ability to recover (Robi et al., 2013). The aim of the functional remodeling phase is to restore full function to the foot and ankle. Exercises in this phase commonly emphasize specific and directed stability training. Patients will typically practice standing on a single leg, using a single plane of tilt wobble board, to improve postural control and ankle stability (Mattacola & Dwyer, 2002 and Roebroeck et al., 1998). Depending on the clinician's assessment and opinion of the patient's progress, patients may also be permitted to carefully reintroduce other activities such as; running, jumping and landing, and controlled pivoting movements. During this phase, return to competition or athletic training is not uncommon (Houghton, 2008 and Roebroeck et al., 1998).

1.5 Joint Stability and Muscle Activity

Joint stability is the resistance offered by the musculoskeletal tissues, including muscles, tendons, and ligaments, surrounding a specific joint in order to maintain joint homeostasis (Riemann & Lephart, 2002). The maintenance of joint homeostasis during movements is known as functional joint stability. Functional ankle instability is often used to describe the inability of an individual to maintain joint homeostasis during movement, thereby leading to repeated ankle inversion injuries. Joint stability is controlled by the sensorimotor system, which is comprised of four main components: sensory feedback, processing, central integration, and motor function. This system of sensory feedback and processing is used to direct and elicits appropriate motor functions in order to maintain joint stability. Characteristic impairments in muscle activity associated with functional ankle instability is typically caused by failures in one or more components of the sensorimotor system. These impairments present with increased muscle activation magnitude, latency, and co-contraction, all of which culminate to increased muscle activity (Klyne et al., 2012, Konradsen, 2002 and Manal et at., 2012).

The high degree of articulation in the ankle means that there are many muscles involved in maintaining ankle joint stability across its 3 planes of movement. Lateral ankle stability is predominantly maintained by inversion produced by the anterior tibialis (AT) and eversion from the peroneus longus (PL). The amount of muscle activity required to maintain lateral ankle joint stability can be extrapolated from the muscle activity of the AT and PL. Electromyography (EMG) is used to measure muscle activity. Although the use of EMG in joint stability research is relatively novel, increased muscle activity, associated with functional ankle joint instability, can be consistently observed and measured using EMG (Klyne et al., 2012, Konradsen, 2002, Manal et at., 2012 and Sefton et at., 2009). Additionally, one prior study examining individuals with ankle joint instability, measured muscle activity magnitude and response time during an induced stability event, which identified an increase in muscle activity and delayed contraction onset time (Karlsson et al., 1992). With over 86% of individuals with functional ankle instability presenting with significantly higher levels of muscle activity and latency than individuals with no sensorimotor impairment (Sefton et at., 2009), the observed level of muscle activity in the muscles of a joint are generally accepted as the inferred level of activity required to stabilize the given joint and maintain balance.

1.6 Effects of Distractor Tasks on Balance and Joint Stability

Prior studies of the effects of various distractor tasks on an individual's performance in novel single leg stability and balance tests found that the level of impact on adaptation to the novel balance and stability task varied greatly depending on the type of distractor. When individuals were instructed to perform a balance task performing a distractor task that required the use of verbal or linguistic skills, balance was not significantly affected (Andersson et al., 1998, Chong et al., 2010 and Laufer et al., 2007). However, when individuals were asked to balance while performing a distractor task that required visual or spatial awareness negatively affected balance (Andersson et al., 1998, Chong et al., 2010 and Laufer et al., 2007). The prevailing theory on how and why different distractor tasks present with such varied outcomes, depending on the type of distractor, involves concept of working memory and the associated limitations of attentional resources. Cognizant and intentional movement and motor functions, originating from the motor cortex in the cerebrum, has been demonstrated to occupy and use attentional resources (Andersson et al., 1998, Chong et al., 2010 and Seidler et al., 2012). The novel balance tasks presented in the prior studies required intentional movement or active adjustments in motor function. Intentional movement requires attentional resources since the visuospatial system of the brain is constantly processing and interpreting various visual and spatial stimuli then coordinating appropriate responses in the form of motor commands, all of which will theoretically utilize working memory resources (Andersson et al., 1998, Chong et al., 2010 and Seidler et al., 2012).

1.7 Working Memory and Visuospatial Distractor Tasks

Working memory, colloquially and commonly referred to as short term memory, is subdivided into two distinct systems; the phonological loop, involved in auditory and linguistic tasks, and the visuospatial sketchpad, involved in tasks that require visual and spatial recognition, orientation, and processing (Baddeley, 1992, Engle, 2002 and Logie, 2014). A system of information integration and processing, known as central executive processing, works to interpret the various information within each system and formulate appropriate responses (Baddeley, 1992). Working memory and central executive processing systems comprise what is considered to be cognition and awareness (Baddeley, 1992 and Engle, 2002).

Working memory is constrained by its limited information holding capacity (Engle, 2002). Distractor tasks are used as a means to occupy one or even both systems, in order to isolate a specific variable or parameter (Lavie, 2005). Additionally, distractor tasks that are strictly visually or spatially oriented will significantly impact an individual's performance on other visuospatial tasks but will not have a substantial impact on auditory, linguistic, or phonological tasks. The inverse is true for phonological distractor tasks not impacting visuospatial tasks (Conway et al., 2001, Corbetta et al., 2002 and Engle, 2002). This suggests that the phonological loop and visuospatial sketchpad each store and process information separately from one another.

A visuospatial distractor task is any form of activity that elicits and occupies visuospatial working memory. It has been demonstrated that visuospatial working memory has a finite and limited holding and processing capacity separate from linguistic processes (Conway et al., 2001, Corbetta et al., 2002 and Engle, 2002). Intuitively, distractor tasks that occupy visuospatial working memory and attentional resources leads to impediments in other concurrent operations that require visuospatial working memory or visuospatial awareness, manifested in lower accuracy, efficiency, and slower performance in both the distractor task and the measured concurrent operations (Geffen et al., 1997 and Woodman & Luck, 2004).

Prior studies have evaluated the implications and impacts of working memory, specifically visuospatial working memory, on novel motor learning, procedural motor skills and sensorimotor adaptation. Novel motor learning is the acquisition of new movements and physical competencies without prior rehearsal, this process requires a high degree of visuospatial working memory and attentional resources (Maxwell et al., 2003 and Seidler et al., 2012). There is high degree of overlap between visuospatial working memory tasks, novel motor skills learning, cognizant motor interventions, and declarative knowledge (Maxwell et al., 2003). The overarching implication of interference between; visuospatial working memory, novel motor skills learning, cognizant motor intervention, and declarative knowledge, suggests that novel motor skills and cognizant motor interventions all rely on the same finite processing capacity (Andersson et al., 1998, Chong et al., 2010, Maxwell et al., 2003 and Seidler et al., 2012). Procedural motor skills, such as, walking, running and playing a piano, or sensorimotor adaptation, such as, joint stability, posture, and balance, are considered a part of implicit memory and do not require attentional or visuospatial working memory resources (Maxwell et al., 2003 and Seidler et al., 2012). In addition to the varying levels of attentional resources required, the motor activation for motor learning, procedural motor skills and sensorimotor adaptation are initiated from three motor command pathways within the nervous system (Grillner, 1985). The cerebral cortex has two main motor command pathways; the motor cortex, which initiates cognizant intentional movement, and the motor cortex - basal ganglia loop, which initiates and controls procedural motor skills (Grillner, 1985 and Sanes & Donoghue, 2000). The cerebellum regulates sensorimotor adaptation. Finally, the spinal cord is responsible for the reflex arc motor pathway (Grillner, 1985).

This separation in storage and processing of information and motor command initiation is important for the experimental design of this study. In order to isolate or target specific variables, it is ideal to apply conditions in which interference, in the form of a visuospatial distractor task, leads to a conflict for attentional resources with the current task of balancing (Conway et al., 2001 and Engle, 2002).

2.0 Materials and Methods

2.1 Participants and Recruitment

21 total participants were selected for this study (Ages 21 - 38); 7 baseline participants with no prior history of ankle sprain and 14 sprain participants with a single leg grade I lateral ankle inversion sprain. The 7 baseline participants acted as a comparison point for the expected level of muscle activity in individuals with no sprain and no explicit stability training. The 14 sprain participants were recruited, screened, medically cleared, and referred from the Carleton Sports Medicine Clinic and Pro Physio Sports Medicine Clinics in Ottawa (Table 1).

2.1.1 Baseline Non-Sprained Without Training Group

A baseline group of 7 participants, none of whom had any prior history of ankle sprains and performed no ankle stability training, were recruited through passive recruitment from the Carleton University campus. This purpose of this additional group, in addition to the control and experimental sprain groups, was to add a reference point of healthy non-sprained individuals to compare the two sprain groups against. Each baseline participant's muscle activity was tested weekly, for 4 consecutive weeks.

2.1.2 Control and Experimental Group Conditions and Assignments

Sprain participants were separated into 2 groups:

Traditional Sprain group – Control group utilizing only traditionally employed ankle stability and balance rehabilitative training once a week for 4 weeks, single leg stance on a wobble board for 15-30 minutes, supervised and administered by consulting clinicians at the participant's respective sports medicine clinic

Experimental Sprain group – Experimental group utilizing a distractor task paired with the traditionally employed ankle stability training once a week for 4 weeks, single leg stance on a wobble board for 15-30 minutes while performing a visuospatial distractor task, completing a specific task in Portal (Figure 9), supervised and administered in the Minto 6070 lab at Carleton University

Table 1. Comparison of baseline and treatment groups by participants, condition description, and stability training protocol

Group **(# of Participants)**	**Condition Description**	**Stability Training Protocol**
Baseline Non-Sprained with No Training (7: 4 male, 3 female)	No history of ankle sprains	- No ankle stability or balance training - Muscle activity measured once a week for 4 weeks
Traditional Stability Training (7: 3 male, 4 female)	Grade 1 lateral ankle inversion sprain	- Ankle stability and balance training, without distractor task, administered by consulting clinicians - Muscle activity measured once a week for 4 weeks
Experimental Stability Training (7: 4 male, 3 female)	Grade 1 lateral ankle inversion sprain	- Ankle stability and balance training paired with a visual-spatial distractor task (Portal) - Muscle activity measured once a week for 4 weeks

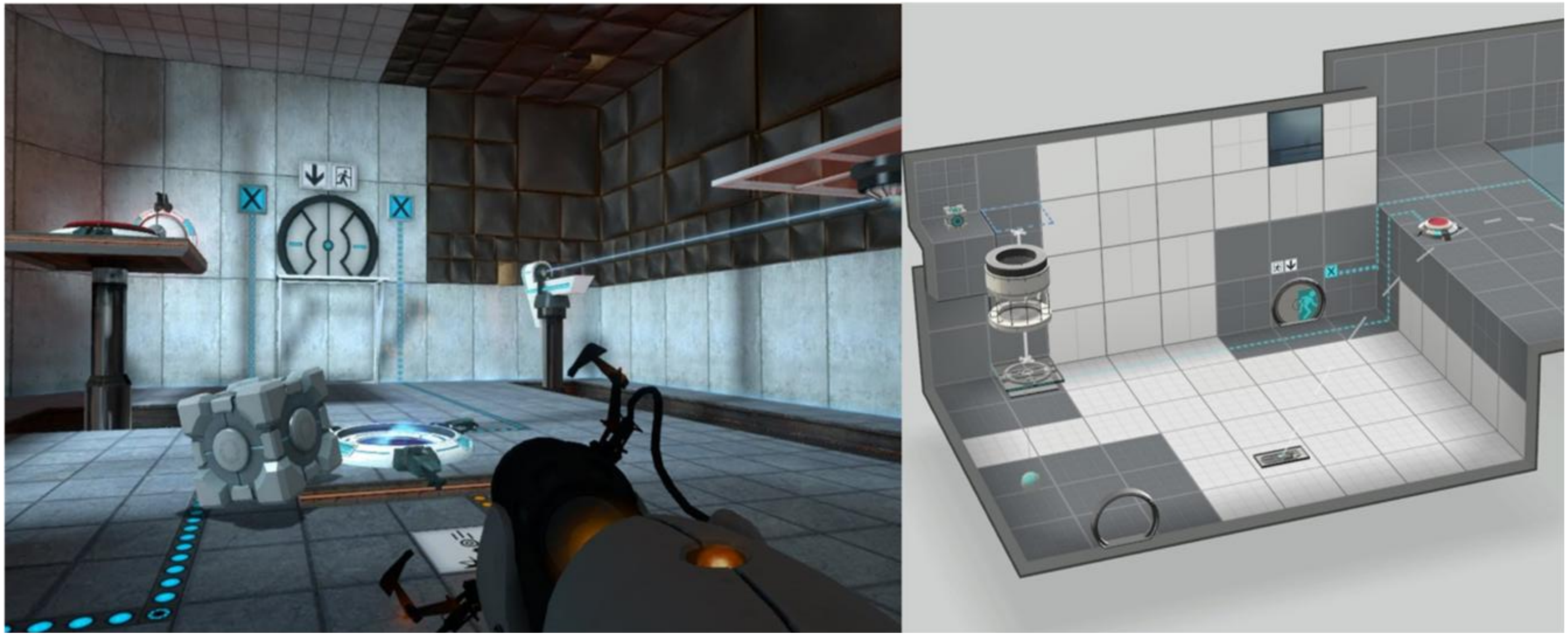

Figure 9. Modified sample screenshot to illustrate course layout of the Experimental Sprain group’s visual spatial distractor task, Portal

Prior to selection into the study, applicants were asked to complete a qualifying questionnaire, to determine suitability for the study. The questionnaire included inquiries into nature of injury, symptoms, background on injury, past health history, as well as experience with video game consoles and 3D video games (Appendix 7.4). At the beginning of the questionnaire, participants were advised that they can refuse to answer any question or questions and that if they choose, may end their participation in the study. Upon completion or termination, a written debriefing was provided. Exclusion criteria for sprain participants in both groups include; prior history of sprains to both ankles and sprains diagnosed as greater than grade I. In addition to the listed exclusion criteria for sprain participants, the experimental group exclusion criteria included prior experience and familiarity with the Sony Playstation game console and any prior experience with 3D video games. Rehabilitative protocol for acute lateral ankle inversion sprains can be summated into three phases: acute phase, recovery phase, and remodeling phase (Robi et al., 2013).

The acute and recovery phases were conducted by a consulting clinicians at Carleton Sports Medicine Clinic and Pro Physio Sports Therapy clinics. The remodeling phase can last several weeks to months, depending on the severity of the sprain and the patient's ability to recover (Robi et al., 2013). Upon entering the remodeling phase of rehabilitation, applicants were screened as having a grade I inversion sprain and medically cleared to participate in the study. Participants had the muscle activity of their anterior tibialis (AT) and peroneus longus (PL) tested once a week. The AT and PL were chosen for two primary reasons; inversion and eversion of the ankle are primarily controlled by these two muscles and the AT and PL muscles and muscle bellies are easy to locate and identify.

