EFFECTS OF SELECTED MODES OF PROPHYLACTIC SUPPORT ON REFLEX MUSCLE FIRING FOLLOWING DYNAMIC PERTURBATION OF THE ANKLE

by

Kevin Michael Conley

BSE, Cortland College, 1990

MS, University of Pittsburgh, 1993

Submitted to the Graduate Faculty of

The School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2005

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

This dissertation was presented

by

Kevin Michael Conley

It was defended on

March 23, 2005

and approved by

G. Kelley Fitzgerald, PhD, PT, OCS

Freddie H. Fu, MD, DSc (Hon), DPs (Hon)

Elaine N. Rubinstein, PhD

David A. Stone, MD

Scott M. Lephart, PhD, ATC
Dissertation Director

EFFECTS OF SELECTED MODES OF PROPHYLACTIC SUPPORT ON REFLEX MUSCLE FIRING FOLLOWING DYNAMIC PERTURBATION OF THE ANKLE

Kevin Michael Conley, PhD

University of Pittsburgh, 2005

Ankle sprains are among the most common injuries in sports. The majority involve the lateral ligaments of the ankle following a rapid inversion of the weight bearing joint. The ability of prophylactic stabilization to minimize the impact of these forces has been studied extensively. An innovative device designed to evoke a 20º inversion perturbation was used to demonstrate that application of ankle prophylaxis is effective in improving muscular response in healthy individuals. Forty one volunteers (21 males, 20 females) underwent EMG analysis of the peroneus longus (PL) and tibialis anterior (TA), measuring reflex latency (RL) and time to peak amplitude (TPA) while performing a dynamic task. Data were collected while subjects were fitted with two types of ankle braces (lace-up and semi-rigid) and standard closed basketweave ankle taping, each compared with a no support control. In addition, a comparison of PL and TA was conducted to determine muscle differences on measures of RL and TPA. Significantly shorter RL in the PL were observed in the lace-up and semi rigid brace conditions compared to the no brace ($p=0.004$, $p<0.001$) control. Similarly, the semi-rigid brace was significantly shorter than the tape ($p<0.001$) condition. In the TA, RL were significantly shorter for the lace-up than the no brace ($p<0.008$) control. TPA values were significantly shorter for the lace-up and semi rigid brace conditions in the TA compared to the no brace ($p=0.007$, $p=0.001$) control; and the semi-rigid brace TPA was significantly shorter than tape ($p<0.001$). No significant differences were observed in either RL or TPA measurements ($p>0.05$) between the PL and TA.

The dynamic task in this study better replicates the conditions which often precipitate ankle injury. Results indicate the application of ankle support may be beneficial in heightening the sensitivity of dynamic restraints, thus minimizing the effects of a rapid inversion mechanism. In particular, the lace-up and semi-rigid braces appeared to be the most effective in hastening muscular responses observed during a dynamic task. The implications for these findings would be of particular interest to the clinician when recommending the type of prophylactic support to be employed during sport activity.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

As no man is an island, I take this opportunity to acknowledge the many individuals who have so graciously contributed their time and talents to assist me in completing this project. I would first like to thank the members of my dissertation committee - Dr. G. Kelley Fitzgerald; Dr. Freddie Fu; Dr. Elaine Rubinstein; and Dr. David Stone. I greatly appreciate your continuous support and valuable counsel throughout this process. To those who played such an instrumental role in the genesis of this project, Ms. Maria Pasquale; Mr. Mark McCartney; Dr. Yan-Ying Ju; and those who so selflessly lent their expertise during its completion, Mr. John Jolly and Dr. John Abt, I am eternally grateful for your passion and the energy you poured into my vision. I am equally grateful to all those in the NMRL who, in one way or another, offered their time and assistance. Your collegial support has been invaluable. To the students and staff of the Athletic Training Education Program, I thank you for your patience and willingness to live this experience with me. Your support has been heartwarming. I reserve my greatest debt of thanks to my Committee Chair and mentor, Dr. Scott Lephart. For fourteen years you have demonstrated a level of professionalism that I have aspired to emulate and supported me in my professional growth. While words are inadequate to express my appreciation, I hope the culmination of my formal education is in some small measure a fitting tribute to the tremendous example you have been for me. To Dr. Tim Henry, thank you for inspiring me and to Ms. Polly Mason, thank you for all you have taught me, not just in the 2nd grade classroom. Finally, to my family and in particular my parents and my wife Jill, your love and encouragement is what got me to the finish line. Thank you all for being a part of helping me reach my goals.

1. INTRODUCTION

1.1. Research Problem

Injuries to the ankle joint remain a difficult challenge for the sports medicine clinician from the standpoint of diagnosis and appropriate treatment options. The prevalence of lateral ankle sprains in recreational and competitive athletic settings has long been established[1-4]. Pathology to the ankle constitutes 4.7-24.4% of all injuries occurring in individual sports[5], and roughly 85% of those involve the lateral ligamentous structures as a result of a combined plantarflexion/inversion mechanism[1, 6]. Of special concern to clinicians is the nearly 80% recurrence rate and the fact that upwards of 40% of these injuries can potentially progress to chronic instability[4, 7-11].

A substantial body of knowledge exists to explain the pathomechanics[7, 8] and diagnosis[9, 10] of lateral ankle sprains as well as the effects of various means of external support employed to prevent such injuries[11-17]. In the ankle, taping and bracing is commonly used prophylactically to prevent injury among healthy at risk athletes, and functionally to minimize the risk of re-injury among athletes with chronic instability. In either case the function of the external support is expected to be a reduction in the maximal range of inversion motion, an increase in rotational stiffness, and an increase in maximal resistance to movement beyond the anatomical limits of subtalar inversion, all without interfering with the normal biomechanics of motion[18-20].

The mechanism by which this effect is achieved is subject to speculation, but has been ascribed to one of two theories. One possible explanation involves a mechanical effect provided by the external support as a function of its construction and application to the lower limb. However, due to the nature of the testing procedures, previous work is conflicting and has fallen short of definitively documenting this mechanical effectiveness largely because the joint moments have been less than that which would be expected to be observed in an actual injury situation[13, 21-30]. In addition, there is evidence to suggest the evertor muscles are capable of producing as much as 4x the resistance of a brace in a simulated injury scenario[31]. The second explanation suggests there may be a proprioceptive effect to wearing some form of external support device.

Previous literature has demonstrated the application of prophylactic support improves various measures of proprioception[32-34]. This is particularly true among subjects who present with suboptimal levels of proprioception or neuromuscular control[33]. In such cases, the application of some form of external support may normalize proprioceptive values[35]. The exact mechanism of these findings has yet to be fully elucidated, however the prevailing notion involves the ability of the external support to stimulate various somatosensory receptors located in the skin and subcutaneous structures and how this stimulation contributes to a heightened dynamic restraint mechanism by way of enhanced reflex activity or through increased joint stiffness, or both[36-38]. These receptors, referred to as mechanoreceptors, include cutaneous, articular and muscle spindle afferents that are found in skin, muscles, joint capsule and ligaments surrounding a joint and provide important sensory feedback for the detection of changes in joint position and excessive loading thus contributing to the dynamic muscle reflex response necessary to protect the joint from forces that exceed the anatomical limits of the primary static restraints. The delicate relationship between the static and dynamic components of the ankle provides the joint with neuromuscular control[39]. As such, compromise of these elements may have a profound effect on functional capabilities and activities of daily living. It appears the contribution of these neurological feedback mechanisms is an important component for the maintenance of functional joint stability by mediating reflex muscle firing and intrinsic stiffness about the joint[40]. Evidence has shown that, in the presence of an ankle injury, reflex and reaction latencies of the peroneal muscles are negatively impacted[41, 42] and that application of external support has been credited with improving these variables[33]. The tactile contribution provided by external ankle supports has been postulated to contribute to the stimulation of mechanoreceptors leading to an increase in sensitivity to changes in force, pressure and displacement and heightened motoneuron excitability and pre-activation of the muscles crossing the joint[43, 44], thus enhancing neuromuscular control and attenuating the forces that lead to joint injury. In light of this, it is often recommended that athletes be equipped with some form of external prophylactic support in an effort to minimize the damaging effects of an ankle inversion mechanism. The question that remains is whether results similar to those observed in subjects with compromised neuromuscular control can be demonstrated in a healthy sample when subjected to the same types of joint forces experienced while performing functional activities, lending credence to the use of these devices to minimize the effects of such injury mechanisms.

Historically, the use of adhesive cloth taping has been well chronicled as an effective means of injury prevention[17, 45-48]. More contemporary advances have ushered in a host of alternative soft and semi-rigid orthoses designed to perform the same task as taping while also minimizing the time required for application by a clinician[19-21, 49, 50]. In addition, the use of these reusable, self-applied braces represents a significant increase in savings over the cost of purchasing adhesive tape, which can only be worn once.

From a functional perspective, there is significant debate as to which intervention provides the most effective means of support without impacting performance. Often times, unfortunately, the choice of an appropriate system to best use is left to the discretion of the patient based on subjective comfort or anecdotal evidence.

Taping has been shown to be effective in limiting subtalar joint inversion[45, 51-53]. However, its ability to maintain adequate stabilizing properties after as little as ten minutes of exercise has raised skepticism[22, 23, 54-56]. Commercial orthoses, on the other hand, can be repeatedly adjusted throughout an exercise, yet here too, their effectiveness in providing a stabilizing presence has garnered conflicting opinion.

The orthoses are typically evaluated on the basis of mechanical stabilizing capabilities and functional impact. The literature is replete with data describing the relative effectiveness of various external ankle supports on measures of static and functional performance variables as they relate to stabilization of the lateral structures of the ankle. Much of the previous work has focused on the ability of these appliances to attenuate talocrural and subtalar joint motion under static conditions[11, 17, 19, 21, 57-59]. Several others have demonstrated differences in orthoses based on performance of functional tests such as vertical jump, broad jump, figure-of-eight course, and sprint speed[13, 14, 20, 32, 46, 59-61]. Fewer still have compared differences in reaction time of the muscles crossing the ankle among various support systems in response to an inversion moment in the closed kinetic chain position[9, 25, 29, 33]. A significant limitation of all of these studies, however, is the absence of a description of the impact these external orthoses have on measures of dynamic reaction occurring at the ankle in response to a sudden inversion perturbation during a functional movement. Moreover, little evidence exists to explain the influence of a dynamic perturbation on the reactive characteristics of the peroneus longus and tibialis anterior. The peroneus longus muscle was chosen because of its evertor function and its role in dynamically stabilizing the inverted ankle. The tibialis anterior was chosen because of its function as an antagonist to the peroneus longus and its role in attenuating the plantarflexion forces observed during an ankle injury mechanism[25, 62, 63].

Based on the disparate outcomes of previous research, further investigation is warranted in an effort to determine the nature of the impact of various modes of ankle stabilizing devices in providing a level of prophylaxis under conditions that are fundamentally consistent with those experienced during ankle injury episodes. The ability to compare EMG activity of the peroneus longus and tibialis anterior musculature using various measurement criteria during a functional movement may shed some greater light on the effectiveness of these external ankle supports.

1.2. Statement of the Purpose

The purpose of this study was to determine the impact of three selected modes of prophylactic ankle support on measures of peroneus longus and tibialis anterior reflex latency and time to peak amplitude when compared to a no support, control condition. These measures were calculated in response to a constant inversion perturbation amplitude of 20º while performing a dynamic lateral movement using a healthy sample of physically active individuals. Of additional interest was the ability to establish if any differences existed between the three selected modes of prophylactic ankle support under these test conditions. Finally, we sought to determine if any differences in muscle activation existed between the peroneus longus and tibialis anterior across the four support conditions.

1.3. Specific Aims and Hypotheses

Specific Aim 1: To determine if external ankle support influences peroneus longus and tibialis anterior reflex latency and time to peak amplitude as measured by EMG, in the presence of a dynamic inversion perturbation and compared to a no support condition.

Hypothesis 1: Reflex latency and time to peak amplitude will be reduced under all support conditions (tape, lace-up brace, and semi-rigid brace) compared to the control (no support).

Specific Aim 2: To determine if differences exist between the three external ankle support conditions, on measures of reflex latency and time to peak amplitude as measured by EMG, in the presence of a dynamic inversion perturbation.

Hypothesis 2: No differences in EMG activity between the three support conditions (tape, lace-up brace, semi-rigid brace) will be elicited

Specific Aim 3: To determine if differences exist between the peroneus longus and tibialis anterior on measures of reflex latency and time to peak amplitude across three different external ankle support conditions and a no support control condition, as measured by EMG, in the presence of a dynamic inversion perturbation.

Hypothesis 3: No significant differences between the peroneus longus and tibialis anterior for any of the support conditions will be elicited.

1.4. Study Significance

The efficacy of external support in providing the ankle with a degree of prophylaxis under simulated functional conditions has long been a topic of investigation. This study attempted to better duplicate these functional conditions by introducing a more dynamic task while accompanied by a true perturbation mechanism. In doing so, it was anticipated the results of this investigation would better illustrate that the heightened sensitivity afforded the dynamic restraint mechanism, through application of selected modes of external ankle support, has the potential to effectively attenuate the forces experienced in the face of an ankle inversion mechanism and in turn equip the clinician with the data necessary to make more informed decisions relative to minimizing the effects of injuries to the ankle.

2. REVIEW OF LITERATURE

Injuries to the ankle pose a number of challenges to clinicians from the standpoint of defining appropriate treatment options and preventative interventions. Lateral ankle sprains remain among the most common injuries suffered by the physically active population[1-5] and occur as a result of an inversion moment imposed on a weight bearing foot, often accompanying a sudden change in direction or more typically from loading the joint on an irregular or compliant surface[1, 6]. Structural damage typically involves the ligamentous tissue that supports the joint. However, increasing evidence points to the implications such mechanisms also have on the musculotendinous and nervous tissues that surround the ankle. In the face of a typical ankle injury mechanism, the peroneal and tibialis anterior muscles provide the necessary dynamic restraint from an increasing inversion moment. The response of these muscles is thought to be mediated by sensory receptors located in the skin, muscles, tendons and ligaments that cross the ankle and the efficacy of this reflex is directly related to the magnitude of extrinsic forces imposed on the joint following an inversion moment and the frequency of exposure to such forces over time.

A number of commercially available appliances, ranging from cloth adhesive tape to a variety of soft and semi-rigid orthoses, are currently being employed to prevent or reduce the occurrence of lateral ankle sprains while simultaneously also minimizing the impact of these devices on performance variables[11, 17, 19-21, 32, 45-50, 57-61].

Previous research in this area has sought to quantify and qualify the effectiveness of various prophylactic ankle support systems on a number of measurable characteristics. Many of these studies, however, were conducted under static conditions that did not accurately reflect the forces imposed on the ankle during functional activities. This current investigation will aim to address these latter variables by examining the effectiveness of several prophylactic orthoses on measures of electromyographic response under conditions that are more representative of those experienced in typical athletic activities.

The following review will present a discussion of current literature relative to the functional characteristics of the ankle, the role of the sensorimotor system in response to imposed joint stress, as well as the impact prophylactic bracing plays in the prevention of ankle injuries. This review will also address the application of EMG and earlier generations of perturbation devices to the present area of study, in particular the influence these instruments have had on previous work in illustrating the efficacy of various forms of intervention in the prevention of ankle injuries.

2.1. Anatomical Considerations of the Foot and Ankle

A sound appreciation of the structure of the foot and ankle is important to the understanding of the function of this lower extremity segment in supporting the weight of the entire body during locomotion. The nature of the bony architecture combined with the stabilization provided by static and dynamic soft tissue elements, as well as the influence of neuromuscular feedback mechanisms, contribute to the adaptive characteristics of the foot and ankle to attenuate the extrinsic forces responsible for musculoskeletal injury to the lower extremity.

2.1.1. Skeletal Composition

The foot/ankle complex is a series of intricate articulations that provide a base of support for the body during ambulation. The ankle, or talocrural, joint is comprised of a syndesmosis between the distal tibia and fibula and a diarthroidal mortise between the distal tibia, fibula and talus. The mortise is characterized as a single axis joint corresponding to a line just distal to the palpated tips of the medial and lateral malleoli[64]. The primary motion allowed is that of dorsiflexion and plantarflexion, occurring in the sagittal plane. However, due to the obliquity of the joint axis and the fact that the lateral articular margin of the talus is longer than that of the medial, some degree of abduction and pronation accompanies the dorsiflexed ankle, while some adduction and supination occurs when the ankle is plantarflexed[65].

The subtalar joint is formed by the articulation of the talus with the calcaneus at three distinct locations. Motion at the subtalar joint is said to be triplanar because the movements that occur there are perpendicular to all three cardinal planes, but collectively are referred to as pronation and supination[64, 66, 67]. In the closed kinetic chain condition, pronation is characterized by eversion of the calcaneus and adduction and plantarflexion of the talus which results in internal rotation of the tibia. Supination, on the other hand, is characterized as inversion of the calcaneus and abduction and dorsiflexion of the talus resulting in external rotation of the tibia. A fairly large concavity called the tarsal sinus separates these articulations into anterior and posterior portions. It is this posterior portion, commonly referred to as the talocalacaneal joint, where calcaneal inversion and eversion take place.

Bony stability of the talocrural joint is influenced by several factors including the shape of the talus. The talar dome is wider anteriorly than posteriorly thus providing greater joint congruency in the closed-packed position of dorsiflexion. In addition, the lateral malleolus projects farther distally than the medial malleolus which lends to greater limitation in eversion than inversion. Finally, because no muscles attach directly to the talus, the stability of this critical structure and its articulations relies heavily on the ligamentous attachments and musculotendinous complexes that cross the ankle and attach distally[68, 69].

2.1.2. Ligamentous Composition

Along with the bony architecture of the joints of the ankle and foot, passive stabilization is also provided by three sets of ligamentous structures. On the medial side of the joint, the deltoid ligament complex is the primary stabilizer functioning as a restraint against lateral excursion of the talus. This triangular network of ligaments consists of four distinct bands including the anterior tibiotalar, posterior tibiotalar, tibiocalcaneal and tibionavicular ligaments. The superficial and deep layers of the deltoid ligament may independently prevent valgus tilting of the talus. The lateral side of the ankle is supported by three ligaments in such a way that at least one is taut regardless of the relative position of the ankle mortise[69]. The anterior talofibular ligament (ATFL) arises from the anterolateral surface of the lateral malleolus and inserts on the talus near the sinus tarsi. This ligament is taut and resists inversion with the foot in the plantarflexed position. The ATFL also limits anterior translation of the talus on the tibia. The calcaneofibular ligament (CFL) arises from the outermost portion of the lateral malleolus and courses inferiorly and posteriorly to attach on the calcaneus. The CFL is taut in extreme ranges of dorsiflexion and is the primary restraint to talar inversion within the midrange of motion. The posterior talofibular ligament (PTFL) arises from the posterior portion of the lateral malleolus and attaches distally on both the talus and calcaneus. The PTFL is the strongest of the lateral ligaments and is responsible for limiting posterior displacement of the talus on the tibia.

Finally, the ligaments of the distal tibiofibular syndesmosis provide stability to the ankle by limiting rotatory forces. The anterior and posterior tibiofibular ligaments along with an extension of the interosseous membrane, the crural interosseous ligament, combine to maintain the structural framework of the mortise. Excessive eversion and dorsiflexion can result in sufficient widening of the ankle mortise to create a compromise in the integrity of the syndesmosis[68, 69].

2.1.3. Musculotendinous Composition

The extrinsic muscles that provide dynamic support to the foot/ankle complex are contained within discernable compartments in the lower leg. The anterior compartment consists of the tibialis anterior, extensor hallucis longus, extensor digitorum longus and the peroneus tertius. The tibialis anterior passes across the anterior surface of the ankle to its insertion on the base of the first metatarsal and medial cuneiform[70]. This muscle functions as the primary dorsiflexor of the foot while also inverting the foot from the dorsiflexed position[71]. Its function in preventing ankle sprains is important as it acts to impede excessive plantarflexion, particularly in the early stages of the stance phase. Tibialis anterior activity before impact may also pre-stretch the gastrocnemius and soleus muscles to enhance ankle plantarflexion and dorsiflexion deceleration capacity to reduce impact joint loading[72].

The superficial posterior compartment contains the gastrocnemius, soleus and plantaris muscles. Each of these muscles shares a common insertion on the posterior calcaneal apophysis by way of the Achilles tendon[70]. Collectively, these muscles function to plantar flex the foot prior to impact, subsequently allowing the eccentric action of these muscles to absorb the impact and reduce joint loading[72].

In the deep posterior compartment the tibialis posterior (TP), flexor digitorum longus (FDL) and flexor hallucis longus (FHL) follow a similar path to their respective distal insertion sights by coursing behind the medial malleolus. The TP inserts on the navicular tubercle, with fibrous expansions to the second, third and fourth metatarsals, the three cuneiforms and the cuboid. It is the primary adductor of the foot, while also assisting in plantarflexion and inversion. The FDL to inserts on the plantar surface of the distal phalanges of toes two through five and serves to flex these lateral four toes. The FHL inserts on the plantar surface of the distal phalynx of the great toe and serves as its primary flexor. The latter two structures also serve as secondary plantarflexors and invertors of the ankle and foot[69].

