Increasing Calcaneal Plantar Flexion as a Method to Improve Weight Bearing Leg Dorsiflexion

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Abstract

Previous research on foot and ankle mechanics has shown that weight bearing leg dorsiflexion range of motion is positively correlated to calcaneal plantar flexion. The gastrocnemius muscle promotes while the plantar aponeurosis and plantar intrinsic muscles restrict calcaneal plantar flexion. Thus, reducing plantar aponeurosis and plantar intrinsic muscle tension while increasing gastrocnemius strength may improve weight bearing leg dorsiflexion range of motion. Twenty-seven participants with poor (< 25°) leg dorsiflexion were enrolled and randomly assigned to one of two six-week intervention groups. Group 1 (n = 14) performed self-massage and stretching of the plantar aponeurosis and plantar intrinsic muscles three days per week. Group 2 (n = 13) performed the same self-massage and stretching in addition to a modified glute-ham-gastroc raise exercise. The weight bearing lunge, the standard assessment for leg dorsiflexion, was assessed before and after the intervention. Additionally, force platforms and three-dimensional motion analysis were used to examine lower extremity kinetics and kinematics during a partial squat exercise, with ankle net joint moments, peak leg dorsiflexion and calcaneal plantar flexion being the primary movements of interest. In the weight bearing lunge, Group 1 improved their leg dorsiflexion by 3.7 ± 2.9° (Effect Size (ES) = 1.16) in the left and 4.2 ± 3.2° (ES = 1.25) in the right. Group 2 experienced greater increases in the left of 4.9 ± 4.4° (ES = 1.80) and 6.4 ± 3.7° for the right (ES = 1.51). In the partial squat, leg dorsiflexion increased -0.6 ± 3.2° for the left (ES = 0.15) and -1.0 ± 2.6° for the right (ES = 0.24) in Group 1, and -2.3 ± 4.2° for the left (ES = 0.55) and -2.1 ± 3.2° for the right (ES = 0.59) in Group 2. There were small increases in calcaneal plantar flexion where Group 1 increased -0.7 ± 2.6° in the left (ES = 0.25) and -0.2 ± 2.7° in the right (ES = 0.08), whereas Group 2 increased -0.3 ± 3.2° in the left (ES = 0.15) and -2.7 ± 6.2° in the right (ES = 0.64). These results suggest that plantar aponeurosis and plantar

intrinsic muscle self-massage and stretching in combination with modified glute-ham-gastroc raise exercise could be an alternative to calf stretching to improve weight bearing leg dorsiflexion range of motion.

Preface

This thesis is an original work by Gabriella vonGaza. The research project, of which this thesis was a part, received research ethics approval from the University of Alberta Research Ethics Board under the name "The Improvement of Calcaneal Plantar Flexion as a Method of Increasing Weight Bearing Leg Dorsiflexion Range of Motion". No. Pro00059756, which was approved November 9, 2015.

Acknowledgements

I would like to thank my supervisor, Dr. Loren Chiu, for his guidance, knowledge, and patience throughout the duration of this research project, as it would not be possible without him.

I would like to thank Kirsten Peters for her help in both the supervision of research participants and the data collection process.

And I am greatly appreciative of the individuals who volunteered their time to participate in my thesis project, because without them this would not have been possible.

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List of Abbreviations

ROM: Range of Motion

GHG: Glute-Ham-Gastroc Raise

NJM: Net Joint Moment

CHAPTER 1

Introduction

Rationale

Leg dorsiflexion range of motion is defined as the leg segment's ability to rotate forward relative to a vertical axis in weight bearing tasks. Rotation of the leg segment is an important contributor to lower extremity movement mechanics and sufficient range of motion is required for the proper execution of several performance-related movement (Chiu, vonGaza & Jean, 2017; Devita & Skelly, 1992; Moolyk, Carey, & Chiu, 2013) Past research has found that decreased dorsiflexion range of motion is related to various lower extremity injuries (Pope, Herbert, & Kirwan, 1998). The standard method of improving dorsiflexion range of motion is through calf muscle stretching programs. This has been shown to cause a statistically significant improvement but this improvement may not be clinically or practically meaningful (Radford et al., 2006). Previous research on foot and ankle mechanics has shown that the ability of the leg segment to rotate anteriorly (leg dorsiflexion) is correlated to the calcaneus' ability to rotate anteriorly (plantar flexion) (Chizewski & Chiu, 2012). This anatomical phenomenon between the two segments allows for new potential methods of improving leg dorsiflexion range of motion during a weight bearing squat task.

Knowledge of the anatomy and biomechanics of the ankle joint complex allows for the derivation of potential alternative strategies of improving calcaneal plantar flexion. One potential method consists of increasing the extensibility of the anatomical structures that would rotate the calcaneus posteriorly into dorsiflexion through the employment of a stretching and self-massage program. These structures would consist of the plantar aponeurosis and the plantar intrinsic musculature of the foot that attach distally to the calcaneus. A second potential intervention is strengthening the gastrocnemius with the aim of increasing the muscle's pull on the proximal calcaneus which creates a moment that can rotate the calcaneus into plantar flexion. The ability of these methods to increase both calcaneal plantar flexion and consequently leg dorsiflexion during weight bearing needs to be examined to further understand the relationship.

Purpose

The purpose of this research study is to examine the effects of two potential methods of increasing calcaneal plantar flexion and how these methods impact leg dorsiflexion range of motion during the weight bearing lunge test as well as a weight bearing squat task.

Hypotheses

It is hypothesized that both methods will increase calcaneal plantar flexion, which will cause an increase in leg dorsiflexion range of motion. Combining stretching and self-massage of the plantar structures of the foot with the strengthening of the gastrocnemius is hypothesized to be more effective compared to stretching and self-massage alone. The combination of these two protocols is hypothesized to increase ankle plantar flexor net joint moment, stretching and self-massage alone will not.

Literature Review

Osteology and Arthrology

The ankle is the articulation between the leg and the foot. The leg is composed of two bones, the tibia and fibula and the foot is composed of twenty-six bones. In anatomical and biomechanical research, the foot is assumed to act as either: 1) a single rigid segment or 2) multiple rigid segments. The foot can be divided into four segments: phalanges, metatarsals, midfoot, and rearfoot (Figure 1). The forefoot is composed of the metatarsals and phalanges, and the midfoot is composed of the navicular, cuboid, and the three cuneiform bones. The rearfoot is composed of the talus and the calcaneus, which are important to consider when examining the ankle joint. The ankle joint is often called the ankle joint complex as it can be functionally broken down into two separate joints (van den Bogert, Smith, & Nigg, 1994). The true ankle – or talocrural – joint is the articulation that occurs between the tibia and fibula with the talus. The second joint in the complex occurs between the talus and the calcaneus and is referred to as the subtalar joint.

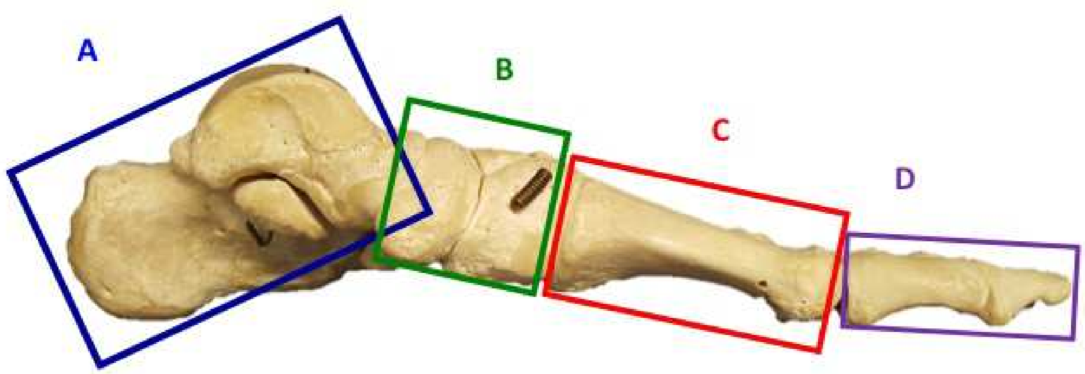

Figure 1: Four Segments of the Foot A: Rearfoot, B: Midfoot, C: Metatarsals, D: Phalanges

The talocrural joint is the articulation specifically between the dorsal or superior surface of the talus and the cavity formed between the medial malleolus of the tibia and the lateral malleolus of the fibula (Neumann, 2002). The dorsal surface of the talus provides a smooth articulating surface for the talocrural joint and has a convex shape anterior-posterior and a slight concave shape medial-lateral (Neumann, 2002). This shape allows it to fit in the cavity of the distal end of the tibia and lie between the malleoli. From the posterior aspect of the talus, the bone widens anteriorly, causing it to be slightly wedged shaped, and projects medially about 30° from the midline of the foot (Neumann, 2002). The shapes of the talus and the distal ends of the tibia and fibula impact the type and amount of motion occurring at the talocrural joint.

Due to the shapes of the bones forming it, the talocrural joint is described as having one degree of freedom and only allows rotation about the medial-lateral/coronal axis (Neumann, 2002). This axis lies along the line connecting the tips of the medial and lateral malleoli and runs through the body of the talus (Neumann, 2002). It is not a true medial-lateral axis, as it does not line up with the coronal axis of the body as it deviates approximately 10° in the frontal plane and 6° in the horizontal (Neumann, 2002). This is due to the location of the medial and lateral malleoli. The lateral malleolus is located inferior and posterior to the medial malleolus and occurs as a result of tibial torsion (Neumann, 2002). Tibial torsion is the natural twisting of the tibia along its inferior-superior axis that runs along the length of the bone. This twisting varies between individuals and tends to be in a range from 20-30° of external/lateral rotation, when comparing the distal end to the proximal end (Neumann, 2002).

The medial-lateral axis allows for movement in the sagittal plane, which for the talocrural joint, is denoted as plantar flexion and dorsiflexion. Plantar flexion is when the anterior angle between the tibia and the talus increases, which is often described as pointing of the toes and dorsiflexion is when the angle between the tibia and the talus decreases, where the toes are brought up towards the shin. The deviation of the medial-lateral axis previously discussed, causes plantar flexion and dorsiflexion to deviate from the sagittal plane of the body. Plantar flexion then occurs with slight adduction and inversion and dorsiflexion occurs with slight abduction and eversion (Wong, Kim, & Ying, 2005). Due to the shape of the talocrural joint, the dorsiflexion range of motion is limited due to the widening of the anterior aspect of the talus, as previously discussed. The anterior part of the talus wedges into the cavity that lies between the malleoli and causes the movement to be restricted when compared to ankle plantar flexion. At the talocrural joint, an average of 48° plantar flexion and 26° dorsiflexion have been measured (Neumann, 2002).

The subtalar joint is the articulation between the inferior surfaces of the talus with the calcaneus. It is designed to transmit the rotations from the leg and ankle to the rest of the foot, as well absorbs forces during gait (Stagni, Leardini, O'Connor, & Giannini, 2003). It has three dorsal facets (posterior, middle, and anterior) that articulate with matching facets on the inferior aspect of the talus (Neumann, 2002). The most prominent articular facet is the posterior facet, which is convex in shape allowing it to conform to the concave shape of the talar bone's posterior facet. This improves joint congruity allowing it to be more stable. The stability is also increased from the surrounding ligaments and musculature, as well as the weight of the body. During weight bearing tasks, such as walking, there is no relative motion between the calcaneus during the majority of the stance phase of gait (Hamel, Sharkey, Buczek, & Michelson, 2004). This causes any movement of the calcaneus to be directly transferred to the talus where both bone move as a solid unit (Hamel et al., 2004). Consequently, the calcaneus and talus move in unison and have the same plantar flexion during gait.