Both rehabilitation groups received treatment and training according to the current clinical rehabilitation methods and protocols. The variation between the two groups in treatment protocol only occurred in the remodeling phase, where the traditional stability training group performed a simplified and standardized stability training program, single leg stance at the center of a wobble board, without the distractor task. The experimental stability training group, performed the same stability training program while being asked to perform a distractor task, play a specified level on the video game, Portal (Figure 9). Portal is a first-person 3-dimensional visuospatial logic puzzle game on Sony's PlayStation 3 console, where the objective is to progress from one side of a room to a designated exit point within that room. To minimize rehearsal confounds associated with an individual participant's potential experience with first-person 3-dimensional games, any prior experience with first person 3-dimensional games on Sony's PlayStation 3 console was an exclusion criterion for participants within the experimental stability protocol. For the purposes of standardization, both remodeling treatment protocols lasted 4 weeks and each participant had both sprained and non-sprained legs undergo the stability training protocol. Each participant's muscle activity for both legs were tested weekly.

The current prescribed ankle rehabilitative protocols primarily utilize a single axis wobble or rocker board (Figure S8). Inversion sprains primarily involve the lateral inversion eversion movement ranges of the ankle and impact the anterior tibialis and peroneus longus. The single axis movement allows for clinicians to isolate the inversion and eversion plane movement in the ankle and specifically train those associated stabilizing muscles. For the purpose of this study, a standardized and simplified late remodeling wobble board stability training protocol was adopted (Mattacola & Dwyer, 2002). The stability training program involved participants standing on a single leg at the center of a Fitterfirst single axis wobble board (Figure S8) for an increasing duration once a week over 4 weeks (Table 2). On the first week, participants were asked to stand on the board once for 1 minute, twice for 2 minutes and once for 2.5 minutes, starting with the non-sprained leg and switching legs between intervals. During the second week, participants were asked to stand once for 1, 2, 3, and 4 minutes on each leg, alternating between intervals. On the third week, participants were asked to stand once for 1 minute, twice for 2 minutes, once for 3 minutes, and once for 4 minutes, alternating between intervals. On the fourth and last week, participants were asked to stand on the board once for 1, 2, 3, 4, and 5 minutes on each leg, alternating between intervals.

Table 2. Stability training and data collection outline (a) and Four-week late remodeling wobble board stability training protocol outline with stance duration, frequency, and distractor task difficulty level (b)

(a)

	Stability Training		
	Traditional	**Experimental**	**Data Collection**
Frequency	1x/week	1x/week	1x/week
Time Constraint	None	None	> 2 days after training
Wobble Board	Yes	Yes	No
Distractor Task	No	Yes	No
EMG Measured	No	No	Yes
Location and Conditions	Participant's respective physiotherapy clinic, administered and supervised by a clinician	Minto 6070 at Carleton University, administered and supervised by lead researcher	Minto 6070 at Carleton University, administered and supervised by lead researcher
Required Task	Single leg stance on wobble board (Figure S6) based on week (Table 2b)	Single leg stance on wobble board (Figure S6) based on week (Table 2b)	Single leg stance on the ground (Figure S7)

(b)

Week	Stance Intervals Per Leg (Minutes)					Stance Duration Per Leg (Minutes)	Total Duration (Minutes)	Experimental Group Distractor Difficulty
1	1	2	2	2.5		7.5	15	Level 01 and 02
2	1	2	3	4		10	20	Level 03 and 04
3	1	2	2	3	4	12	24	Level 05, 06, and 07
4	1	2	3	4	5	15	30	Level 08, 09, and 10

2.1.3 Data Collection and Electrode Placement

Participants were asked to stand on a single leg while surface electromyography (EMG) was used to measure the muscle activity in the AT and PL. Muscle bellies for the AT and PL were located using prominent landmarks (Reimer & Wikstrom, 2010 and Taser et al., 2006). Skin was prepped for surface EMG (sEMG) electrode placement by wiping the placement sites with a 70% alcohol prep pad. Covidien H59P electrodes were then placed 2 cm apart in line with the muscle bellies of the AT and PL, on both the sprained and non-sprained side, a ground electrode was placed on the patella (Figure 11). Once skin prep was completed and the electrodes were placed, participants performed 3 trials of maximal voluntary isometric contractions (MVIC), the averaged MVIC data was used to normalize each participant's EMG data. MVIC data was collected by statically fixing the foot and ankle's position while the subject executes maximal dorsiflexion (AT) and eversion (PL) contractions for 5 seconds. Subjects were then instructed to execute a single leg stance for 35 seconds on each leg while EMG data is collected. Surface EMG data was collected through a bipolar technique using a wireless 8 channel Great Lakes Neurotechnologies BioRadio system (Great Lakes Neurotechnologies Inc., 10055 Sweet Valley Dr, Cleveland, OH 44125) at a sampling rate of 1000 Hz. The wireless BioRadio system permits the subjects to be unencumbered by wiring, thus ensuring that the subject's stability is not influenced by any instrument wiring. Since most muscle activity occurs below 400 Hz, doubling the highest sample frequency to obtain the Nyquist frequency of 800 Hz. To minimize the likelihood of aliasing an oversampled rate of 1000 Hz was chosen. A 60 Hz notch filter was applied to eliminate power line interference from lights and other electronic sources.

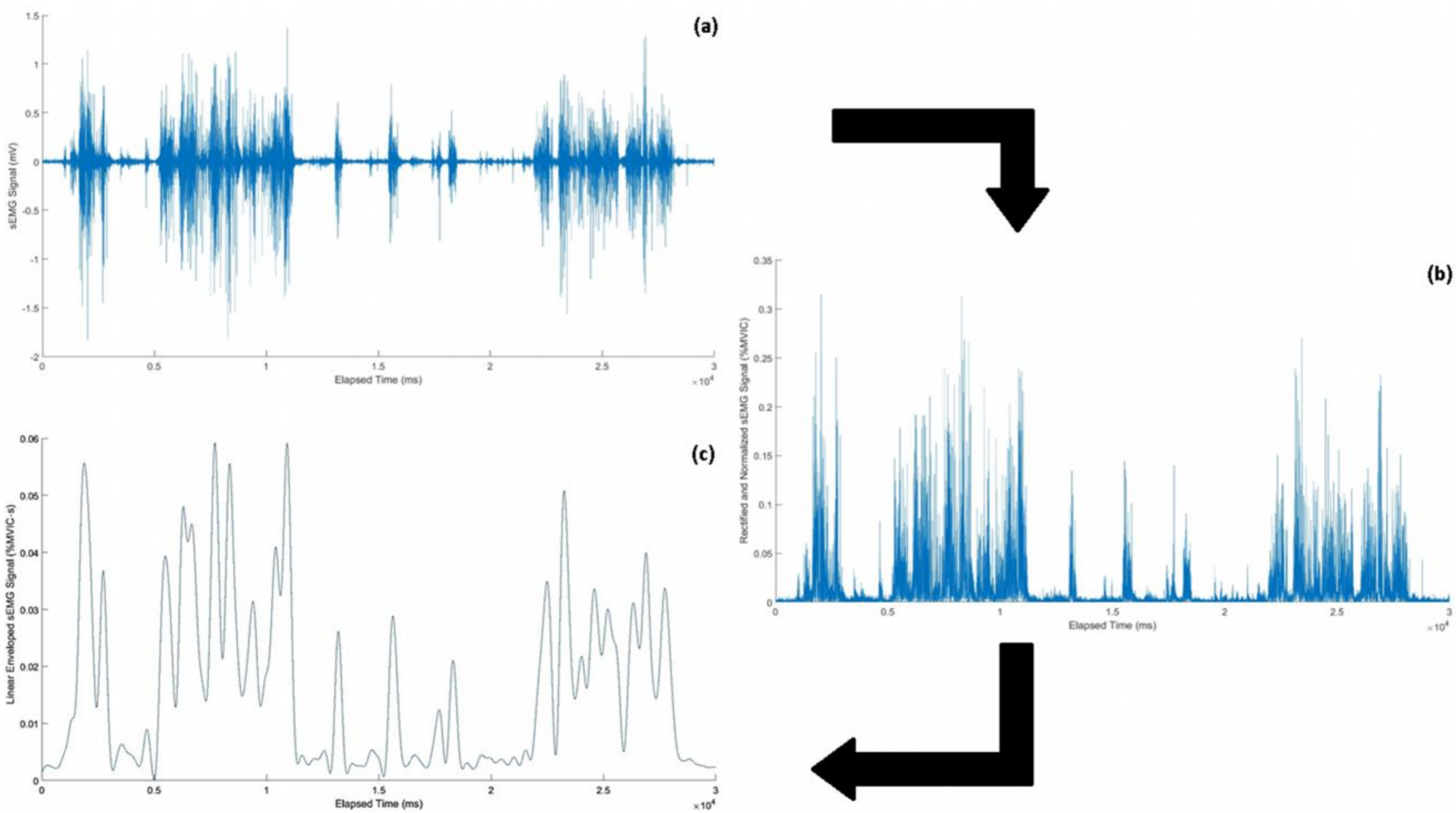

Figure 10. Sample raw (a), normalized (b), and linear enveloped (c) EMG signal of the anterior tibialis, sampled at 1000 Hz.

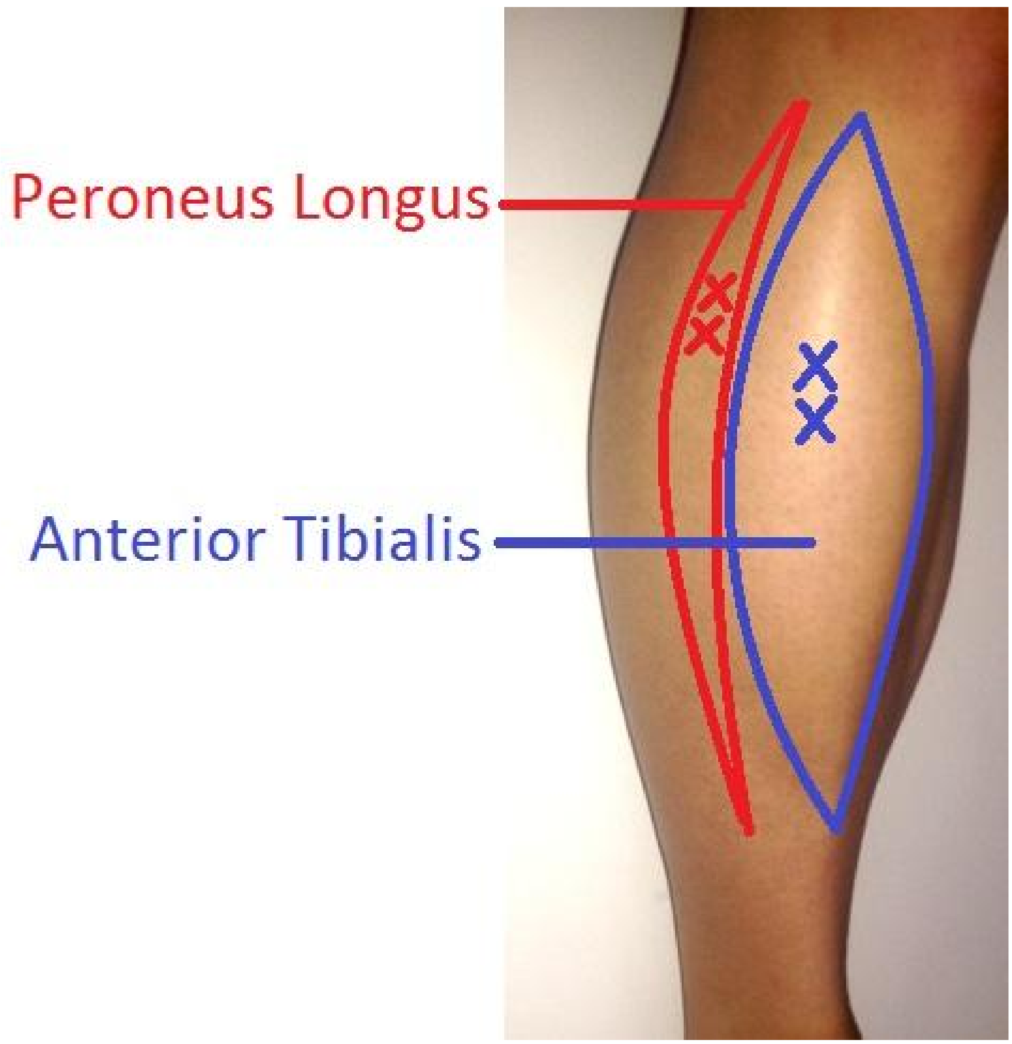

Figure 11: Right lower leg showing muscle belly and bipolar electrode locations (X) for the anterior tibialis (AT) and peroneus longus (PL).

2.1.4 Data Analysis and Statistical Analysis

The raw EMG signal was filtered using a 1st order high pass Butterworth filter with a 30 Hz cutoff (Figure 10a) to eliminate motion artifacts, since motion artifacts are typically low frequency, around the 10-20 Hz range. The signal was then rectified (full wave) and normalized as % of maximal voluntary isometric contraction (Figure 10b). Since the observed electric potential from each individual varies based on factors specific to the individual, such as skin thickness, muscle composition, body hair etc., normalization of the participant's data allows for comparison of data between participants. Lastly, the area under the curve of the EMG signal is needed to identify the muscle activity over time. To calculate the area under the curve, the rectified and normalized EMG signal was linear enveloped using a 4th order low pass Butterworth filter with a 4 Hz cutoff (Figure 10c). The integrated EMG (iEMG), area under the curve of the linear enveloped EMG signal, was then calculated using Trapezoidal Rule.