The lateral compartment contains the peroneus longus and peroneus brevis muscles. The peroneus longus is the more superficial of the two, covering all but the most inferior portion of the peroneus brevis. The tendons of these two muscles pass in parallel behind the lateral malleolus and diverge as they approach the peroneal tubercle. The peroneus brevis reaches its insertion on the base of the fifth metatarsal, while the peroneus longus passes along the plantar aspect of the foot to insert on the base of the first metatarsal and medial cuneiform. Collectively, these muscles are strong evertors and provide dynamic restraint to excessive inversion of the ankle while also contributing to plantarflexion[69].

2.2. Role of the Sensorimotor System

The sensorimotor system is a relatively novel term that has been adopted to define the sensory, motor and central integration and processing mechanisms that exist to impact the execution of functional performance tasks and joint stabilization, characteristics previously described using the term proprioception[73]. The concept of proprioception was first advanced by Sherrington[74] in 1906 as the awareness of body segment position and orientation and considered a specialized variation of the sensory modality of touch encompassing the sensations of joint movement (kinesthesia), joint position (joint position sense) and sensation of resistance[39, 75]. Kinesthesia has been defined as the conscious appreciation of joint movement, either from internal (active) or external (passive) forces. Joint position sense refers to the conscious recognition of limb segment position in relation to the rest of the body[73]. Further, sensation of resistance is described as one's ability to appreciate force generated within a joint[76]. Contemporary interpretations of Sherrington's early work, which define proprioception as only those mechanisms and processes occurring along the afferent or sensory pathways and lends little credence to central nervous system processing or activity along the efferent or motor pathways of the sensorimotor system, suggests that the nervous system plays a much greater role and that the reflexive components are much more sophisticated than originally thought[73]. Proprioceptive information is conveyed from the periphery as well as visual and vestibular centers and is processed in each of the three centers of motor control, including spinal, brain stem and cerebral cortex (Figure 1)[77]. This information is then integrated in the CNS to generate a motor response[78, 79].

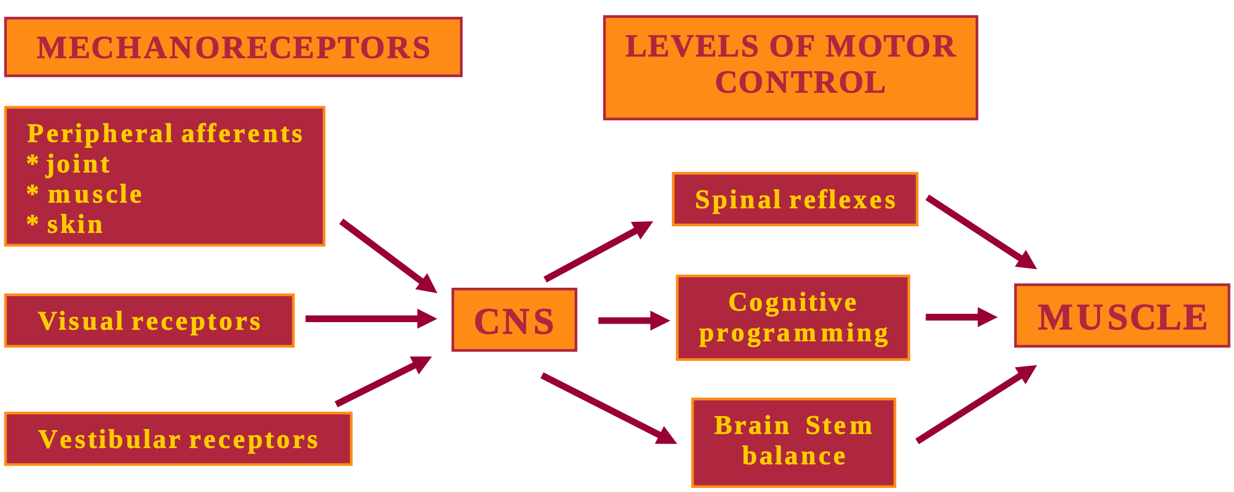


Figure 1: Neuromuscular control pathways (Reprinted with permission[77])

At the highest level of motor control, the somatosensory cortex processes proprioceptive information to provide conscious awareness of joint position sense and kinesthesia[73]. Likewise, the motor cortex stores information received from the periphery, the cerebellum, basal ganglia and somatosensory cortex for the performance of future motor tasks[80]. The spinal level of motor control is responsible for muscle activation through reflex pathways by integrating and processing proprioceptive information unconsciously[73]. Between the spinal cord and the cortex, the brain stem integrates proprioceptive information received from visual and vestibular centers and other somatosensory inputs to directly control automatic tasks such as postural control and functions as an indirect relay station between the cerebral cortex and the spinal cord to unconsciously modify descending motor commands[73].

Hilton's law states that joints are innervated by articular branches of the nerves supplying the muscles that cross the joint[81]. In addition to these elements, articular structures also include nociceptive free nerve endings. The neural feedback imparted on the CNS by cutaneous, muscle and joint mechanoreceptors is the basis for the concept of proprioception.

The somatosensory system functions to detect sensory stimuli such as touch, pain, pressure and movements such as joint displacement[82]. Mechanoreceptors for proprioception are found in skin, muscles, joint capsule, ligaments, tendons and fasciae about a joint and provide input to the CNS regarding tissue deformation[82-85]. Activation of joint mechanoreceptors stems from changes in the length and tension of soft tissue components of the joint. The resulting stimulus travels to the CNS for interpretation and integration via cortical and reflex pathways[85]. Two types of articular mechanoreceptors exist which possess adaptive properties depending on their response to a particular continuous stimulus.

Quick-adapting (QA) mechanoreceptors decrease their discharge rate to extinction within milliseconds of the onset of a continuous stimulus[86]. Thought to mediate the sensation of joint motion, the QA receptors, such as the Pacinian corpuscle, are very sensitive to changes in position. Slow-adapting (SA) mechanoreceptors such as the Ruffini ending, Ruffini corpuscle and Golgi tendon-like organs, on the other hand, respond by continuing their discharge in the presence of a continuous stimulus. These are thought to mediate the sensation of joint position as they are maximally stimulated at specific joint angles[39]. These receptors have been identified histologically to be present throughout the ankle ligaments, with the Pacinian and Golgi tendon-like organs comprising the majority of mechanoreceptors residing here[87].

Another form of the SA receptors is the complex, fusiform muscle spindle receptor found within skeletal muscle. The muscle spindle receptor, composed of a small bundle of modified muscle fibers called intrafusal fibers, function to measure muscle tension over a large range of extrafusal muscle length, which makes up the bulk of the muscle and is responsible for generating force. The intrafusal fibers are innervated by gamma-motor neurons (γ-MN), whereas the extrafusal fibers are innervated by alpha-motor neurons (α-MN). Activation of γ-MN allows the readjustment of spindle sensitivity throughout the entire range of motion in the case where extrafusal fibers are shortened, thus signaling continuous alterations in both muscle length and rate-of-length changes[39, 75]. It is the co-activation of the α-γ-MN, in the presence of a muscle contraction, that is thought to be the mechanism through which muscle length and tension are monitored[88].

Historically, the role of joint afferents in functional joint stability has been described as having a direct reflexive activation of α-MN, referred to as a ligament-muscle reflex[89]. This theory has since drawn criticism as it appears the loads required to elicit α-MN responses often exceed normal physiological loads[90]. Freeman and Wyke[91] were the first to suggest γ-MN activation is likely responsible for the increases observed in muscle activity following joint mechanoreceptor stimulation, as opposed to activation α-MNs. In comparison, the threshold load for the appearance of a reflex stimulated by the muscle spindles has been found to be significantly lower, between 5an 10 N[92].

Increased γ-MN activation, which may occur from input arising from cutaneous, articular or muscle sources, serves to heighten muscle spindle sensitivity and in turn may contribute more effectively to sensorimotor control of joint stability by increasing the intrinsic and extrinsic stiffness properties of the muscles crossing a joint resulting in increased joint stiffness[93]. Since γ-MN activation is largely influenced by peripheral afferent input, the ability to stimulate these receptors by the application of an external ankle support may enhance the functional stability of the joint in the presence of an ankle injury mechanism through a heightened response of the dynamic restraints. The compression and increased rigidity of the ankle and lower leg by ankle taping and bracing allows for stimulation of the skin and subcutaneous structures and greater pressure on the underlying musculature[38]. Afferent signals from cutaneous sources may provide proprioceptive information or facilitate proprioception and neuromuscular control through increased motorneuron excitability[43].

Input provided to the CNS by the somatosensory subsystem results in joint movement and position sense, reflexive muscle contraction, and regulation of muscle tone and stiffness[75, 94, 95]. Because the capsuloligamentous and cutaneous afferents influence the muscle spindle, it appears the musculotendinous, capsuloligamentous and cutaneous mechanoreceptors play a complimentary role in movement and joint position sense[64]. This phenomenon, referred to as ensemble coding, suggests that proprioceptive information is transferred to the CNS through an encoding across a neural population of receptors rather than discrete units from the individual receptors. This theory proposes that receptors possess unique, but overlapping, ranges of sensitivity and may help explain the improved conscious proprioceptive acuity and reduction in subjective instability associated with application of an external ankle support[75].

The second subsystem supplying the CNS with sensory input is the vestibular system. The vestibular system receives information from the vestibules and semicircular canals of the ear, for use in maintaining body posture. This can be accomplished in three ways - by controlling eye musculature so as to maintain visual focus when the head changes position; to maintain upright posture; and for conscious awareness of body and joint position and motion[96].

The visual system, the third component to CNS sensory input, also contributes to the maintenance of balance. This system provides the body with visual cues for use as reference points in orienting the body in space. It is generally agreed that, under normal conditions, the somatosensory and visual subsystems are the primary mediators of balance and postural awareness[96].

2.3. Modes of Prophylactic Ankle Support

A number of materials and devices currently exist to prophylactically safeguard the ankle against injury or in a protective and functional role following acute injury. In either case, the objective of these devices is to reinforce the passive stabilizing properties of the static tissues that surround the ankle and restrict sub-talar range of motion beyond the anatomical limits of the joint. Generally speaking, there is agreement within the literature to date that the application of some form of external ankle support is effective in limiting the incidence of lateral ankle sprains. While much of the effectiveness of these prophylactic devices has been attributed to the mechanical stability provided[11, 17, 19, 21, 57, 58], and the impact such devices have on the functional capabilities of the wearer[13, 14, 20, 32, 46, 59-61], relatively little evidence exists as to the ability of taping or bracing to enhance motor control through heightened sensitivity of the peripheral afferents in achieving the desired efferent response, particularly during the performance of functional tasks. In addition, the preponderance of work describing the usefulness of ankle support devices has been conducted on subjects with a history of lateral ankle dysfunction and as such makes generalizing similar results to a healthy population difficult.

As technology has evolved, the desired characteristics of a chosen ankle support have not changed. Ideally, the device should be easy to apply, provide support over time, permit functional range of motion in plantarflexion and dorsiflexion, while limiting excessive inversion and eversion, and be inexpensive[15]. Over time, the number of styles and designs of ankle support has grown dramatically, yet all can be assigned to one of three categories: adhesive cloth taping, soft shell brace, and semi-rigid brace.

2.3.1. Adhesive Cloth Taping

Adhesive cloth taping has long been used in an effort to decrease the incidence of lateral ankle sprains. A number of studies have been conducted which advocate the use of ankle taping for its joint motion restricting properties[15, 45, 51-53, 97]. The earliest of these studies, by Quigley et al.[97], found that taping was beneficial in reducing injury by its ability to limit the amount of ankle inversion and eversion, while permitting full dorsiflexion and plantarflexion. Garrick and Requa[45] were among the first to demonstrate the effectiveness of ankle taping in reducing the incidence of ankle sprains as compared to the no tape condition. This landmark study was supported by a number of similar investigations that yielded conflicting results as to the efficacy of this mode of external support[23, 28, 54, 98].

Much of the debate regarding ankle taping centers around its effectiveness over time during physical activity. Rarick et al.[99] reported that tape loses 40% of its supportive properties after as little as 10 minutes of vigorous exercise. Fumich et al.[54] were able to demonstrate very similar results while Myberg et al.[23] concluded that tape offered no significant ankle support after one hour of exercise. Other criticisms of ankle taping are its cost and the need for trained personnel for application purposes. Rovere et al.[28] in 1988, for example, calculated the cost of taping both ankles of a collegiate football player for a whole season at more than $400. Similarly, Paris[60] estimated the cost of taping a 12-player basketball team over the course of a typical 25-week season to be approximately $5220. When compared to alternative methods of prophylactic support, namely soft or semi-rigid braces, these costs are significantly greater, not to mention the substantial time required by an athletic trainer to apply appropriate taping techniques, limiting his or her ability to adequately complete other job related tasks. Nevertheless, ankle taping continues to be a popular choice for ankle support due, in most part, to athlete preference based largely on comfort and perceived effectiveness in preventing injury.

2.3.2. Soft Shell Prophylactic Braces

Soft shell prophylactic braces were first introduced, as an alternative to ankle taping, in the early 1980's by Swede-O-Universal™ (Swede-O-Universal, North Branch, MN)[100]. Since that time, a number of similar type braces have been introduced and have yielded positive results with regard to their effectiveness in providing a level of support comparable to ankle taping[101-103]. The most common type of soft shell brace is the re-useable lace up variety[15]. These braces are constructed of a number of materials including canvas, neoprene and nylon[100]. Typically, the braces come in sizes based on the shoe size of the wearer and can be worn on either foot. The obvious advantages of these braces are that they are re-usable, can be re-adjusted throughout activity and they do not require the presence of trained personnel for application. In addition, these braces can be cleaned and present less of a threat of causing skin irritation or adverse reaction as compared to adhesive tape, and represent a substantial savings over ankle taping[28, 60]. The most common braces used in this category, aside from the Swede-O ankle brace include the McDavid™ 195 Ultralight Ankle Brace (McDavid Sports/Medical Products, Woodridge, IL), the DonJoy™ Rocket Soc® (DonJoy Orthopedics, Vista, CA) and the Arizona Ankle Brace (Pro Orthopedics, Tucson, AZ).

2.3.3. Semi-Rigid Prophylactic Braces

The first non-commercial semi-rigid ankle stabilizer, developed in 1974, was constructed of Orthoplast® (Johnson & Johnson, New Brunswick, NJ)[104] and was designed as an alternative to plaster casting. Today, these orthoses are made of various thermoplastics and plastic polymers[100] and vary in their utility from supportive to functional to prophylactic. The first generation of commercial semi-rigid ankle braces was the Aircast® Air-Stirrup (Aircast, Inc., Summit, NJ). Due to the size of the bi-malleolar strut, this brace was found to be most effective when used following acute injury as a means of support during weight bearing[104]. To address the potential uses of such a brace as a prophylactic stabilizer, modifications of the original design have resulted in a more streamlined, lighter brace that permits greater functional capability while not sacrificing the original notion of maximizing ankle stabilization. Over time, many others have followed suit and today there are a number of semi-rigid prophylactic ankle braces available commercially including the Aircast® Air-Sport™ (Aircast, Inc., Summit, NJ), the DonJoy™ ALProtector Plus (DonJoy Orthopedics, Vista, CA), and the Active Ankle "CF Pro" (Active Ankle Systems, Louisville, KY).

2.4. Comparison of Ankle Taping versus Bracing in Preventing Ankle Injury

A considerable volume of literature has been reported to illustrate the effectiveness of taping[45, 48, 51-54, 57, 97, 99] and bracing[14, 25, 30, 32, 49, 50, 55, 57, 58, 61, 104-107] in reducing injuries to the ankle. Equally substantial are the number of investigations comparing these two modes under various experimental conditions[11, 13, 17, 19-21, 23, 28, 33, 45-47, 60, 61, 108]. Based on reported literature, no clear consensus has yet to be reached as to the most effective method of prophylaxis. From the perspective of reducing excessive sub-talar joint motion in the ankle, both taping and bracing have been proven to be effective[11, 17, 19, 21, 23, 28, 30, 33, 46, 49-55, 57, 58, 99, 105]. When considering functional performance, a critical variable when selecting an external support, both ankle taping[13, 21, 60, 109] and bracing[13, 14, 55, 59-61, 106, 109] have been met with much debate with respect to which support style provides the greatest degree of prophylaxis while simultaneously minimizing impact on performance. To date there has been no consensus reached due in large measure to the wide variety of possible functional tasks to be considered as well as the considerable variation involved in subjective preference of the wearer.

While all researchers agree the application of some form of external ankle support is preferential to the unprotected ankle for decreasing the incidence of lateral ankle sprains, the mechanism by which these supports afford additional protection remains unclear. Taping and bracing share the applied moment with the ankle and achieve a stiffness that is higher than the ankle alone provides[19]. However, it is questionable whether taping and bracing can withstand the forces of an inversion sprain[12].

From a functional point of view, the mechanical limitation of extreme inversion should be a requirement. At the same time, a high degree of neuromuscular activation is desirable to protect the joint against inversion injury[110]. Relative to this position, more emphasis is now being placed on defining the role external ankle supports play in influencing the neuromuscular characteristics of the ankle joint and how such influence might impact the ability of the support device to contribute to injury prevention.

2.5. Impact of Prophylactic Ankle Support on Measures of Proprioception

There is increasing evidence to suggest the application of external support may contribute to ankle joint proprioception and an increase in neuromuscular control. What remains unclear is the mechanism by which this proprioceptive influence is achieved be it through stimulation of the various peripheral afferent receptors surrounding the joint leading to improved reflex responses or heightened pre-activation of the muscles crossing the ankle resulting in greater stiffness of the joint, or both. Many investigators[83, 91, 111-113] have demonstrated that peripheral afferents are present in different concentrations in and around various joints in the body and have been identified in the skin, muscle, ligaments and joint capsule. These receptors contribute to the proprioceptive input of the ankle in response to deformation and loading of the tissues that compose the joint[39]. Based on the conflicting results of experiments measuring the mechanical efficacy of external ankle supports, it has been suggested that the true benefit of prophylactic devices may not be biomechanical reinforcement but, rather, proprioceptive enhancement[18]. The extent to which neural receptors contribute to observed support-related changes in neuromuscular function of the ankle, and the conditions under which they contribute are not entirely clear[18].

It is clear that muscle and ligament mechanoreceptors play an important role in functional joint stability[114], but cutaneous receptors have often been overlooked[115]. In normal, healthy individuals, the protective muscular reflex arc is initiated by mechanoreceptors and muscle spindle receptors. Stimulation of the cutaneous and/or articular afferents may result in increased speed and quality of muscle activation[103]. This heightened state of readiness may possibly decrease the incidence or severity of injury. Nishikawa and Grabiner[43] demonstrated that application of an external support was responsible for an increase in peroneal motoneuron excitability compared to the non-braced condition. They attributed this increased motoneuron excitability to stimulation of peripheral afferents possibly arising from a number of candidate mechanoreceptors, one of which was likely cutaneous receptors. The application of ankle tape or a brace, through greater tissue and joint compression, may heighten the sensitivity of the cutaneous receptors and contribute to an increased dynamic restraint mechanism in the face of imposed joint stresses and tissue deformation[43]. These results are supported by Ashton-Miller et al.[31] who demonstrated prophylactic support may protect the ankle at 15º of inversion by almost doubling its baseline resistance to further inversion through increased activation of the peroneal muscles as compared to the unprotected ankle.

Measures of postural control have often been employed to assess the efficacy of prophylactic support in the ankle. Feuerbach and Grabiner[116] determined the application of an Aircast® brace resulted in a significant reduction of medial-lateral and anterior-posterior center of force position and amplitude measurements. Calmels et al.[117] found that an elastic stocking reduced anterior-posterior sway, but not medial-lateral sway. In both of these investigations, results were demonstrated in healthy subjects. In contrast to these findings, Kinzey et al.[118] assessed the effects of three selected ankle braces on postural control and found that center of pressure patterns in the anteroposterior and mediolateral directions were increased with the eyes opened and remained unchanged when sensory modalities were conflicted under the braced conditions. Further, Bennell and Goldie[24] compared different types of ankle support on postural sway and error measurements as determined by nonsupport foot contacts. Their results showed an increase in mediolateral sway measurements as well as error measurements under both ankle taping and a lace up brace conditions.

Joint position sense measures have traditionally been another method of determining prophylactic support effectiveness. Based on observed results of position sense investigations, it appears the application of a commercial prophylactic brace or adhesive tape may enhance ankle joint proprioception in both healthy and injured subjects. Using a healthy sample, Heit et al.[103] demonstrated improved joint position sense in both plantarflexion and inversion under the taped condition, while braced condition improvements were seen only in plantarflexion as compared to non-support controls. These results are reflective of findings in studies examining similar variables about the knee as well. Lephart et al.[119] found knee joint kinesthesia was enhanced following the application of a neoprene sleeve, while Barrett et al.[120] demonstrated patients with osteoarthritis and those who underwent total knee arthroplasty had improved joint position sense when wearing an elastic bandage. At the ankle, Feuerbach et al.[121] determined both absolute and variable error in the passive reproduction of passive positioning was significantly reduced with the application of an Aircast® Air-Stirrup brace. In this study, the introduction of anesthesia into one or two of the lateral ligaments of the ankle (anterior talofibular and calcaneofibular ligaments) had no effect on error measures relative to the non-anesthetized ligaments. These results suggest ligament mechanoreceptors contribute little to ankle joint proprioception and lend greater credence to the influence of cutaneous receptors in providing adequate feedback for positioning tasks. These authors[121] are clear in stressing that it remains unknown whether anesthesia of an ankle ligament would affect ankle joint proprioception during a more challenging task, although there is some evidence of similar findings at the knee[122] and in a more recent investigation at the ankle[123].