In a non-weight bearing position the subtalar joint allows for movement of the calcaneus relative to the talus (Neumann, 2002). The axis of rotation for subtalar joint movements varies between individuals and typically runs from the lateral-posterior heel through the subtalar joint in anterior, medial, and superior direction (Neumann, 2002). This axis of rotation has been reported by different researchers to lie 42° (Hicks, 1953; Manter, 1941; Isman & Inman, 1969) from the transverse plane but there has been differing values of the sagittal plane deviations. In the sagittal plane 16° (Manter, 1941), 17° (Root et al., 1966), and 23° (Isman & Inman, 1969) have been reported.

The deviations in the axis of rotation for the subtalar joint cause the movements of the joint to occur in all three planes of the body. The boney movements are often simplified into pronation and supination. They are composed of the movements in the transverse and frontal plane where supination is composed of both inversion and adduction and pronation is composed of eversion and abduction (Neumann, 2002). The subtalar joint experiences more inversion that eversion, where the average inversion range of motion has been reported to be 23° and eversion averages 13° (Neumann, 2002). In the sagittal plane, the calcaneus is able to plantar flex and dorsiflex relative to the talus, but to a lesser degree than movements in the other planes (Neumann, 2002). Leardini et al. (2001) examined motions of the bones of the ankle complex and found that at the subtalar joint an average of 9° and 4° of plantar flexion and dorsiflexion respectively, was experienced between the talus and the calcaneus.

Ankle Versus Leg Dorsiflexion

When examining movement at the ankle it is important to examine the terminology used to describe dorsiflexion range of motion as well as how it is measured. Since ankle dorsiflexion occurs at the talocrural joint it requires the examination of the orientation of both the tibia and the talus. However, it is hard to measure the movement occurring between these two bones so the movement between the foot and the leg segment is what is often measured. Traditionally, ankle dorsiflexion has been measured in non-weight bearing which is limited to approximately 26° (Neumann, 2002). These measurements are taken with both the knee extended (long-sit) and knee flexed to 90° (short-sit) (Hankemeier & Thrasher, 2014; Rome, 1996). Non-weight bearing measures have also been performed actively and passively. The active ROM refers to the ability to pull one's foot into a dorsiflexed position, whereas passive ROM is measured with an external force applied to the ball of the foot (Rome, 1996) (Figure 2). These are typically measured with a goniometer with the axis of rotation at the lateral malleolus, one arm following the line of the fibula, and the second arm parallel to the plantar surface of the foot (Rome, 1996).

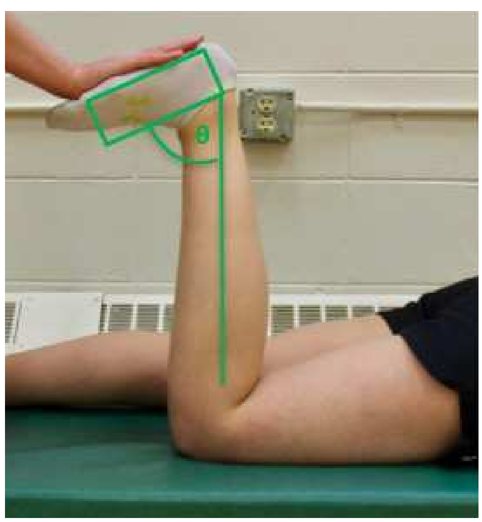

Figure 2: Short-sit non-weight bearing ankle dorsiflexion

The dorsiflexion achieved when the foot's plantar surface is in contact with the ground can be referred to as leg dorsiflexion, which is the ROM achieved during squatting and landing from a jump (Figure 3). This would be considered the forward rotation of the leg segment rather than the movement of the foot relative to the leg or vice versa. It would be expected that leg dorsiflexion range of motion would yield similar values to non-weight bearing ankle dorsiflexion. However, in tasks such as squatting and landing from a vertical jump, leg dorsiflexion exceeds 35° (Moolyk et al., 2013; Chiu, vonGaza, & Jean, 2017). Leg dorsiflexion is most commonly measured using the weight bearing lunge test by finding the angle of inclination of the leg relative to the floor but is often reported relative to the vertical (Dickinson, Hollman-Gage, Ojofeitimi, & Bronner 2012; Rome, 1996). Since this range of motion has been shown to exceed 26°, there is not only movement occurring at the talocrural joint but movement must also occur within the foot to allow the high leg dorsiflexion angles observed during weight-bearing tasks (Figure 3).

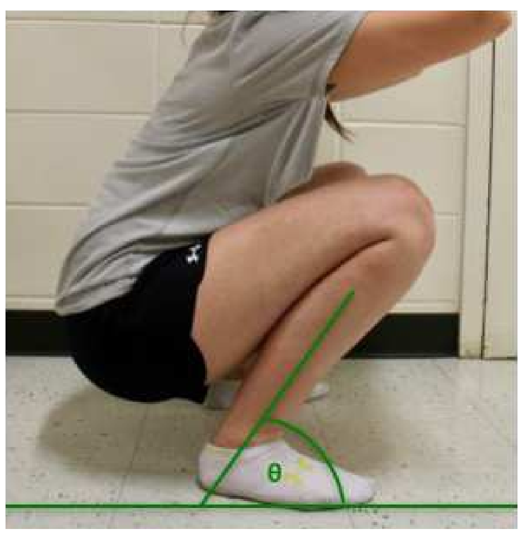

Figure 3: Leg dorsiflexion achieved during a deep squat exercise

Chizewski & Chiu (2012) examined the sagittal plane rotations of the calcaneus and the leg and their contributions to ankle dorsiflexion range of motion during a weight bearing squat task. For their investigation, ankle dorsiflexion was the measure of the relative motion between the calcaneus and the leg segment. Segment and joint angle excursions were measured during a partial squat where participants were instructed to achieve maximum dorsiflexion while keeping their torso upright. On average, the amount of ankle dorsiflexion excursion experienced was an average of 19° with a range of 12°-29° for the left and an average of 18° and a range of 9°-27° for the right (Chizewski & Chiu, 2012). The calcaneus experienced an average of 10° of plantar flexion with a range of 5-15° and 5-18° for the left and right sides respectively (Chizewski & Chiu, 2012). In the sagittal plane the leg segment experienced an average forward rotation of 30° with a range of 17-43° for the left and an average forward rotation of 29° and a range of 15-42°for the right. They found that the rotation of the leg segment was positively correlated to ankle dorsiflexion but calcaneal rotations were negatively correlated to ankle dorsiflexion (Chizewski & Chiu, 2012). However, the rotation of the leg and the rotation of the calcaneus in the sagittal plane were positively correlated to one another (Chizewski & Chiu, 2012). The plantar flexion of the calcaneus allows for the repositioning of the talus (into increased plantar flexion) which allows there to be a shift in the talocrural joint, thus allowing greater forward inclination of the leg (Chizewski & Chiu, 2012) (Figure 4). This demonstrates that upon weight bearing, the movements of the tarsal bones have the potential to influence rotations at the talocrural joint as well as the leg segment.

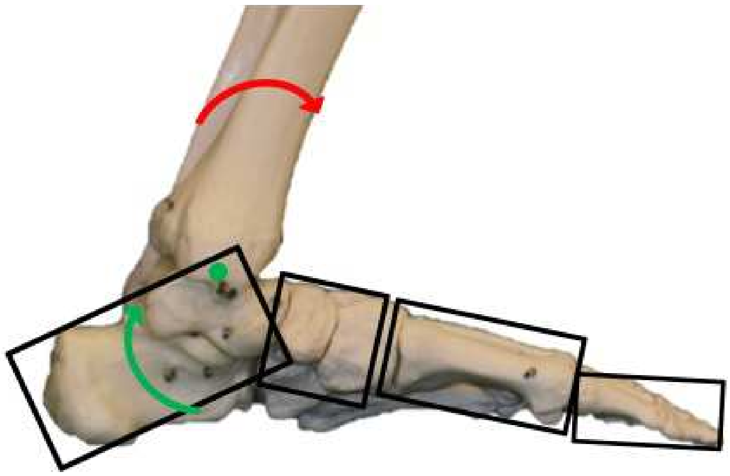

Figure 4: Leg rotation (red arrow) is limited by talocrural joint morphology. Calcaneal rotation (green arrow) reorients talocrural joint to allow more leg dorsiflexion.

Soft Tissue Structures

Movements at the talocrural joint are caused by the musculature that cross from the leg segment and attach to the foot. This consists of the musculature that lies anteriorly and laterally on the leg as well as those that form the calf on the posterior aspect. A primary function of the musculature that surround the leg, ankle, and foot is to provide both static and dynamic control as well as aid in the shock absorption of the lower extremity (Neumann, 2002). In terms of motion at the subtalar joint, motions are indirectly determined by the musculature that crosses the talocrural, subtalar, and transverse tarsal joints since there are no muscles that directly cross the subtalar joint attaching to both the talus and the calcaneus (Stagni et al., 2003). Of the musculature that indirectly causes movement at the subtalar joint, those that attach to the calcaneus play a crucial role. These structures consist of the triceps surae that attach proximally on the calcaneus and the plantar aponeurosis and the plantar intrinsic muscles of the foot, which attach distally.

The location of the musculature determines the resultant action about the ankle. Four muscles make up the anterior compartment, and have proximal attachments on the anterior portion of the tibia, fibula, and interosseous membrane and cross the dorsal aspect of the angle where they then attach distally to various aspects of the foot (Neumann, 2002). These muscles are commonly referred to as the ‘dorsiflexors’ as they are responsible for actively dorsiflexing the foot relative to the leg. The lateral compartment contains two muscles, which are primarily responsible for causing ankle eversion. They attach proximally to the lateral aspect of the fibula and distally to the lateral aspect of the foot. The posterior compartment can be further divided into a superficial group and a deep group (Neumann, 2002). They are collectively considered ankle plantar flexors, but the deep group is also characterized by being ankle inverters (Neumann, 2002). The superficial group is also referred to as the triceps surae and it made up of two separate muscles: the soleus and the medial and lateral heads of the gastrocnemius which attached distally on the calcaneus (Figure 2).

The other musculature that affects the rotation about the subtalar joint are those that attach to the distal aspect of the calcaneus. These structures consist of the plantar intrinsic muscles of the foot and the plantar aponeurosis, which have the primary role of supporting the longitudinal arch of the foot (Cheung, Zhang, & An, 2006; Perry, 1982; Thordarson, Schmotzer, Chong, & Peters, 1995). The intrinsic musculature of the foot are those muscles that have both proximal and distal attachment sites within the foot segment. These muscles are also responsible for supporting the arch of the foot and are involved in postural control and maintenance of balance especially in single limb standing tasks (Kelly, Kuitunen, Racinais, & Cresswell, 2011).