Since variables and parameters of the experiment contain both fixed and random effects, a Generalized Linear Mixed Model (GLMM) was used. A mixed model provides flexibility in evaluating both fixed and random effects. Fixed effects are the individual effects that may have an impact on the dependent variables and are related to the independent variables. Random effects are the individual effects within a statistical model that may have an impact on the dependent variables but are not related to the independent variables. Since time and the two treatment groups are the independent variables within this experiment and each treatment group is independent of the other, time and treatment were both considered fixed effects. Since each specific participant within a given group and the multiple treatments for that specific participant was not independent of the previous treatment, participants were considered to be a random effect (Jiang, 2007). Statistical analysis software, JMP, was used to perform the GLMM analysis of the interrelation between individual, time, and treatment effects. The restricted maximum likelihood (REML) method was used to estimate variance and covariance parameters. REML component estimates examine and measure what level or amount of the variance observed in the results can be or is attributable to the random effect, in this case, the variance in each specific individual participant. The REML model calculates the ratio of the fixed variance components to the total variance component for all effects and the ratio of the variance components from the random effect, the participants, to the total variance components. The REML is then presented as a percentage of the observed variances estimated to be resultant from random effects, the participants. The least squares mean (LSM) values of the iEMG data were calculated for each effect. The iEMG values were analyzed using linear mixed-effects regression (LMER) in JMP. The coefficient of determination, r^2, estimates the proportion of the variation in the observations that can be attributed to the variables within the model, as opposed to, random error (Jiang, 2007). The r^2 describes the predictive capacity of the model and explains the total variance in the measured responses that can be explained by the predictors within the model (Jiang, 2007). Since the number of parameters within the model vary, an adjusted r^2 was calculated using degrees of freedom. The F value was calculated using the mean square for the effect divided by the mean square for the error (Jiang, 2007). The degrees of freedom denominators were calculated using the Kenward-Roger first order approximation (Arnau et al., 2009). The critical F value was calculated using a significance level of $\alpha = 0.001$.

2.2 Confidentiality, Anonymity, and Risk to Participants

All practical measures were taken to ensure responses remain anonymous and confidential. All data collected was stored on a password protected 500GB Western Digital External Hard Drive. Data collected and stored on the hard drive was aggregated, anonymized and will be retained for 5 years after publication, after which the data will be permanently deleted. While there should be no physical or psychological risk to participants of this study, there was the potential for participants to experience very mild temporary discomfort during any rehabilitation protocol. However, it was expected that the likelihood and magnitude of risk associated with participation was no greater than the risk presented to participants in those aspects of daily life. This project has been reviewed and cleared by the Carleton University Research Ethics Board (Project #101527).

3.0 Results

3.1 Overview of Results and Four-Week Least Squares Mean

Since the AT and PL are the primary inverter and everter muscles in the ankle joint, the iEMG data for these two muscles are compared across treatment groups to extrapolate the level of muscle activity required to maintain ankle joint stability. Therefore, reductions in muscle activity of the AT and PL represents an improvement in the level of muscle activity needed to maintain lateral ankle joint stability. A generalized linear mixed model (GLMM) was used to evaluate five major components of the iEMG data; least squares mean (LSM) of all four weeks, restricted maximum likelihood (REML), two-factor least squares mean, fixed effects tests, and linear mixed effects regression (LMER). Although the primary focus was the evaluation of treatment effects on muscle activity of the sprained leg, data from the non-sprained leg was also analyzed and evaluated as a within group control and point of comparison.

The LSM of all four weeks gives the overall difference between muscle activation between experimental and traditional treatment groups. The four-week averaged treatment effect least squares mean (LSM) of the anterior tibialis and peroneus longus iEMG values for the sprained were substantially different between the experimental and traditional sprain groups (Table 3). Difference in the LSM of the 4 weeks indicate that there is indeed an observable and significant effect associated with the treatment conditions. In the experimental group, the AT was 353.267 with a standard error of 2.105 and 316.521 with a standard error of 3.354 in the PL (Table 3). In the traditional group, the LSM of the AT was 540.491 with a standard error of 2.273 and 498.974 with a standard error of 3.623 in the PL (Table 3). The restricted maximum likelihood (REML) component estimate examined the amount of the observed variance in the results that is attributable to the variances in each specific individual participant within a given treatment group. Most experimental designs studying specific treatment effects aim to reduce variability from random effects, such as, individual differences between participants. Experimental designs that are able to eliminate confounds will typically have lower random effect variances. The REML component estimate for the sprained leg was 0% in both AT and PL, meaning the observed variances over the 4 weeks and between both treatments are the result of the fixed effects (Supplemental Table S1 and Table S2). LSM of the modelled 4 weeks in the non-sprained ankle did not present with as large of a difference between experimental and traditional treatments, albeit still a significant result. The AT in both the experimental and traditional group were 288.448 and 339.101, respectively with standard errors of 4.647 and 5.019. While the PL in both groups were 223.129 and 285.654 with standard errors of 3.767 and 4.069 (Table 3). The REML component estimate for the non-sprained leg was 56.4% in the AT and 32.3% in the PL, suggesting that the observed changes in muscle activity levels within each group and throughout the 4 weeks in the non-sprained leg, can partly or largely be attributed to the variations in individual participants (Table S3 and Table S4).

3.2 Treatment by Week Interactions

To evaluate muscle activity improvement trends over the four-week treatment period, data was transposed from each treatment group against time, in weeks. Organizing and analyzing the muscle activation data by group and week allows for the evaluation of improvements from week to week, observable trends, and potential outliers. The iEMG treatment by week LSM data was examined for both sprained (Table 4) and non-sprained (Table 5) legs.

In the sprained leg, there is an observed trend of increasingly significant differences in iEMG LSM values between the two treatment groups week after week. Suggesting a significant difference in the experimental treatment's rate of improvement over the traditional treatment group. Between week 1 and week 2, the experimental treatment group's AT LSM lowered significantly from 551.952 to 370.819, representing a 32.82% drop in muscle activation levels (Table 4). The traditional treatment group's AT LSM only dropped by 1.66% from 549.629 to 540.509 (Table 4). A similar trend is observed in the participant's sprained leg PL, as muscle activation levels in the experimental stability training group reduce muscle activation by 34.95%, from 481.254 to 313.037 (Table 4). The traditional stability training group lowered PL activation by 0.899%, from 515.351 to 510.718 (Table 4).

The divergent trend in ankle stability muscle activation improvements continues through all 4 weeks. The experimental stability training group's fourth week muscle activation level dropped, below the baseline reference group, to 225.345 for the AT and 199.530 for the PL (Table 4). This represents an overall improvement of 59.17% for the AT and 58.54% for the PL compared to total AT and PL muscle activation from week 1. The traditional stability training group's week

1 to week 4 muscle activation levels also lowered, albeit by a significantly lower magnitude and at a slower rate. AT and PL activation levels reduced by 2.73% and 5.95%, respectively (Table 4).

In the non-sprained leg, a similar divergent trend in the rate of improvement between the two groups was observed, with both groups' initial level of muscle activity relatively similar to each other and the baseline.

Over the course of the four weeks, the traditional treatment group's level of muscle activity remained relatively stagnant with only minor improvements to AT muscle activity, from 346.420 in week 1, 337.381 in week 2, 339.069 in week 3, and 333.534 in week 4. PL muscle activity appeared to worsen from 280.567 in week 1 to 288.756 in week 2, 285.483 in week 3, and 287.811 in week 4.

Two factor LSM plots for interaction with treatment and week factors transposed in the experimental and tradition treatment groups with the reference iEMG values from the baseline group, shows the LSM and standard error of iEMG values for sprained and non-sprained anterior tibialis (AT) and peroneus longus (PL) muscles in the experimental and tradition treatment groups (Figure 12, and Figure 13, and Supplemental Figure S1 and Figure S2). Decreases in muscle activity in the LSM plots signify a reduction in the required level of muscle activity in order to maintain balance and ankle joint stability. The baseline group's level of muscle activity acts as a benchmark for the normal level of muscle activity required in an ankle that has not been injured nor has been through any specialized ankle stability training.

Table 3. Least squares mean (LSM) and standard error of iEMG values for sprained and non-sprained anterior tibialis (AT) and peroneus longus (PL) muscles in the experimental and tradition treatment groups

Leg	Treatment	Anterior Tibialis Least Squares Mean	AT Std Error	Peroneus Longus Least Squares Mean	PL Std Error
Sprain	**Experimental**	353.267	2.105	316.521	3.354
	Traditional	540.491	2.273	498.974	3.623
Non-Sprain	**Experimental**	288.448	4.647	223.129	3.767
	Traditional	339.101	5.019	285.654	4.069

Table 4. Two factor (treatment by week) least squares mean and standard error of iEMG values for sprained anterior tibialis (AT) and peroneus longus (PL) muscles in the experimental and tradition treatment groups

Treatment	Week	Anterior Tibialis Least Squares Mean	AT Std Error	Peroneus Longus Least Squares Mean	PL Std Error
Experimental	1	551.952	4.598	481.254	6.978
	2	370.819		313.037	
	3	264.951		272.264	
	4	225.345		199.530	
Traditional	1	549.629	4.967	515.351	7.537
	2	540.509		510.718	
	3	537.200		485.159	
	4	534.628		484.667	
Baseline	1 - 4	337.359		283.822	

Table 5. Two factor (treatment by week) least squares mean and standard error of iEMG values for non-sprained anterior tibialis (AT) and peroneus longus (PL) muscles in the experimental and tradition treatment groups

Treatment	Week	Anterior Tibialis Least Squares Mean	AT Std Error	Peroneus Longus Least Squares Mean	PL Std Error
Experimental	1	341.539	5.666	280.277	5.369
	2	307.907		233.551	
	3	275.622		199.241	
	4	228.722		179.448	
Traditional	1	346.420	6.119	280.567	5.799
	2	337.381		288.756	
	3	339.069		285.483	
	4	333.534		287.811	
Baseline	1 - 4	337.359		283.822	

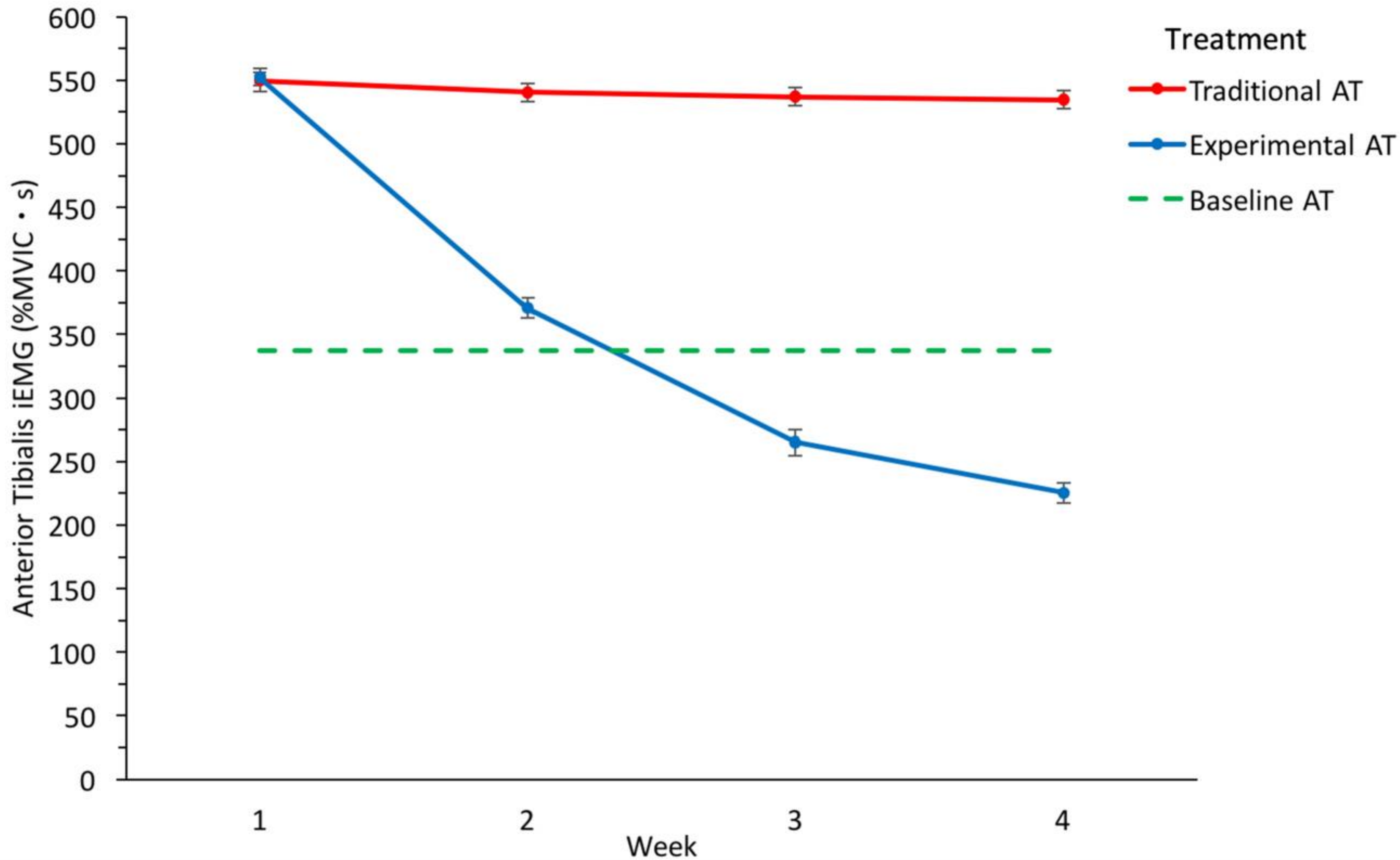

Figure 12. Sprained anterior tibialis (AT) iEMG least squares means plot for interaction with treatment and week factors transposed in the experimental and tradition treatment groups with reference AT iEMG value, 337.359, from baseline group