In general, postural sway and position sense data are only of limited functional relevance because they describe the mechanism of proprioception in terms of balance during a minimally challenging stance task, or on the unloaded foot in an open kinetic chain position. As such, functional perturbation testing appears to be of greater value because the pathophysiologic inversion injury movement is similar. The assessment of external ankle support based exclusively on range of motion tests is also questionable because it does not adequately take into account the functional unity of mechanical and neurophysiologic actions and their relation to the external stimulus[110].

2.6. Ankle Neuromuscular Response to Sudden Inversion

In order to further elucidate the contribution of the neuromuscular elements in minimizing the effects of a lateral ankle sprain mechanism, several investigators have conducted research in which the ankle was subjected to a sudden inversion by means of a number of unilateral tilt platform designs. In doing so, the focus of this research has been to substantiate the activity of the muscles that play a role in attenuating the imposed forces on the loaded ankle joint. More specifically, this work has centered on identifying reflex latencies, defined as the time from the onset of an inversion moment to the first motor response. This is often determined by calculating amplitude percentages in relation to a maximal voluntary contraction (MVC) or multiples of standard deviations above resting baseline EMG values[124, 125]. To date, much of the work in this area has been limited to studies conducted on subjects who demonstrated varying degrees of confirmed clinical and/or functional instability, absent the application of some form of external ankle stabilizer[33, 41, 42, 126, 127]. Further, the majority of findings have been reported on peroneal muscle activity[29, 33, 42, 125, 127, 128], but, to a lesser extent, the tibialis anterior[25, 41, 124, 126, 129].

Of the limited evidence that does exist to qualify the effect of a lateral perturbation moment and the application of an external stabilizer on the healthy ankle, there does not appear to be any statistically significant difference between the supported and unsupported ankle with regard to reflex latencies of the peroneus longus or tibialis anterior[25, 29]. This is not an unexpected result considering previous authors have reported similar findings in patients with unstable ankles as compared to normal controls[126, 128, 130].

It remains to be seen if these same results would be observed if subjects were exposed to a more demanding dynamic task. During functional activity, there is a level of pre-activation that exists in the muscle contributing to increased joint stiffness and stabilization. Due to the fact that little evidence exists to assess the impact of an ankle stabilizing device during a dynamic landing task, such an influence can only be speculated at this time. All of the studies reported to date in which a perturbation variable was introduced have been conducted in either a static stance or step down position. While it is difficult to recreate the exact mechanism of injury in a laboratory setting, it is apparent that injuries rarely occur with the person standing at rest. Also of interest is the degree of perturbation subjects are exposed to during sudden inversion trials in previous investigations. The classic model for these studies has used ankle inversion perturbations ranging from 18º[124] to 50º[58, 131]

2.7. Role of Electromyography in Assessing Ankle Neuromuscular Activity

The measurement of electrical activity within a resting or contracting muscle is called electromyography (EMG). The raw EMG signal is a collection of information from representative motor unit action potentials and is measured in millivolts. The individual motor unit action potential is a sinusoidal wave generated at the z-line of the sarcomere[132]. Deformation of muscle-tendon tissue causes a mechanically gated release of stored sodium from the transverse tubular system, eliciting an increase in action potentials, thereby increasing neural input to the central nervous system[133].

EMG recordings can provide useful information relative to the amplitude and duration of EMG activity. The signals are recorded using either surface or fine wire, indwelling electrodes. As this investigation was limited to the use of surface EMG recordings, the following review will focus only on this method.

Surface electrodes are utilized for more superficial recordings and tend to collect information from a large area. This method has been shown to be a reliable means of EMG assessment for both the tibialis anterior and peroneal muscles[63, 124, 125]. However, the use of surface electrodes introduces the possibility of recording unwanted information from other muscles, referred to as crosstalk[124]. This can be reduced by the use of the double differential technique as described by Koh and Grabiner[134]. Equally important is appropriate electrode placement in limiting the risk of crosstalk. Basmajian and Blumenstein[135] have authored the classic description of appropriate electrode placement for the tibialis anterior and peroneus longus as follows: a) tibialis anterior - junction of the proximal and middle one third of the tibia, 1cm lateral to the subcutaneous lateral border; b) peroneus longus - junction of the proximal and middle one third of the fibula, over the palpable lateral compartment. An earth electrode is also required and is typically placed over an area of little muscle activity, usually a bony prominence.

Following electrode placement, the desired sampling frequency must be determined. This is based on the expected speed of the movement that is being observed and is normally set at twice the level of the highest frequency of the signal itself[132]. If analyzing between subject data, the EMG signal then requires normalization. As stated previously, amplitude values are typically normalized as a percentage of the MVC or as a percentage of the baseline resting values[124, 125, 136].

When measuring the reflex response of ankle musculature in the face of an inversion perturbation mechanism, evidence from previous investigations using EMG data have been useful in describing the speed of conduction of the neural signal from the afferent receptor, through central processing, and finally to the efferent end organ response. In essence, EMG data for muscles can be divided into three subsets as defined by Lynch et al.[124] In the passively lengthened or stretched muscle group, a short-loop latency reflex occurs within 50 ms, representative of a monosynaptic (only one synapse) reflex arc in which the afferent neuron synapses directly with the α-MN. This reflex is not present in every muscle group. An example of this type is the stretch reflex in which the muscle spindle is stimulated in response to tissue deformation of the muscle. This stimulus provides afferent information that synapses directly with the α-MN of the stretched muscle, ending in a reflexive muscle contraction.

Next, a medium-loop reflex occurs between 70 and 120 ms. This reflex occurs in the stretched muscle group as well and is thought to represent a polysynaptic (more than one synapse) reflex arc[124]. The polysynaptic reflex involves a synapse between the afferent neuron, carrying information from the periphery (muscle or joint), with one or more interneurons where the signal is processed and finally transmitted through a synapse with the α-MN. Clinically, the ligamentous-muscular reflex is used to illustrate the polysynaptic reflex[137]. Solomonow et al.[89] demonstrated that deformation of the anterior cruciate ligament in the knee elicited an excitatory response of the hamstring musculature and a concomitant inhibitory response of the quadriceps musculature.

The final reflex response is the long loop reflex which occurs approximately 75 ms after the onset of the medium-loop reflex and may represent a transcortical reflex. This is the antagonistic response seen with postural disturbances in the non-stretched muscle group[124].

The work by Lynch et al.[124] confirmed the findings of Brunt et al.[129] who observed no short-loop reflex in either the peroneus longus or tibialis anterior. Latencies were measured from medium-loop reflexes for the stretched muscle group and long-loop reflexes from the non-stretched muscle group. In interpreting this information, it is apparent that the peroneus longus responds quickly to counter the inversion moment following perturbation, while the tibialis anterior follows soon after to overcome a plantarflexion torque and place the ankle in the more stable dorsiflexed position. Historically, these reflex arcs were believed to play a primary role in joint stabilization. The prevailing evidence, however, is that the latencies that result may be too long and the reflexes not strong enough to avoid joint injury[138].

It has become clear that reflexes from joint afferents may be transmitted via pathways other than those projecting to the α-MN. Thus, the pathways from joint afferents to the muscle spindles via γ-MN have drawn increasing attention, particularly since the effects on the γ-MN are often more potent and elicited at lower stimulation thresholds[92]. The development of this theory has helped to better define what are referred to as the feedback and feedforward mechanisms of motor control[73].

The feedback mechanism is considered more of a reactive reflex characterized by numerous reflex pathways that continuously adjust muscle activity. Feedback control describes actions occurring in response to the detection of the direct effects of the arrival of an event or stimulus to the system. The inherent electromechanical delays that result from this mechanism, however, raise the question of whether this reactive process is effective enough on its own to provide joint stabilization and protection[73, 75]. The feedforward mechanism, on the other hand, describes actions occurring in anticipation of and in response to an impending event or stimulus and suggests proprioception is valuable in the preparation for anticipated loads. It implies that an internal model is developed by utilizing information from previous experiences and integrated with current conditions in order to generate a preprogrammed strategy. The integration of these two mechanisms contributes to motor activation resulting in coordinated motor skills and dynamic joint stabilization, processes not exclusive of one another[73, 75].

As a means of illustrating this system, the preparatory excitation of α-MN is frequently accompanied by the activation of γ-MN, referred to as α-γ-MN co-activation. This co-activation increases the sensitivity of the muscle spindle to evoke a more vigorous stretch reflex. The pre-activated muscle is therefore stiffer which decreases the electromechanical delay and provides for greater joint stabilization during functional tasks. The information gathered via feedforward motor control is used to evaluate the results of a particular motor task in order to help preprogram future muscle activation strategies[73]. Based on the existing data from Ashton-Miller[138] describing joint velocities and the magnitude of force generated at the ankle joint during inversion perturbation studies, it appears the α-γ-MN co-activation is vital to preventing or minimizing the effects of an inversion ankle sprain. It appears, too, that the application of an external ankle support may also prove useful from the standpoint of stimulating peripheral afferent receptors resulting in heightened muscle spindle sensitivity through increased γ-MN activation thus contributing to greater mechanical stiffness of the ankle joint. At the spinal level, various peripheral receptors such as cutaneous and articular receptors have been shown to strongly influence the activity of the γ-MN system

2.8. Summary

It is apparent that conflict exists in the literature with regard to the effects of prophylactic ankle support on the prevention of lateral ankle sprains. Clearly the application of some form of external ankle support is effective in limiting the incidence of these injuries. However, the mechanism by which this effect is reached has yet to be fully explained. There is a great deal of evidence in the existing literature to support the use of either taping or bracing as a means of achieving greater mechanical stabilization and a growing body of literature which points to a proprioceptive benefit of such interventions.

Until recently, the role of the sensorimotor system in protecting the ankle from joint injury has not been as thoroughly investigated as other joints, but clearly its impact is substantial. The ability to further define its contribution is dependent upon the development of appropriate instrumentation that will allow for experimental measurements to be analyzed under more functional conditions.

The use of electromyography has created the opportunity to develop a reliable means for modeling the function of the sensorimotor system in an effort to better characterize the role and interactions of its component parts. Despite this, a gap remains to explain the influence of prophylactic stabilizers in further contributing to improved proprioception as measured by joint position sense, postural sway and reflex muscle latencies. The use of a dynamic model may help to close this gap by more accurately recreating the extrinsic forces imposed on the weight bearing joint while also permitting the measurement of the muscular response to such forces that is more reflective of the type of demanding tasks observed in a typical lateral ankle sprain mechanism.

3. METHODOLOGY

3.1. Experimental Design

This investigation utilized a within subjects repeated measures design. The independent variable during testing was the external support with four conditions (control - no support; closed basketweave taping; McDavid™ 195 Ultralight Ankle Brace (McDavid Sports/Medical Products, Woodridge, IL); and Aircast® Air-Sport™ (Aircast, Inc., Summit, NJ). The dependent variables during testing were the measures of peroneus longus and tibialis anterior 1) reflex latency and 2) time to peak amplitude measured by electromyographic (EMG) recording. The study was approved by the Committee for Biomedical Research of the Institutional Review Board at the University of Pittsburgh for safe use of human subjects.

3.2. Subjects

41 physically active college-aged volunteers (21 males, 20 females) with no previous history of balance disorders, neurological conditions or injury to the dominant lower extremity within the past two years comprised the sample for this investigation. For these purposes, physically active was defined as participating in regular physical activity, at least three times per week, for a duration of at least 30 minutes each. The dominant extremity was defined as the leg normally used to kick a soccer ball. Prior to any testing, subjects were explained all procedures

and were given the opportunity to ask any questions. Once the subjects were familiarized with the procedures, each was asked to sign informed consent as outlined by the Institutional Review Board for use of human subjects.

Sample size calculations were computed *a priori* using the Sample Power 1.2 (SPSS, Chicago, IL) software package. Previous data reported by Cordova et. al.[25] in a study substantially similar to this investigation were used to estimate the necessary sample size to reach a power of P=.80. Cordova compared two brace conditions to a no-treatment control with respect to the average EMG of the peroneus longus and tibialis anterior muscles. Based on the results reported by Cordova[25], the observed effect size for condition (Cohen's d) was found to be .48, considered a medium effect according to Cohen's conventions. For this study, it was found that a sample size of 40 would be necessary to reach a power of P=.80 given an effect size of η^2=.48 and an alpha of .05.

3.3. Instrumentation

All testing was conducted in the Neuromuscular Research Laboratory, located at the University of Pittsburgh Medical Center Health System Center for Sports Medicine. All subject EMG measurements for each external support condition were collected while the dominant extremity was subjected to random dynamic perturbations using a custom designed, uniaxial plate that, when loaded, imparted an inversion moment on the subtalar joint and placed stress on the lateral stabilizing structures of the ankle. A constant inversion perturbation angle of 20º was used in order to determine the influence of this mechanism on reflex latency and time to peak amplitude for the peroneus longus and tibialis anterior muscles.

3.3.1. Perturbation Device

Previous research has relied on assessing neuromuscular and musculotendinous adaptations in response to ankle perturbations using instruments which placed the subject in a static or quasi static position[29, 33, 42, 124-126, 128-130, 139]. Cordova et al.[25] advanced this model by measuring ground reaction forces and EMG responses of various lower leg muscles in response to a functional lateral movement. However, measurements were recorded on a force platform and the ankle was never exposed to a true perturbation. Grüneberg, et al.[140] developed a trap door instrument that evoked a 25º inversion perturbation following a drop landing from a 30 cm height. From this, researchers examined EMG responses of several lower leg muscles during both inversion and non-inversion landings. Similarly, Ubell et al.[36] utilized a detachable fulcrum that could be positioned on the medial aspect of the sole the shoe to generate a 24º subtalar inversion upon touchdown from a 60 cm forward jump onto a force plate. In this case researchers were interested in determining if subjects could maintain their balance and resist making contact with the lateral aspect of the foot to assess the dynamic capabilities of the peroneal musculature while wearing selected stabilizers.

For the purposes of this investigation, a custom-designed device was utilized to elicit the desired perturbation on the ankle while the subject performed a functional lateral movement. This device had the capability of resulting in an inversion stress on the subtalar joint at random intervals throughout the trial using the acceleration of gravity to carry out the perturbation. In addition, the device was designed to reset automatically to allow seamless completion of each trial.

Figure 2: Functional perturbation device

Situated within a 70”x37”x7” platform constructed of ¾” plywood (Figure 2), the functional component of this unique perturbation device consisted of a 20”x20”x1” aluminum plate that rotated on a single axis to permit inversion of the ankle in the frontal plane (Figure 3). The plate was offset from the center of the platform by 10” to permit a larger landing area opposite the direction of tilt of the plate. The stable landing platform was constructed of two pieces, latched together in line with the center of rotation of the plate. The entire surface of the platform was covered with a non-skid material to increase coefficient of friction and minimize subject slipping during the testing session. The contact area of the plate was also covered with a non-skid material and a landing marker was applied with adhesive tape which served as a target for the subject during each trial to maximize standardization of the lateral jumping task.

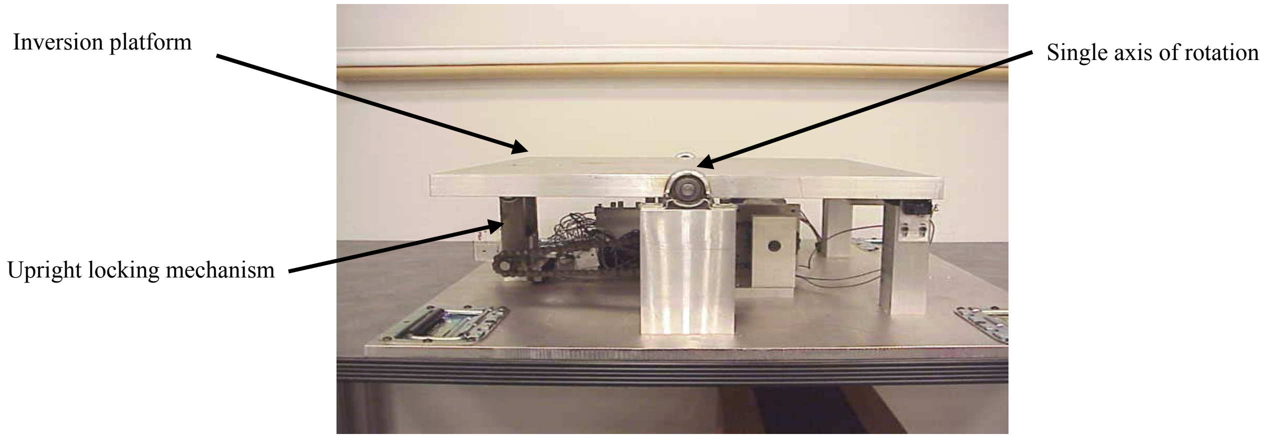


Figure 3: Functional component of ankle perturbation device

The mechanism for executing the repetitions of a particular trial were carried out by the coordinated effort of a series of switches placed in strategic locations beneath the plate. An infrared laser positioned perpendicular to the path of the subject was utilized to indicate the initiation of each trial and to count each repetition within the trial. A random number generator originating from a personal computer, and synchronized with the laser, determined when the locking mechanism of the plate was to be released to allow for a perturbation repetition to be executed. A sprocket and chain attached to a DC motor at one end, and to the locking mechanism at the other, moved the locking mechanism into and out of position depending on the signal delivered from the random number generator (Figure 4a).

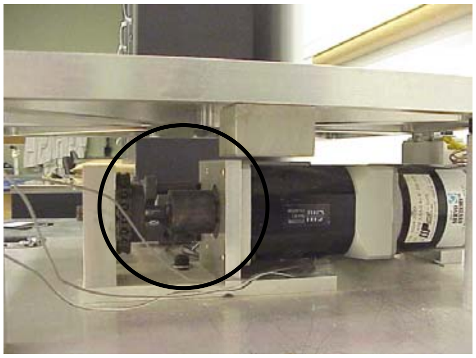
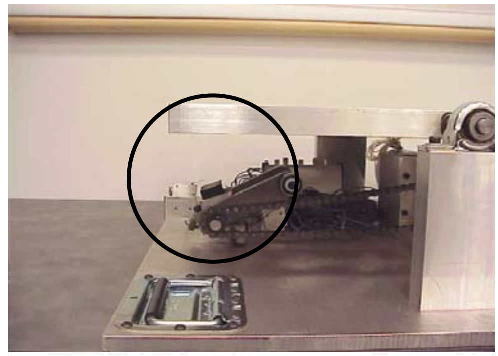
a.  b. 

Figure 4: **Mechanism enabling release of plate creating perturbation of the ankle: (a) motor and sprocket/chain assembly; (b) locking mechanism in inverted position**

When signaled to do so, the motor rotated the locking mechanism to a position that would enable a perturbation repetition to occur (Figure 4b). The absence of the locking mechanism permitted movement from the neutral to the perturbated position. The amplitude of the inversion perturbation was held constant at 20º by a rotation stopping block affixed to the frame of the device. As a load was applied, a switch connected to the underside of the plate was broken, signaling subject contact. More importantly, this signal was used to set an event marker indicating the onset of the perturbation and the period in the repetition when the reflex latency and time to peak amplitude measurements were to be initiated (Figure 5).

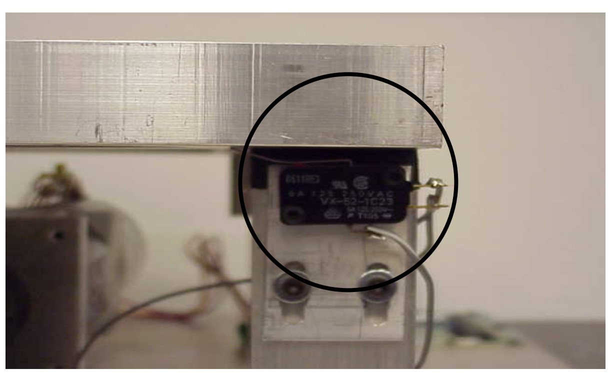


Figure 5: Switch designed to signal subject contact and indicate onset of perturbation

This information was then synchronized with the EMG data to determine the length of the reflex latency period and the time elapsed to reach peak amplitude for both the peroneus longus and tibialis anterior. A switch attached to the stopping block communicated with the plate and signaled the fully inverted position (Figure 6). As the plate was unloaded, a counterweight facilitated its movement back to the neutral position. This movement interrupted the communication between the plate and the switch on the stopping block and signaled the motor to return the locking mechanism to the upright and locked position.