The plantar aponeurosis is made up of thick and dense connective tissue bands aligned both along anterior-posterior and medial-lateral directions (Neumann, 2002). It can be further divided into superficial and deep fibers. The superficial fibers are attached to the dermis and aid in shock absorption (Neumann, 2002). The deep fibers make up the bulk of the plantar aponeurosis and attach proximally to the medial process of the calcaneal tuberosity. The deep fibers have medial, lateral and central portions with corresponding distal attachments (Chen et al., 2014). The medial and lateral portions are smaller and attach abductor hallucis muscle and the abductor digiti minimi respectively, and can also be referred to as the 'fascia' portion (Chen et al., 2014). The central portion is the largest and is considered the 'aponeurosis', it separates into five smaller bundles that attaches to the proximal phalanges via the plantar plates (Figure 2) (Chen et al., 2014).

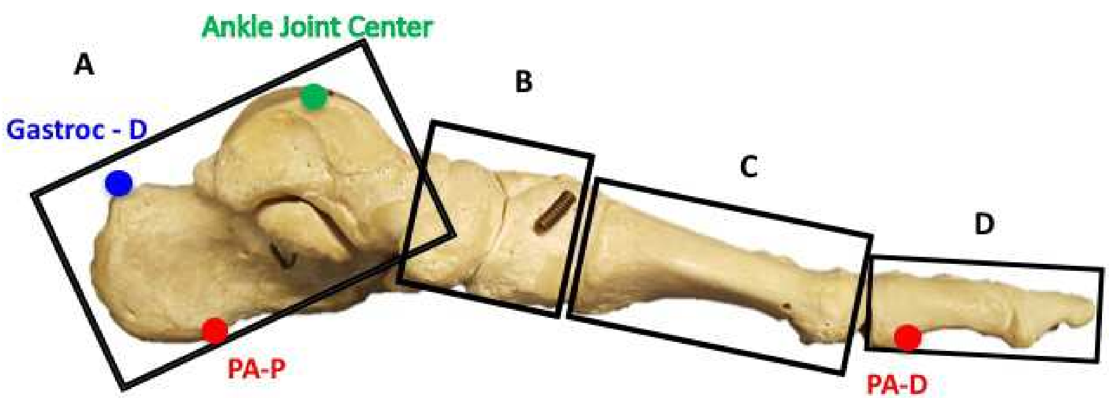

Figure 5: Distal attachment site for the gastrocnemius (Gastroc-D) and the proximal (PA-P) and distal (PA-D) attachments of the plantar aponeurosis, and the ankle joint center

Functional Implications

The kinematics of the foot, leg, and ankle will impact the entire lower extremity, which may affect posture, performance, and injury risk. Specifically, leg dorsiflexion range of motion is required for both activities of daily living and sport performance. In regard to activities of daily living, research has shown that dorsiflexion range of motion is required during stair descent where a maximum of 27º was reported (Andriacchi et al., 1980). It has also been shown to contribute to greater standing balance and functional ability in elderly individuals (Menz, Morris, & Lord, 2005). It is necessary for jumping, landing, and squatting as it allows for greater quadriceps loading contributing to concentric force production as well as eccentric force absorption. (Chiu & Salem, 2006; Moolyk, Carey, & Chiu, 2013). Limited dorsiflexion range of motion has also been correlated with lower extremity injury risk. These injuries can vary from shin splints, stress fractures to the tibia and the calcaneus, ankle sprains, plantar fasciitis, Achilles tendonitis, patellar tendinosis, as well as anterior cruciate ligament tears (Kaufman et al., 1999; Malliaras, Cook & Kent, 2006; Pope et al., 1998; Walhstedt & Rasmussen-Barr, 2014).

Landing from a jump with less ankle dorsiflexion has been shown to be correlated with less knee flexion displacement, greater vertical and posterior ground reaction forces, which can increase an individual's risk for ACL injury (Devita & Skelly, 1992; Fong et al., 2011). Stiff landings, characterized by less joint flexion, have a decreased floor contact phase, so less time for force absorption (Devita & Skelly, 1992). This type of landing causes the ankle to perform more work when compared to soft landings, where more work is performed by the knee and hip (Devita & Skelly, 1992). In order to rely on the knee extensors when landing, the leg segment needs to rotate forward into dorsiflexion; at least 40 degrees at the time of peak knee flexion in order to increase the knee extensor net joint moment (Moolyk, Carrey, & Chiu, 2013). This also applies to other exercises that require larger knee extensor net joint moment, such as weight lifting and squatting exercises.

Since one of the major goals of lower extremity resistance training is to increase the strength and power of the quadriceps, it is important to achieve greater dorsiflexion range of motion. Higher dorsiflexion range of motion allows for greater posterior thigh rotation, which causes knee flexion angles and consequently squat depth to be greater (Chiu et al., 2017). Research conducted by Chiu et al. (2017) compared back squats performed with both restricted and unrestricted leg dorsiflexion. They found that squats performed with unrestricted dorsiflexion resulted in ankle plantar flexor and knee extensor net joint moments that were greater than those experienced during vertical jumping and landing. For the squats that were performed with restricted dorsiflexion the net joint moment for the ankle plantar flexors and knee extensors was less than the NJM experienced during jumping and landing. These results show the importance of performing squat exercises through a full range of motion with unrestricted dorsiflexion range of motion. This allows for greater adaptations of the knee extensor and ankle plantar flexor muscle groups.

The typical method of improving dorsiflexion range of motion is reducing the tension of the ankle plantar flexors through various calf-stretching programs. These programs are often prescribed as part of a treatment plan for various injuries that are associated with decreased dorsiflexion range of motion, such as Achilles tendonitis and plantar fasciitis (Radford et al., 2006). A systematic review and meta-analyses conducted by Radford et al. (2006) examined five different studies that compared the ankle dorsiflexion range of motion of those who completed static calf stretching programs to those who performed no stretches. There was a statistically significant improvement, and the pooled data showed a 2-3 degree increase after a calf-stretching program (Radford et al., 2006).

Even with this statistically significant increase in dorsiflexion range of motion it is not known whether it is clinically meaningful and if individuals will notice the improvement in terms of both injuries and movement mechanics (Radford et al., 2006). A study done by Pope et al. (1998), looked at using calf stretching before exercise to decrease the risk of injury in army recruits and they found that the calf stretching program was not enough to reduce the number of the typical lower extremity injuries experienced by army recruits.

Results from the study done by Chizewski and Chiu (2012) help to further understand the relationship between the bones of the foot and lower extremity movement mechanics. Extrapolating from their results, improving calcaneal plantar flexion range of motion through the manipulation of the soft tissue structures acting on the calcaneus could lead to an improvement in leg dorsiflexion. The manipulation of the tissues surrounding the ankle joint complex can be determined from on the anatomy and biomechanics of the ankle joint complex and determining what structure will improve calcaneal plantar flexion.

The amount of calcaneal plantar flexion can be increased through two different mechanisms. Firstly, it can be increased by improving the pull of the muscles that attach to the proximal aspect of the calcaneus. If gastrocnemius or soleus exert greater force, the moment about the ankle joint center increases, which has the tendency to rotate the calcaneus into plantar flexion (Figure 6). Secondly, the moment generated by the structures that attach to the distal aspect of the calcaneus can be decreased. The force exerted by these structures generates moment about the ankle joint center which has the tendency to rotate the calcaneus into dorsiflexion (Figure 7). By reducing the stiffness of these structures, the force they exert will decrease, and the ability to restrict calcaneal plantar flexion is reduced.

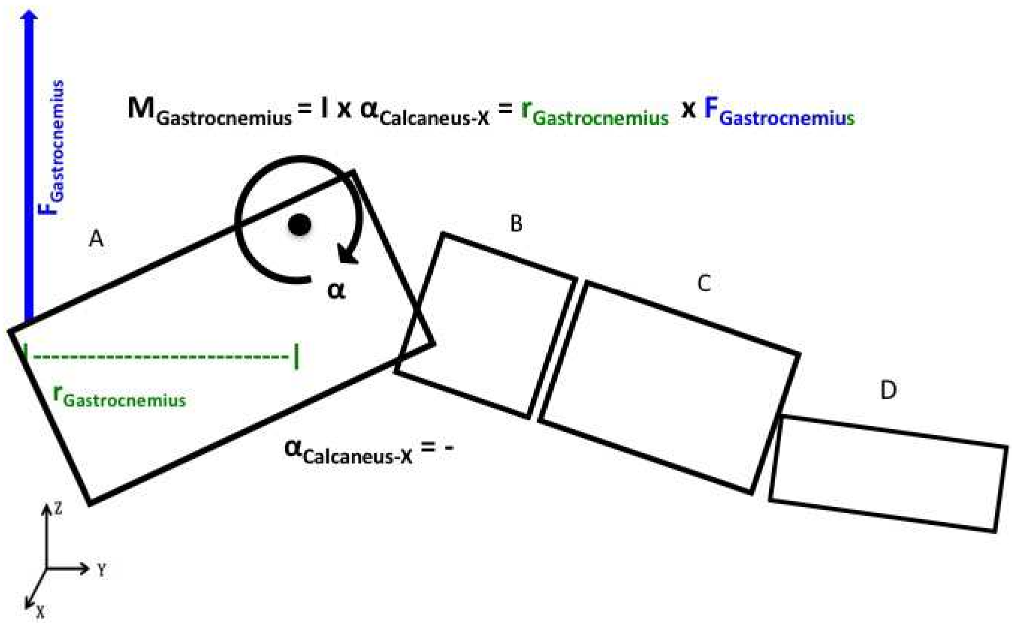

Figure 6: Calcaneal plantar flexor moment about the ankle joint center caused by the force exerted on the calcaneus from the gastrocnemius muscle

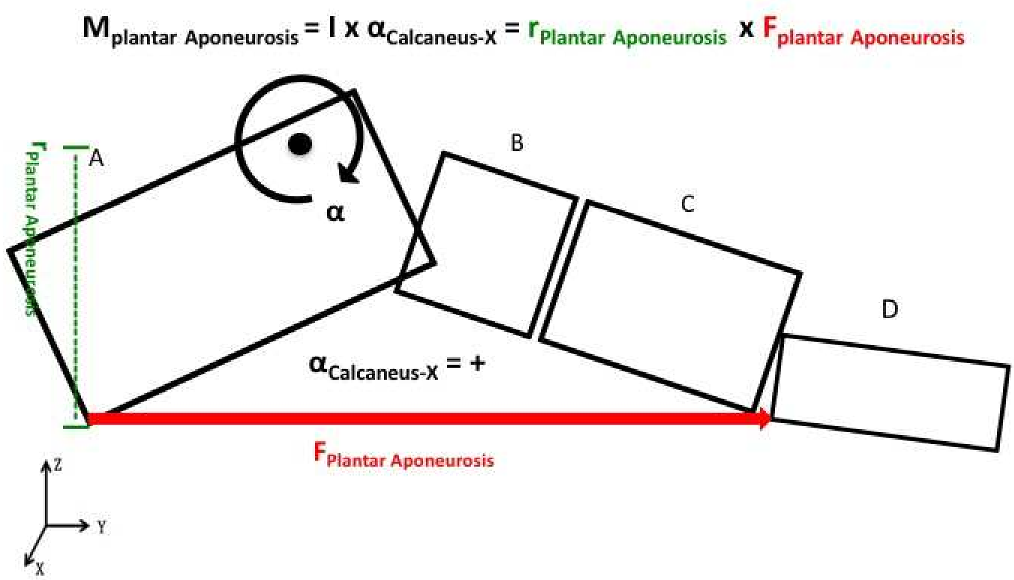

Figure 7: Calcaneal dorsiflexor moment about the ankle joint center caused by the force exerted on the calcaneus from the plantar aponeurosis

Calcaneal plantar flexor muscles are those with a distal attachment site on the proximal aspect of the calcaneus. The muscles that fit this criterion are those that make up the triceps surae: the soleus and the gastrocnemius. The may share the same distal attachment of the calcaneus via the Achilles tendon but the proximal attachment sites differ between the muscles. The soleus attaches to the tibia and fibula, and the gastrocnemius inserts onto the femoral condyles. The resultant actions differ as a result of these proximal attachments. The soleus acts on the leg segment pulling it into plantar flexion and/or restricting leg dorsiflexion, which is the opposite of the desired effect. Whereas the gastrocnemius pulls on the thigh segment, causing flexion of the thigh on the leg and does not restrict leg dorsiflexion range of motion.