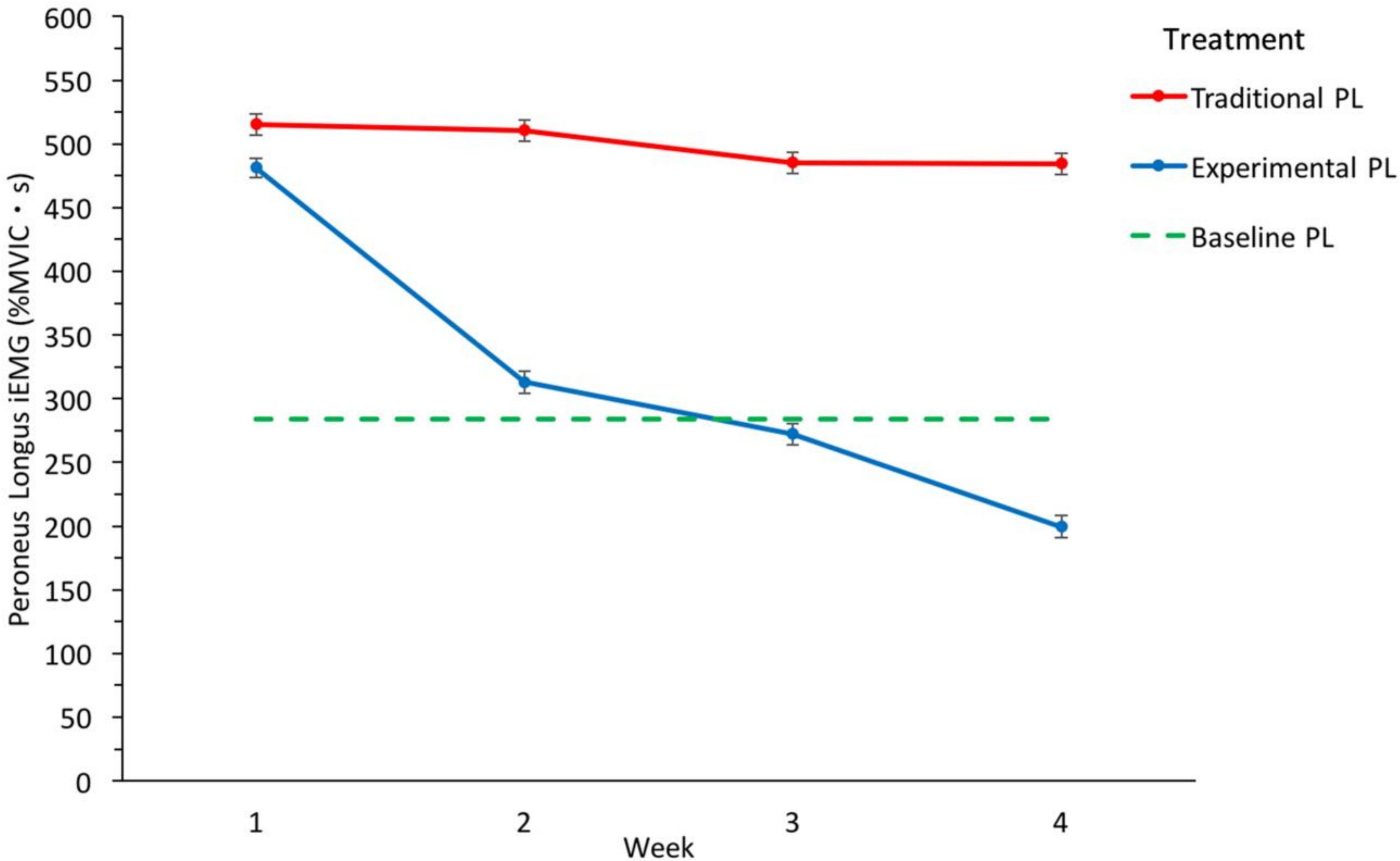

Figure 13. Sprained peroneus longus (PL) iEMG least squares means plot for interaction with treatment and week factors transposed in the experimental and tradition treatment groups with reference PL iEMG value, 283.822, from the baseline group

The LSM plots for the AT muscle activity levels show noticeable differences between the experimental treatment improvements compared to the traditional treatment. The LSM plots for AT and PL of the sprained leg initially show iEMG muscle activation levels to be fairly consistent and similar, approximately 550 for the AT and around 500 for the PL (Figure 12 and Figure 13). For context and as a point of reference, the baseline group, representing individuals who have not suffered or have any history of an ankle sprain, have average AT and PL muscle activation levels of 337.359 and 283.822, respectively (Table 4). The experimental treatment group's level of muscle activity decreases below the baseline AT muscle activation level between week 2 and week 3 (Figure 12). Improvements continue, albeit at a diminished rate after week 3. A similar trend is observed in the experimental group's PL muscle activity, however, the trend does not demonstrate an obvious diminishing rate of return trend as seen in the AT (Figure 13). The two factor LSM plots of AT and PL muscle activity shows a minor trend of improvement in the traditional group (Figure 12 and Figure 13).

3.3 Fixed Effects Tests

Analysis of variance (ANOVA) was used to evaluate the means and variance of each fixed effect parameter, between weeks, treatment groups, and treatment groups by weeks. F-tests were used to statistically evaluate the equality of each of these fixed effect parameter means. The F-test examines the ratio of variances between the effect parameter and the mean. A greater F-ratio value represents a greater dispersion between groups. The advantage to using the F-statistic is its use of mean squares, an estimate of population variance which accounts for the degrees of freedom (DF) used to calculate that estimate. The critical F value, $F_{Critical}$, was calculated using a significance level of $\alpha = 0.001$. $F_{Critical}$ for Treatment (DF is 1 and DF Denominator is 11) = 19.68678564 and $F_{Critical}$ for Week, and Week X Treatment (DF is 3 and DF Denominator is 33) = 6.88276657.

The null hypothesis, H_0, was rejected based on the calculated F-ratio values in the sprained ankle. The results in the non-sprained ankle were also sufficiently significant to reject the null hypothesis as well. In the sprained ankle, treatment effects were significant for both anterior tibialis and peroneus longus, $F(1, 11) = 3652.66$ and $F(1, 11) = 1365.56$, $p < 0.0001$, respectively (Table 6). Additionally, even after factoring for time, fixed effect of 'Weeks', treatment effects were still found to be significant in both the AT and PL, $F(1, 11) = 402.87$ and $F(1, 11) = 103.91$, $p < 0.0001$, respectively (Table 6). Similarly, the non-sprained ankle treatment effects were significant for both AT and PL, $F(1, 11) = 54.84$ and $F(1, 11) = 127.17$, $p < 0.0001$, respectively (Table 6). When factoring for time, as the fixed effect of 'weeks', treatment effects were still significant in both the AT and PL, $F(1, 11) = 61.94$ and $F(1, 11) = 51.95$, $p < 0.0001$, respectively (Table 6).

The F-test demonstrated that the differences observed between treatment groups measurements of muscle activity was statistically significant. Thereby, the difference observed was due to the effect of the treatment. The two factor F-test of treatment by week validated the the significance of the treatment effects. Furthermore, the non-sprained leg that underwent the experimental treatment also presented statistically significant differences between treatment groups and improvements in muscle activity from the experimental treatment.

Table 6. Fixed effects test for Week, Treatment, and Treatment by Week parameters of the sprained and non-sprained legs of participants

Leg Condition	Muscle		df	F-Ratio	p-value	r^2 Adjusted
Sprained	**AT**	Week	3	481.75	<0.0001	0.99067
		Treatment	1	3652.66	<0.0001	
		Treatment x Week	3	402.87	<0.0001	
	PL	Week	3	164.84	<0.0001	0.97558
		Treatment	1	1365.56	<0.0001	
		Treatment x Week	3	103.91	<0.0001	
Non-Sprained	**AT**	Week	3	92.17	<0.0001	0.95706
		Treatment	1	54.84	<0.0001	
		Treatment x Week	3	61.94	<0.0001	
	PL	Week	3	40.96	<0.0001	0.94211
		Treatment	1	127.17	<0.0001	
		Treatment x Week	3	51.95	<0.0001	

* The critical F value, $F_{Critical}$, was calculated using a significance level of $\alpha = 0.001$.
$F_{Critical}$ for Treatment (DF is 1 and DF Denominator is 11) = 19.68678564
$F_{Critical}$ for Week, and Week X Treatment (DF is 3 and DF Denominator is 33) =6.88276657

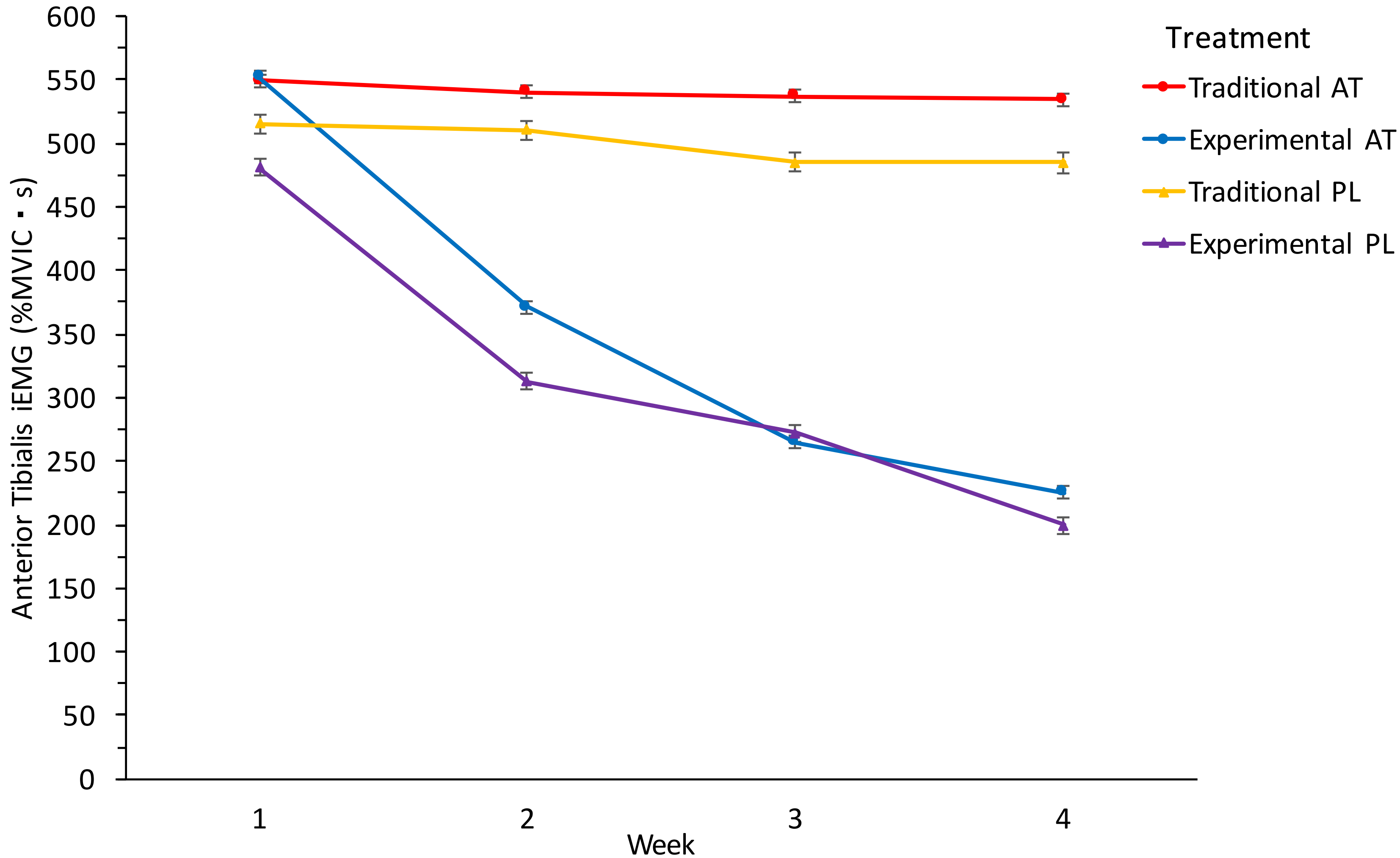

Figure 14. Sprained anterior tibialis (AT) and peroneus longus (PL) iEMG least squares means plot for interaction with treatment and week factors transposed in the experimental and tradition treatment groups

3.4 Linear Mixed Effect Regression

The iEMG values of the anterior tibialis and peroneus longus for the sprained and non-sprained ankles of both experimental and traditional treatment groups were analyzed using linear mixed effects regression (LMER). A LMER provides an estimation of the relationship between the independent variables, both random and fixed effects, and the dependent variable, muscle activity. The resultant regression analysis provides a linear relationship that factors both random and fixed effects to estimate and describe the predicted muscle activity value. Since the linear regression is a descriptive statistic of the relationship between treatment by week and the predicted or modelled muscle activity values, the slope can be interpreted as the rate of improvement. An adjusted correlation coefficient, adjusted r^2, was used to evaluate and compare the explanatory power of the modelled LMER slope. Adjusted r^2 factors and accommodates for the number of incorporated predictors, only increasing if a given predictor improves the model greater than what could be expected by chance and decreasing if a predictor improves the model less than chance. The adjusted r^2 for the sprained AT and PL were 0.99067 and 0.97558, respectively (Table 6). The non-sprained adjusted r^2 AT and PL were 0.95706 and 0.94211, respectively (Table 6). The adjusted r^2 coefficients indicate that LMER model has a strong explanatory power of the relationship between treatment by week and expected muscle activity.

The LMER plots show iEMG values for their respective muscles with treatment as an overlay variable (Figure 15 and Figure 16). iEMG values, as a %MVIC • s, are plotted against time, in weeks, and show a scatter plot of the AT and PL iEMG values, respectively, from the sprained leg of both treatment groups with the LMER fit line. Supplemental Figure S3 and Figure S4 show the iEMG values scatter plot and LMER of the AT and PL, respectively, from the non-sprained leg of both treatment groups. The experimental group's sprained leg LMER slope for AT was -108.60 and -88.59 for the PL. The traditional group's sprained leg slope was -4.83 for the AT and -11.76. for the PL. AT LMER slopes for the non-sprained leg were -37.07 for the experimental treatment and -3.69 for the traditional treatment. Experimental PL LMER slopes for the non-sprained leg was -33.68 and the traditional slope was 1.85. The significantly greater magnitude of the negative slope value of the experimental group shows a greater modelled improvement in muscle activity over time.