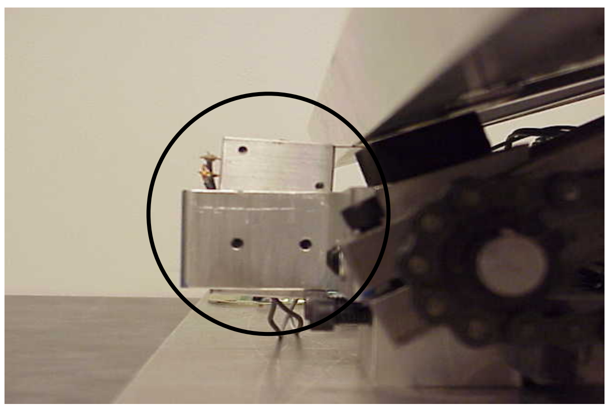


Figure 6: Switch designed to signal fully inverted position

3.3.2. Ankle Orthoses

For this investigation, a traditional closed basketweave method of ankle taping was utilized as one mode of external support (Figure 7)[141]. This method employed the use of 1-1/2 inch adhesive cloth tape, applying a series of three alternating stirrups and horseshoes to restrict motion of the talocrural joint. Next, a figure-of-eight strap was applied followed by two consecutive heel locks to secure the subtalar joint. The procedure was completed by applying circumferential strips to close any gaps in the tape and to anchor any loose ends. An adhesive spray and layer of underwrap was applied to the lower leg prior to beginning the taping procedure to prevent any irritation from the tape-skin interface. In the event that a subject reported an allergy to any of these materials, hypoallergenic replacement materials were available as an alternative. All taping procedures were performed by the Principal Investigator in order to maintain consistency of this condition.

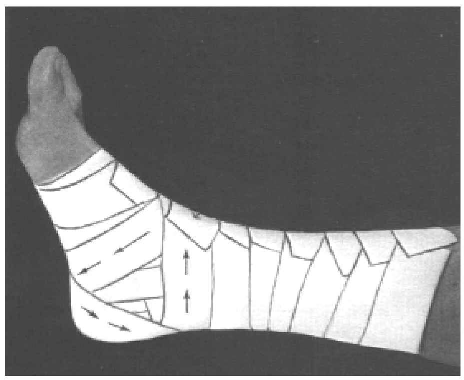


Figure 7: Closed basket weave ankle taping

The second mode of external support used was the McDavid™ 195 Ultralight Ankle Brace (McDavid Sports/Medical Products, Woodridge, IL) (Figure 8). This is a soft orthosis, fashioned as a lace-up brace, with two subtalar straps that closely resemble the function of the heel lock mechanism of the cloth taping procedure. This device is fitted according to the shoe size of the wearer. It is slipped onto the foot and ankle over an athletic sock and laced sufficiently tight to provide compression to the joint while not compromising the subject's comfort. The straps are then alternately crossed over the dorsum of the foot and passed through the medial and lateral longitudinal arch where they are then secured by Velcro® fastening to the medial and lateral aspect of the lower leg.

Figure 8: McDavid™ 195 Ultralight Ankle Brace

The third mode of external support was the Aircast® Air-Sport™ (Aircast, Inc., Summit, NJ) (Figure 9). This is a second generation air stirrup constructed of a nylon and neoprene shell with two semi-rigid lateral struts lined with a foam filled air cell on the surface that contacts the wearer's leg. This device is also fitted based on the shoe size of the wearer. The brace is open in the back and is similarly slipped onto the foot and ankle over an athletic sock. It is then secured by a single posterior strap to stabilize the lateral struts and finally by a single subtalar strap that obliquely crosses the dorsum of the foot and anterior lower leg to attach at the top of the brace by a Velcro® fastener.

Figure 9: Aircast® Air-Sport™

The order in which the external support conditions were assigned was counterbalanced using a Latin squares design, as suggested in Cochran and Cox,[142] in order to negate the order effect of the treatments, and was determined prior to the first testing session for each subject.

3.3.3. Electromyography System

Electromyographic activity was recorded and assessed using the Noraxon Telemyo Electromyography System (Noraxon USA, Inc. Scottsdale, AZ). The Telemyo system is a frequency modulated (FM) telemetry system. EMG signals collected from the electrodes were passed through a single-ended amplifier (gain 500) to an eight channel FM transmitter. A receiver unit obtained the telemetry signals from the transmitter where they were amplified and filtered (15 Hz low pass, 500 Hz high pass Butterworth filter, common mode rejection ratio of 130 db). Signals from the receiver were converted from analog to digital data by way of a PCM

16S/12 (16 channel, 12 bit) A/D board (ComputerBoards, Middleboro, MA) at a rate of 1000 Hz. The digital data were collected and stored with Myoresearch 2.02 (Noraxon, Scottsdale, AZ) on a personal computer for data reduction.

3.4. Experimental Protocol

Following the completion of informed consent and a brief screening to determine inclusion criteria had been satisfied, subjects were given an orientation of the testing procedures. The preparation and instrumentation being employed in the study was explained and demonstrated and subjects were given an opportunity to practice the functional protocol to be utilized. In addition, subjects were required to complete a 10 minute warm-up on a bicycle ergometer to minimize the potential for injury during the testing procedures.

3.4.1. EMG Acquisition

Prior to testing, the subject's skin was prepared by marking the midpoint of the muscle bellies of the peroneus longus and tibialis anterior. This was followed by the removal of any visible hair, lightly abrading the area with a callous file and cleaning the skin with isopropyl alcohol to minimize skin-electrode impedance. Electrode placement was accepted if resistance was <10 kΩ. Two bipolar Ag/Ag-Cl surface electrodes (Medicotest, Inc., Rolling Meadows, IL) were then placed on the skin over the most prominent portion of the muscle bellies perpendicular to the line of function of the muscle fibers. A single ground electrode was also placed on the anteromedial tibial flare (Figure 10). Excessive movement of the wires connecting the electrodes to the FM transmitter was controlled with the use of foam underwrap and adhesive tape. A five-second isometric manual muscle test of each muscle was then conducted to ensure proper electrode placement and to verify minimal crosstalk between electrodes[135]. Reliability of surface electrode EMG has been previously established[143]. For this investigation, intraclass correlation coefficients were calculated within session for the peroneus longus (r=.73) and the tibialis anterior (r=.87). In this case, surface EMG was found to be reliable and repeatable.

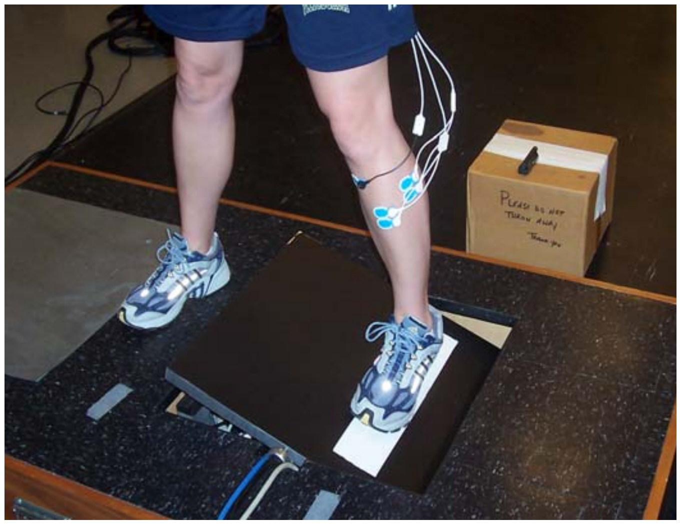


Figure 10: Electrode placement for EMG analysis of PL and TA

Two channels were used to measure the electrical activity of the peroneus longus and tibialis anterior. EMG signals were conveyed to the FM transmitter worn by the subject in a custom back pack. The receiver filtered and further amplified the analog signals before converting them to digital data by means of an A/D card (ComputerBoards PCM 16S/12, ComputerBoards, Inc., Middleboro, MA). The signals were then passed to a computer where they were stored for offline processing.

3.4.2. Testing Procedures

The specific testing procedures required each subject to perform a series of lateral jumps starting from a position on the landing platform of the perturbation device such that the dominant limb was adjacent to the moving plate. The subject was instructed to jump onto the plate, making contact on the landing marker with the dominant limb only, followed by a return to the starting position as quickly as possible. This sequence was continued for a total of 18 repetitions, seven of which included a release of the locking mechanism of the plate to facilitate perturbation of the ankle when loaded. Following each trial for a given condition, the subjects were given a period of two minutes to rest. The procedure was then repeated a second time before the support condition was changed. Any knowledge of when the platform was released by way of audible cues was eliminated by employing white noise (static) delivered through headphones to the subject. A computer-generated flashing metronome set at 72 beats·min^{-1} was utilized to pace the subjects during the jumping task and to further standardize the procedures across subjects. The repetitions for each condition in which a perturbation occurred were sampled to determine mean reflex latency and time to peak amplitude for each muscle. All data for the four support conditions was collected in a single session, which took approximately 90 minutes to complete. All subjects were asked to wear similar cross-training athletic shoes.

3.5. Trial Data Reduction

Muscle reflex latency and time to peak amplitude was calculated for the peroneus longus and tibialis anterior (Figure 11). Reflex latency was calculated as the time interval in milliseconds between the onset of the perturbation and a rise in the EMG amplitude of 3 standard deviations above the mean value of EMG activity at the instant immediately preceding foot contact with the rotating plate prior to perturbation [124, 136, 144]. Reflex latency durations within a 20ms and 150ms window (shadow box) following perturbation onset were considered legitimate as these values reflect the predicted response latency of a short or medium loop reflex[108, 110, 140, 144]. Trials in which the EMG values did not reach the 3SD threshold, or which fell outside of the 20-150 ms window, were not included in the analysis. Time to peak amplitude was calculated as the time in milliseconds within the same 20-150 ms window following perturbation when the highest amplitude of muscle activity was recorded.

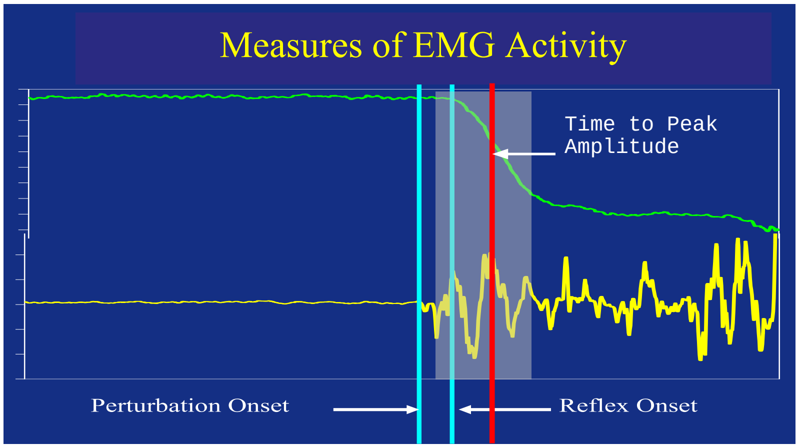


Figure 11: Illustration of EMG with perturbation event, reflex onset and time to peak amplitude markers

3.6. Data Analysis

A one-way repeated measures analysis of variance (ANOVA) was employed to determine if significant differences existed in reflex latency and time to peak amplitude for the peroneus longus and tibialis anterior muscles across the four support conditions. When applicable, this was followed by multiple dependent t-tests with Bonferroni corrections to identify which conditions were statistically different to address hypotheses described in Specific Aim 1. From these tests, any differences that existed between the three support conditions were also established to address the hypotheses in Specific Aim 2. Additionally, multiple independent t-tests were conducted to determine if any significant differences existed between the peroneus longus and tibialis anterior across the four support conditions to address hypotheses in Specific Aim 3. Statistical significance was set *a priori* at an alpha level of $p<.05$.

4. RESULTS

The purpose of this study was to determine the impact of three selected modes of prophylactic support on measures of peroneus longus and tibialis anterior muscle activity relative to a no support, control condition and calculated in response to a constant inversion perturbation amplitude of 20º. A within-subject repeated measures design was utilized for this investigation. The dependent variables were 1) reflex latency measured as the time interval (milliseconds) between the onset of the perturbation and a three standard deviation rise from the muscle activity immediately prior to the perturbation; and 2) time to peak amplitude defined as the time (milliseconds) following perturbation when the greatest amount of muscle activity was recorded. Each was calculated independently for the peroneus longus and tibialis anterior respectively. The independent variable was prophylactic support with four conditions (control - no support; closed basketweave taping; McDavid™ 195 Ultralight Ankle Brace (McDavid Sports/Medical Products, Woodridge, IL); and Aircast® Air-Sport™ (Aircast, Inc., Summit, NJ).

4.1. Subject Characteristics

The subjects in this study consisted of 41 healthy male and female college-aged volunteers (21 males, 20 females). Descriptive statistics (mean ± standard deviation) for subjects are presented in Table 1. All of the participants were physically active, defined as taking part in moderate exercise at least three days per week for a minimum of 30 minutes each day.

Additionally, all subjects reported no history of injury to the lower extremities during a two year period prior to testing. Finally, 39 of the 41 subjects were right foot dominant, defined as the foot that would be used to kick a ball.

Table 1: Subject characteristics

	Males (21)	Females (20)	Total
Age	21.9 ± 2.5	22.5 ± 2.7	22.2 ± 2.62
Height (m)	1.80 ± .06	1.66 ± .06	1.73 ± .09
Weight (kg)	81.56 ± 10.93	60.60 ± 6.02	71.08 ± 13.73

4.2. Muscle Reflex Latency

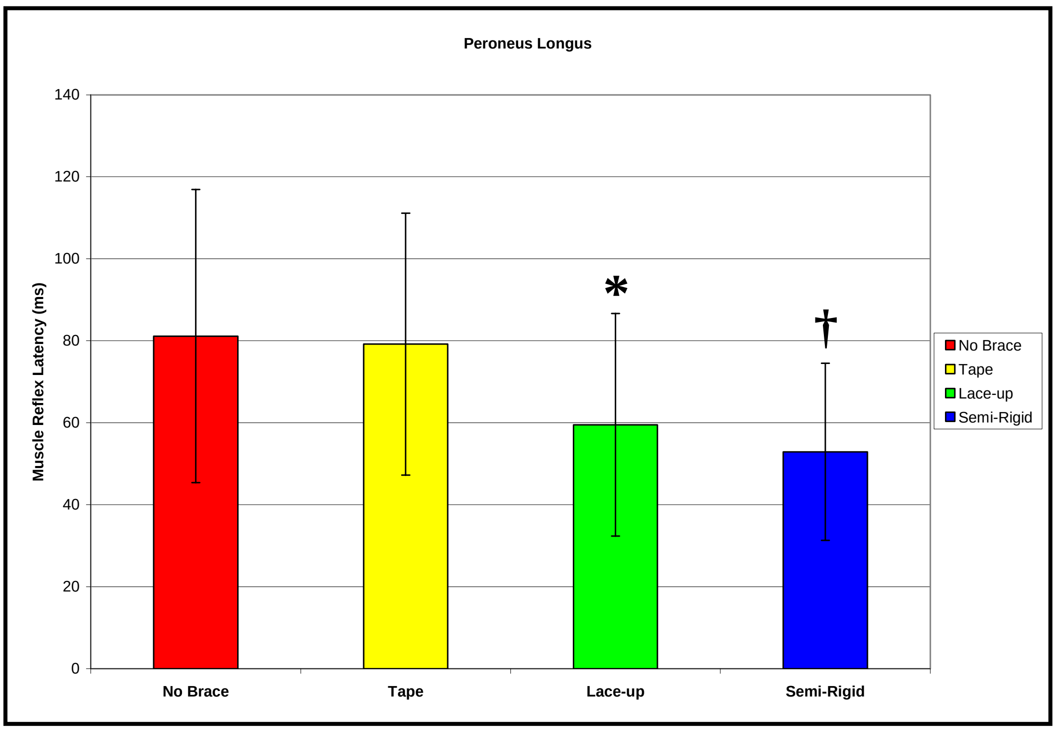
Muscle reflex latency for the peroneus longus and tibialis anterior was defined as the time period between the onset of the perturbation and a three standard deviation rise from the muscle activity immediately prior to the perturbation, and within a 20 ms to 150 ms window following perturbation onset which reflects the predicted response latency of an intermediate or long loop reflex. The descriptive statistics (mean ± standard deviation) for muscle reflex latency data for the peroneus longus and tibialis anterior appear in Table 2 and Table 3 respectively. A graphical representation of the peroneus longus muscle reflex latency is presented in Figure 12, while the tibialis anterior is presented in Figure 13. A separate one-way repeated measures ANOVA was used to evaluate the effect of prophylactic support condition on the reflex latencies of each of the two muscles in question. When applicable, multiple dependent t-tests with Bonferroni corrections were conducted to identify which conditions were statistically different.

In calculating the reflex latency values for the peroneus longus and tibialis anterior, the selection of the criteria for reflex onset of 3 standard deviations resulted in attrition equal to six subjects for the peroneus longus and four subjects for the tibialis anterior. The goal of these statistical tests was to average the maximum number of trials that would permit the maintenance of a power of $P=.80$ for a given sample size. Considering this, the maximum number of three trials was arrived upon. This resulted in $n=35$ (85%) and an observed power of $P=.994$ for the peroneus longus and $n=37$ (90%), $P=.916$ for the tibialis anterior.

Significant differences were observed across conditions for the peroneus longus ($F=8.754$, $p<0.001$) and tibialis anterior ($F=5.162$, $p=0.002$). Statistical significance was set at $p<0.008$ for individual brace condition differences after Bonferroni correction was applied. Specifically, with respect to the peroneus longus, the lace-up brace condition demonstrated a significantly shorter reflex latency than the no brace ($t=3.128$, $p=0.004$) condition. Additionally, the semi-rigid brace condition demonstrated statistically significant shorter reflex latencies than the no brace ($t=4.042$, $p<0.001$) and tape ($t=4.197$, $p<0.001$) conditions respectively. No significant differences were observed when comparing the tape condition to the no brace ($t=-0.266$, $p=0.16$) and lace-up brace ($t=2.661$, $p=0.01$) conditions respectively nor when comparing the lace-up and semi-rigid ($t=1.232$, $p=0.16$) brace conditions.

Table 2: Muscle reflex latencies for peroneus longus across four conditions

Brace Condition	Peroneus Longus (n=35)
No Brace	81.14 ± 35.75
Tape	79.19 ± 31.94
Lace-up Brace	59.51 ± 27.14
Semi-Rigid Brace	52.90 ± 21.61



* Muscle reflex latency was significantly shorter for the lace-up brace condition compared to the no brace condition

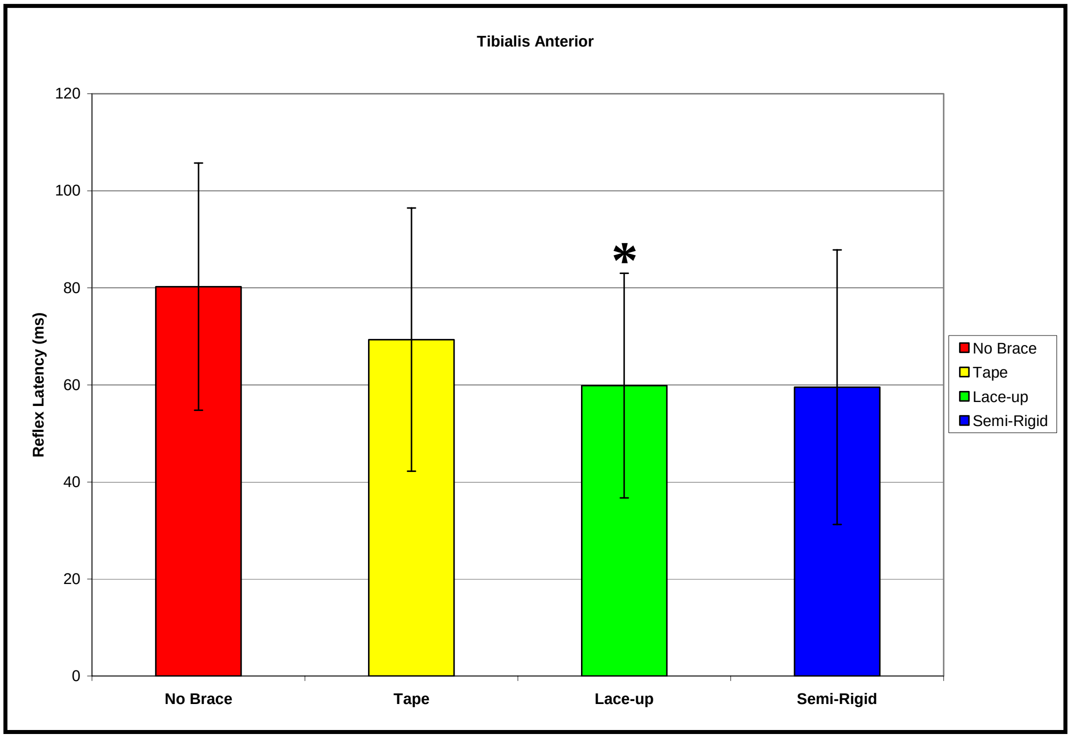
† Muscle reflex latency was significantly shorter for the semi-rigid brace condition compared to the no brace and tape conditions

Figure 12: Peroneus longus muscle reflex latencies

For the tibialis anterior, the lace-up brace condition demonstrated a statistically significant shorter reflex latency than the no brace ($t=3.708$, $p<0.001$) condition. Non-significant values were observed when comparing the tape condition to the no brace ($t=-2.038$, $p=0.05$), lace-up ($t=1.507$, $p=0.13$), and semi rigid ($t=1.468$, $p=0.14$) brace conditions; the lace-up to the semi-rigid ($t=0.074$, $p=0.16$) conditions; and the semi-rigid and no brace ($t=-2.703$, $p=0.01$) conditions.