This differentiation between gastrocnemius and soleus is demonstrated in a study done by Stewart et al. (2007) where increased soleus and gastrocnemius activation was examined during gait. When the soleus activation was increased there was a slight reduction in leg dorsiflexion during gait. This differs from increased gastrocnemius activation, where there was an increase in leg dorsiflexion as well as calcaneal plantar flexion and thigh flexion (Stewart et al., 2007).

The difference between the soleus and gastrocnemius has also been evaluated in terms of differences in calcaneal rotations in order to determine the differences in muscle function at the distal aspect (Arndt, Bruggerman, Koebke, & Segesser, 1999). Calcaneal rotations were determined in all three planes: plantar flexion/dorsiflexion, abduction/adduction, and inversion/eversion. In terms of sagittal plane rotations, the gastrocnemius produced a greater plantar flexor moment at the calcaneus, when compared the soleus with same amount of force applied to the muscles (Arndt et al., 1999). This could be due to the gastrocnemius having a more advantageous lever arm in the sagittal plane (Arndt et al., 1999). When the two heads of the gastrocnemius were examined independently of one another it was found that isolated lateral gastrocnemius activation caused an eversion moment to occur. This was significantly different from the frontal plane moments caused by the soleus, medial gastrocnemius, and gastrocnemius as a whole, which cause an inversion moment of the calcaneus (Arndt et al., 1999).

Since the plantar aponeurosis attaches to the phalanges, this allows it to be influenced by movements of the phalanx as well as the calcaneus. When the phalanges are raised into dorsiflexion, it causes the aponeurosis to tighten. The increase in tension of the plantar structures transmits force to the calcaneus pulling the calcaneal tuberosity anteriorly, rotating the bone posteriorly into dorsiflexion. This causes the height of the arch to increase, as the longitudinal arch is essential compressing anterior-posteriorly; this is known as the windlass mechanism (Figure 8) (Hicks, 1954).

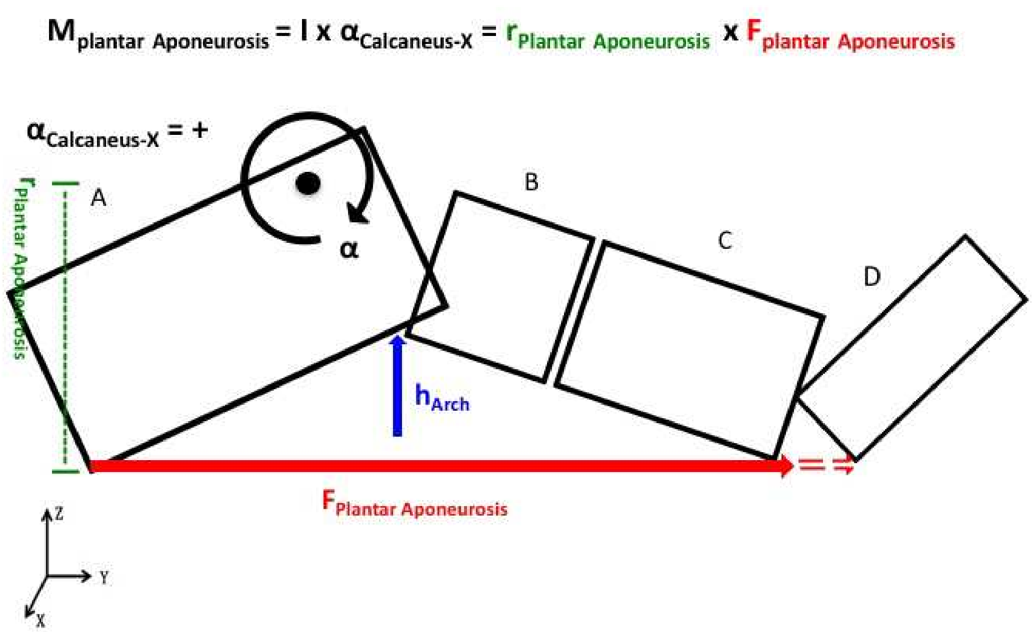

Figure 8: Windlass Mechanism: As the toes dorsiflex the plantar aponeurosis pulls on the calcaneus, causing a calcaneal dorsiflexor moment about the ankle joint center, resulting in an increase in height of the arch

The plantar aponeurosis is typically thought of in terms of arch support and the windlass mechanism, but the influence of the intrinsic musculature is not as widely supported. A study done by Kelly et al. (2014), examined arch deformation and muscle activity of intrinsic muscles of the foot during external load conditions as well as the response of foot structure to the electric stimulation of the individual foot muscles. The muscles examined were abductor hallucis, flexor digitorum brevis, and quadratus plantae. The results show that as the load placed on the body increased, the height of the arch decreased and the muscle activation increased. When a load was placed on the body the arch experienced deformation but then when the muscles were involuntarily activated, the deformation of the longitudinal arch was minimized (Kelly et al., 2014). This study shows that the intrinsic musculature of the foot also plays a key role in the maintenance and support of the structure of the longitudinal arch.

The relationship between the plantar aponeurosis and calcaneal rotation has been demonstrated in the research conducted on plantar fasciitis. The examination of the sagittal plane changes of the foot during weight bearing show that reduced foot mobility and plantar aponeurosis inelasticity are correlated to plantar fasciitis and heel pain (Sahin, Ozturk, & Atici, 2010). The differences between individuals with plantar fasciitis and heel pain in weight bearing and non-weight bearing was compared to those without pain (Sahin et al., 2010). The changes in calcaneal position were reported and calcaneal inclination angle (relative to horizontal) of those with heel pain was found to be higher in weight bearing than those without pain (Sahin et al., 2010). Simkin and Leichter (1990) also examined calcaneal inclination and found that the energy storage capacity of the longitudinal arch is highest at an intermediate angle of calcaneal inclination. When the angle of inclination is low or high there is a reduction in the storage capacity, suggesting that the position of the calcaneus is correlated to the function of the arch and potentially the plantar aponeurosis (Simkin & Leichter, 1990).

As previously discussed, on the proximal side of the calcaneus there is the Achilles tendon that pulls on the calcaneus rotating it anteriorly or into plantar flexion. This has the opposite effect on arch height. As a study done by Thordarson et al. (1995) examined the different ways the longitudinal arch of the foot is dynamically supported during plantar loads of 350N and 700N with varying tensions on the tendons that attach to the foot. It was found that the plantar aponeurosis provided the greatest amount of arch support with improvements of 4° and 2° in arch height for the 350N and 700N trials respectively (Thordarson et al., 1995). The triceps surae was then found to have the opposite effect. It had a detrimental effect on arch height, flattening it 3° with 350N of force and 4° with 700N of force (Thordarson et al., 1995).

This is similar to what was found by Cheung et al. (2006). A 3D foot model was used to test the effects of Achilles tendon loading on plantar aponeurosis and longitudinal arch deformation. To replicate double limb standing, 350N of compressive forces were used on the foot, which was then accompanied by varying forces (0-700N) applied to the Achilles tendon (Cheung et al. 2006). The results showed that as the vertical compressive forces increased so did the strain on the plantar aponeurosis. As Achilles tendon forces increased so did arch deformation, up until the heel started to lift, occurring around 550N of tendon force (Cheung et al. 2006). Cheung et al.'s (2006) results ultimately demonstrate that the Achilles tendon force creates larger strain in the plantar aponeurosis, and a larger decrease in arch height when compared to the force of body weight on the foot.

Individuals with decreased arch height have been shown to have a shortened Achilles tendon, or Achilles tendon contracture (Blackman, Blevins, Sangeorzan & Ledoux, 2009). Blackman et al. (2009) examined fresh frozen cadaver feet and ankles placed at a position that replicates the mid-stance of gait. They compared normal feet to simulated flat feet, and found that the calcaneus experienced significantly greater plantar flexion in the simulated flat foot as well as when Achilles tendon overpull was simulated (Blackman et al, 2009). Research done on the arch demonstrates how the plantar aponeurosis and the Achilles tendon influence arch height via the manipulation of the sagittal plane rotation of the calcaneus

Research shows that the calcaneus has the ability to be manipulated through changes in the surrounding soft tissue structures. The gastrocnemius, plantar aponeurosis, and plantar intrinsic muscles have all been shown to cause sagittal plane motions of the calcaneus and impact the height of the longitudinal arch. The research conducted by Chizewski and Chiu (2012) shows that calcaneal rotations impact leg dorsiflexion range of motion, so the manipulation of calcaneal plantar flexion has the potential to be a new method of improving leg dorsiflexion range of motion.

Anatomical and biomechanical research suggests that the gastrocnemius is the more desirable muscle to increase calcaneal plantar flexion and subsequently leg dorsiflexion. This dictates that the gastrocnemius should be strengthened preferentially over the soleus. The traditional method of improving gastrocnemius muscle strength is through a variety of heel or calf raise exercises, which typically utilize ankle plantar flexion as the resisted movement. Relying solely on this lower extremity movement makes it difficult to know which of the plantar flexor muscles are being targeted.

An exercise that targets the gastrocnemius is referred to as the glute-ham-gastroc raise. This exercise is advantageous as it incorporates both resisted ankle plantar flexion and knee flexion; this targets both medial and lateral heads of the gastrocnemius, as these are the non-weight bearing actions of the muscle. Limited research has been done on the glute-ham-gastroc raise but it has similarities to the Russian/Nordic curl in terms of knee flexion.

The research done on the Russian/Nordic curl has shown that it primarily uses the biceps femoris short head muscle rather than the biarticular hamstring muscles (biceps femoris long head, semitendinosus, and semimembranosus) (Mendiguchia et al., 2013). This difference is due to the different attachments sites of these muscles. The biceps femoris short head attaches to the femur and the tibia whereas the biarticular hamstring muscles attach to the pelvis and the tibia. This evidence helps to explain how the exercise is executed. Russian/Nordic curls and consequently glute-ham-gastroc raises, achieve knee flexion through the flexion of the thigh on the leg rather than the flexion of the leg on the thigh. This distinction is important as it relates back to the action of the gastrocnemius, which assists in knee flexion by flexing the thigh on the leg. By increasing the strength of the gastrocnemius, it will be able to impart more force on the calcaneus, thus pulling it into plantar flexion.