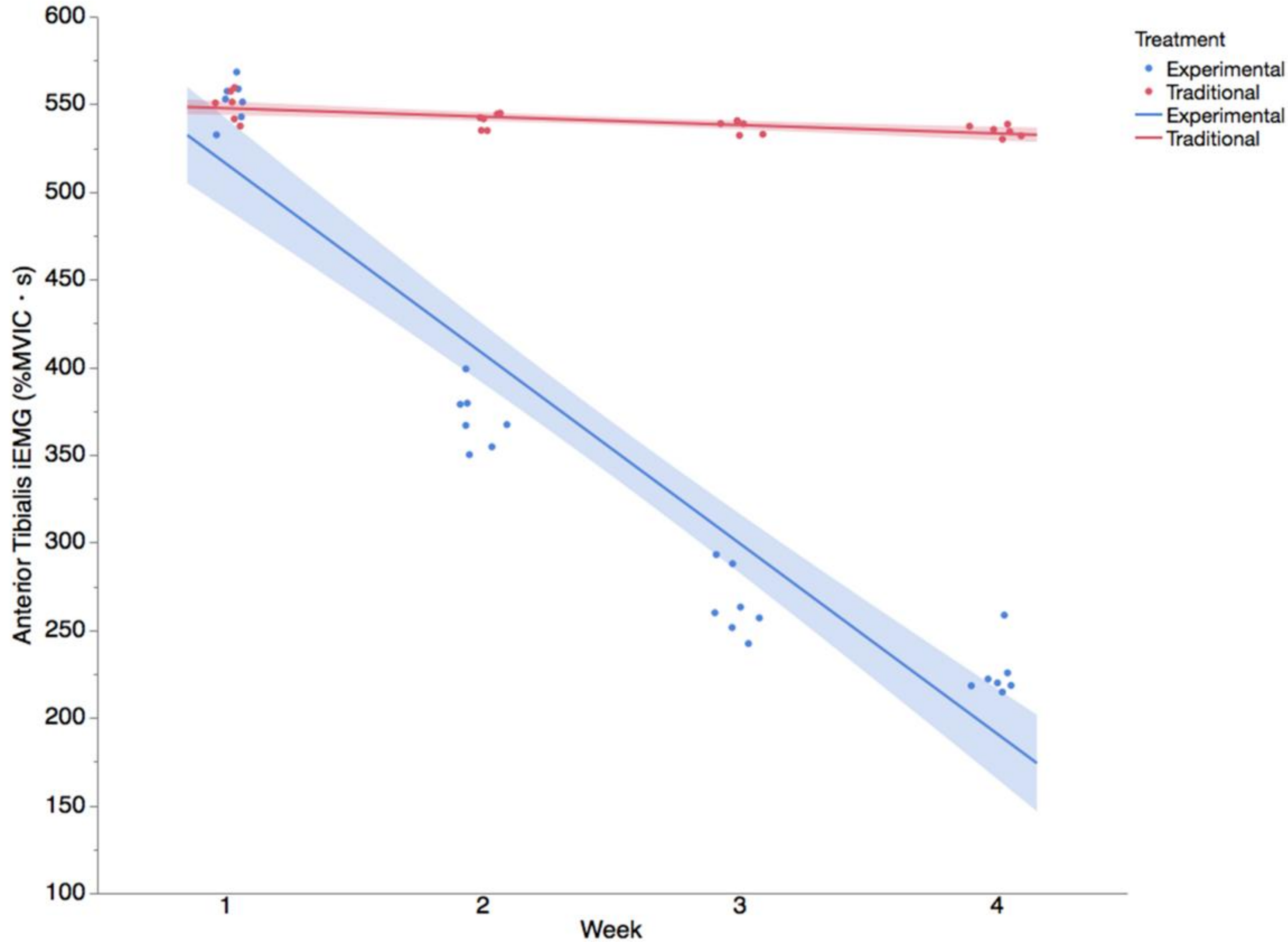

Figure 15. Linear mixed effects regression (LMER) of the anterior tibialis (AT) on the sprained ankle of experimental and traditional sprain treatment groups.

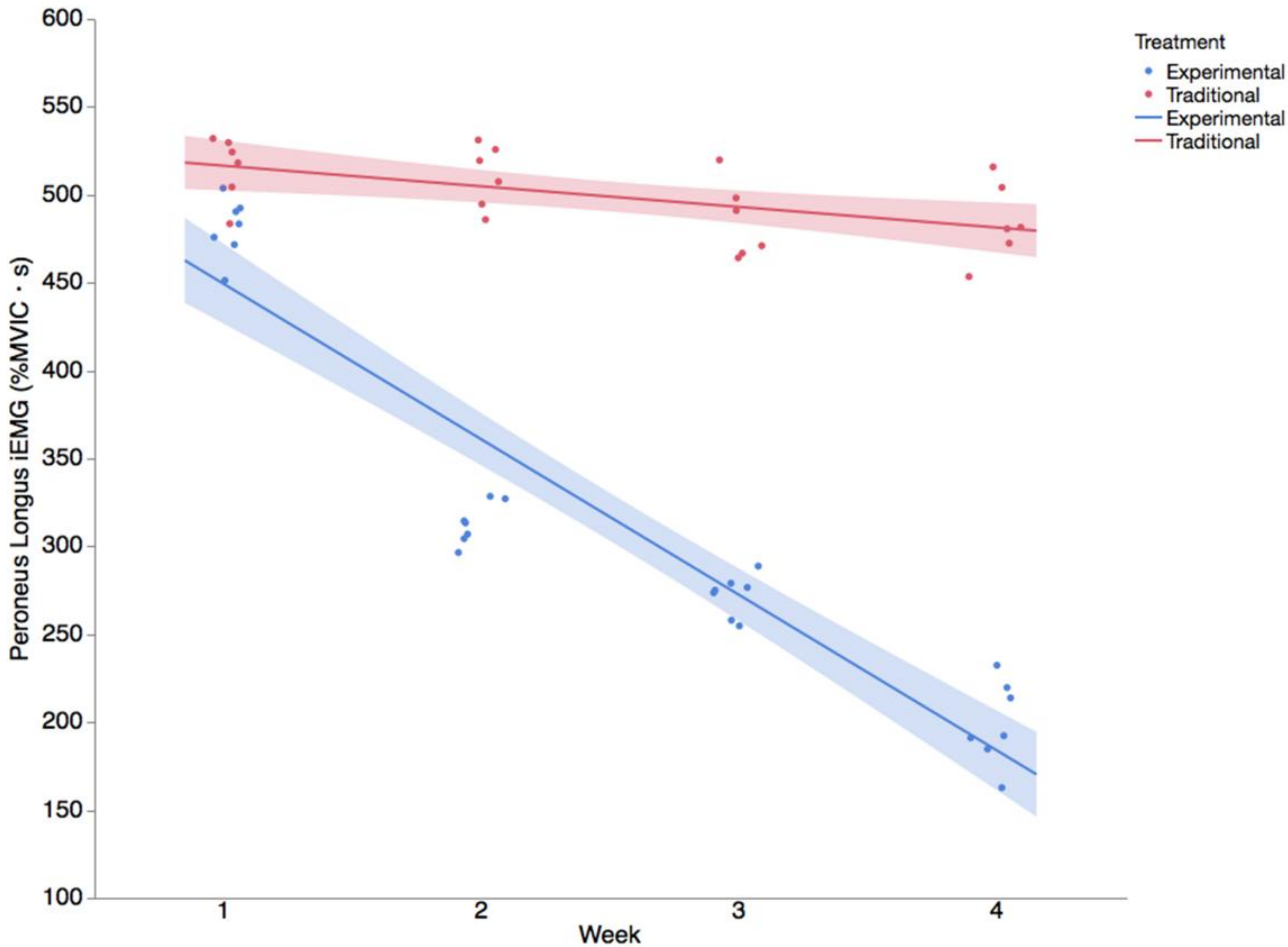

Figure 16. Linear mixed effects regression (LMER) of the peroneus longus (PL) on the sprained ankle of experimental and traditional sprain treatment groups.

4.0 Discussion

4.1 Implications of Treatment Outcomes on Sprained Ankle Stability

The data supported the prediction that pairing a visuospatial distractor task with stability training provides a measurable and statistically significant improvement in muscle activation as indicated by the reduction in iEMG values (Table 4, Figure 12 and Figure 13). Participants in the experimental sprain treatment group revealed, over the course of the 4-week remodeling phase treatment, significant improvements in muscle activation compared to the traditional sprain treatment group (Table 6), suggesting significant improvements in ankle stability and balance.

Evaluating the LSM plot of AT and PL muscle activation of the sprained leg (Figure 12 and Figure 13) visually illustrates the significant separation in rates of improvement between the experimental and traditional stability training protocols. The relationship between the experimental protocol and muscle activation appears to yield a drastic improvement within the first 2 weeks and by the third week, LSM iEMG values in the experimental group are lower than the baseline group, suggesting that the ankle stability of the experimental group is better than individuals who have not suffered a sprain but also perform no explicit stability training (Figure 12 and 13). The LMER plots and slope values for both treatment conditions of the sprained leg further supports the observed divergent rates of improvements in ankle stability and balance between experimental and traditional treatments (Figure 15 and Figure 16). Although the modelled LMER slope gives a predicted rate of improvement in the experimental group's required level of AT and PL muscle activation in order to maintain balance and joint stability, the modelled relationship does not appear to be completely linear (Figure 15 and Figure 16). There appears to be a diminishing rate of return in the AT muscle activation improvements from the experimental stability training (Figure 12). However, the same diminishing rate of return trend is not discernable in the improvements to muscle activation of the PL (Figure 13). This observed pattern of diminished rate of return, specifically a decrease in marginal efficacy past a given point, is expected and observable in many other fields of medicine and rehabilitative therapy (Mold et al., 2010). The efficacy of the experimental training protocol and the observed diminishing returns phenomena can intuitively be viewed as the individual's base level of required muscle activation to maintain ankle stability and balance reaching an improved equilibrium level (Figure 14). Despite the observed potential reduction in marginal efficacy after the third week of treatment in the AT, the greater efficacy of rehabilitative ankle stability training paired with a visuospatial distractor task in reducing the required level of muscle activity to maintain balance and ankle stability has been supported by the results and treatment outcomes.

Based on the results and observed trend of greater magnitude and higher rate of improvements in the experimental treatment suggests that a factor specific to the visuospatial distractor task elicits a process to correct a deficit in joint stability. Joint stability is usually maintained through a passive process where sensory feedback is instinctively processed and appropriate motor functions are automatically enacted to maintain joint homeostasis without cognizant effort (Konradsen, 2002, Manal et at., 2011 and Riemann & Lephart, 2002). However, an individual can intervene and enact active motor control to override or enhance joint stability (Riemann & Lephart, 2002). The prevailing theory on chronic joint instability, as a result of an ankle sprain, is the failure of the passive neural control mechanisms that maintain balance and joint stability (Riemann & Lephart, 2002). This passive neural control mechanism that aids in joint stability and balance through the maintenance of an innate awareness of the body and its limb positions is called proprioception.

4.2 Proprioceptive System

Proprioception is an individual's, largely unconscious, awareness of their joint, limb, and body position relative to itself and the surrounding space. This sense is formed by a combination of vestibular feedback, and proprioceptive stretch receptors that are found within the skin, muscles, tendons, and ligaments (Proske & Gandevia, 2012 and Valbo et al., 1979). The dorsal spinocerebellar tract carries the various signals from the muscle spindles and Golgi tendon organs to the cerebellum, which amalgamates this sensory information into a conceptualized image of the joint and limb's position relative to the rest of the body and surrounding space (Jones, 1994 and Proske & Gandevia, 2012). Proprioception is one of the primary contributing senses in mediating basal cerebellar muscle tone and balance. It is important to recognize the differentiation of proprioception from kinesthetics. Proprioception strictly involves the awareness of movement, applied force, and the recognition of body positioning relative to itself and the surrounding space. Kinesthetics relates to motion with the integration of visual cues

(Proske & Gandevia, 2009 and Proske & Gandevia, 2012). To be effective, proprioception requires coherence and congruity in the sensory information received from all sources. Incongruent or disrupted sensory information often leads to impairment in balance and coordination (Proske & Gandevia, 2012 and Raymond et al., 2012). For example, fluid within the inner ear will impede the vestibular senses, which then leads to incongruity in the sensory signals received from the receptors in the skin, muscles, tendons and ligaments, and the vestibular signals. This incongruity often manifests in impediment to the individual's sense of balance, which is caused by the cerebellum's inability to properly coordinate basal muscle tone. Similar, albeit subtler, incongruity is hypothesized to occur when a sprain damages the stretch receptors located in the muscles, tendons, and ligaments of a joint. When these receptors are damaged, their afferent sensory signal is no longer congruent with the signals from the surrounding, undamaged, receptors. This incongruity leads to deficits in the cerebellum's ability to properly detect and control basal muscle tone.

It has been demonstrated that after an acute ankle sprain, the likelihood of recurrence is significantly higher than for those who have no prior history of ankle injury (Hubbard & Cordova, 2009 and Sefton et al., 2009). There are currently two prevailing theories behind the cause of ankle sprain recurrence: proprioceptive deficit and connective tissue laxity. Proprioception is the nervous system's ability to recognize the positioning of the body and limbs at any given time. Proprioceptive deficits occur when there is a conflict between the nervous system's perception of the ankle's position and the true position of the ankle. Connective tissue laxity relates to the loss of appropriate tension in the tendons and ligaments associated with the sprain. Most clinicians and researchers would agree that the factors affecting ankle stability are not dichotomous to poor proprioception or laxity in connective tissue, rather factors that would determine ankle instability and by extension, ankle sprain injury and recurrence rates lies on a spectrum between both of these factors (Jerosch & Prymka, 1996 and Raymond et al., 2012). Indeed, whilst traditional rehabilitative protocol is predicated on returning functionality of the connective tissue and musculature in the ankle to a pre-sprain state, previous studies have also demonstrated that dysfunction in sensorimotor function and proprioception are accurate predictors of the likelihood of recurrence (Raymond et al., 2012 and Sefton et al., 2009).

4.3 Implications of Visuospatial Distractor Task on Sensorimotor Adaptation

Proprioceptive and kinesthetic deficiencies caused by peripheral nervous system damage, sustained during forceful inversion, to the nerves that innervate the lateral ankle ligaments are the main supposition and inference of the underlying mechanism associated with the high re-injury rates of ankle sprains. The theorized unique and distinctive contribution of a distractor task that visuospatial stimuli primarily relies on how specific tasks are delegated to different processing pathways, based on attentional resource demands (Andersson et al., 1998, Chong et al., 2010 and Laufer et al., 2007). When there is no distractor task, ankle joint stability and balance activities did not rely on the sensorimotor adaptation motor pathway to regulate balance, rather balance was managed by utilizing visuospatial working memory resources. This directed and active management of balance elicited intentional motor responses originating from the primary motor cortex in the cerebrum. (Andersson et al., 1998, Chong et al., 2010 and Laufer et al., 2007). Conversely, when a distractor task places a significant strain on visuospatial attentional resources, the task of managing ankle joint stability and balance was directed to the largely automatic sensorimotor adaptation motor pathway, while visuospatial working memory resources were occupied with completing the distractor task (Andersson et al., 1998, Chong et al., 2010 and Laufer et al., 2007). Sensorimotor adaptation and basal postural motor control are regulated by the cerebellum. Theoretically, the underlying mechanism and why a distractor task yielded the observed results is ultimately that rehabilitative ankle stability training that allows an individual the ability to utilize their full capacity of attentional resources to stabilize the ankle joint will elicit the primary motor cortex to override the cerebellum's normal task of regulating sensorimotor adaptation of the ankle joint. Thereby, improving the individual's ability to stabilize their ankle joint when attentional resources are used but not allowing the cerebellum and the sensorimotor adaptation pathway to recognize any deficits in proprioception or joint stability, as evidenced by the muscle activity levels and the rates of improvement between groups. Since ankle sprain re-injuries overwhelmingly occur when the individual is not utilizing attentional resources on maintaining ankle joint stability, it can be inferred that stability training to improve attentive ankle joint stability would be less effective than training that explicitly aims to improve sensorimotor adaptation and cerebellar motor control. The stability training paired with a visuospatial distractor task in principle could elicit the cerebellum to recognize and reconcile the proprioceptive and kinesthetic deficiency through proprioceptive engagement during stability training. This would explain the variance in treatment outcomes between traditional and experimental groups and the positive treatment impacts associated with the stability training protocol paired with a visuospatial distractor task in the experimental group.