Table 3: Muscle reflex latencies for tibialis anterior across four conditions

Brace Condition	Tibialis Anterior (n=37)
No Brace	80.26 ± 25.48
Tape	69.32 ± 27.11
Lace-up Brace	59.86 ± 23.15
Semi-Rigid Brace	59.52 ± 28.31



* Muscle reflex latency was significantly shorter for the lace-up brace condition compared to the no brace condition

Figure 13: Tibialis anterior muscle reflex latencies

4.3. Time to Peak Amplitude

Time to peak amplitude for the peroneus longus and tibialis anterior was defined as the time (milliseconds) within a 20 ms to 150 ms window following perturbation when the highest amplitude of muscle activity was recorded. The descriptive statistics (mean ± standard deviation) for time to peak amplitude data for the peroneus longus and tibialis anterior appear in Table 4 and Table 5 respectively. A graphical representation of the peroneus longus time to peak amplitude is presented in Figure 13, while the tibialis anterior is presented in Figure 14. A one-way repeated measures ANOVA was used to evaluate the effect of prophylactic support condition on the time to peak amplitude of the two muscles. When applicable, multiple dependent t-tests with Bonferroni corrections were conducted to identify which conditions were statistically different.

Significant differences were observed across conditions for the tibialis anterior (F=7.533, p<0.001). Statistical significance was set at p<0.008 for individual brace condition differences after Bonferroni correction was applied. Specifically, the lace-up brace condition demonstrated statistically significant shorter time to peak amplitude than the no brace (t=2.815, p=0.007) condition. Additionally, the semi-rigid brace condition demonstrated a statistically significant shorter time to peak amplitude value than the no brace (t=3.474, p=0.001) and tape (t=4.154, p<0.001) conditions respectively. Non-significant values were observed for the tibialis anterior when comparing the tape to the no brace (t=-0.160, p=.16) and lace-up brace (t=2.298, p=0.026) conditions, as well as when comparing the lace up to the semi-rigid (t=1.050, p=0.16) brace condition. No significant differences were observed across any of the brace conditions for the peroneus longus (F=2.378, p=0.073).

Table 4: Time to peak amplitude for peroneus longus across four conditions

Brace Condition	Peroneus Longus (n=41)
No Brace	115.98 ± 29.52
Tape	113.52 ± 31.72
Lace-up Brace	106.28 ± 29.02
Semi-Rigid Brace	101.59 ± 25.36

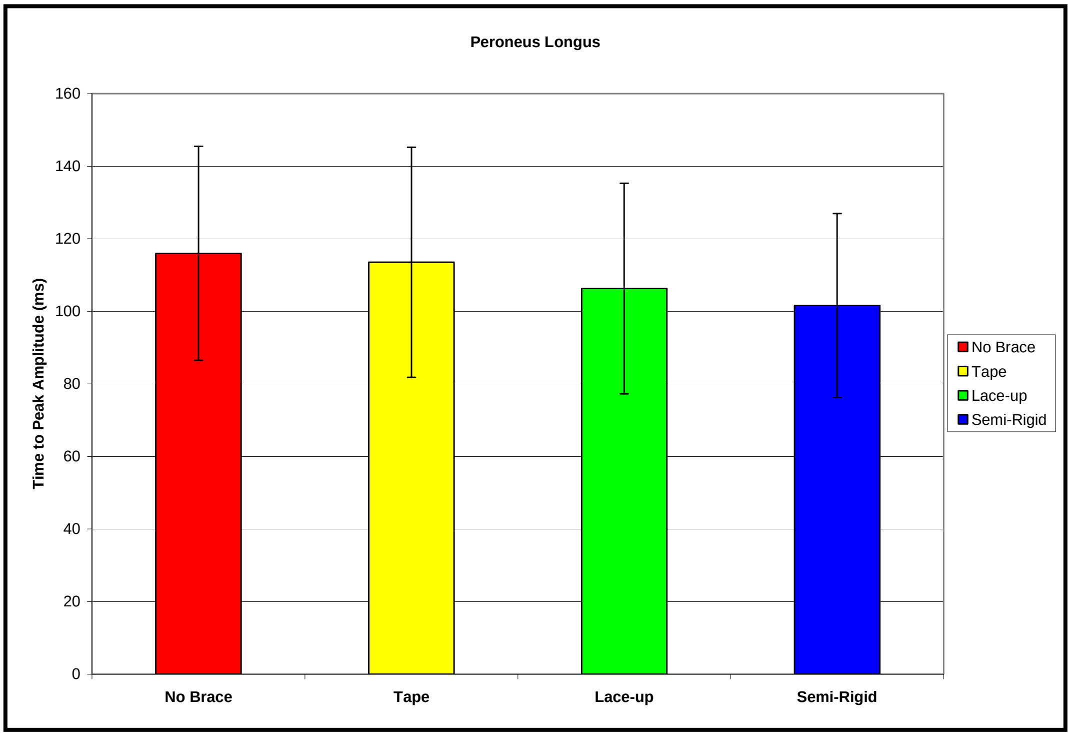
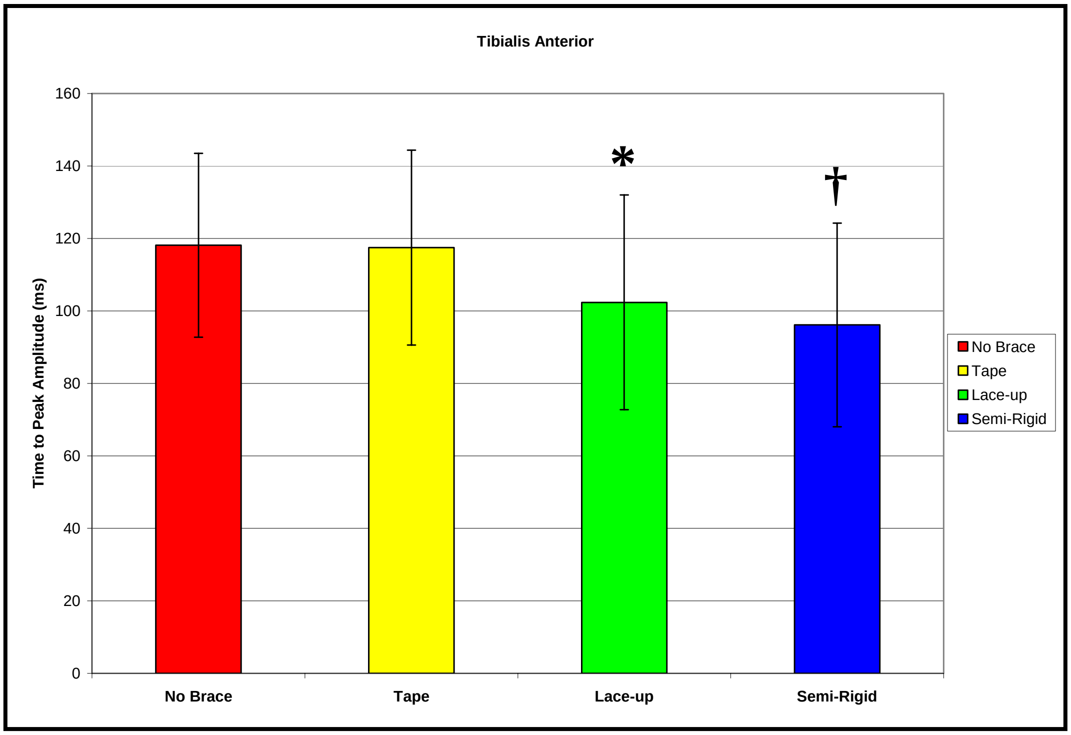


Figure 14: Peroneus longus time to peak amplitude

Table 5: Time to peak amplitude for tibialis anterior across four conditions

Brace Condition	Tibialis Anterior (n=41)
No Brace	118.13 ± 25.36
Tape	117.47 ± 26.88
Lace-up Brace	102.37 ± 29.64
Semi-Rigid Brace	96.15 ± 28.08



* Time to peak amplitude was significantly shorter for the lace-up brace condition compared to the no brace condition
† Time to peak amplitude was significantly shorter for the semi-rigid brace condition compared to the no brace and tape conditions

Figure 15: Tibialis anterior time to peak amplitude

4.4. Comparison of Peroneus Longus and Tibialis Anterior

Independent t-tests were utilized to determine if any statistically significant differences in muscle reflex latency and time to peak amplitude respectively existed between the peroneus longus and tibialis anterior across the four prophylactic support conditions. Descriptive statistics (mean ± standard deviation) for muscle reflex latency data for the peroneus longus and tibialis anterior appear in Table 2 and Table 3 respectively. A graphical representation of the peroneus longus and tibialis anterior muscle reflex latency comparison data is presented in Figure 16. No statistically significant differences were observed between the peroneus longus and tibialis anterior with respect to muscle reflex latency for the no brace (t=.025, p=0.98), tape (t=1.431, p=0.16), lace-up (t=.139, p=0.89), or semi-rigid (t=-1.12, p=0.27) conditions.

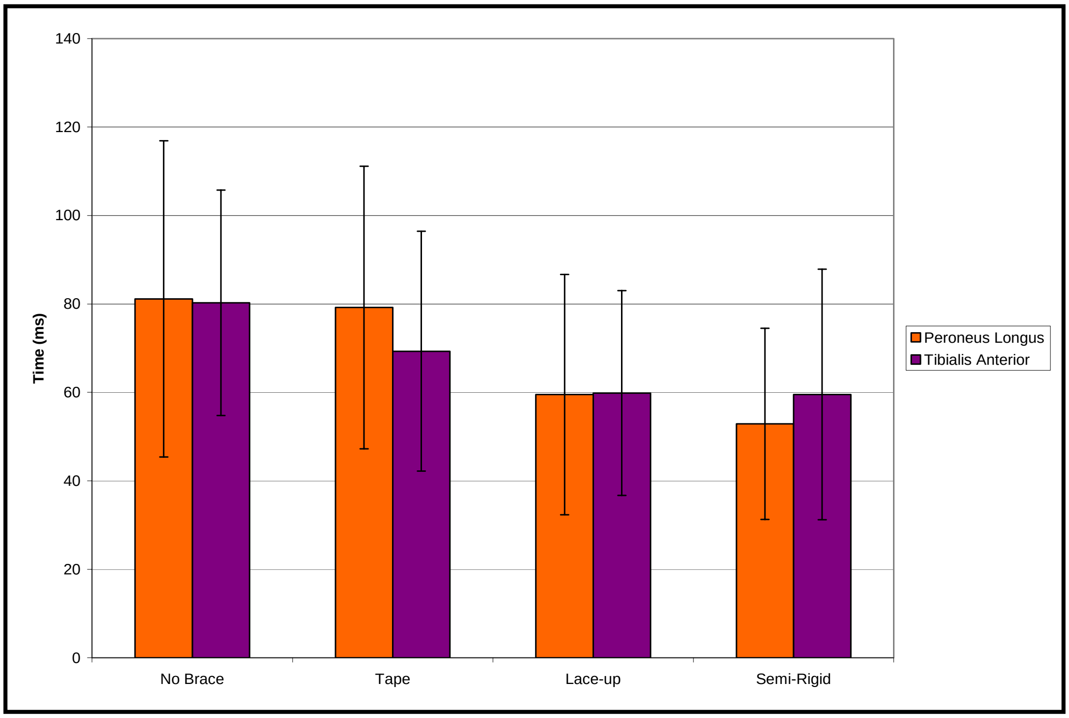


Figure 16: Peroneus longus and tibialis anterior muscle reflex latency comparisons

Relative to time to peak amplitude, descriptive statistics (mean ± standard deviation) for the peroneus longus appear in Table 4 and for the tibialis anterior in Table 5. A graphical representation of the peroneus longus and tibialis anterior time to peak amplitude data is presented in Figure 17. No statistically significant differences were observed between the peroneus longus and tibialis anterior with respect to time to peak amplitude for the no brace (t=-.335, p=0.72), tape (t=-.609, p=0.55), lace-up (t=.602, p=0.55), or semi-rigid (t=.919, p=0.36) conditions.

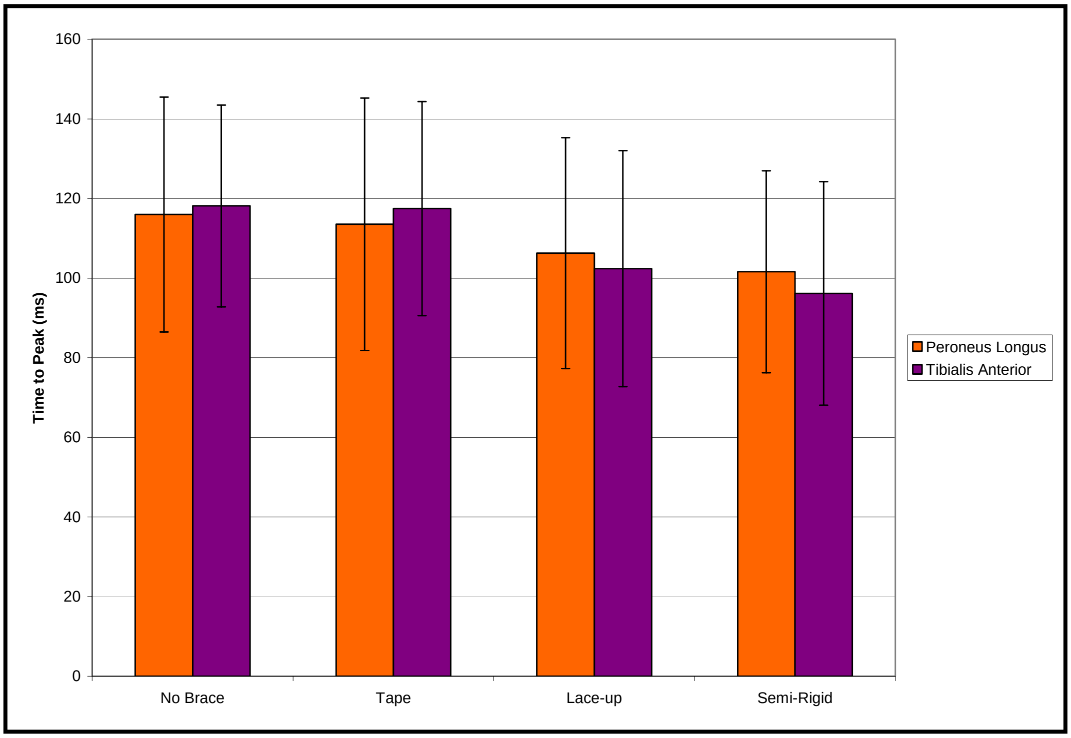


Figure 17: Peroneus longus and tibialis anterior time to peak amplitude comparisons

4.5. Summary

The results of this study support the proposed hypothesis for Specific Aim 1. All of the brace conditions were shown to demonstrate shorter reflex latencies than the no brace condition for both the peroneus longus and the tibialis anterior. In particular, the reflex latencies for the lace-up and semi-rigid brace conditions were significantly shorter than the no brace condition with respect to the peroneus longus. Additionally, reflex latency for semi-rigid brace condition was also shown to be significantly shorter than the tape condition. Similar results were observed relative to the tibialis anterior, although only the lace-up brace condition was shown to produce significantly shorter reflex latencies than the no brace condition. As for the time to peak amplitude variable, similar findings were observed in that all brace condition values were shown to be shorter than the no brace condition for both the peroneus longus and the tibialis anterior. However, statistically significant differences were only seen in the tibialis anterior, in particular when comparing the lace-up and semi-rigid braces to the no brace condition and also when comparing the semi-rigid brace to the tape condition.

The hypothesis for Specific Aim 2 was not supported by the results of this study. As eluded to previously, the results of multiple dependent t-tests with Bonferroni corrections demonstrated that the semi-rigid brace condition elicited significantly improved reflex latency values in the peroneus longus and time to peak amplitude values in the tibialis anterior when compared to the tape condition.

The hypothesis for Specific Aim 3 was also supported by the results of this study. The results of independent t-tests comparing the peroneus longus to the tibialis anterior demonstrated that no statistically significant differences existed between the two muscles under any of the brace conditions.

5. DISCUSSION

Ankle sprains are among the most common injuries occurring in sports. The vast majority of these sprains involve the lateral ligaments of the ankle following a rapid and unanticipated plantarflexion and inversion force applied to the weight bearing lower extremity. The ability of prophylactic stabilization to minimize the impact of these inversion forces on the ankle has long been a topic of investigation. One explanation for this effect has typically been ascribed to the mechanical properties of these stabilizers to limit subtalar joint motion[11, 17, 19, 57, 58], while another has been the ability of the orthoses to influence sensorimotor elements of the static and dynamic structures that cross the ankle[24, 31, 43, 103, 116-118, 120, 121]. A number of methodological approaches to mimic the types of forces observed which result in damage to the lateral stabilizing components of the ankle have been attempted previously. Traditional methodology has employed static stance instrumentation to assess the effectiveness of various prophylactic interventions. More recently dynamic models have been developed to investigate the influence of a functional perturbation on reflex responses of the musculature surrounding the ankle using drop landings and lateral movements designed to simulate an inversion mechanism. While these designs have improved researchers' ability to make predictions as to the types of responses expected during conditions that represent those which often precipitate ankle injury, a more realistic model including continuous functional activity accompanied by a dynamic perturbation has yet to be introduced. The purpose of this study, therefore, was to determine the impact of three selected modes of prophylactic support on measures of peroneus longus and tibialis anterior muscle activity compared to a no support, control condition in response to a random inversion perturbation while performing a dynamic lateral task. The three modes of prophylactic support included closed basketweave taping, McDavid™ 195 Ultralight Ankle Brace (McDavid Sports/Medical Products, Woodridge, IL), and Aircast® Air-Sport™ (Aircast, Inc., Summit, NJ). It was hypothesized that the three modes of prophylactic support would all contribute to a reduction in reflex latency and time to peak amplitude as measured by surface EMG. It was further hypothesized that no differences would be elicited between the peroneus longus and tibialis anterior relative to the same measures of muscle activity within each brace condition.

The results of this study demonstrated the that application of a prophylactic support may be beneficial in reducing the response times of selected lower leg musculature, thus minimizing the effects of a rapid and unexpected inversion injury mechanism. In particular, the lace-up and semi-rigid braces used in this study appeared to be the most effective in stimulating faster muscle onsets and more rapid attainment of peak amplitude values which may contribute to attenuating the forces observed during a demanding physical task among a sample of healthy, physically active subjects.

Under all brace conditions, reflex latency and time to peak amplitude values were shown to consistently decrease when compared to the no brace control. In general, from a statistical standpoint, the lace-up and semi-rigid brace conditions demonstrated the best performance relative to the peroneus longus on measures of reflex latency, while these same interventions were shown to significantly improve time to peak amplitude measures in the tibialis anterior. The semi-rigid brace condition was further shown to elicit statistically shorter reflex latency and time to peak amplitude values that the tape condition.

A detailed discussion of these results as they relate to the uniqueness of this methodology will follow. In addition, an overview of the historical explanations purporting the mechanisms for the effectiveness of ankle taping and bracing as well as the degree to which the findings of this current study contribute to supporting or refuting the prevailing literature as to the role of ankle taping and bracing in stimulating the sensorimotor system in response to an ankle inversion perturbation will be discussed.

5.1. Current Methodology

To date, the preponderance of research investigating the effects of a sudden inversion perturbation[29, 33, 41, 42, 63, 103, 124-129, 131, 145-148] has been accomplished through the use of various forms of mechanized platforms under static and quasi-static conditions. The most significant limitation of these studies is that the methodology does not permit extrapolation of the results to reflect the conditions that normally result in ankle injury. The introduction of a dynamic task has been described in recent work examining the effects of ankle bracing on EMG and ground reaction force variables[25] as well as the impact of a drop landings on measures of peroneal reflex response[36, 140]. Despite improvements in their design, these studies, too, fall short of accurately replicating the mechanism that contributes ankle injury during a functionally demanding task.