The calcaneal dorsiflexors have to increase their extensibility in order for calcaneal plantar flexion to improve. This can be achieved through different soft tissue work done on the plantar aponeurosis and plantar intrinsic muscles. Soft tissue work involving massage and stretching has been shown to be an effective means of increasing the extensibility of the plantar aponeurosis. The combination of self-stretching in addition trigger point manual therapy was found to be more effective than self-stretching alone for the treatment of plantar fasciitis and plantar heel pain (Renan-Ordine et al., 2011). Another study on plantar fasciitis examined the impact of a plantar aponeurosis-stretching program versus an Achilles tendon stretching program. It was found that the non-weight bearing plantar aponeurosis stretching program was more effective for improving plantar fasciitis symptoms than the standard Achilles tendon stretch.

Evaluating Ankle and Leg Flexibility

The range of motion about a joint or a series of joints is known as flexibility. There are many different ways to measure flexibility, but the majority of these tests measure ranges of motion in static position and do not consider range of motion during active movements. Since ankle flexibility is important for a variety of dynamic tasks such as squatting and landing from a jump it is important to consider the different ways dorsiflexion is measured. These methods of evaluation primarily involve static tasks and consist of both weight bearing and non-weight bearing measures. Studies that examine stretching as a method of improving poor range of motion predominantly rely on non-weight bearing measures, where only a few of these studies relying on weight bearing measures. Investigations that examine the correlation between poor dorsiflexion range of motion and lower extremity injuries tend to rely more on weight bearing measures (Malliaras et al., 2006; Pope et al., 1998).

As previously discussed, it is important to make the distinction between weight bearing and non-weight bearing dorsiflexion, as it is two different movements being measured. A study by Rabin

& Kozol (2012) compared weight bearing to non-weight bearing dorsiflexion measures and found the weight bearing to be twice as high as non-weight bearing with only a moderate correlation between the two. Weight bearing dorsiflexion flexion is typically the measure of the forward inclination of the tibia/shank, which is also known as leg dorsiflexion. This is a higher range of motion as leg dorsiflexion is a result of the movement occurring at the entire ankle joint complex. This differs from true ankle dorsiflexion, which, as previously stated, is the anterior angle between the tibia and the talus. In order to measure this movement at the talocrural joint it needs to be measured in a non-weight bearing position with no movement occurring at the subtalar joint (Rabin & Kozol, 2012). These methods of evaluation should not be used interchangeably as weight bearing measures are evaluating the combined movements of the independently moving bones of the foot and ankle joint complex.

It is also important to evaluate these different methods of measuring dorsiflexion range of motion in terms of functional relevance. The range of motion measured during a weight bearing task provides more useful information than non-weight bearing. It has a greater ability to relate to movement tasks, as they are all performed while weight bearing with the leg moving relative to the foot as it is planted on the ground. Non-weight bearing ankle dorsiflexion only provides information about the movement that occurs at the talocrural joint and exams the foot moving relative to the leg, which is not always practically meaningful.

The most common way to measure leg dorsiflexion is the weight bearing lunge test, which has been demonstrated to be a reliable method (Dickson et al., 2012; Powden, Hoch, & Hoch, 2015). The weight bearing lunge test can be executed with a goniometer or an inclinometer to measure either the angle of the front leg or the back leg. It can also be conducted by measuring the furthest distance that the first toe is from the wall with the knee maintaining contact with the wall and the heel maintaining contact with the ground. But this method provides a distance measurement rather than an angle and only has a moderate correlation to the weight bearing lunge test performed with a goniometer (Dickinson et al., 2012). The method of using a regular goniometer, has high intra-rater reliability with a very high intra-class correlation coefficient of 0.90, a 95% CI of 0.85-0.93, and a standard error of measurement of 2° (Dickson et al., 2012). Even though weight bearing measures provide more practical information, it is measured in a static position which may differ from the range of motion achieved during a dynamic activity. It is important to consider this difference as active muscle stiffness has been shown to increase as muscle activity increases (Hunter & Spriggs, 2000)

A recent study by Fuglsang, Telling, & Sørensen (2017) examined the relationship between dorsiflexion range of motion and trunk lean during a parallel back squat. They found a difference between the weight bearing lunge test measures and the dorsiflexion achieved during a back squat where both measures were conducted with 3-dimensional motion analysis. The weight bearing lunge test resulted in greater max dorsiflexion by 11.4 ± 4.4° when compared to the max dorsiflexion achieved during the parallel during a back squat. This study shows that dorsiflexion range of motion needs to be evaluated in a variety of different ways in order to see how it relates functional movements.

Conclusion

In regard to increasing leg dorsiflexion range of motion, previous research has mainly focused on the inextensibility of the plantar flexor musculature. However, previous biomechanical and anatomical research has shown that the complexity of the foot segment and the independently moving bones impacts leg dorsiflexion range of motion (Chizewski & Chiu, 2012). By examining the anatomy of the foot and leg, it can be hypothesized that the gastrocnemius as well as the plantar aponeurosis and plantar intrinsic muscles of the feet could be manipulated in order to increase calcaneal plantar flexion as a means to increase leg dorsiflexion range of motion. By decreasing the pull of the plantar aponeurosis and plantar intrinsic muscles and increasing the pull of the gastrocnemius, calcaneal plantar flexion and subsequently leg dorsiflexion have the potential to increase. Research into these potential methods is necessary to expand on the understanding of the foot and ankle joint complex and how it relates to leg dorsiflexion range of motion. Previous studies done on dorsiflexion range of motion also predominantly rely on non-weight bearing measures, and those done in weight bearing are done in static positions. It is important for future research to understand both static and dynamic flexibility by measuring leg dorsiflexion range of motion in both static and dynamic tasks.

CHAPTER 2: Increasing Calcaneal Plantar Flexion as a Method to Improve Weight bearing Leg Dorsiflexion

Introduction

The ankle joint complex includes two separate articulations: 1) the talocrural and 2) the subtalar (van den Bogert, Smith, & Nigg, 1994). The true ankle joint, or talocrural joint, is the articulation that occurs between the tibia and fibula with the talus. The second articulation in the complex occurs between the talus and the calcaneus and is referred to as the subtalar joint. True ankle dorsiflexion occurs solely at the talocrural joint and the range of motion has been reported to have an average of 26° (Neumann, 2002). The dorsiflexion achieved when the foot's plantar surface is in contact with the ground can be referred to as leg dorsiflexion, which is the ROM achieved during squatting and landing from a jump. It would be expected that leg dorsiflexion range of motion would yield similar values to non-weight bearing ankle dorsiflexion. However, in tasks such as squatting and landing from a vertical jump, leg dorsiflexion exceeds 35° (Moolyk et al., 2013; Chiu, vonGaza, & Jean, 2017). This greater range of motion is due to the complexity of the foot segment and the interaction of the independently moving bones rather than the movement occurring specifically at the talocrural joint.

Measuring the range of motion about a joint requires the examination of the articulating bones relative to one another. To accurately measure ankle dorsiflexion, the rotation of the talus relative to the leg segment needs to be examined. This is difficult to do with traditional methods of measurement. Non-weight bearing dorsiflexion measures are considered to examine true ankle dorsiflexion but they do not consider the position of the talus, but instead rely on surface landmarks to measure the rotation of the foot relative to the leg (Rome, 1996). It has often been instructed to position the talocrural joint in a neutral position with little inversion or eversion, but no standard procedure has been determined (Rome, 1996). In previous biomechanics research, ankle dorsiflexion has been measured by analyzing the rotation of the calcaneus relative to the leg (Chizewski & Chiu, 2012).

Traditionally, leg dorsiflexion has been measured with the weight bearing lunge test by measuring the angle of inclination of the leg relative to the floor but is often reported relative to the vertical (Dickinson et al., 2012; Rome, 1996). This type of measurement is considered a segmental approach. It examines the rotation of a segment relative to its surroundings rather than trying to examine the rotations of two different segments or bones rotating about a joint. This is preferential to the joint approach as it eliminates any variation in methods of measurement. This is important when considering movements of the foot and ankle joint complex, as previous research has shown that the foot is not a rigid segment, but that the bones move independently to one another (Chizewski & Chiu, 2012; Stamm & Chiu, 2016).

Leg dorsiflexion has the ability to impact the kinematics of the entire lower extremity in terms of proper movement mechanics, performance, and injury risk. It is necessary for jumping, landing, and squatting as it allows for greater quadriceps loading, contributing to concentric force production as well as eccentric force absorption (Chiu & Salem, 2006; Moolyk, Carey, & Chiu, 2013). As the forward inclination of the leg increases so does the moment arm of the vertical joint reaction forces which causes there to be an increase in knee extensor NJM (Chizewski & Chiu, 2012; Chiu et al. 2017). Limited leg dorsiflexion range of motion has also been associated with lower extremity injury risk. These injuries can vary from shin splints, stress fractures to the tibia and the calcaneus, ankle sprains, plantar fasciitis, Achilles tendonitis, patellar tendinosis, as well as anterior cruciate ligament tears (Kaufman et al., 1999; Malliaras, Cook & Kent, 2006; Pope et al., 1998; Walhstedt & Rasmussen-Barr, 2014). Therefore, it is important to consider various methods of improving leg dorsiflexion range of motion in order to improve the movement mechanics of the lower extremity.

The traditional method of improving ankle and leg dorsiflexion range of motion is to increase the extensibility of the ankle plantar flexor muscles – specifically the soleus and gastrocnemius – through various calf-stretching programs. One such study compared the effectiveness of non-weight bearing stretch to a weight bearing stretch (Dinh et al., 2011). Their results from the weight bearing lunge test found that the weight bearing stretch caused an average increase of 4.2° for the left and 4.3° for the right, whereas the non-weight bearing stretch resulted in an average increase of 1.6° for the left and 5° for the right. The stretching approach has two problems. First, poor soleus and gastrocnemius extensibility is only one factor that limits ankle dorsiflexion. Since the talus is a wedge-shaped bone that widens anteriorly, the shape of the talocrural articulation also limits range of motion. As dorsiflexion range of motion increases this anterior portion wedges into the cavity that lies between the malleoli and causes the movement to be restricted (Neumann, 2002). Second, poor ankle dorsiflexion may not be the only factor that limits leg dorsiflexion, particularly during weight bearing tasks.

Previous research on squatting mechanics has examined the relationship between the orientation of the calcaneus and maximum leg dorsiflexion (Chizewski & Chiu, 2012). They found that the sagittal plane rotation of the calcaneus was positively correlated to the sagittal plane rotations of the leg segment but negatively correlated to ankle dorsiflexion range of motion (Chizewski & Chiu, 2012). This shows that during a squatting task; both the leg and calcaneus rotate anteriorly. If only the leg segment were to rotate during weight bearing the range of motion achieved would be less. For each degree of calcaneal plantar flexion, an additional degree of leg dorsiflexion is possible. Therefore, calcaneal plantar flexion repositions the rearfoot and allows greater forward leg rotation (Chizewski & Chiu, 2012). These results suggest that restricted calcaneal plantar flexion range of motion is a factor that could explain poor leg dorsiflexion.

Calcaneal plantar flexion range of motion may be limited by the surrounding musculature. The plantar aponeurosis and the intrinsic muscles of the foot that attach to anterior aspect of the calcaneus can generate a calcaneal dorsiflexor moment, causing restricted calcaneal plantar flexion. If the stiffness of these structures decreased, the force they exert will decrease, and the ability to restrict calcaneal plantar flexion is reduced. The triceps surae muscles attach to the posterior aspect of the calcaneus and would be responsible for generating a calcaneal plantar flexor moment. If the gastrocnemius were to exert greater force, the moment exerted increases, which would promote calcaneal plantar flexion.