4.4 Improvements to Non-Sprained Leg Ankle Joint Stability

Although no predictions were made relating to the stability and muscle activation levels of the non-sprained ankle, each participant's non-sprained leg also underwent the same respective stability training protocol as their sprained leg. Since both legs were subjected to the same treatment protocols but varied in the sprain condition, each participant within each treatment protocol had an intrinsic control to compare the collected data against. Evaluating the data from each treatment of the non-sprained leg revealed that improvements to stability and muscle activation were not limited to the sprained ankle. The non-sprained ankle of participants also demonstrated significant ankle stability and muscle activation improvements from the experimental stability training protocol compared to the traditional stability training protocol (Table 6, Supplemental Table S5, Figure S1 and Figure S2). Although it is important to note that the REML variance component of the non-sprained leg was substantially higher, which implies that the variance between individual participants had a larger impact on the observed results (Supplemental Table S3 and Supplemental Table S4). Despite this greater REML variance component, the modelled LMER still showed a significantly greater rate of improvement in the experimental treatment group compared to the traditional treatment group (Table 6), with the the adjusted r^2 supporting the explanatory power and validity of the LMER. Since the efficacy and effects of the distractor-paired stability training on a non-sprained ankle was not the primary focus of this study, further study into the phenomena or deeper analysis of the data could potentially yield a richer understanding of the potential benefits and improvements to ankle joint stability of individuals who have not suffered ankle sprain injuries.

5.0 Conclusion

Current clinical rehabilitative therapy emphasizes a proprioceptive rehabilitation protocol that utilizes cognizant and intentional stabilization of the ankle. However, conditions associated with most recurrent ankle sprains are in circumstances where the individual is not utilizing cognitive or attentional resources to stabilize the ankle. The experimental, distractor paired stability training, protocol has demonstrated significant improvements in the level of muscle activity required to stabilize the ankle and maintain balance. The results suggest that the benefits extend beyond simply returning the ankle to a pre-injury state, rather required muscle activity improved to a new equilibrium point of muscle activity lower than that of studied individuals who have no prior history of ankle sprains. This improvement to the new equilibrium level applies to the anterior tibialis and peroneus longus of both sprained and non-sprained legs.

Further research is needed to determine if the supposed underlying mechanism is indeed proprioceptive and kinesthetic deficiencies and if the distractor paired stability training protocol addresses those issues or if an alternative explanation exists for this phenomena. The addition of other measurements concurrently, such as kinematics analysis or force production and distribution using a force plates could assist in enriching the study. Additionally, longitudinal studies into the whether the observed outcomes are persistent over the long term and the recurrence rates over a longer time period could provide further insight into the functional outcomes of visuospatial distractor task paired stability training in rehabilitating ankle sprains.

6.0 References

Akbari, M., Karimi, H., Farahini, H., & Faghihzadeh, S. (2006). Balance problems after unilateral lateral ankle sprains. *The Journal of Rehabilitation Research and Development*, *43*(7), 819.

Andersson, G., Yardley, L., & Luxon, L. (1998). A dual-task study of interference between mental activity and control of balance. *The American Journal of Otology*, *19*(5), 632–637.

Arnau, J., Bono, R., & Vallejo, G. (2009). Analyzing small samples of repeated measures data with the mixed-model adjusted F test. *Communications in Statistics: Simulation and Computation*, *38*(5), 1083–1103.

Baddeley, A. (1992). Working memory and conscious awareness. In Theories of memory (pp. 11-20). Lawrence Erlbaum Associates.

Baddeley, A. D. (1983). Working memory. *Philosophical Transactions of the Royal Society of London*.

Burks, R. T., & Morgan, J. (1994). Anatomy of the lateral ankle ligaments. *The American journal of sports medicine*, *22*(1), 72-77.

Brown, C., Padua, D., Marshall, S. W., & Guskiewicz, K. (2008). Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clinical Biomechanics*, *23*(6), 822–831.

Chong, R. K. Y., Mills, B., Dailey, L., Lane, E., Smith, S., & Lee, K. H. (2010). Specific interference between a cognitive task and sensory organization for stance balance control in healthy young adults: Visuospatial effects. *Neuropsychologia*, *48*(9), 2709–2718.

Conway, A. R., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. Psychonomic bulletin & review, 8(2), 331-335.

Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. Journal of cognitive neuroscience, 14(3), 508-523.

de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. Science, 291(5509), 1803-1806.

De Jong, A., Kilbreath, S. L., Refshauge, K. M., & Adams, R. (2005). Performance in different proprioceptive tests does not correlate in ankles with recurrent sprain. *Archives of Physical Medicine and Rehabilitation*, *86*(11), 2101–2105.

De Noronha, M., Refshauge, K. M., Herbert, R. D., Kilbreath, S. L., & Hertel, J. (2006). Do voluntary strength, proprioception, range of motion, or postural sway predict occurrence of lateral ankle sprain? *British Journal of Sports Medicine*, *40*(10), 824–828.

Engle, R. W. (2002). Working memory capacity as executive attention. Current directions in psychological science, 11(1), 19-23.

Fautrelle, L., Kubicki, A., Babault, N., & Paizis, C. (2017). Immediate effects of shoes inducing ankle-destabilization around Henke's axis during challenging walking gaits: Gait kinematics and peroneal muscles activities. *Gait and Posture*, *54*, 259–264.

Garrick, J. G. (1977). The frequency of injury, mechanism of injury, and epidemiology of ankle sprains. *The American Journal of Sports Medicine*, *5*(6), 241–242.

Geffen, G. M., Wright, M. J., Green, H. J., Gillespie, N. a, Smyth, D. C., Evans, D. M., & Geffen, L. B. (1997). Effects of memory load and distraction on performance and event-related slow potentials in a visuospatial working memory task. *Journal of Cognitive Neuroscience*, *9*(6), 743–57.

Guillodo, Y., Le Goff, A., & Saraux, A. (2011). Adherence and effectiveness of rehabilitation in acute ankle sprain. *Annals of Physical and Rehabilitation Medicine*, *54*(4), 225–235.

Grillner, S. (1985). Neurobiological bases of rhythmic motor acts in vertebrates. *Science*, *228*, 143-150.

Houghton, K. M. (2008). Review for the generalist: evaluation of pediatric foot and ankle pain. *Pediatr Rheumatol Online J*, *6*, 6.

Hubbard, T. J., & Cordova, M. (2009). Mechanical Instability After an Acute Lateral Ankle Sprain. *Archives of Physical Medicine and Rehabilitation*, *90*(7), 1142–1146.

Hupperets, M. D., Verhagen, E. A., & van Mechelen, W. (2009). Effect of unsupervised home based proprioceptive training on recurrences of ankle sprain: randomised controlled trial. *Bmj*, *339*(jul09 1), b2684–b2684.

Hupperets, M. D., Verhagen, E. A., & van Mechelen, W. (2008). The 2BFit study: is an unsupervised proprioceptive balance board training program, given in addition to usual care, effective in preventing ankle sprain recurrences? Design of a Randomized Controlled Trial. *BMC Musculoskeletal Disorders*, *9*(1), 71.

Ivins, D. (2006). Acute ankle sprain: An update. *American Family Physician*, *74*(10).

Johnson, M. B., & Johnson, C. L. (1993). Electromyographic response of peroneal muscles in surgical and nonsurgical injured ankles during sudden inversion. *The Journal of Orthopaedic and Sports Physical Therapy*, *18*(3), 497–501.

Jerosch, J., & Prymka, M. (1996). Proprioception and joint stability. *Knee Surgery, Sports Traumatology, and Arthroscopy*, *4*(3), 171–179.

Jiang, J. (2007). *Linear and Generalized Linear Mixed Models and Their Applications*. New York: Springer Science & Business Media.

Jones, L. a. (1994). Peripheral mechanisms of touch and proprioception. *Canadian Journal of Physiology and Pharmacology*, *72*(5), 484–487.

Kannus, P., & Renström, P. (1991). Treatment for acute tears of the lateral ligaments of the ankle. Operation, cast, or early controlled mobilization. *The Journal of Bone and Joint Surgery. American Volume*, *73*(2), 305–12.

Karlsson, J., Peterson, L., Andreasson, G., & Högfors, C. (1992). The unstable ankle: a combined EMG and biomechanical modeling study. *International Journal of Sport Biomechanics*, *8*(2), 129-144.

Kelikian, A. S., & Sarrafian, S. K. (2011). *Sarrafian's anatomy of the foot and ankle: descriptive, topographic, functional*. Lippincott Williams & Wilkins.

Kiers, H., Brumagne, S., Van Dieën, J., Van Der Wees, P., & Vanhees, L. (2012). Ankle proprioception is not targeted by exercises on an unstable surface. *European Journal of Applied Physiology*, *112*(4), 1577–1585.

Klyne, D. M., Keays, S. L., Bullock-Saxton, J. E., & Newcombe, P. A. (2012). The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: a study of alterations in EMG measures and their relationship to knee joint stability. *Journal of Electromyography and Kinesiology*, *22*(3), 446-455.

Kong, A., Cassumbhoy, R., & Subramaniam, R. M. (2007). Magnetic resonance imaging of ankle tendons and ligaments: Part I–Anatomy.*Australasian radiology*, *51*(4), 315-323.

Konradsen, L. (2002). Sensori-motor control of the uninjured and injured human ankle. *Journal of Electromyography and Kinesiology*, *12*(3), 199–203.

Korhonen, R., & Saarakkala, S. (2011). Biomechanics and Modeling of Skeletal Soft Tissues, Theoretical Biomechanics, Dr Vaclav Klika (Ed.), ISBN: 978-953-307-851-9, InTech, DOI: 10.5772/19975.

Kumai, T., Takakura, Y., Rufai, A., Milz, S., & Benjamin, M. (2002). The functional anatomy of the human anterior talofibular ligament in relation to ankle sprains. *Journal of Anatomy*, *200*(5), 457–465.

Laferriere, P., Lemaire, E. D., & Chan, A. D. C. (2011). Surface Electromyographic Signals Using Dry Electrodes. *IEEE Transactions on Instrumentation and Measurement*, *60*(10), 3259–3268.

Laufer, Y., Rotem-Lehrer, N., Ronen, Z., Khayutin, G., & Rozenberg, I. (2007). Effect of Attention Focus on Acquisition and Retention of Postural Control Following Ankle Sprain. *Archives of Physical Medicine and Rehabilitation*, *88*(1), 105–108.

Lavie, N. (2005). Distracted and confused: Selective attention under load. Trends in cognitive sciences, 9(2), 75-82.

Leanderson, J., Bergqvist, M., Rolf, C., Westblad, P., Wigelius-Roovers, S., & Wredmark, T. (1999). Early influence of an ankle sprain on objective measures of ankle joint function. *The Knee*, *7*, 51–58.

Lee, A. J. Y., & Lin, W. H. (2008). Twelve-week biomechanical ankle platform system training on postural stability and ankle proprioception in subjects with unilateral functional ankle instability. *Clinical Biomechanics*, *23*(8), 1065–1072.

Logie, R. H. (2014). Visuo-spatial working memory. Psychology Press.

Lynch, S.A. (2002). Assessment of the Injured Ankle in the Athlete. *J. Athl. Train.* **37(4),** 406-412.

Manal, K., Gravare-Silbernagel, K., & Buchanan, T. S. (2012). A real-time EMG-driven musculoskeletal model of the ankle. *Multibody System Dynamics*, *28*(1–2), 169–180.

Mansour, R., Jibri, Z., Kamath, S., Mukherjee, K., & Ostlere, S. (2011). Persistent ankle pain following a sprain: A review of imaging. *Emergency Radiology*, *18*(3), 211–225.

Mattacola, C. G., & Dwyer, M. K. (2002). Rehabilitation of the ankle after acute sprain or chronic instability. *Journal of Athletic Training*, *37*(4), 413–429.

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2003). The role of working memory in motor learning and performance. *Consciousness and Cognition*, *12*(3), 376–402.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. Journal of experimental psychology: General, 130(4), 621.

McMinn, R. H. M., Hutchings, R. T., & Logan, B. M. (1996). Foot and ankle anatomy.

Mold, J. W., Hamm, R. M., & McCarthy, L. H. (2010). The Law of Diminishing Returns in Clinical Medicine: How Much Risk Reduction is Enough? *The Journal of the American Board of Family Medicine*, *23*(3), 371–375.

Ozer, D., Senbursa, G., Baltaci, G., & Hayran, M. (2009). The effect on neuromuscular stability, performance, multi-joint coordination and proprioception of barefoot, taping or preventative bracing. *Foot*, *19*(4), 205–210.

Polzer, H., Kanz, K. G., Prall, W. C., Haasters, F., Ockert, B., Mutschler, W., & Grote, S. (2011). Diagnosis and treatment of acute ankle injuries: development of an evidence-based algorithm. *Orthopedic Reviews*, *4*(1), 5.

Potvin, J. R., & Brown, S. H. M. (2004). Less is more: High pass filtering, to remove up to 99% of the surface EMG signal power, improves EMG-based biceps brachii muscle force estimates. *Journal of Electromyography and Kinesiology*, *14*(3), 389–399.

Proske, U., & Gandevia, S. C. (2012). The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. *Physiological Reviews*, *92*(4), 1651–1697.

Proske, U., & Gandevia, S. C. (2009). The kinaesthetic senses. *The Journal of Physiology*, *587*(17), 4139–4146.

Raheem, O. A., & O'Brien, M. (2011). Anatomical review of the lateral collateral ligaments of the ankle: a cadaveric study. *Anatomical Science International*, 1–5.

Raymond, J., Nicholson, L. L., Hiller, C. E., & Refshauge, K. M. (2012). The effect of ankle taping or bracing on proprioception in functional ankle instability: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, *15*(5), 386–392.

Refshauge, K. M., Kilbreath, S. L., & Raymond, J. (2000). The effect of recurrent ankle inversion sprain and taping on proprioception at the ankle. *Medicine and Science in Sports and Exercise*, *32*(1), 10–15.