The current study introduced an innovative instrument designed to allow continuous motion and random execution of an inversion perturbation. Coupled with traditional EMG measurements, this appears to be the first *in vivo* model to examine the reactive responses of the muscles most often cited as being responsible for providing dynamic restraint to plantarflexion and inversion of the ankle. In contrast to previous studies examining the dynamic reflex response characteristics of ankle musculature to an inversion perturbation from a static starting position, this study was able to bring to light the impact of muscle pre-activation during a more challenging dynamic task which serves to increase the intrinsic stiffness of the joint and thus heighten the sensitivity of the dynamic restraints. Along with the positive influence provided by the prophylactic support through increased compression of sensory afferents and improved mechanical stabilization, the current methodology is unique in its ability to more appropriately describe the effects of ankle prophylaxis in response to an inversion perturbation. While the results reached in the current investigation may be similar, in some cases, to those found in earlier work, the degree of the muscular response observed in this study is likely to be more representative of the expected response during functional activity. Of significance in this study and those like it that have employed a more dynamic task is the increased velocity of the inversion moment. As would be expected, the velocity of rotation has been shown to be much greater ($595^{o} \cdot s^{-1}$) during jumping on a tilting surface[149] as compared with previous static stance studies (up to $200^{o} \cdot s^{-1}$)[124, 130, 144], the difference being attributed to the greater impact observed during the jumping task. Equally as important when considering comparisons between this current study and previous investigations into the influence of prophylactic support is the lack of standardized criteria for defining the reflex onset, which varied from 3-10 standard deviations[124, 144, 150], or a percentage of EMG activity[42, 139], above resting baseline values, or as the first electrical activity following the beginning of the perturbation[33, 41, 42, 130]. In addition, the wide variety of brace types used in previous research poses a challenge for making any direct comparisons between the current findings and those of published results examining the effectiveness of the interventions used in providing a level of prophylaxis. Nevertheless, the instrumentation employed in and the resultant findings from this study represent a positive shift toward providing more accurate information as to the reactive properties of the lower leg musculature and the capabilities of prophylactic support to enhance the protective dynamic restraint mechanism in order to minimize the effects of an ankle inversion injury.

5.2. Explanations for the Effectiveness of Prophylactic Support

Ankle taping and bracing have been used to decrease the incidence and severity of ankle joint injury for many years [28, 45, 49]. The results of this current study demonstrate that taping and bracing the ankle may contribute to protecting the joint through an enhanced dynamic restraint mechanism leading to greater joint stabilization. A large body of evidence exists purporting the effectiveness of ankle taping and bracing in reducing the impact of a forced inversion when compared to the unprotected joint[14, 25, 30, 32, 45, 48-55, 57, 58, 61, 97, 99, 104-107]. The explanation for this improved stabilization has been attributed to a number of schools of thought that include mechanical joint restriction, damping of angular acceleration and velocity, and contributions to sensorimotor facilitation.

5.2.1. Mechanical Joint Restriction

The first explanation for the effectiveness of prophylactic support centers on the theory that the tape or brace should offer protection against excessive inversion motion and provide an increase in rotational stiffness arising from the material properties of the orthoses(ren00). The results in this study demonstrate the three support conditions were increasingly more successful in generating a reflex response more quickly from the tape to the lace-up to the semi-rigid brace conditions in both the peroneus longus and tibialis anterior. This is likely a function of the progressively increasing tensile strength and rotational stiffness of each of these support conditions which helped to limit excessive motion at the subtalar joint. This explanation is supported by the work of Gross et al.[21] who examined inversion and eversion ROM before and after a 10 minute exercise bout and compared results using tape and a semi-rigid brace. Post-application and post-exercise ankle ROM was significantly less than pre-application motion for both treatment groups. Following exercise, however, inversion motion was significantly greater than pre-exercise motion for the tape condition while the semi-rigid brace provided significantly greater restriction of joint motion than the tape. Similar evidence was reported by Greene et al.[11] who demonstrated inversion support provided by semi-rigid brace application was reduced by only 8% following 90 minutes of exercise as compared to a 35% decline during lace-up brace application. Further, the restrictive properties of ankle taping have been shown to decrease after 20 minutes of volleyball practice, whereas inversion restriction properties in a semi-rigid brace were maintained after three hours of practice[55].

The effective restraint characteristics of taping and bracing during exercise have also demonstrated similar results. Martin et al.[151] compared the effects of taping with lace-up and semi-rigid support braces using video analysis and found that all three conditions offered significant pre-activity restriction of active ankle inversion. A 20 minute obstacle course protocol was inserted between bouts of walking and running on an 8.5º laterally tilted treadmill and it was shown that inversion restriction was significantly greater in the lace-up and semi-rigid brace conditions compared to the tape. These differences were most dramatic during the running phase of the treadmill bout. The differences between the lace-up and semi-rigid braces were regarded as negligible.

These findings have led many investigators to conclude that a semi-rigid or lace-up brace is preferable to taping in providing a mechanical restraint to subtalar joint motion during exercise lasting more than 10 minutes[11, 23, 55, 151]. In a recent meta-analysis[152], statistical comparisons of various research published in this area led to the formation of several consensus statements regarding the effects of taping and bracing on restricting inversion range of motion. In essence, semi-rigid braces restricted inversion ROM 21.3% more than tape and 26.2% more than lace-up braces. Further, after exercise, semi-rigid braces restricted inversion ROM 72.1% more than tape and 59.5% more than lace-up braces[152].

There is little evidence, however, to suggest that any support intervention possesses the mechanical capability to protect joint ligaments from the kinds of harmful loads responsible for causing injury as the nature of such interventions are designed to protect the wearer from excessive joint translations at the end range of motion. Additionally, current modeling is restricted in its ability to recreate, in a laboratory setting, the angular displacements, forces and speeds experienced during real life situations[18].

5.2.2. Damping of Angular Acceleration and Velocity

A second explanation for the mechanical effectiveness of taping and bracing involves the ability of the stabilizer to reduce time to inversion and inversion velocity. The findings of this investigation point to the shorter reflex latencies and time to peak amplitude values observed, particularly in the lace-up and semi-rigid brace conditions which may result in a more effective dynamic response to sudden inversion and an ability to slow both the rate and magnitude of the inversion provocation. Recent investigations have corroborated this claim, demonstrating a significant decrease in rearfoot inversion average velocity with the use of adhesive tape and a lace-up and semi-rigid brace[19, 148, 153, 154] when compared to a control condition. Additionally, the application of a semi-rigid stirrup was shown to substantially decrease inversion average velocity in comparison with taping[19, 148] and a lace-up brace[153]. These studies suggest that ankle prophylaxes may be effective in attenuating the forces that cause subtalar joint inversion during a simulated ankle injury.

The ability to quantify rearfoot angular velocity and acceleration can provide detailed information regarding the mechanical properties of ankle taping and bracing above and beyond angular displacement which is concerned only with change in position of the subtalar joint over time. It does not measure the rate at which the change in angular position occurs and often times it is the rate of displacement and not the displacement itself that dictates the severity of the joint injury. The viscoelastic properties of external supports like the ones used in this current study can differ significantly as can the levels of strain that each can withstand, depending on the rate at which the stress is applied. As such it is quite possible that different modes of ankle support may offer the same amount of joint restriction but demonstrate entirely different strain rates[155]. This is clearly an area deserving of further investigation.

5.2.3. Contribution to Sensorimotor Facilitation

While the effects of taping and bracing on the kinematics of the ankle joint have been studied extensively, the ability of these interventions to influence proprioception and facilitate improvement in sensorimotor function has been less well chronicled. Historical evidence suggesting the main function of ankle taping and bracing is a mechanical one is well established[102]. The results of this study offer evidence of the contribution of taping and bracing on the enhancement of sensorimotor function. In particular, the lace-up and semi-rigid brace conditions were shown to significantly improve peroneus longus reflex latency and tibialis anterior time to peak amplitude. As such, it appears these orthoses are effective in heightening the sensitivity of the peripheral afferent receptors housed in and around the ankle joint which facilitates improved proprioception and greater sensorimotor control of joint functions.

The work of Feuerbach et al.[116] supports the findings of this current experiment. These researchers demonstrated postural sway measurements were decreased in the anteroposterior and mediolateral directions following the application of a semi-rigid brace. This improved performance was attributed to enhanced proprioceptive input in a follow-up study in which the effect of the brace on joint position sense was measured before and after the introduction of joint anesthesia. No differences in error measurements were observed between the anesthetized and nonanesthetized conditions; however constant and variable errors in matching reference points were significantly less with the brace when compared to the no brace condition. The researchers concluded that ligament mechanoreceptors contributed little to ankle joint proprioception when measuring joint replication. Afferent feedback from the cutaneous receptors in the foot and lower leg, on the other hand, was said to be enhanced following application of the semi-rigid brace[121]. Simoneau et al.[156] offered further evidence of this enhanced proprioception by demonstrating improvements in joint position sense following the application of tape straps to the skin over the lateral ankle. Similarly, Matsusaka[157] reported a two week earlier correction in postural sway with the application of tape strips over the lateral ankle. Each of these studies attributed the enhanced effects of the tape to increased afferent input from cutaneous receptors stimulated by traction of the skin by the tape. In another study of joint position sense, the positive effects of external support were reported where tape, a lace-up brace and a semi-rigid brace were compared. The lace-up brace was shown to generate less angle reproduction error than the semi-rigid brace and tape. All three treatments were significantly improved over the control condition. In a similar study[103], the effects of a lace-up brace and adhesive tape resulted in enhanced plantarflexion and inversion joint replication.

The mechanism for the improved performance demonstrated in all of these studies increasingly points to the heightened sensitivity of the peripheral afferents that populate the area about the ankle and lower leg. This heightened sensitivity not only contributes to improved joint position sense, but has also been linked to a protective reflex response following joint perturbation. Several measurement techniques have been used to explain this proprioceptive effect including peroneus longus reflex latency[33, 110, 158, 159] and reflex amplitude measures[102, 110]. While the findings in these studies are not wholly consistent or in agreement with one another, the mechanism for this enhanced proprioception appears to be related to the compression afforded the lower leg and ankle joint which stimulates peripheral afferent receptors found in ligament, muscle, joint capsule and cutaneous tissue around the ankle and has been described in greater detail in a previous section (section 2.5). These results support the findings in this study as well.

Several investigators have measured the reaction time, or latency, of the peroneal and tibialis anterior muscles in response to a simulated ankle injury mechanism[41, 42, 126-128, 130, 131, 139]. Few have examined the impact of ankle taping and bracing on measures of peroneus longus latency[33, 110, 158, 159] and reflex amplitude measures[102, 110].

5.2.3.1. Role of Taping and Bracing on Reflex Latency

The current study demonstrated the application of external ankle support was effective in decreasing peroneus longus and tibialis anterior reflex latencies when compared to a no support control. More specifically, the lace-up and semi-rigid brace conditions were shown to significantly decrease peroneus longus reflex latency, while the lace-up brace alone was successful in significantly decreasing the reflex latency of the tibialis anterior relative to the no support control. In addition, the semi-rigid brace performed significantly better than the tape on measures of peroneus longus latency as well. These results appear to be supported by the findings of Glick et al.[160] who first demonstrated a possible benefit to prophylactic support beyond its obvious mechanical influence. The researchers found that by taping the ankles of subjects with known clinical instability, the peroneal muscles were observed to contract prior to heel strike during a running task. This suggested a possible proprioceptive benefit to taping[54, 110] or bracing[102] the ankle. These results were confirmed by Karlsson et al.[33] who measured peroneal latencies in a group of subjects with chronic ankle instability and found the taped ankles demonstrated faster reaction times than the unsupported ankles in response to a rapid inversion. The finding in this study that taping did not significantly improve peroneus longus or tibialis anterior reflex latency was supported by several investigations that have reported no change in peroneal muscle latency after the application of adhesive tape. Alt et al.[158], using a sample of healthy ankles, found no change in peroneus longus latency before or after exercise. Similar results were described by Lohrer et al.[110] who found no differences between taped and untaped ankles before and after exercise when subjected to an ankle sprain simulation. Further, our evidence of a significant improvement in reflex latency following the application of a brace was inconsistent with the findings of Cordova et al.[159] who demonstrated peroneal latencies were not affected by sudden inversion following the application of a lace-up or semi-rigid brace. It could be argued that in these latter three experiments[110, 158, 159] as well as in the current study where ankle taping was found to not influence peroneus longus or tibialis anterior latency, the challenge presented was not adequately sufficient to stimulate a response from the muscles in question. Couple this with the use of subjects with no known history of ankle injury and it is plausible to explain the differences described by these authors versus those of Glick et al.[160] and Karlsson et al.[33].

5.2.3.2. Role of Taping and Bracing on Time to Peak Amplitude

The results of this study on measures of time to peak amplitude once again demonstrated the lace-up and semi-rigid braces were superior to taping. However, these findings were only elicited in the tibialis anterior where the time to peak amplitude values for the two braces were shown to be significantly better than the no support control. In addition, the semi-rigid brace condition generated significantly faster time to peak amplitude values than the tape condition. None of the treatment conditions had a significant effect on the time to peak amplitude values calculated for the peroneus longus. Although the magnitude of these amplitude values was not calculated for direct comparative purposes, certain inferences can be drawn between these findings and those who have previously measured the magnitude of the peak amplitude. Lohrer et al.[110], for example, demonstrated a significantly greater proprioceptive amplification ratio (ratio of integrated EMG activity over the maximum angular displacement) after the application of adhesive tape. These increases were attributed to a proprioceptive activated effect of taping which contributed to not only a reduction in angular displacement, but also a reduction in the angular velocity. This reduction in velocity enabled the functional reflexes to be exercised more quickly in an effort to protect the joint. The tibialis anterior is most active during the first part of the stance phase (heel strike) as it is eccentrically contracting to absorb the shock of the body's weight and to dampen the plantarflexion moment[110]. In the presence of an ankle injury mechanism, tibialis anterior activity continues in an effort to slow the plantarflexion component of supination to avoid injury to the lateral ligaments of the ankle[161]. Application of an external support may assist in facilitating the proprioceptive activated effect described by Lohrer[110] to hasten the response of the tibialis anterior as demonstrated by the lace-up and semi-rigid brace conditions in this current study.

While such a response was neither observed nor measured in the peroneus longus in this study, other authors have reported inconsistent findings related to the reflex amplitude of the peroneus longus following both acute and long-term application of tape and bracing. Cordova[37] demonstrated peroneus longus peak amplitude was significantly enhanced immediately following the application of a lace-up brace. The same result was observed after 8 weeks of use. Interestingly, the lace-up brace resulted in greater peak amplitude than the semi-rigid stirrup. It was postulated that this effect was due to increased afferent information provided to the central nervous system primarily by cutaneous mechanoreceptors and perhaps other joint mechanoreceptors. The fact that the lace-up brace covered more surface area than the semi-rigid stirrup may have meant more receptors were being stimulated. No other data exists, however, to explain the influence of ankle bracing on peroneus longus reflex amplitude[37]. In this current study, no differences were observed between the lace-up and semi-rigid braces for either the peroneus longus or tibialis anterior time to peak amplitude. This may be explained by the nature of the semi-rigid brace (Figure 9) used in this study which incorporates a neoprene component across the anterior aspect of the brace into its construction allowing for greater surface area contact, similar to that of the lace-up brace. Neoprene sleeves and braces have been shown to have a positive effect on knee[35, 119, 162] and shoulder[163] proprioception by providing a more uniform circumferential compression. In the ankle, and in particular with the brace used in this study, this enhanced compression likely stimulated more peripheral afferent receptors than other types of semi-rigid braces would, narrowing the differences seen in the Cordova study[37].

In contrast to Cordova's findings, Alt et al.[158] reported a decrease in the integrated EMG of the peroneus longus following the application of tape. The researchers, however, portrayed this finding as a positive one suggesting the mechanical stiffness caused by the tape contributed to enhanced joint stability. Joint stability was influenced positively by neuromuscular, proprioceptive and physiological processes, characterized by relatively increased EMG activity[158].

Based on this evidence, it appears taping and bracing have an excitatory effect on the muscles responsible for stabilizing the ankle against inversion mechanisms. This further supports the theory that ankle taping and bracing positively enhance the dynamic defense mechanism through heightened input from somatosensory afferent mechanoreceptors[155].

In the absence of significant comparative data, we are left to speculate as to the observed effects of the ankle support interventions used in this study. All of the treatment conditions demonstrated at least some improvement in peroneus longus and tibialis anterior reflex latency and time to peak amplitude relative to the no support control under the unique conditions introduced in this study. It is apparent that these results cannot be explained simply by the mechanical effect offered by these interventions since the magnitude of the perturbation employed did not approach the terminal range of ankle inversion motion nor that which would be expected to cause tissue damage. However, growing evidence from previous research has demonstrated the application of ankle tape or a brace influences proprioceptive input to the central nervous system[37, 103, 121, 156], which may be equally as important as the mechanical effects offered by the external support.

5.3. Contribution of Ankle Prophylaxis to Functional Joint Stability

Evidence has been provided which illustrates the facilitative effects of external ankle support application on heightened afferent receptor stimulation resulting in greater muscle spindle sensitivity and faster reflex activation in the presence of a perturbation provocation. However, this increased muscle spindle sensitivity is also said to have an effect on active muscle stiffness thereby increasing stiffness of the joint and contributing to improved functional joint stability[93].

Joint stiffness is mediated by all of the static and dynamic structures that surround and are contained within a joint and has been defined as the ratio of the change in force to the change in length of a given tissue[90]. In muscle, total active stiffness consists of two components, intrinsic and reflex mediated stiffness. Intrinsic stiffness is dependent on the viscoelastic properties of the contractile apparatus (muscle) and passive tissues (tendon and fascia) as well as the number of actomyosin bonds at a given moment. The greater the number of actomyosin bonds present at a given level of muscle contraction, the greater the preparatory activation of that muscle, owing to increased intrinsic stiffness. This is a function of preceding reflexes and descending influences of the α-γ-motoneuron pool. Because intrinsic stiffness is always present, it is widely considered the body's first line of defense against perturbation[90, 93, 161].

Reflex mediated stiffness arises from increased reflexive neural activation of the α-motoneuron pool. This is largely dependent on the sensitivity of the primary muscle spindle afferents and their influence on autogenetic and heterogenetic reflexes as well as descending neural commands. Ligament receptors, as well as receptors in the muscle, joint capsule and skin have the capability of significantly heightening the sensitivity of the muscle spindle afferents, which in return plays a critical role in regulating muscle stiffness through activation of the α-motoneuron pool. Therefore if ligament and other receptors significantly contribute to reflex-mediated muscle stiffness and intrinsic stiffness is reliant upon preceding reflexes, then it can be said that the role of these receptors is of equal importance to intrinsic stiffness as well, thus providing protection from potentially harmful joint rotations[92, 93].

Increased muscle stiffness contributes to increased joint stiffness. This is particularly beneficial in the presence of compromised joint stability as increased intrinsic stiffness enhances reflex-mediated stiffness by transmitting loads to the muscle spindles more quickly, thereby reducing the delay associated with the initiation of a reflex response. Other variables such as eletromechanical delay may also be diminished in muscles with heightened activation and greater intrinsic stiffness. As such, both the initial resistance to joint displacement and the ability to generate a more efficient reflex response are products of greater intrinsic stiffness[63, 92, 93].

At the ankle, it has been shown that reflex-mediated stiffness has the potential to double the overall stiffness of the joint[90]. Despite this, many researchers agree that the peroneal muscles cannot react quickly enough to protect the ankle from injury in cases of sudden inversion[42, 130, 164]. Mathematical and cadaveric models suggest it takes 40 ms to reach the limit of physiological range of inversion[164]. However, the first measurable eversion torque has been reported to surface anywhere from 100 to several hundred milliseconds following the initiation of a perturbation mechanism[127, 144]. As such, it does not seem possible that an active response to a sudden inversion can be established in time to protect the lateral capsule and ligaments. This hypothesis, though, is based on the assumption that the inversion moment proceeds in the absence of any mitigating factors that can inhibit this process such as peroneal muscle preparatory activity, the application of an external ankle stabilizer, or both[165].

In a study comparing healthy and unstable ankles[131], research has demonstrated that motor response time (80 ms) was shorter than total inversion time (105-110 ms) when subjects were exposed to a sudden and unexpected 50º inversion of the ankle. This points to the need for early control of inversion, which is lacking in unstable ankles, and that there may be time for the start of a protective muscle intervention before the inversion reaches 50º. The authors were careful to mention, however, that an ample recruitment of motor units is necessary to generate sufficient power to actually decelerate the falling body weight and that further research is needed to determine if this can be accomplished in the 25-30 ms observed in this study[131].

Konradsen et al.[144] have illustrated that the application of a brace decreased the time interval for subjects to generate maximal eversion torque by 25%. When coupled with sub-maximal pre-activation of the peroneal muscles, this time was reduced by nearly 79%. This was characterized as a biomechanical adaptation either by forcing a static, concentrically activated muscle into a dynamic eccentric state or as a result of increased excitability due to the isometric contraction. These results highlight the fact that not only is ankle bracing effective in increasing muscle fiber activation but that they may also significantly contribute to increased preparatory muscle activation[144].

Ankle taping and bracing has the capacity to resist inversion by increasing the rotational stiffness of the subtalar joint to forced inversion. In the presence of such forces, however, the inversion moment must be resisted by a combination of the neuromuscular system activity, namely the stiffness of the passive and dynamic components of the joint, and the rotational stiffness of the support applied about the subtalar joint axis. As such, the application of some form of external support facilitates the absorption of greater resistance upon contact with the ground and in turn the forces placed on the ligaments and muscles supporting the ankle are increasingly attenuated relative to the stiffness of the support being employed[36].

Taping or bracing the ankle also plays a role in normalizing subtalar joint positioning in a more neutral alignment. In landing tasks, this may be beneficial in preventing excessive inversion and permitting adequate time for the dynamic restraints to generate an eversion torque response[36].