The purpose of this research is to determine if reducing the force of the calcaneal dorsiflexors and increasing the force of the calcaneal plantar flexors can alter the position of the calcaneus and subsequently leg dorsiflexion. The first aim is to examine if stretching and self-massage of the plantar aponeurosis and plantar intrinsic muscles have on weight bearing calcaneal plantar flexion and leg dorsiflexion range of motion. The second would be examining the effectiveness of combining the stretching and self-massage with a specific gastrocnemius strengthening exercise and comparing it to stretching and self-massage alone. Flexibility, or the range of motion about a joint or a series of joints, is often only considered passively and in a static position. This investigation will evaluate the changes in leg dorsiflexion range of motion in a static position using the weight bearing lunge test as well as dynamically during a partial squat task.

Using anatomical and biomechanical rationales, hypotheses can be made predicting the outcomes of the interventions. It can be hypothesized that increases in leg dorsiflexion will be seen in the weight bearing lunge test and increases in calcaneal plantar flexion and leg dorsiflexion will be seen in a partial squat task. Where specifically, the stretching and self-massage of the plantar aponeurosis and plantar intrinsic muscles will improve calcaneal plantar flexion and leg dorsiflexion range of motion. Secondly, the addition of gastrocnemius strengthening to the stretching and self-massage will be more effective at improving calcaneal plantar flexion and leg dorsiflexion. Furthermore, with gastrocnemius strengthening, it can be hypothesized that ankle plantar flexor net joint moment during the partial squat task will increase.

Methods

Experimental Design

Using a randomized parallel trial study design, men and women (ages 18-35) with poor dorsiflexion were recruited and randomly assigned into one of two six-week intervention groups. Group 1 performed stretching and self-massage of the plantar aponeurosis and plantar intrinsic muscles and Group 2 performed a gastrocnemius strengthening program in addition to the stretching and self-massage program. Prior to and following the interventions weight bearing leg dorsiflexion was assessed using two tasks: 1) weight bearing lunge test and 2) squat test.

Participants

Twenty-seven individuals with poor leg dorsiflexion (men (n=11); women (n=16)) volunteered to participate in this research study (Figure 9). Potential participants were recruited through the use of posters placed throughout the University of Alberta campus as well as through recruitment presentations carried out in various lectures in the Faculty of Physical Education and Recreation at the University of Alberta. Potential participants were screened for inclusion based on their leg dorsiflexion range of motion during a lunge (described below). Only individuals with poor leg dorsiflexion, defined as less than 25°, were enrolled in the study. This value is derived from the results from the study (Chiu, Yaremko, & vonGaza 2017) which established that physically active individuals had a weight bearing leg dorsiflexion range of motion of 30° ± 5° (mean ± standard deviation). Therefore, poor leg dorsiflexion was defined as greater than or equal to one standard deviation below the mean.

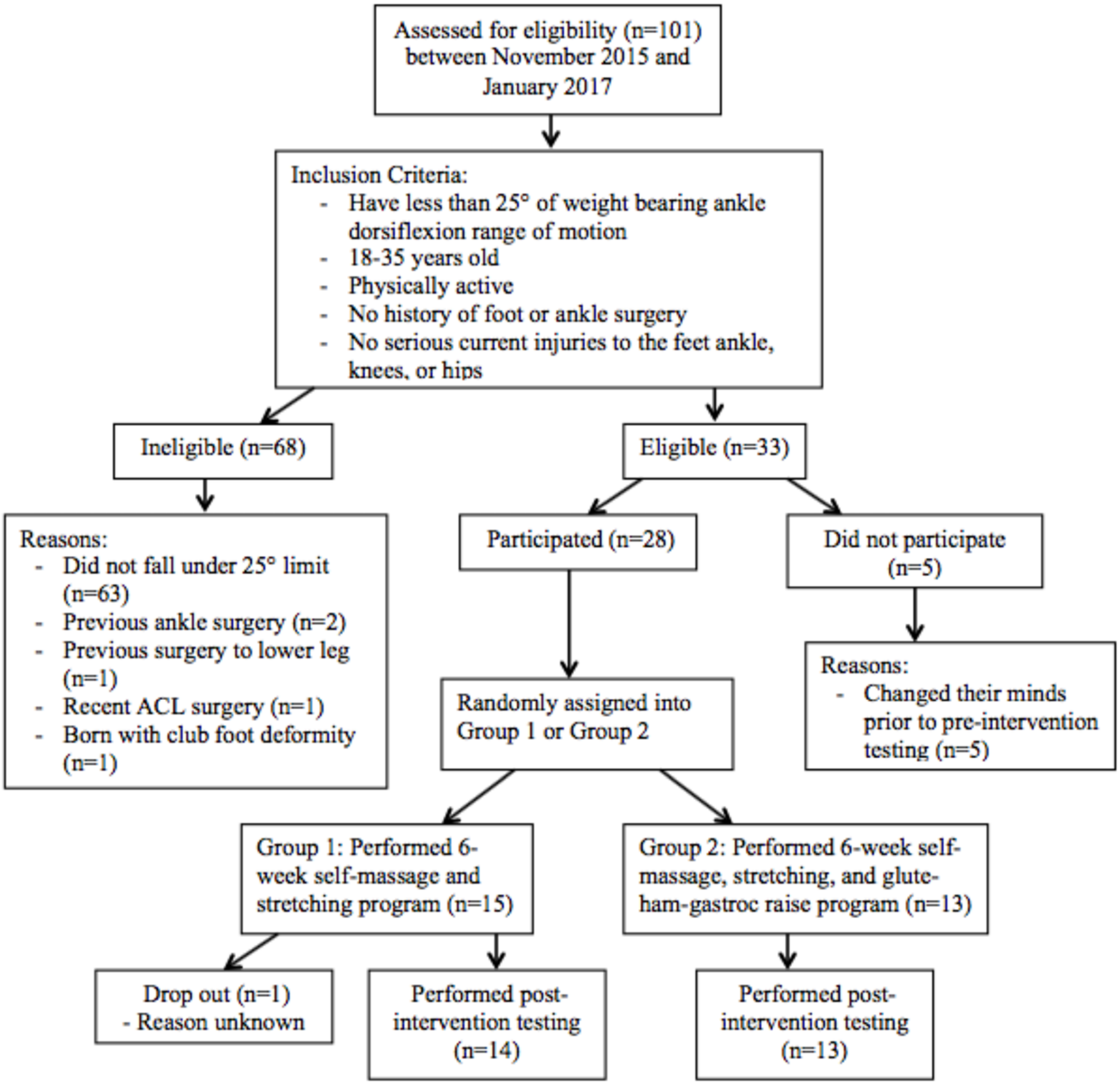

Figure 9: Participant Flow Chart

The screening was conducted using a weight bearing lunge test (Figure 10), which is the standard method of measuring weight bearing leg dorsiflexion (Powden et al., 2015; Dickson et al., 2012). The participant stood facing a bench in a lunge a position with their feet in a tandem stance and hands against the bench for balance. The forward foot was planted firmly on the ground; the participant was instructed to bend at the ankle and push their kneecap as far forward as possible without allowing the heel to come off the ground (Figure 10). Leg dorsiflexion was measured on the front leg and was taken from the lateral side using a digital goniometer. The angle measured was between the horizontal (the floor) and the longitudinal axis of the leg segment, following the line of the fibula. This angle was subtracted from 90° to give the angular displacement of the leg segment from the vertical. Leg dorsiflexion angle was measured three times and averaged for each of the left and right lower limbs. The lead investigator conducted all measurements for all individuals.

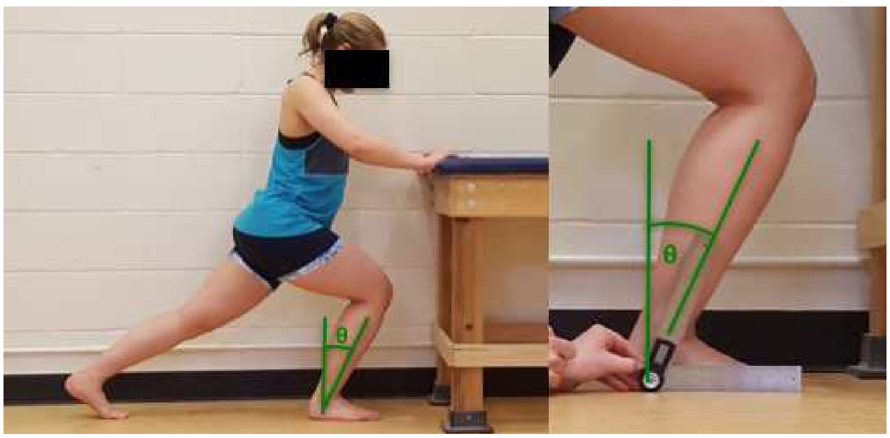

Figure 10: Weight bearing lunge test

Some individuals were excluded from participating based on additional exclusion criteria. The participants had to be considered healthy adults with no current injuries or health problems that would prevent them performing the required tasks. They were not included if the individual had any prior foot or ankle surgery or if they were currently performing a structured exercise program that included any type of calf stretching or strengthening. This was to prevent any interference with the intervention being prescribed in this research study

Interventions

The participants in both intervention groups were required to complete six weeks of a stretching and self-massage program for the plantar aponeurosis and plantar intrinsic muscles. The self-massage was performed with a golf ball where each foot was massaged for two minutes. While seated, the participant placed the golf ball under the arch of the foot, pushing down with a comfortable amount of pressure. For the duration of the two minutes, the participant moved their foot over top of ball, so that the golf ball was moving longitudinally across the arch to ensure that the plantar structures were targeted. The stretching component consisted of the individual placing their foot on the opposite thigh and pulling the toes and the ankle back into a dorsiflexed position until they could feel a stretch in the arch (DiGiovanni et al., 2003). The stretching was confirmed by the palpation the arch of the foot with the opposite hand to see if there is an increase in tension in the plantar structures (DiGiovanni et al., 2003). The stretches were performed twice on each foot with each repetition being held for 30 seconds.

For Group 2, the gastrocnemius strengthening exercise was completed in addition to the stretching and self-massage within the same session. The subjects performed the glute-ham-gastroc raise exercise as it focuses on knee flexion as well as ankle plantar flexion (Figure 11). This distinction is important as it demonstrates how the glute-ham-gastroc raise preferentially activates and therefore strengthens the gastrocnemius, as the gastrocnemius assists in knee flexion through the flexion of the thigh on the leg. It is important to isolate the gastrocnemius over the soleus, as the soleus would pull the leg segment rearward, restricting leg dorsiflexion range of motion. A recent training study (Chiu et al., 2017) completed by the lab examined the impact that glute-ham-gastroc raises have on ankle plantar flexor mechanical effort during jumping and landing performance and mechanics. The initial results and analysis of this study reveal that the exercise has resulted in the strengthening of the gastrocnemius.

As the participants went through the six weeks of training they went through a progression of the exercise, similar to what was used in the labs previous gastrocnemius training study (Appendix A). The first progression emphasized the knee flexion and ankle plantar flexion components (GHG-1). This was to ensure that the recruitment of the gastrocnemius to perform the exercise. At first the participants performed three sets of five repetitions with increases in repetitions each subsequent week. The first three weeks focused on the first progression and for the second half of the program full hip extension was added, therefore completing the full exercise (GHG-2).