Reimer, R. C., & Wikstrom, E. A. (2010). Functional fatigue of the hip and ankle musculature cause similar alterations in single leg stance postural control. *Journal of Science and Medicine in Sport*, *13*(1), 161–166.

Richie, D. H. (2001). Functional instability of the ankle and the role of neuromuscular control: A comprehensive review. *The Journal of Foot and Ankle Surgery*, *40*(4), 240–251.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: The physiologic basis of functional joint stability. *Journal of Athletic Training*, *37*(1), 71–79.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, Part II: The role of proprioception in motor control and functional joint stability. *Journal of Athletic Training*, *37*(1), 80–84.

Robi, K., Jakob, N., Matevz, K., & Matjaz, V. (2013). The physiology of sports injuries and repair processes. *Current issues in sports and exercise medicine*, 43-86.

Roebroeck, M. E., Dekker, J., Oostendorp, R. A., & Bosveld, W. (1998). Physiotherapy for patients with lateral ankle sprains: a prospective survey of practice patterns in Dutch primary health care. *Physiotherapy*, *84*(9), 421-432.

Sanes, J. N., & Donoghue, J. P. (2000). Plasticity and primary motor cortex. *Annual review of neuroscience*, *23*(1), 393-415.

Sefton, J. M., Hicks-Little, C. A., Hubbard, T. J., Clemens, M. G., Yengo, C. M., Koceja, D. M., & Cordova, M. L. (2009). Sensorimotor function as a predictor of chronic ankle instability. *Clinical Biomechanics*, *24*(5), 451–458.

Seidler, R. D., Bo, J., & Anguera, J. A. (2012). Neurocognitive contributions to motor skill learning: The role of working memory. *Journal of Motor Behavior*, *44*(6), 445–453.

Stecco, A., Stecco, C., MacChi, V., Porzionato, A., Ferraro, C., Masiero, S., & De Caro, R. (2011). RMI study and clinical correlations of ankle retinacula damage and outcomes of ankle sprain. *Surgical and Radiologic Anatomy*, *33*(10), 881–890.

Taser, F., Shafiq, Q., & Ebraheim, N. A. (2006). Anatomy of lateral ankle ligaments and their relationship to bony landmarks. *Surgical and Radiologic Anatomy*, *28*(4), 391–397.

Van Den Bekerom, M. P. J., Oostra, R. J., Alvarez, P. G., & Van Dijk, C. N. (2008). The anatomy in relation to injury of the lateral collateral ligaments of the ankle: A current concepts review. *Clinical Anatomy*, *21*(7), 619–626.

Van Rijn, R. M., Van Os, A. G., Bernsen, R. M., Luijsterburg, P. A., Koes, B. W., & Bierma-Zeinstra, S. M. (2008). What is the clinical course of acute ankle sprains? A systematic literature review. *The American journal of medicine*, *121*(4), 324-331.

Verhagen, E., van der Beek, A., Twisk, J., Bouter, L., Bahr, R., & van Mechelen, W. (2004). The Effect of a Proprioceptive Balance Board Training Program for the Prevention of Ankle Sprains. *The American Journal of Sports Medicine*, *32*(6), 1385–1393.

Verhagen, R. A. W., de Keizer, G., & van Dijk, C. N. (1995). Long-term follow-up of inversion trauma of the ankle. *Archives of Orthopaedic and Trauma Surgery*, *114*(2), 92–96.

Waldecker, U. (2000). Subtalar instability in acute, lateral sprain of the ankle? *Foot and Ankle Surgery*, *6*(2), 113–118.

Waterman, B. R., Owens, B. D., Davey, S., Zacchilli, M. A., & Belmont, P. J. (2010). The epidemiology of ankle sprains in the US. *The Journal of Bone & Joint Surgery*, *92*(13), 2279-2284.

Wheaton, M., & Jensen, N. (2010). The ligament injury connection to osteoarthritis. *Journal of Prolotherapy*, *2*(1), 294-304.

Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., & Borsa, P. A. (2006). Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. *Sports Medicine (Auckland, N.Z.)*, *36*(5), 393–410.

Willems, T., Witvrouw, E., Verstuyft, J., Vaes, P., & De Clercq, D. (2002). Proprioception and muscle strength in subjects with a history of ankle sprains and chronic instability. *Journal of Athletic Training*, *37*(4), 487–493.

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, *11*(2), 269–74.

Yeung, M., Chan, K., So, C., & Yuan, W. (1994). An epidemiological survey on ankle sprain. *British Journal of Sports Medicine*, *28*(2), 112–116.

Yildiz, S., & Yalcin, B. (2013). The anterior talofibular and calcaneofibular ligaments: An anatomic study. *Surgical and Radiologic Anatomy*, *35*(6), 511–516.

Zhang, S., Wortley, M., Silvernail, J. F., Carson, D., & Paquette, M. R. (2012). Do ankle braces provide similar effects on ankle biomechanical variables in subjects with and without chronic ankle instability during landing? *Journal of Sport and Health Science*, *1*(2), 114–120.

7.0 Supplemental Appendix

7.1 Appendix 1 - Restricted Maximum Likelihood (REML) Variance Component Estimates

Table S1. REML Variance Component Estimate of Sprained leg AT

Random Effect	Variance Ratio	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of Total
Participant	-0.051269	-7.998491	16.339193	-40.02272	24.025738	0.6245	0.000
Residual		156.01078	38.407198	101.49527	270.30226		100.000
Total		156.01078	38.407198	101.49527	270.30226		100.000

-2 Log Likelihood = 370.57974101
Note: Total is the sum of the positive variance components.
Total including negative estimates = 148.01229

Table S2. REML Variance Component Estimate of Sprained leg PL

Random Effect	Variance Ratio	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of Total
Participant	-0.024588	-8.591055	39.87739	-86.7493	69.567193	0.8294	0.000
Residual		349.3967	86.015522	227.30553	605.36022		100.000
Total		349.3967	86.015522	227.30553	605.36022		100.000

-2 Log Likelihood = 407.44191998
Note: Total is the sum of the positive variance components.
Total including negative estimates = 340.80565

Table S3. REML Variance Component Estimate of Non-Sprained leg AT

Random Effect	Variance Ratio	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of Total
Participant	1.291331	126.62834	64.729738	-0.239613	253.4963	0.0504	56.357
Residual		98.060326	24.140783	63.79469	169.89806		43.643
Total		224.68867	66.94272	135.11047	445.7739		100.000

-2 Log Likelihood = 372.681618
Note: Total is the sum of the positive variance components.
Total including negative estimates = 224.68867

Table S4. REML Variance Component Estimate of Non-Sprained leg PL

Random Effect	Variance Ratio	Variance Component	Std Error	95% Lower	95% Upper	Wald p-Value	% of Total
Participant	0.477038	65.168514	43.177231	-19.4573	149.79433	0.1312	32.297
Residual		136.61075	33.631242	88.874277	236.69003		67.703
Total		201.77927	49.293037	131.6578	347.92533		100.000

-2 Log Likelihood = 379.00428863
Note: Total is the sum of the positive variance components.
Total including negative estimates = 201.77927

7.2 Appendix 2 - Non-Sprained Ankle Least Squares Means (LSM) and Linear Mixed Effects Regression (LMER) Plots

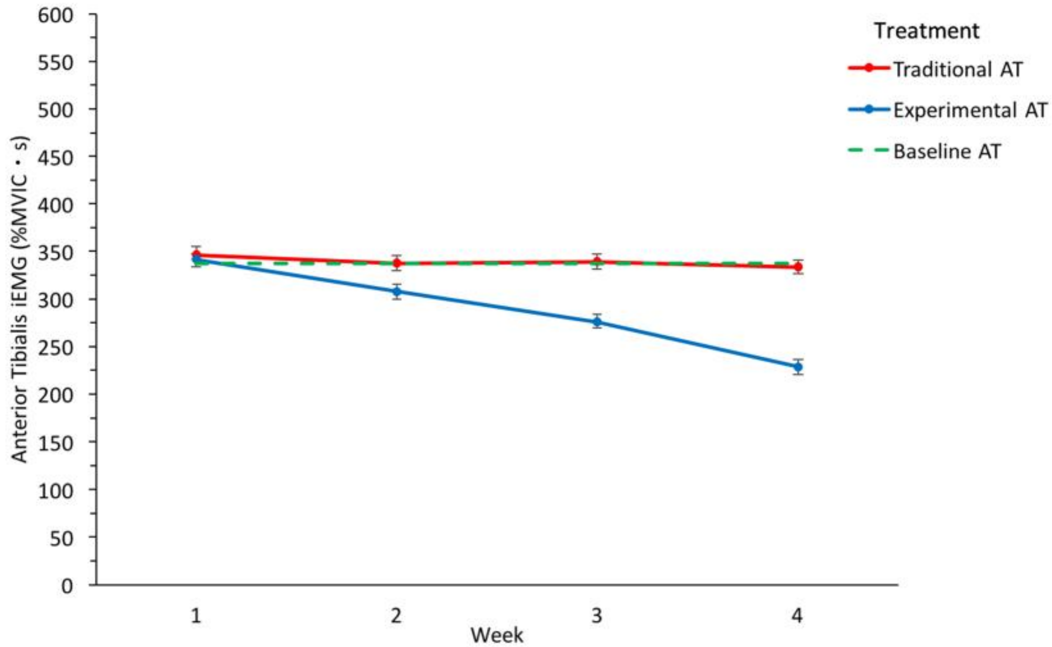

Figure S1. Non-Sprained anterior tibialis (AT) iEMG least squares means plot for interaction with treatment and week factors transposed in the experimental and tradition treatment groups with reference AT iEMG value, 337.359, from the baseline group

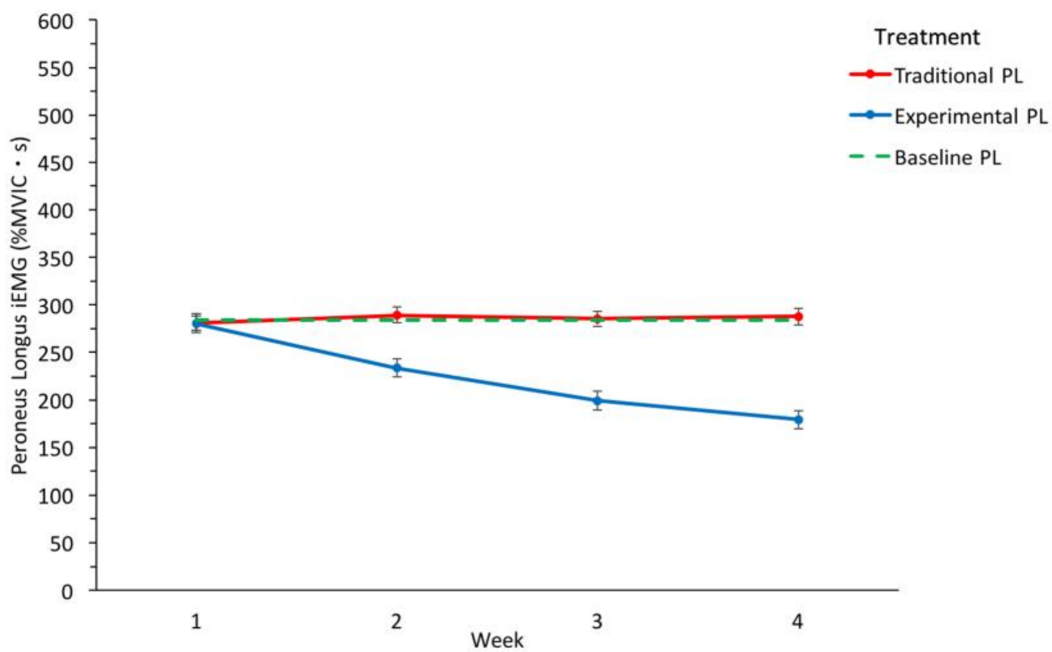

Figure S2. Non-Sprained peroneus longus (PL) iEMG least squares means plot for interaction with treatment and week factors transposed in the experimental and tradition treatment groups with reference PL iEMG value, 283.822, from the baseline group

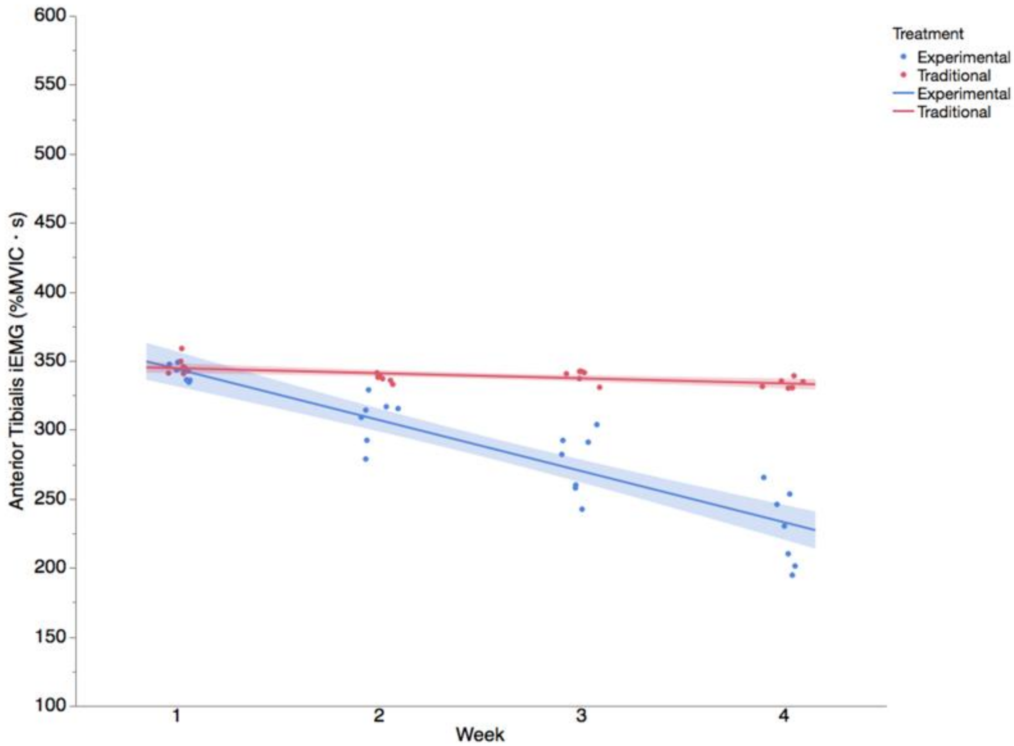

Figure S3. Linear mixed effects regression (LMER) of the anterior tibialis (AT) on the non-sprained ankle of experimental and traditional sprain treatment groups