The finding in the current study that as the tensile properties of the support condition increased, the performance measures were also improved is supported by a recent study in which the effects of three types of ankle braces were examined (1lace-up, 2 semi-rigid) in subjects attempting to resist a 24º ankle inversion. Participants were asked to perform a single leg jump landing with a 27 mm high fulcrum affixed to the sole of the shoe. It was the goal of the researchers to determine if the braces impacted the success rate of the subjects' ability to resist an unwanted inversion stimulus if given no advanced knowledge of the presence of the fulcrum on the shoe. The results indicated that all three brace conditions increased the subjects' success rates in resisting the inversion stimulus when compared to the no brace control. Further, the two semi-rigid braces were more effective than the lace-up brace in preventing inversion[36].

Based on its construction, it is clear that the semi-rigid brace is more restrictive than the lace-up brace and tape. However, as mentioned previously, the restrictive properties of ankle support play a role only at the physiological limits of joint motion. We have provided evidence that the peroneus longus and tibialis anterior muscles, on the other hand, are active long before this physiological limit is reached, perhaps suggesting the ankle support plays an equally important role in stimulating the dynamic restraint mechanism to facilitate greater joint stiffness in addition to its mechanical function.

Several authors[31, 36, 110, 160] are in agreement that ankle taping and bracing provide an effective means of reducing the impact of a forced and unanticipated inversion of the ankle by stimulation of a protective evertor response. Others have advocated the need for pre-activation of the peroneal muscles through heightened intrinsic stiffness in order to minimize the effects of an ankle inversion mechanism[42, 63, 165]. In either case, it appears pre-contracted and strong evertors muscles are the most effective means of mounting an active muscular defense reaction to an unexpected ankle inversion[31, 42, 165]. Further, because these reactions are under supraspinal control, they may be potentially responsive to training.

5.4. Clinical Implications

This study demonstrated that a lace-up and semi-rigid brace was more effective than taping in stimulating peripheral afferent receptors to generate a faster dynamic restraint response during a demanding task and in response to a functional perturbation. Ankle taping and bracing, for the purpose of preventing ankle injuries, have been used by sports medicine clinicians for decades and is perhaps the skill most commonly associated with the Certified Athletic Trainer. During the late 1970's and early 1980's, various types of soft and semi-rigid ankle braces were introduced as an alternative to traditional ankle taping. Since that time, studies conducted comparing taping and bracing have largely focused on a number performance variables, while only recently has more evidence been introduced that demonstrates their ability to influence proprioception. It seems apparent, however, that despite widespread use and years of research investigating the effectiveness of these treatments that neither is definitively capable of preventing injury[18]. On the other hand, a wealth of knowledge exists which demonstrates both taping and bracing may be effective in reducing the impact of a sudden and unexpected inversion of the ankle. Data from many of these investigations have been challenged based on study design and an inability to generalize the results to the larger population outside of the sample set. While no conclusive evidence has been provided to date which identifies the most effective mode of ankle support, it is clear that some form of protection is better than none in minimizing ankle injuries.

As such, it may be of value to examine the findings of a study in which the effectiveness of ankle taping and bracing were compared using calculations for numbers-needed-to-treat (NNT) and cost-benefit ratio (CBR). Olmsted et al.[166] examined many of the previously published reports comparing the effectiveness of ankle taping and bracing and established the value for NNT (number of treatments necessary to prevent one ankle injury) and CBR for three of the more widely referenced studies in the area of ankle taping and bracing injury prevention. These studies were selected based on the fact that they were randomized clinical trials in which a control group was included. These researchers determined that bracing the ankle over the course of an entire competitive season is roughly 3 times more cost effective than taping. To illustrate this, in one of the studies examined[49], it was determined that to tape both ankles of intramural basketball participants over the course of a season would cost nearly $6100.00. To brace this same group would cost roughly $1900.00. In addition, these calculations did not factor in the time spent by the clinician to apply the ankle tape or the percentage of the clinician's salary representative of this time[166].

It does not appear that the elimination of ankle taping is likely to occur at any point in the future. From the athlete's perspective, this is still a popular choice for ankle support, particularly when taking into account comfort. From the clinician's perspective, there are many useful adjuncts of ankle taping that a brace alone cannot provide. For these reasons, it is logical to suggest that ankle taping is a useful tool in reducing the incidence of lateral ankle sprains. Ankle bracing has been shown to be equally as effective in reducing the incidence of ankle injuries and based on clinical research, including the findings reported in this study, it appears to be superior to taping as a means of minimizing the effects of an sudden and unexpected inversion mechanism.

5.5. Limitations

As mentioned in an earlier section, a measurement of the magnitude of the peak torque value may have been more useful than was the time to peak torque, for comparison's sake to previously published investigations. However, because of the window in which this peak torque was measured, it is not likely that this information would have shed any additional light on the effectiveness of the tape or braces since the torque produced in this short period of time would not likely be enough to afford the ankle any significant stability.

A determination of the velocity of the perturbation was not made in this study. This along with kinematic data would have permitted the calculation of angular velocity and deceleration of the subjects' ankle as well as the behavior of each of the treatment conditions and which may have shed more light on the effectiveness of each of the interventions.

5.6. Conclusions

Ankle sprains continue to be one of the most frequently suffered injuries in the athletic setting. A tremendous amount of information currently exists in the literature which has examined the efficacy of ankle taping and bracing to prevent injury. While no consensus has yet to be reached as to the most effective form of prophylaxis, it is apparent that some form of stabilization is preferred versus the unprotected ankle. To date, much of the research has been conducted under static and quasi-static conditions that do not reflect the prevailing environment during an injury. This study has introduced a unique form of instrumentation that enabled the performance of a functional task while also subjecting the subject to dynamic perturbation. The dynamic task carried out in this study better replicates the conditions which often precipitate ankle injury. The results indicate that the application of prophylactic ankle support may be beneficial in heightening the sensitivity of the dynamic defense mechanism of selected lower leg muscles, thus minimizing the effects of a rapid and unexpected inversion injury mechanism. In particular, the lace-up and semi-rigid braces used in this study appeared to be the most effective in hastening the muscular responses observed during a dynamic perturbation.

5.7. Future Research

While this study was able to more realistically assess the impact of external ankle support under conditions that reflect what occurs during typical functional activities, it would be interesting to investigate additional variables that might shed even greater light on the effectiveness of ankle taping and bracing. In particular, the ability to measure the kinetic and kinematic characteristics of a dynamic task under various support conditions would be of clinical value in determining the form of prophylaxis that offers both the greatest mechanical effect along with the greatest motor control effect.

This study examined the effects of prophylactic ankle support in a single session using healthy subjects and in the absence of any fatiguing stimulus. Future research with this model should also be coupled with other measures of proprioception and neuromuscular control and take into consideration the effect of fatigue to determine if this additional variable has any impact on the reaction time of the dynamic restraints under various braced and unbraced conditions.

Finally, it will eventually be necessary to employ this same methodology using samples of subjects with diagnosed clinical and functional instability as well as those having undergone surgical repair to determine definitively if the results observed in this current study could be generalized to an injured population as well.

BIBLIOGRAPHY

1. Garrick, J.G. and R.K. Requa, *The epidemiology of foot and ankle injuries in sports.* Clin Sports Med, 1988. **7**(1): p. 29-36.

2. Holmer, P., L. Sondergaard, L. Konradsen, P.T. Nielsen, and L.N. Jorgensen, *Epidemiology of sprains in the lateral ankle and foot.* Foot Ankle Int, 1994. **15**(2): p. 72-4.

3. Rijke, A.M., B. Jones, and P.A. Vierhout, *Injury to the lateral ankle ligaments of athletes. A posttraumatic followup.* Am J Sports Med, 1988. **16**(3): p. 256-9.

4. Yeung, M.S., K.M. Chan, C.H. So, and W.Y. Yuan, *An epidemiological survey on ankle sprain.* Br J Sport Med, 1994. **28**(2): p. 112-6.

5. Garrick, J.G., *Characterization of the patient population in a sports medicine facility.* Physician Sportsmed, 1985. **13**(10): p. 73-76.

6. Ekstrand, J. and H. Tropp, *The incidence of ankle sprains in soccer.* Foot Ankle, 1990. **11**(1): p. 41-4.

7. Bullock-Saxton, J.E., *Sensory changes associated with severe ankle sprain.* Scand J Rehabil Med, 1995. **27**(3): p. 161-7.

8. Safran, M.R., R.S. Benedetti, A.R. Bartolozzi, 3rd, and B.R. Mandelbaum, *Lateral ankle sprains: a comprehensive review: part 1: etiology, pathoanatomy, histopathogenesis, and diagnosis.* Med Sci Sports Exerc, 1999. **31**(7 Suppl): p. S429-37.

9. Karlsson, J., L. Peterson, G.O. Andreasson, and C. Hogfors, *The unstable ankle: a combined EMG and biomechanical modeling study.* Int J Sport Biomech, 1992. **8**: p. 129-44.

10. Rijke, A.M. and P.A. Vierhout, *Graded stress radiography in acute injury to the lateral ligaments of the ankle.* Acta Radiol, 1990. **31**(2): p. 151-5.

11. Greene, T.A. and S.K. Hillman, *Comparison of support provided by a semirigid orthosis and adhesive ankle taping before, during, and after exercise.* Am J Sports Med, 1990. **18**(5): p. 498-506.

12. Callaghan, M.J., *Role of ankle taping and bracing in the athlete.* Br J Sports Med, 1997. **31**(2): p. 102-8.

13. MacKean, L.C., G. Bell, and R.S. Burnham, *Prophylactic ankle bracing vs. taping: effects on functional performance in female basketball players.* J Orthop Sports Phys Ther, 1995. **22**(2): p. 77-81.

14. Macpherson, K., M. Sitler, I. Kimura, and M. Horodyski, *Effects of a semirigid and softshell prophylactic ankle stabilizer on selected performance tests among high school football players.* J Orthop Sports Phys Ther, 1995. **21**(3): p. 147-52.

15. Miller, E.A. and A.C. Hergenroeder, *Prophylactic ankle bracing.* Pediatr Clin North Am, 1990. **37**(5): p. 1175-85.

16. Shrier, I., *Treatment of lateral collateral ligament sprains of the ankle: a critical appraisal of the literature.* Clin J Sport Med, 1995. **5**(3): p. 187-95.

17. Vaes, P.H., W. Duquet, F. Handelberg, P.P. Casteleyn, R. Van Tiggelen, and P. Opdecam, *Influence of ankle strapping, taping and nine braces: a stress roentgenologic comparison.* J Sport Rehabil, 1998. **7**(3): p. 157-71.

18. Renstrom, P.A., L. Konradsen, and B. Beynnon, *Influence of knee and ankle support on proprioception and neuromuscular support*, in *Proprioception and Neuromuscular Control in Joint Stability*, S.M. Lephart and F.H. Fu, Editors. 2000, Human Kinetics: Champaign, IL.

19. Shapiro, M.S., J.M. Kabo, P.W. Mitchell, G. Loren, and M. Tsenter, *Ankle sprain prophylaxis: an analysis of the stabilizing effects of braces and tape.* Am J Sports Med, 1994. **22**(1): p. 78-82.

20. Verbrugge, J.D., *The effects of semirigid Air-Stirrup bracing vs. adhesive ankle taping on motor performance.* J Orthop Sports Phys Ther, 1996. **23**(5): p. 320-5.

21. Gross, M.T., M.K. Bradshaw, L.C. Ventry, and K.H. Weller, *Comparison of support provided by ankle taping and semirigid orthosis.* J Orthop Sports Phys Ther, 1987. **23**(5): p. 320-25.

22. Bunch, R.P., K. Bednarski, D. Holland, and R. Macinanti, *Ankle joint support: a comparison of reusable lace-on braces with taping and wrappping.* Physician Sportsmed, 1985. **13**(5): p. 59-62.

23. Myburgh, K.H., C.L. Vaughan, and S.K. Isaacs, *The effects of ankle guards and taping on joint motion before, during, and after a squash match.* Am J Sports Med, 1984. **12**(6): p. 441-6.

24. Bennell, K.L. and P.A. Goldie, *The differential effects of external ankle support on postural control.* J Orthop Sports Phys Ther, 1994. **20**(6): p. 287-95.

25. Cordova, M.L., C.W. Armstrong, J.M. Rankin, and R.A. Yeasting, *Ground reaction forces and EMG activity with ankle bracing during inversion stress.* Med Sci Sports Exerc, 1998. **30**(9): p. 1363-70.

26. Hamill, J., K.M. Knutzen, B.T. Bates, and G. Kirkpatrick, *Evaluation of two ankle appliances using ground reaction force data.* J Orthop Sports Phys Ther, 1986. **7**(5): p. 244-49.

27. Hughes, L.Y. and D.M. Stetts, *Comparison of ankle taping and a semirigid support.* Physician Sportsmed, 1983. **11**(4): p. 99-103.

28. Rovere, G.D., T.J. Clarke, C.S. Yates, and K. Burley, *Retrospective comparison of taping and ankle stabilizers in preventing ankle injuries.* Am J Sports Med, 1988. **16**(3): p. 228-33.

29. Sprigings, E.J., J.D. Pelton, and B.R. Brandell, *An EMG analysis of the effectiveness of external ankle support during sudden ankle inversion.* Can J Appl Sport Sci, 1981. **6**(2): p. 72-5.

30. Carroll, M.J., A.M. Rijke, and D.H. Perrin, *Effect of the Swede-O ankle brace on talar tilt in subjects with unstable ankles.* J Sport Rehabil, 1993. **2**(4): p. 261-7.

31. Ashton-Miller, J.A., R.A. Ottaviani, C. Hutchinson, and E.M. Wojtys, *What best protects the inverted weightbearing ankle against further inversion? Evertor muscle strength compares favorably with shoe height, athletic tape, and three orthoses.* Am J Sports Med, 1996. **24**(6): p. 800-9.

32. Gross, M.T., L.M. Clemence, B.D. Cox, H.P. McMillan, A.F. Meadows, C.S. Piland, and W.S. Powers, *Effect of ankle orthoses on functional performance for individuals with recurrent lateral ankle sprains.* J Orthop Sports Phys Ther, 1997. **25**(4): p. 245-52.

33. Karlsson, J. and G.O. Andreasson, *The effect of external ankle support in chronic lateral ankle joint instability. An electromyographic study.* Am J Sports Med, 1992. **20**(3): p. 257-61.

34. Glencross, D. and E. Thornton, *Position sense following joint injury.* J Sports Med Phys Fitness, 1981. **21**(1): p. 23-7.

35. Perlau, R., C. Frank, and G. Fick, *The effect of elastic bandages on human knee proprioception in the uninjured population.* Am J Sports Med, 1995. **23**(2): p. 251-5.

36. Ubell, M.L., J.P. Boylan, J.A. Ashton-Miller, and E.M. Wojtys, *The effect of ankle braces on the prevention of dynamic forced ankle inversion.* Am J Sports Med, 2003. **31**(6): p. 935-40.

37. Cordova, M.L. and C.D. Ingersoll, *Peroneus longus stretch reflex amplitude increases after ankle brace application.* Br J Sports Med, 2003. **37**(3): p. 258-62.

38. Styf, J.R., O. Lundin, and D.H. Gershuni, *Effects of a functional knee brace on leg muscle function.* Am J Sports Med, 1994. **22**(6): p. 830-4.

39. Lephart, S.M., D.M. Pincivero, J.L. Giraldo, and F.H. Fu, *The role of proprioception in the management and rehabilitation of athletic injuries.* Am J Sport Med, 1997. **25**(1): p. 130-7.

40. Lephart, S.M., D.M. Pincivero, and S.L. Rozzi, *Proprioception of the ankle and knee.* Sports Med, 1998. **25**(3): p. 149-55.

41. Löfvenberg, R., J. Karrholm, G. Sundelin, and O. Ahlgren, *Prolonged reaction time in patients with chronic lateral instability of the ankle.* Am J Sports Med, 1995. **23**(4): p. 414-7.

42. Konradsen, L., M. Voigt, and C. Hojsgaard, *Ankle inversion injuries. The role of the dynamic defense mechanism.* Am J Sports Med, 1997. **25**(1): p. 54-8.

43. Nishikawa, T. and M.D. Grabiner, *Peroneal motoneuron excitability increases immediately following application of a semirigid ankle brace.* J Orthop Sports Phys Ther, 1999. **29**(3): p. 168-73; discussion 174-6.

44. Nishikawa, T., T. Ozaki, K. Mizuno, and M.D. Grabiner, *Increased reflex activation of the peroneus longus following application of an ankle brace declines over time.* J Orthop Res, 2002. **20**(6): p. 1323-6.

45. Garrick, J.G. and R.K. Requa, *Role of external support in the prevention of ankle sprains.* Med Sci Sports Exerc, 1973. **5**(3): p. 200-3.

46. Metcalfe, R.C., G.A. Schlabach, M.A. Looney, and E.J. Renehan, *A comparison of moleskin tape, linen tape and lace up brace on joint restriction and movement performance.* J Athl Training, 1997. **32**(2): p. 136-40.

47. Jerosch, J., L. Thorwesten, T. Frebel, and S. Linnenbecker, *Influence of external stabilizing devices of the ankle on sport-specific capabilities.* Knee Surg Sports Traumatol Arthrosc, 1997. **5**(1): p. 50-7.

48. Leanderson, J., S. Ekstam, and C. Salomonsson, *Taping of the ankle--the effect on postural sway during perturbation, before and after a training session.* Knee Surg Sports Traumatol Arthrosc, 1996. **4**(1): p. 53-6.

49. Sitler, M., J. Ryan, B. Wheeler, J. McBride, R. Arciero, J. Anderson, and M. Horodyski, *The efficacy of a semirigid ankle stabilizer to reduce acute ankle injuries in basketball. A randomized clinical study at West Point.* Am J Sports Med, 1994. **22**(4): p. 454-61.

50. Kimura, I., D.A. Nawoczenski, M. Epler, and M.G. Owen, *Effect of the AirStirrup in controlling ankle inversion stress.* J Orthop Sports Phys Ther, 1987. **9**(5): p. 190-3.

51. Abdenour, T.E., W.A. Saville, R.C. White, and M.A. Abdenour, *Effect of ankle taping upon torque and range of motion.* Athl Training, J Nat Athl Train Assn, 1979. **14**(4): p. 227-8.

52. McIntyre, D.R., M.A. Smith, and N.L. Denniston, *Effectiveness of strapping techniques during prolonged dynamic exercises.* Athl Training, J Nat Athl Train Assn, 1983. **18**(1): p. 52-5.

53. Morris, H.H. and W. Musnicki, 3rd, *The effect of taping on ankle mobility following moderate exercise.* J Sports Med Phys Fitness, 1983. **23**(4): p. 422-6.

54. Fumich, R.M., A.E. Ellison, G.J. Guerin, and P.D. Grace, *The measured effect of taping on combined foot and ankle motion before and after exercise.* Am J Sports Med, 1981. **9**(3): p. 165-70.

55. Greene, T.A. and C.R. Wright, *A comparative support evaluation of three ankle orthoses before, during, and after exercise.* J Orthop Sports Phys Ther, 1990. **11**(10): p. 453-66.

56. Seitz, C.J. and A.J. Goldfuss, *The effect of taping and exercise on passive foot inversion and ankle plantarflexion.* Athl Training, J Nat Athl Train Assn, 1984. **19**(3): p. 178-82.

57. Pederson, T.S., M.D. Richard, G. Merrill, S.S. Schulthies, and P.E. Allsen, *The effects of spatting and ankle taping on inversion before and after exercise.* J Athl Training, 1997. **32**(1): p. 29-33.

58. Vaes, P.H., W. Duquet, P.P. Casteleyn, F. Handelberg, and P. Opdecam, *Static and dynamic roentgenographic analysis of ankle stability in braced and nonbraced stable and functionally unstable ankles.* Am J Sports Med, 1998. **26**(5): p. 692-702.

59. Bocchinfuso, C., M. Sitler, and I. Kimura, *Effects of two semirigid prophylactic ankle stabilizers on speed, agility and vertical jump.* J Sport Rehabil, 1994. **3**(2): p. 125-34.

60. Paris, D.L., *The effects of the Swede-O, New Cross, and McDavid ankle braces and adhesive ankle taping on speed, balance, agility, and vertical jump.* J Athl Training, 1992. **27**(3): p. 253-56.

61. Pienkowski, D., M. McMorrow, R. Shapiro, D.N. Caborn, and J. Stayton, *The effect of ankle stabilizers on athletic performance. A randomized prospective study.* Am J Sports Med, 1995. **23**(6): p. 757-62.

62. Louwerens, J.W., B. van Linge, L.W. de Klerk, P.G. Mulder, and C.J. Snijders, *Peroneus longus and tibialis anterior muscle activity in the stance phase. A quantified electromyographic study of 10 controls and 25 patients with chronic ankle instability.* Acta Orthop Scand, 1995. **66**(6): p. 517-23.

63. Myers, J.B., B.L. Riemann, J.H. Hwang, F.H. Fu, and S.M. Lephart, *Effect of peripheral afferent alteration of the lateral ankle ligaments on dynamic stability.* Am J Sports Med, 2003. **31**(4): p. 498-506.