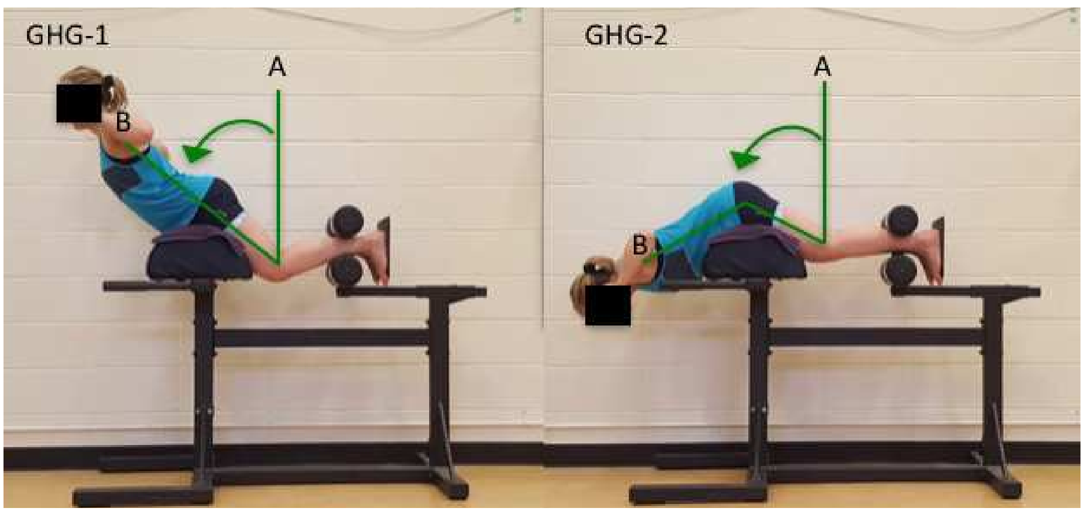

Figure 11: Glute-ham-gastroc raise exercise. GHG-1 demonstrates the first progression and GHG-2 demonstrates the second progression.

Both intervention groups completed the program three days a week for the duration of six weeks (Table 1). All sessions were completed using the same equipment and were supervised by the lead investigator in order to ensure compliance, proper technique, and proper progressions. With a total of 18 sessions the participants had to complete at least 16 in order to still be included in the study. Out of the 27 participants 24 completed all 18 sessions and 3 participants completed 17 sessions in the six weeks.

Experimental Procedure

Flexibility is often only considered passively and in a static position and is rarely examined during active movements. Therefore, it is important to examine changes in leg dorsiflexion range of motion during a dynamic task. Movement tasks require greater muscle activation, which could impact the range of motion achieved. This is why participants performed a partial plate squat exercise in addition to the weight bearing lunge test in order to further examine any increases in leg dorsiflexion range of motion.

Their lower extremity movement mechanics during a weight bearing squat task were analyzed prior to and following the 6 weeks of prescribed interventions. The analysis focused on calcaneal plantar flexion and leg dorsiflexion during a plate squat exercise (Figure 12). Plate squats have been used as a teaching progression and warm up in the weight room (Chiu & Burkhardt, 2011). Participants were instructed to squat as deep as they can, achieving their maximum leg dorsiflexion without the heels rising of the ground and keeping their torso upright without any flexion of the trunk on the thigh (Figure 12). A 10kg plate was placed on top of the head, with additional support from the hands, and the head facing straight forward with a neutral spine. Foot width and turnout was consistent between the pre- and post-data collection. Participants squatted with their preferred stance, which was then measured by the lead investigator to ensure all reps were completed with the same foot position. Participants were instructed to line up the center of their second toe and center of their heel with the inside line of tape on the floor to insure consistent foot placement. The participants performed 3 sets of 5 repetitions with two minutes of rest between every set, following a standardized warm up of lighter repetitions of plate squats.

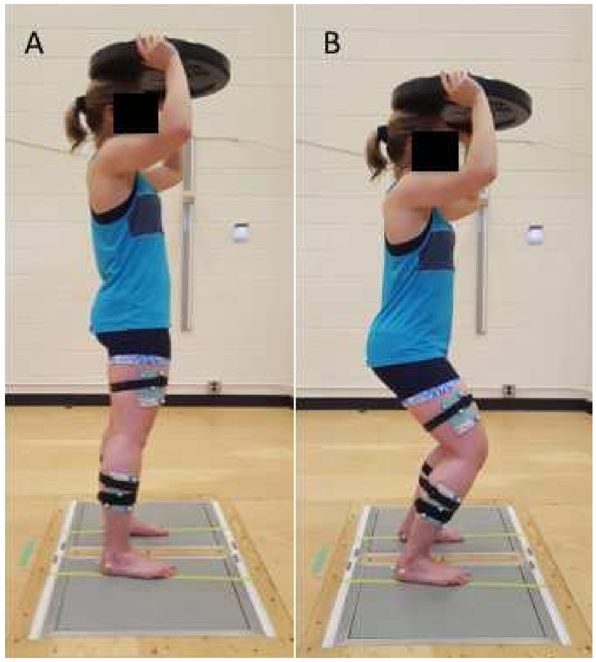

Figure 12: Squat test exercise focusing on achieving max dorsiflexion. A: Top of squat; B: Bottom of squat. Green tape demonstrates width and turnout of participant's preferred squatting stance.

Motion Analysis

The data collection took place in the biomechanics lab using a 7-camera optoelectronic motion capture system (collected at 120 Hz) (Qualisys ProRelax MCU240; Qualisys, Sweden) with ground reaction forces measured using two force platforms built into the floor (collected at 1200 Hz) (AMTI OR6-6; AMTI, Watertown, MA, USA). Retro-reflective calibration and tracking markers were placed on the participants' lower extremity by an experienced investigator. The calibration markers were placed at boney anatomical landmarks that have been used in previous biomechanics research in order to identify the proximal and distal ends of each lower extremity segment analyzed (Chiu & Salem, 2006) (Figure 13). The tracking markers consisted of 4 markers adhered to a rigid plastic frame that were placed laterally on the participants' leg and thigh. A standing calibration trial was recorded in order to determine the location of the calibration marker set in relation to the tracking markers. The movement trials were performed with only the tracking cluster markers and those on the calcaneus.

Using the 3D motion analysis data, the lower extremity was reconstructed using standard rigid body modeling techniques using the Visual 3D software (C-Motion; Germantown, MD). This was used to determine the segment angles of calcaneus and the leg the at the bottom position of the partial squat. The data collected from the force platform combined with the video data was used to calculate the ankle net joint moments through the use of inverse dynamics.

The thigh segment was modeled with proximal markers placed on the greater trochanters and distal markers placed on the medial and lateral femoral epicondyles. The leg segment was modeled with proximal markers placed at the medial and lateral femoral epicondyles and distal markers at the medial and lateral malleoli. For both the thigh and leg segments the vertical axis (z) ran through the midpoint of both the distal and proximal markers. The sagittal axis (y) and the transverse axis (x) ran through the midpoint of the proximal segment markers lying orthogonal to one another and the vertical axis. The calcaneus was modeled with three markers, two placed on the medial and lateral sides and the other placed on the posterior aspect of the calcaneus. For the calcaneus, the sagittal axis (z) ran from the midpoint between the medial and lateral markers and through the posterior marker. The transverse axis (x) and the vertical axis (y) ran orthogonal to one another as well as to the sagittal axis and through the posterior aspect of the calcaneus.

All coordinate systems on the right leg followed the right-hand rule and those on the left leg were processed to conform to the right-hand rule. The segment rotations of the calcaneus and the leg were processed using an ZYX Cardan sequence and in reference to the lab coordinate system.

Figure 13: Calibration marker set

Statistical Analyses

The data collected pre- and post-intervention was compared within and between intervention groups. With the primary variables examined being the segment angles of the calcaneus and the leg as well as plantar flexion net joint moment calculated from the 3-dimensional motion analysis as well as the leg dorsiflexion angle measured using the weight bearing lunge test. The average changes from pre- to post-intervention were calculated for both intervention groups for both the weight bearing lunge test and squat test. Effect sizes were calculated to examine the magnitude of differences. Where trivial effects were considered less than 0.2, small effects 0.2-

0.5, moderate 0.5-0.8 and large effects were greater than 0.8. P-value was also determined for each variable in both groups.

Results

Pre-Intervention

Pre-intervention participant characteristics are shown in Table 1. Prior to the intervention, there was no difference in leg dorsiflexion between groups during the weight bearing lunge or during the squat test. For calcaneal plantar flexion, there was a slight difference between groups for the right side and no difference for the left. There was also no difference between groups for pre-intervention ankle plantar flexor NJM.

	Group 1	**Group 2**
Age (years)	23.2 ± 4.4	22.6 ± 2.9
Height (cm)	171.7 ± 7.9	173.5 ± 8.6
Weight (kg)	73.3 ± 16.6	77.9 ± 17.0
Left Leg Dorsiflexion – Lunge (°)	22.1 ± 2.6	22.5 ± 1.8
Right Leg Dorsiflexion – Lunge (°)	21.3 ± 2.6	23.2 ± 3.3
Left Leg Dorsiflexion – Squat (°)	-24.5 ± 4.1	-24.9 ± 3.7
Right Leg Dorsiflexion – Squat (°)	-25.6 ± 4.8	-26.3 ± 3.5
Left Calcaneal Plantar Flexion – Squat (°)	-4.1 ± 3.3	-3.8 ± 2.6
Right Calcaneal Plantar Flexion – Squat (°)	-4.4 ± 3.2	-1.6 ± 3.8
Left Ankle Plantar flexor NJM – Squat ($Nm \cdot kg^{-1}$)	-0.435 ± 0.159	-0.456 ± 0.191
Right Ankle Plantar Flexor NJM – Squat ($Nm \cdot kg^{-1}$)	-0.450 ± 0.164	-0.450 ± 0.162

Table 1: Pre-Intervention Participant Characteristics

Weight Bearing Lunge Test

Participants in both groups experienced large increases in leg dorsiflexion range of motion during the weight-bearing lunge test following the 6-week intervention. Group 2 experienced greater increases than Group 1. Group 1 increased leg dorsiflexion in the left limb by 3.7 ± 2.9° (ES=1.16; P<0.001) and in the right limb by 4.2 ± 3.2° (ES=1.25; P <0.001). Group 2 increased leg dorsiflexion in the left limb by 4.9 ± 4.4° (ES=1.80; P <0.001) and in the right limb by 6.4 ± 3.7° (ES=1.51; P <0.001).

Squat Test

During the squat test Group 2 experienced moderate increases in leg dorsiflexion where Group 1 only experienced small and trivial increases. Group 1 experienced trivial increases in the left leg of -0.6 ± 3.2° (ES=0.15; P=0.472) and small increases in the right of -1.0 ± 2.6° (ES=0.24; P=0.163). Whereas, Group 2 experienced an increase of -2.3 ± 4.2° (ES=0.55; P=0.472) in the left leg and increases of -2.1 ± 3.2° (ES=0.59; P=0.163).

The change in the angle of the calcaneus from pre- to post-intervention was greater in Group 2 than Group 1. In Group 1, the left calcaneus experienced an increase in calcaneal plantar flexion of -0.7 ± 2.6° (ES=0.25; P=0.338) and the right calcaneus experienced an increase of -0.2 ± 2.7° (ES=0.08; P=0.779). In Group 2, calcaneal plantar flexion increased by -0.3 ± 3.2° (ES=0.15; P=0.338) in the left and -2.7 ± 6.2 (ES=0.64; P=0.779) in the right.