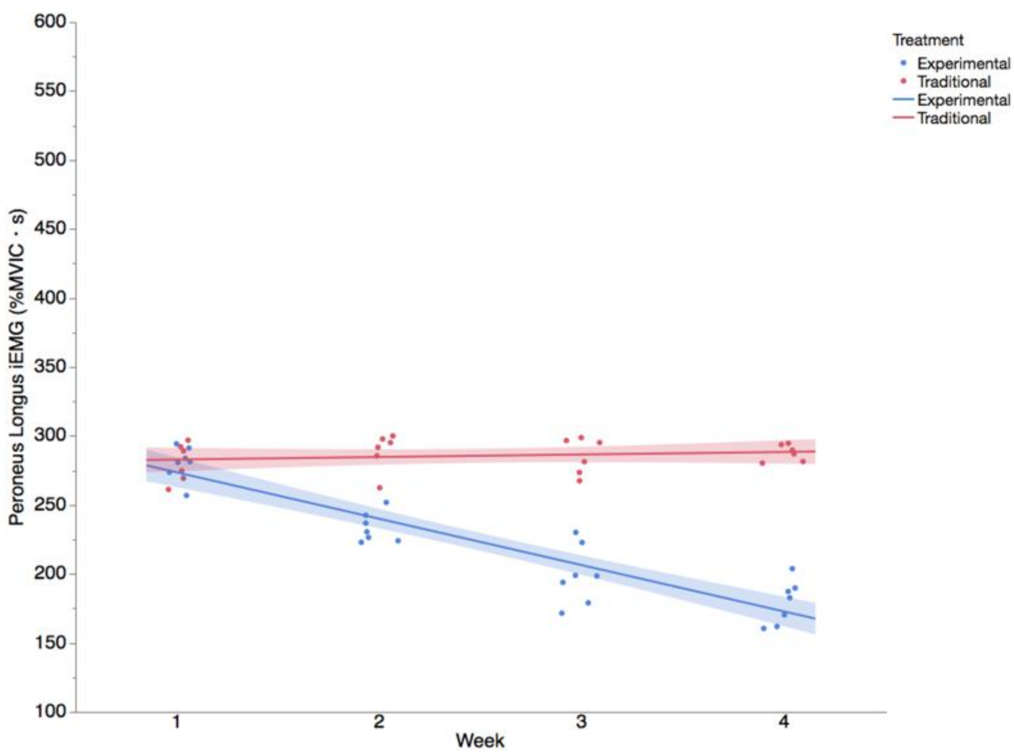

Figure S4. Linear mixed effects regression (LMER) of the peroneus longus (PL) on the non-sprained ankle of experimental and traditional sprain treatment groups

7.3 Appendix 3 - Raw EMG signals for both treatment groups of the anterior tibialis and peroneus longus

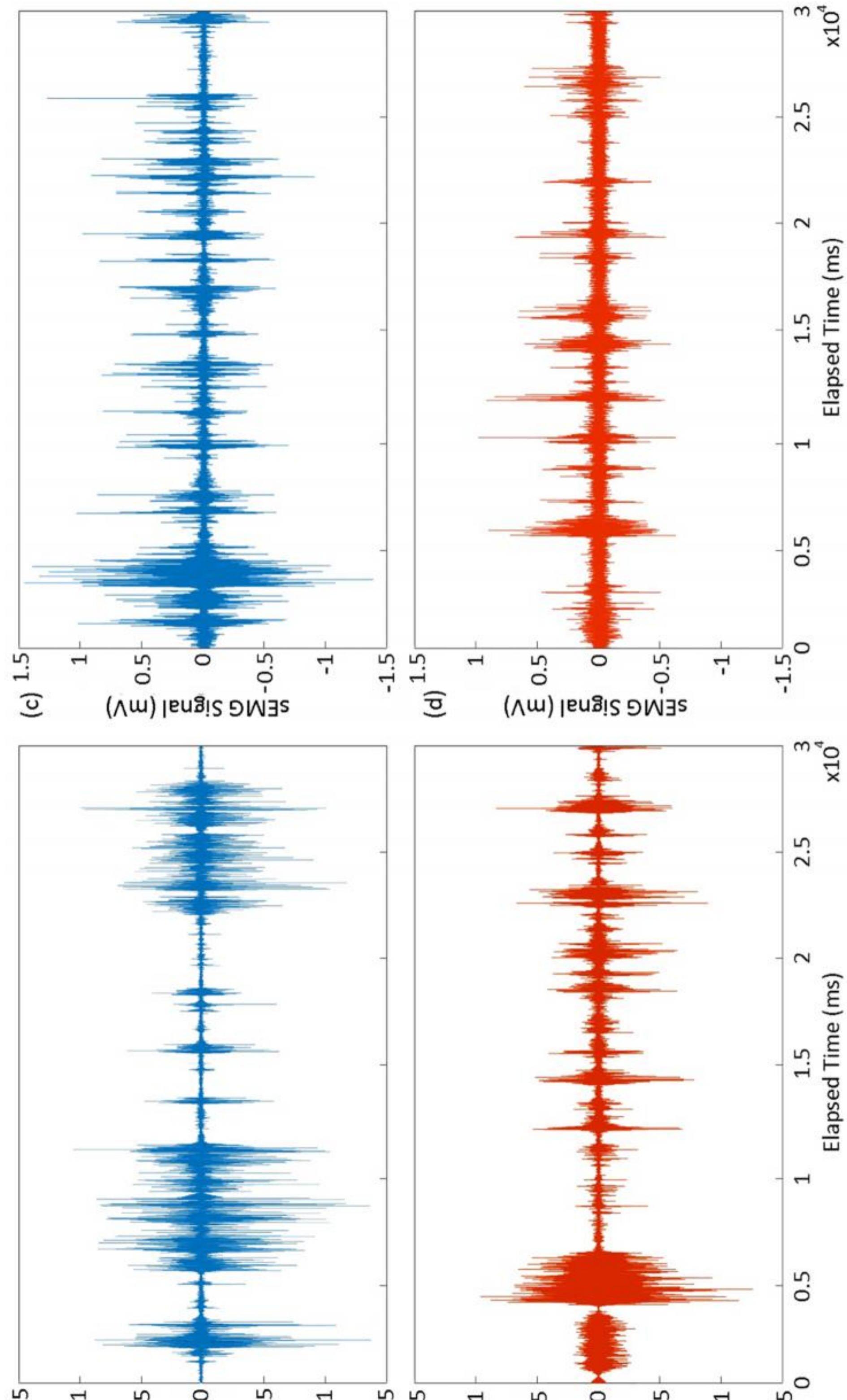

Figure S5. Raw EMG signals from the experimental anterior tibialis (a), peroneus longus (b), and the traditional anterior tibialis (c) and peroneus longus (d), sampled at 1000 Hz with a 60 Hz notch filter applied

Table S5. iEMG data for both treatment groups of the anterior tibialis and peroneus longus

Experimental	AT				PL			
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
P1	558.662	367.201	256.933	222.074	490.424	327.118	288.758	184.715
P2	532.489	398.977	293.082	219.863	475.864	314.487	275.035	232.362
P3	552.894	354.541	287.875	214.662	503.748	328.457	257.996	162.746
P4	542.742	366.745	263.124	225.604	483.422	304.368	254.783	219.690
P5	551.225	379.423	251.460	218.444	492.411	313.356	278.989	213.799
P6	568.294	350.059	242.300	218.265	471.641	306.973	276.641	191.105
P7	557.359	378.784	259.883	258.504	451.266	296.497	273.645	192.293
Mean	551.952	370.819	264.951	225.345	481.254	313.037	272.264	199.530
SE	11.593	16.613	18.732	15.012	17.029	11.717	11.939	23.748

Traditional	AT				PL			
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
P1	551.200	542.294	538.905	530.014	483.560	531.137	519.802	504.167
P2	557.389	544.325	532.182	537.382	529.657	525.740	464.147	453.452
P3	343.609	360.320	330.704	333.130	277.147	268.550	283.984	257.546
P4	550.676	544.847	540.581	535.543	532.020	507.480	498.190	515.832
P5	559.444	541.647	538.792	538.571	524.303	494.674	466.747	480.630
P6	541.543	534.896	539.928	531.928	504.412	485.858	491.063	481.490
P7	537.521	535.043	532.813	534.327	518.149	519.420	471.007	472.430
Mean	549.629	540.508	537.200	534.627	515.350	510.718	485.159	484.667
SE	8.627	4.455	3.708	3.245	18.444	17.912	21.843	22.370

7.4 Appendix 4 - Consent form, Questionnaire, and Supplemental Protocol Figures

Consent Form - Adult

I, the undersigned, do hereby acknowledge:

- My consent to perform a comprehensive evaluation of ankle function; consisting but not limited to stepping on raised steps, walking on a treadmill, measurements of balance, flexibility, and strength, the results of which will assist in determining the course of any subsequent treatments related to ankle rehabilitation;
- My understanding that muscle activity, using electromyographic equipment, will be measured prior to, during and after the evaluation;
- My understanding that heart rate and blood pressure may be measured prior to, during and after the evaluation and subsequent treatments;
- My consent to answer questions concerning my health history, my physical activity participation and my lifestyle;
- My consent to the evaluation and prescribed treatment measures conducted by a researcher who has been trained to administer the evaluation and treatment.
- My understanding that there are potential risks; i.e., episodes of transient light-headedness, leg cramps, and nausea, and that I assume willfully those risks;
- My obligation to immediately inform the researcher of any pain, discomfort, fatigue, or any other symptoms that I may suffer during and immediately after the evaluation;
- My understanding that I may stop or delay any further testing and/or treatment if I so desire and that the experiment may be terminated by the researcher upon observation of any symptoms of undue distress or abnormal response;
- My understanding that I may ask any questions or request further explanation or information about the procedures at any time before, during and after the evaluation;

This project was reviewed by the Carleton University Research Ethics Board, which provided clearance to carry out the research (Project #101527). Should you have questions or concerns related to your involvement in this research, please contact: ethics@carleton.ca

_______________________________________ ____________________________

Signature Date

_______________________________________ ____________________________

Witness Date

NOTE: This form must be completed, signed and submitted to the researcher, at the time of evaluation.

Ankle Sprain Questionnaire

Thank you for taking the time to fill out this brief questionnaire regarding ankle sprains and the rehabilitation process. My name is Simon Chan. I am a researcher in the Department of Biology at Carleton University. I am conducting a research study on ankle sprains and rehabilitation. This survey will ask you questions about the nature and severity of your ankle sprain to see if you qualify to participate in this study. You may feel uncomfortable answering some of the questions. You do not have to answer any questions that you do not wish to. If you qualify for the study, based on your answers on this questionnaire, you will receive rehabilitative therapy for the ankle sprain at no cost to you. If you withdraw from the study prior to completing the rehabilitation protocol, you will not be able to receive the full benefits of the rehabilitation process. Taking part in the study is your decision. You do not have to be in this study if you do not want to. You may also quit being in the study at any time or decide not to answer any question you are not comfortable answering.

I would be happy to answer any questions you have about the study. You may contact me at simon.chan@cmail.carleton.ca or my supervisors, Dr. Iain McKinnell, 613-520-2600 x 7549 and iain_mckinnell@carleton.ca or Dr. Jeff Dawson, 613-520-2600 x 3881 and jeff_dawson@carleton.ca, if you have study related questions or problems.

Is this your first time spraining this ankle?	☐ Yes ☐ No
Was there significant swelling?	☐ Yes ☐ No
Was there significant bruising?	☐ Yes ☐ No
Have you re-sprained or re-injured that ankle since?	☐ Yes ☐ No
Have you re-sprained or re-injured that ankle since?	☐ Yes ☐ No
Have you sprained both ankles before?	☐ Yes ☐ No
Have you played a 3D video game before?	☐ Yes ☐ No
Have you played the Sony PlayStation 3 console before?	☐ Yes ☐ No
Are you familiar with Portal the video game?	☐ Yes ☐ No

This project has been reviewed and cleared by the Carleton University Research Ethics Board (Project #101527). Contact CU-REB at 613-520-2517 or ethics@carleton.ca

Figure S6: Illustration of stability training exercise utilizing a fitterfirst single axis wobble board

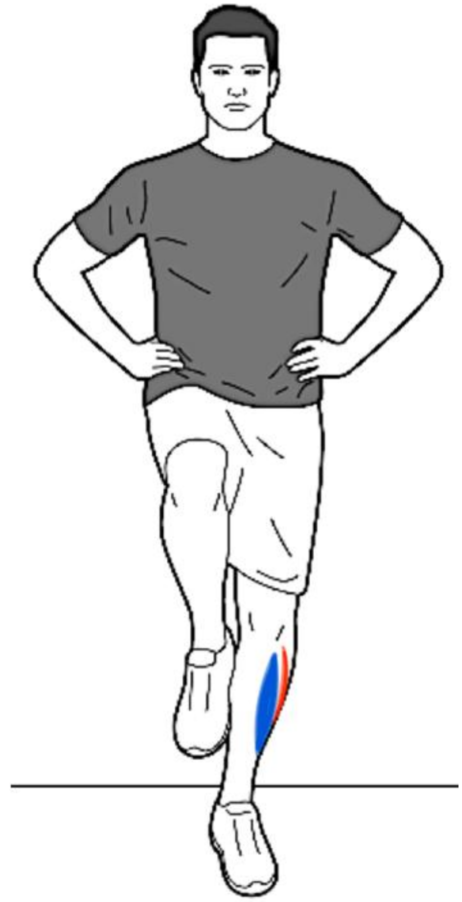

Figure S7: Illustration of single leg stance used in data collection showing the anterior tibialis (in blue) and peroneus longus (in red) muscle bellies

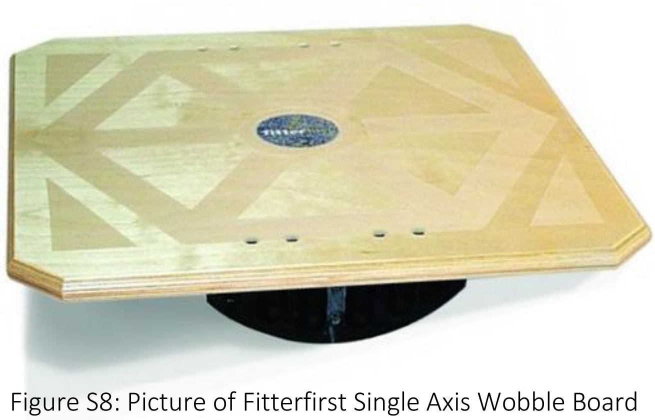

Figure S8: Picture of Fitterfirst Single Axis Wobble Board