64. Inman, V.T., *The Joints of the Ankle*. 1976, Baltimore: Williams and Wikins.

65. Nuber, G.W., *Biomechanics of the foot and ankle during gait.* Clin Sports Med, 1988. **7**(1): p. 1-13.

66. Rockar, P.A., Jr., *The subtalar joint: anatomy and joint motion.* J Orthop Sports Phys Ther, 1995. **21**(6): p. 361-72.

67. Rogers, M.M., *Dynamic foot biomechanics.* J Orthop Sports Phys Ther, 1995. **21**: p. 306-16.

68. Anderson, M.K., S.J. Hall, and M. Martin, *Sports Injury Management*. 2000, Baltimore: Lippencott Williams and Wilkins.

69. Starkey, C. and J. Ryan, *Evaluation of Orthopedic and Athletic Injuries*. 2 ed. 2002, Philadelphia: FA Davis Company.

70. Tortora, G.J., *Principles of Human Anatomy*. 8 ed. 1999, New York: John Wiley and Sons, Inc.

71. Kotwick, J.E., *Biomechanics of the foot and ankle.* Clin Sports Med, 1982. **1**(1): p. 19-34.

72. Neptune, R.R., I.C. Wright, and A.J. van den Bogert, *Muscle coordination and function during cutting movements.* Med Sci Sports Exerc, 1999. **31**(2): p. 294-302.

73. Lephart, S.M., B.L. Riemann, and F.H. Fu, *Introduction to the sensorimotor system*, in *Proprioception and Neuromuscular Control in Joint Stability*, S.M. Lephart and F.H. Fu, Editors. 2000, Human Kinetics: Champaign, IL.

74. Sherrington, C.S., *The Integrative Action of the Nervous System*. 1906, New Haven, CT: Yale University Press.

75. Riemann, B.L. and S.M. Lephart, *The sensorimotor system. Part I. The physiologic basis of functional joint stability.* J Athl Training, 2002. **37**(1): p. 71-9.

76. Myers, J.B. and S.M. Lephart, *The role of the sensorimotor system in the athletic shoulder.* J Athl Training, 2000. **35**(3): p. 351-63.

77. Lephart, S.M. and T.J. Henry, *The physiological basis for open and closed kinetic chain rehabilitation for the upper extremity.* J Sport Rehabil, 1996. **5**(1): p. 71-87.

78. Lephart, S.M. and T.J. Henry, *Functional rehabilitation for the upper and lower extremity.* Orthop Clin North Am, 1995. **26**(3): p. 579-92.

79. Voight, M.L. and G. Cook, *Clinical application of closed kinetic chain exercise.* J Sport Rehabil, 1996. **5**(1): p. 25-44.

80. Ghez, C., *The control of movement*, in *Principles of Neural Science*, Kandel, Schwartz, and Jessell, Editors. 1991, Elsevier Science: New York.

81. Hilton, J., *On the Influence of Mechanical and Physiological Rest in the Treatment of Accidents and Surgical Diseases and the Diagnostic Value of Pain. A Course of Lectures*. 1863, London: Bell and Daldy.

82. Tyldesley, B. and J.I. Grieve, *Muscle, Nerve and Movement: Kinesiology in Daily Living*. 1989, Boston: Blackwell Scientific Publications.

83. Kennedy, J.C., I.J. Alexander, and K.C. Hayes, *Nerve supply of the human knee and its functional importance.* Am J Sports Med, 1982. **10**(6): p. 329-35.

84. Nyland, J., T. Brosky, D. Currier, A. Nitz, and D. Caborn, *Review of the afferent neural system of the knee and its contribution to motor learning.* J Orthop Sports Phys Ther, 1994. **19**(1): p. 2-11.

85. Grigg, P., *Peripheral neural mechanisms in proprioception.* J Sport Rehabil, 1994. **3**: p. 2-17.

86. Boyd, I.A., *The histological structure of the receptors in the knee-joint of the cat correlated with their physiological response.* J Physiol, 1954. **124**(3): p. 476-88.

87. Michelson, J.D. and C. Hutchins, *Mechanoreceptors in human ankle ligaments.* J Bone Joint Surg Br, 1995. **77**(2): p. 219-24.

88. Moffett, D.F., S.B. Moffett, and C.L. Schauf, *Human Physiology: Foundations and Frontiers*. 1993, St. Louis: Mosby-Year Book, Inc.

89. Solomonow, M., R. Baratta, B.H. Zhou, H. Shoji, W. Bose, C. Beck, and R. D'Ambrosia, *The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability.* Am J Sports Med, 1987. **15**(3): p. 207-13.

90. Johansson, H. and P. Sjolander, *The neurophysiology of joints*, in *Mechanics of Joints: Physiology, Pathophysiology and Treatment*, V. Wright and E.L. Radin, Editors. 1993, Marcel Dekker, Inc.: New York. p. 243-290.

91. Freeman, M.A. and B. Wyke, *Articular reflexes at the ankle joint: an electromyographic study of normal and abnormal influences of ankle-joint mechanoreceptors upon reflex activity in the leg muscles.* Br J Surg, 1967. **54**(12): p. 990-1001.

92. Johansson, H., J. Pederson, M. Bergenheim, and M. Djupsjobacka, *Peripheral afferents of the knee: their effects on central mechanisms regulating muscle stiffness, joint stability and propriocetion and coordination*, in *Proprioception and Neuromuscular Control in Joint Stability*, S.M. Lephart and F.H. Fu, Editors. 2000, Human Kinetics: Champaign, IL.

93. Riemann, B.L. and S.M. Lephart, *The sensorimotor system. Part II: The role of proprioception in motor control and functional joint stability.* J Athl Train, 2002. **37**(1): p. 80-84.

94. Pederson, J., J. Lonn, F. Hellstrom, M. Djupsjobacka, and H. Johansson, *Localized muscle fatigue decreases the acuity of the movement sense in the human shoulder.* Med Sci Sports Exerc, 1999. **31**: p. 1047-52.

95. Nichols, T.R. and J.C. Houk, *Improvement in linearity and regulation of stiffness that results from actions of stretch reflex.* J Neurophysiol, 1976. **39**(1): p. 119-42.

96. Guskiewicz, K.M. and D.H. Perrin, *Research and clinical applications of assessing balance.* J Sport Rehabil, 1996. **5**: p. 45-63.

97. Quigley, T.B., J. Cox, and J. Murphy, *Protective wrapping for the ankle.* JAMA, 1946. **132**: p. 441-6.

98. Surve, I., M.P. Schwellnus, T. Noakes, and C. Lombard, *A fivefold reduction in the incidence of recurrent ankle sprains in soccer players using the Sport-Stirrup orthosis.* Am J Sports Med, 1994. **22**(5): p. 601-6.

99. Rarick, L., G. Bigley, and R. Karst, *The measurable support of the ankle joint by conventional methods of taping.* J Bone Joint Surg Am, 1962. **44A**: p. 1183-90.

100. Sitler, M.R. and M. Horodyski, *Effectiveness of prophylactic ankle stabilisers for prevention of ankle injuries.* Sports Med, 1995. **20**(1): p. 53-7.

101. Jerosch, J., I. Hoffstetter, H. Bork, and M. Bischof, *The influence of orthoses on the proprioception of the ankle joint.* Knee Surg Sports Traumatol Arthrosc, 1995. **3**(1): p. 39-46.

102. Cordova, M.L. and C.D. Ingersoll, *The effect of chronic ankle brace use on peroneus longus stretch reflex amplitude (abstract).* Med Sci Sports Exerc, 2000. **32 (suppl)**: p. 274.

103. Heit, E.J., S.M. Lephart, and S.L. Rozzi, *The effect of ankle bracing and taping on joint position sense in the stable ankle.* J Sport Rehabil, 1996. **5**(3): p. 206-13.

104. Stover, C.N., *Air stirrup management of ankle injuries in the athlete.* Am J Sports Med, 1980. **8**(5): p. 360-5.

105. Anderson, D.L., D.J. Sanderson, and E.M. Hennig, *The role of external nonrigid ankle bracing in limiting ankle inversion.* Clin J Sport Med, 1995. **5**(1): p. 18-24.

106. Beriau, M.R., W.B. Cox, and J. Manning, *Effects of ankle braces upon agility course performance in high school athletes.* J Athl Training, 1994. **29**(3): p. 224-30.

107. Bot, S.D. and W. van Mechelen, *The effect of ankle bracing on athletic performance.* Sports Med, 1999. **27**(3): p. 171-8.

108. Hopper, D., G. Allison, N. Fernandes, L. O'Sullivan, and A. Wharton, *Reliability of the peroneal latency in normal ankles.* Clin Orthop, 1998(350): p. 159-65.

109. Burks, R.T., B.G. Bean, R. Marcus, and H.B. Barker, *Analysis of athletic performance with prophylactic ankle devices.* Am J Sports Med, 1991. **19**(2): p. 104-6.

110. Lohrer, H., W. Alt, and A. Gollhofer, *Neuromuscular properties and functional aspects of taped ankles.* Am J Sports Med, 1999. **27**(1): p. 69-75.

111. Robbins, S., E. Waked, and R. Rappel, *Ankle taping improves proprioception before and after exercise in young men.* Br J Sports Med, 1995. **29**(4): p. 242-7.

112. Schutte, M.J., E.J. Dabezies, M.L. Zimny, and L.T. Happel, *Neural anatomy of the human anterior cruciate ligament.* J Bone Joint Surg Am, 1987. **69**(2): p. 243-7.

113. Clarke, F.J., R.C. Burgess, and J.W. Chapin, *Role of intramuscular receptors in the awareness of limb position.* J Neurophysiol, 1985. **54**: p. 1529-40.

114. McCloskey, D.I., *Kinesthetic sensibility.* Physiol Rev, 1978. **58**(4): p. 763-820.

115. Moberg, E., *The role of cutaneous afferents in position sense, kinaesthesia, and motor function of the hand.* Brain, 1983. **106 (Pt 1)**: p. 1-19.

116. Feuerbach, J.W. and M.D. Grabiner, *Effect of the aircast on unilateral postural control: amplitude and frequency variables.* J Orthop Sports Phys Ther, 1993. **17**(3): p. 149-54.

117. Calmels, P., M. Escafit, M. Domenach, and P. Minaire, *Posturographic evaluation of the proprioceptive effect of ankle orthoses in healthy volunteers.* Int Disabil Stud, 1991. **13**(2): p. 42-5.

118. Kinzey, S.J., C.D. Ingersoll, and K.L. Knight, *The effects of ankle bracing on postural sway.* J Athl Training, 1994. **29**: p. 170-1.

119. Lephart, S.M., M.S. Kocher, F.H. Fu, P.A. Borsa, and C.D. Harner, *Proprioception following anterior cruciate ligament reconstruction.* J Sport Rehabil, 1992. **1**: p. 188-96.

120. Barrett, D.S., A.G. Cobb, and G. Bentley, *Joint proprioception in normal, osteoarthritic and replaced knees.* J Bone Joint Surg Br, 1991. **73**(1): p. 53-6.

121. Feuerbach, J.W., M.D. Grabiner, T.J. Koh, and G.G. Weiker, *Effect of an ankle orthosis and ankle ligament anesthesia on ankle joint proprioception.* Am J Sports Med, 1994. **22**(2): p. 223-9.

122. Barrack, R.L., H.B. Skinner, M.E. Brunet, and R.J. Haddad, Jr., *Functional performance of the knee after intraarticular anesthesia.* Am J Sports Med, 1983. **11**(4): p. 258-61.

123. Myers, J.B., B.L. Riemann, J.H. Hwang, S.M. Lephart, and F.H. Fu. *Effect of proprioceptive alteration of the lateral ankle ligaments on dynamic stability*. in *American Academy of Orthopedic Surgeons/American Orthopedic Society for Sports Medicine*. 2002. Dallas, TX.

124. Lynch, S.A., U. Eklund, D. Gottlieb, P.A. Renstrom, and B. Beynnon, *Electromyographic latency changes in the ankle musculature during inversion moments.* Am J Sports Med, 1996. **24**(3): p. 362-9.

125. Fernandes, N., G.T. Allison, and D. Hopper, *Peroneal latency in normal and injured ankles at varying angles of perturbation.* Clin Orthop, 2000(375): p. 193-201.

126. Ebig, M., S.M. Lephart, R.G. Burdett, M.C. Miller, and D.M. Pincivero, *The effect of sudden inversion stress on EMG activity of the peroneal and tibialis anterior muscles in the chronically unstable ankle.* J Orthop Sports Phys Ther, 1997. **26**(2): p. 73-7.

127. Konradsen, L. and J.B. Ravn, *Ankle instability caused by prolonged peroneal reaction time.* Acta Orthop Scand, 1990. **61**(5): p. 388-90.

128. Nawoczenski, D.A., M.G. Owen, M.L. Ecker, B. Altman, and M. Epler, *Objective evaluation of peroneal response to sudden inversion stress.* J Orthop Sports Phys Ther, 1985. **7**(3): p. 107-9.

129. Brunt, D., J.C. Andersen, B. Huntsman, L.B. Reinhert, A.C. Thorell, and J.C. Sterling, *Postural responses to lateral perturbation in healthy subjects and ankle sprain patients.* Med Sci Sports Exerc, 1992. **24**(2): p. 171-6.

130. Isakov, E., J. Mizrahi, P. Solzi, Z. Susak, and M. Lotem, *Response of the peroneal muscles to sudden inversion of the ankle during standing.* Int J Sport Biomech, 1986. **2**(2): p. 100-9.

131. Vaes, P., W. Duquet, and B. Van Gheluwe, *Peroneal Reaction Times and Eversion Motor Response in Healthy and Unstable Ankles.* J Athl Training, 2002. **37**(4): p. 475-480.

132. Winter, D.A., *Biomechanics and Motor Control of Human Movement*. 2 ed. 1990, New York: John Wiley and Sons, Inc.

133. Martini, F., *Fundamentals of Anatomy and Physiology*. 4 ed. 1997, Upper Saddle River, NJ: Prentice Hall.

134. Koh, T.J. and M.D. Grabiner, *Evaluation of methods to minimize cross talk in surface electromyography.* J Biomech, 1993. **26 Suppl 1**: p. 151-7.

135. Basmajian, J.V. and R. Blumenstein, *Electrode placement in electromyographic feedback*, in *Biofeedback: Principles and Practice for Clinicians*, Basmajian, Editor. 1989, Williams and Wilkins: Baltimore.

136. Moffroid, M., J. Tranowski, and A. Ricamato, *Computer solutions to identify EMG latency of automatic postural reactions.* IEEE Eng Med Biol, 1992. **11**(4): p. 48-51.

137. Myers, J.B., *Assessment of muscle joint complex stiffness and reflex latencies in anterior glenohumeral instability patients*. 2001: University of Pittsburgh.

138. Ashton-Miller, J.A., *Proprioceptive thresholds at the ankle: implications for prevention of ligament injury*, in *Proprioception and Neuromuscular Control in Joint Stability*, S.M. Lephart and F.H. Fu, Editors. 2000, Human Kinetics: Champaign, IL.

139. Johnson, M.B. and C.L. Johnson, *Electromyographic response of peroneal muscles in surgical and nonsurgical injured ankles during sudden inversion.* J Orthop Sports Phys Ther, 1993. **18**(3): p. 497-501.

140. Grüneberg, C., P.H. Nieuwenhuijzen, and J. Duysens, *Reflex responses in the lower leg following landing impact on an inverting and non-inverting platform.* J Physiol, 2003. **550**(Pt 3): p. 985-93.

141. Perrin, D.H., *Athletic Taping and Bracing*. 1995, Champaign, IL: Human Kinetics.

142. Cochran, W.G. and G.M. Cox, *Experimental Designs*. 2 ed. 1957, New York: John Wiley and Sons, Inc.

143. Komi, P.V. and E.R. Buskirk, *Reproducibility of electromyographic measurements with inserted wire electrodes and surface electrodes.* Electromyography, 1970. **10**(4): p. 357-67.

144. Konradsen, L., *Ankle eversion torque response to sudden ankle inversion: Torque response in unbraced, braced, and pre-activated situations.* J Orthopaed Res, 2005. **In Press**.

145. Osborne, M.D., L.S. Chou, E.R. Laskowski, J. Smith, and K.R. Kaufman, *The effect of ankle disk training on muscle reaction time in subjects with a history of ankle sprain.* Am J Sports Med, 2001. **29**(5): p. 627-32.

146. Khin Myo, H., T. Ishii, M. Sakane, and K. Hayashi, *Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle.* Foot Ankle Int, 1999. **20**(9): p. 554-9.

147. Shima, N., A. Maeda, and K. Hirohashi, *Delayed latency of peroneal reflex to suddne inversion with ankle taping or bracing.* Int J Sport Med, 2004. **25**: p. 1-5.

148. Nishikawa, T., M. Kurosaka, K. Mizuno, and M. Grabiner, *Protection and performance effects of ankle bracing.* Int Orthop, 2000. **24**(5): p. 285-8.

149. Nieuwenhuijzen, P.H., C. Gruneberg, and J. Duysens, *Mechanically induced ankle inversion during human walking and jumping.* J Neurosci Methods, 2002. **117**(2): p. 133-40.

150. Konradsen, L., J.B. Ravn, and A.I. Sorensen, *Proprioception at the ankle: the effect of anaesthetic blockade of ligament receptors.* J Bone Joint Surg Br, 1993. **75**(3): p. 433-6.

151. Martin, N. and R.A. Harter, *Comparison of inversion restraint provided by ankle prophylactic devices before and after exercise.* J Athl Train, 1993. **28**(4): p. 324-329.

152. Cordova, M.L., C.D. Ingersoll, and M.J. LeBlanc, *Influence of ankle support on joint range of motion before and after exercise: a meta-analysis.* J Orthop Sports Phys Ther, 2000. **30**(4): p. 170-7; discussion 178-82.

153. Dorrough, J.L., K.L. Orton, M.L. Cordova, C.D. Ingersoll, and M.L. Merrick, *Effects of ankle bracing on rearfoot motion during sudden inversion (abstract).* J Athl Train, 2001. **33 (suppl)**: p. S-51.

154. Ricard, M.D., S.M. Sherwood, S.S. Schulthies, and K.L. Knight, *Effects of tape and exercise on dynamic ankle inversion.* J Athl Train, 2000. **35**: p. 31-37.

155. Cordova, M.L., C.D. Ingersoll, and R.M. Palmieri, *Efficacy of Prophylactic Ankle Support: An Experimental Perspective.* J Athl Train, 2002. **37**(4): p. 446-457.

156. Simoneau, G.G., R.M. Degner, C.A. Cramper, and K.H. Kittelson, *Changes in ankle joint proprioception resulting from strips of athletic tape applied over the skin.* J Athl Train, 1997. **32**: p. 141-147.

157. Matsusaka, N., S. Yokoyama, T. Tsurusaki, S. Inokuchi, and M. Okita, *Effect of ankle disk training combined with tactile stimulation to the leg and foot on functional instability of the ankle.* Am J Sports Med, 2001. **29**(1): p. 25-30.

158. Alt, W., H. Lohrer, and A. Gollhofer, *Functional properties of adhesive ankle taping: neuromuscular and mechanical effects before and after exercise.* Foot Ankle Int, 1999. **20**(4): p. 238-45.

159. Cordova, M.L., C.V. Cardona, C.D. Ingersoll, and M.A. Sandry, *Long-term ankle brace use does not affect peroneus longus muscle latency during sudden inversion in normal subjects.* J Athl Train, 2000. **35**: p. 407-411.

160. Glick, J.M., R.B. Gordon, and D. Nishimoto, *The prevention and treatment of ankle injuries.* Am J Sports Med, 1976. **4**(4): p. 136-41.

161. Sinkjaer, T., E. Toft, S. Andreassen, and B.C. Hornemann, *Muscle stiffness in human ankle dorsiflexors: intrinsic and reflex components.* J Neurophysiol, 1988. **60**(3): p. 1110-21.

162. Birmingham, T.B., J.F. Kramer, J.T. Inglis, C.A. Mooney, L.J. Murray, P.J. Fowler, and S. Kirkley, *Effect of a neoprene sleeve on knee joint position sense during sitting open kinetic chain and supine closed kinetic chain tests.* Am J Sports Med, 1998. **26**(4): p. 562-6.

163. Chu, J.C., E.J. Kane, B.L. Arnold, and B.M. Gansneder, *The Effect of a Neoprene Shoulder Stabilizer on Active Joint-Reposition Sense in Subjects With Stable and Unstable Shoulders.* J Athl Train, 2002. **37**(2): p. 141-145.

164. Thonnard, J.L., L. Plaghki, P. Willems, J.C. Benoit, and J. De Nyer, *[Pathogenesis of ankle sprain: testing of a hypothesis].* Acta Belg Med Phys, 1986. **9**(2): p. 141-5.

165. Konradsen, L., *Sensori-motor control of the uninjured and injured human ankle.* J Electromyogr Kinesiol, 2002. **12**(3): p. 199-203.

166. Olmsted, L., L. Vela, C. Denegar, and J. Hertel, *Prophylactic ankle taping and bracing: a numbers-needed-to-treat and cost-benefit analysis.* J Athl Train, 2004. **39**(1): p. 95-100.