The increases in ankle plantar flexor NJM was greater in Group 2 than in Group 1. Group 1 only experienced an increase of -0.035 ± 0.151 $Nm \cdot kg^{-1}$ (ES=0.13; P=0.587) in the left and -0.029 ±

0.123 Nm·kg^{-1} (ES=0.17; P=0.386) in the right. Group 2 experienced an increase of -0.051 ± 0.167 Nm·kg^{-1} (ES=0.29; P=0.587) for the left and -0.068 ± 0.179 Nm·kg^{-1} (ES=0.49; P=0.386) for the right.

Discussion

The purpose of this research was to investigate if increasing calcaneal plantar flexion could be an alternative method for increasing leg dorsiflexion range of motion during a weight bearing task. This approach is an alternative to traditional approaches to increase leg dorsiflexion, which make the assumption that limited leg dorsiflexion range of motion is caused by the inextensibility of the ankle plantar flexor musculature. The main findings from this study were that: 1) performing self-massage and stretching of the plantar aponeurosis and plantar intrinsic muscles increased leg dorsiflexion range of motion and 2) the addition of the glute-ham-gastroc raise exercise resulted in greater increases. Leg dorsiflexion range of motion was measured during a weight bearing lunge test using a digital goniometer as well as during a squat test using motion analysis, where we expected to see increases in range of motion in both tests.

The results showed greater improvements during the weight bearing lunge test when compared to the squat test in both groups. For the weight bearing lunge, Group 1 had increases of 3.7 ± 2.9° for the left and 4.2 ± 3.2° for the right but did not show an improvement during the squat test. Group 2 had improvements of 4.9 ± 4.4° in the left and 6.4 ± 3.7° for the right in the weight bearing lunge but only improved -2.3 ± 4.2° in the left and -2.1 ± 3.2° in the right during the squat test. The weight bearing lunge test is currently the most common method to measure leg dorsiflexion. However, intervention studies have predominantly used non-weight bearing measures. Therefore, there are few studies to which the results of the current investigation can be directly compared.

Dinh et al. (2011) used the weight bearing lunge test to compare the effects of two different three-week calf-stretching protocols on dorsiflexion range of motion. One group performed stretches every day in a weight bearing position and the other in non-weight bearing; pre- and post-measurements were taken in both weight bearing and non-weight bearing positions. This study used a different version of the weight bearing lunge test compared to ours, as they measured the back leg with the knee extended, as opposed measuring the front leg with the knee in a slightly flexed position. Their results from the weight bearing test found that the weight bearing stretch caused an average increase of 4.2° for the left and 4.3° for the right, whereas the non-weight bearing stretch resulted in an average increase of 1.6° for the left and 5° for the right. The participants in this study and ours completed close to the same number of total sessions. In Dinh et al., participants completed twenty-one days of stretching over three weeks while ours completed eighteen days of exercises over six weeks. Our results from the weight bearing lunge test found comparable results in leg dorsiflexion to Dinh et al. (2011).

Even though the weight bearing lunge test is the most commonly used measure for weight bearing ankle dorsiflexion it is only evaluating the range of motion in a static, passive position. It provides more information than non-weight bearing measures, as greater forces are applied which can change the inter-segmental alignment of the foot (Kelly et al., 2014). However, it may not fully represent foot and ankle mechanics during dynamic movement tasks. Fuglsang, Telling, & Sørensen (2017) found greater max dorsiflexion during the weight bearing lunge test by 11.4 ±

4.4° when compared to the max dorsiflexion achieved during the parallel during a back squat. Therefore, it was important that we measure leg dorsiflexion range of motion during a dynamic task in order to further evaluate the efficacy of our protocols and how it translates to a functional movement task.

In addition to being more dynamic then the lunge, the squat was performed with an additional load. When additional load is applied to an exercise it causes an increase in vertical ground reaction force, NJM, and work performed by the lower extremity (Flanagan & Salem, 2008). This distinction between the squat test and the lunge test is important as it can help to explain the differences in the leg dorsiflexion results, as the results from the squat test were not as great as initially expected. It can be hypothesized that this increase in load and ground reaction force could cause there to be an increase in plantar intrinsic muscle activation which could impact leg dorsiflexion range of motion.

The plantar intrinsic muscles are contractile tissues that exert forces depending on their activation level. Previous research has shown that the recruitment of the plantar intrinsic muscles varies between tasks. Kelly et al. (2014), examined the height of the longitudinal arch as well as the stretch and activation levels experienced by the plantar intrinsic muscles during incremental increases of mechanical loading. In order for the muscle activity of the flexor digitorum brevis, quadratus plantae, and abductor hallucis to be evident loads of 50%, 75%, and 100% body mass had to be applied respectively (Kelly et al., 2014). As load, and subsequently muscle activity increased, so did the deformation of the longitudinal arch. However, arch height started to plateau around 125% body mass and muscle activity steadily increased after 100% body mass up to the max load tested of 150% body mass (Kelly et al., 2014). This demonstrates that a large activation of the plantar intrinsic muscles requires a large load to be applied, one that is greater than one's body mass.

In order to build upon their findings, Kelly et al. (2014) incorporated a second part to their study. They examined whether the stimulation of the plantar intrinsic muscles of the foot could generate large enough forces to impact longitudinal arch deformation at loads of 50% and 100% body mass. The results show that the stimulation reduced the amount of longitudinal arch deformation under load by changing the position of the calcaneus and metatarsals (Kelly et al., 2014). The calcaneus experienced extension, abduction, and inversion and the metatarsals experienced flexion and adduction when the muscles were stimulated causing an increase in height of the arch (Kelly et al., 2014). This change in arch height has the potential to impact the rotation of the leg segment as calcaneal dorsiflexion has been shown to correlate with less leg dorsiflexion range of motion (Chizewski & Chiu, 2012).

This also relates to the calcaneal plantar flexion results as they were not as large as initially expected. It was predicted that both groups would experience increases in calcaneal plantar flexion, with larger increases seen in Group 2. However, Group 2 only experienced moderate increases in calcaneal plantar flexion in the left calcaneus and trivial increases in the right and Group 1 experienced minimal increases for both the left and right. The major assumption in our hypothesis was that the plantar aponeurosis and plantar intrinsic muscles of the foot could be considered as a single unit that exerted tension passively. The self-massage and stretching protocol was designed to reduce passive tension in both the plantar aponeurosis and plantar intrinsic muscles by increasing their inextensibility. However, if the plantar intrinsic muscles were active during the squat, the self-massage and stretching would not be expected to have an effect on the active force exerted.

Without calcaneal plantar flexion values for the lunge, we are unable to confirm whether there was a difference in calcaneal plantar flexion between the two tests. This would have provided support for the hypothesis that the lesser leg dorsiflexion experienced during the squat could be related to the activation level of the intrinsic muscles of the foot. It is also unknown whether the increases in leg dorsiflexion in the lunge are related to increases in calcaneal plantar flexion. Since our protocols focused on manipulating the soft tissue structures that act on the calcaneus, the increases in leg dorsiflexion during the lunge can be used to support our initial hypothesis that increasing calcaneal plantar flexion can serve as an alternative method for increasing leg dorsiflexion range of motion.

Since Group 2 performed the glute-ham-gastroc raise exercise to strengthen the gastrocnemius, it was predicted that they would experience an increase in ankle plantar flexor NJM during the squat test. Group 2 did have a small increase in their ankle plantar flexor NJM, whereas Group 1 did not experience an increase. As previously discussed the squat was loaded with a 10kg plate. This increase in load from body weight, would cause there to be an increase in ground reaction force and NJM as a larger force is required to perform the exercise. Previous research has shown that ankle plantar flexor relative muscular effort increases as load increases (Bryanton, Kennedy, Carey & Chiu, 2012). Therefore, a larger load would elicit larger ankle plantar flexor NJM. Even this small increase in ankle plantar flexor NJM in Group 2 shows that the gastrocnemius-strengthening program was successful in terms of training the gastrocnemius as Group 1 did not experience any increases.

Our study shows the importance of using weight bearing measures, but more significantly the use of both static and dynamic methods of measurement. The differences found between the weight bearing lunge test and the squat test show the limitations of the standard methods of measuring leg dorsiflexion range of motion. Measuring leg dorsiflexion range of motion during a static task may not be representative of dynamic human movement and these results may not transfer to dynamic tasks. This impacts how results are interpreted and applied to the practical situations. For example, previous research has examined the relationship between dorsiflexion range of motion and its impact on reducing the risk of lower extremity injury. If dorsiflexion is only measured in a static position it will not be known if those increases in range of motion will be experienced by an individual during dynamic movements such as squatting or landing from a jump. Range of motion should be measured during dynamic movements that are representative of regularly performed tasks in order to better understand movement mechanics and the efficacy of various intervention protocols.

The results show that combining self-massage and stretching of the plantar structures of the foot in addition to the glute-ham-gastroc raise exercise can be used as an alternative method of increasing leg dorsiflexion range of motion. These methods expand on traditional methods, which make the assumption that limited leg dorsiflexion is only caused by the inextensibility of plantar flexor musculature. However, this investigation shows that the complexity of the foot segment, how the tarsal bones interact, and the intrinsic muscles of the foot contribute. The relationship between plantar intrinsic muscles of the foot and leg dorsiflexion range of motion needs to be examined in order to further understand their role in impacting range of motion during a dynamic movement task. Once this relationship is further understood our methods can be improved in order to increase the effectiveness.

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CHAPTER III: GENERAL DISCUSSION

Main Findings

The main finding from this investigation is that self-massage and stretching of the plantar aponeurosis and plantar intrinsic muscles in addition to a specific gastrocnemius strengthening exercise results in increases in leg dorsiflexion. However, greater increases were experienced during the static weight bearing lunge test when compared to the dynamic squat test.

Experimental Considerations & Limitations

The first limitation of this study was conducting the weight bearing lunge test with only a goniometer rather than using 3-dimensional motion analysis. Motion analysis would allow for calcaneal plantar flexion to be measured during the lunge. The results from the weight bearing lunge test could then be easily compared to the squat test, in order to determine if both calcaneal plantar flexion and leg dorsiflexion differed between tasks. With this information greater conclusions could be in made in regard to the potential involvement of the plantar intrinsic musculature during a dynamic task.

The second limitation was not using electromyography (EMG) to examine the activity levels of the muscles involved. This would be beneficial in examining the effectiveness of the glute-ham-gastroc raise exercise in targeting the gastrocnemius muscle. Motion analysis was used to examine any changes in ankle plantar flexor NJM, but this is unable to determine which ankle plantar flexors are being used. With the use of EMG, the activation level of the gastrocnemius could be compared to other ankle plantar flexor muscles pre- and post-intervention to examine if there was an increase in the activation of the gastrocnemius. EMG could also be used to examine the differences in the activation levels of the plantar intrinsic muscles in both the weight bearing lunge and the squat. This could be used to determine if there is a correlation between the level of activation of the plantar intrinsic muscles and calcaneal plantar flexion and leg dorsiflexion range of motion.

A third limitation is that the only exercise that has been proposed to specifically target the gastrocnemius is the glute-ham-gastroc raise (Chiu, Yaremko, & vonGaza, 2017). Typically, the standing calf raise exercise is performed to train the gastrocnemius, however other plantar flexor musculature is also recruited. Research has shown that the soleus in also recruited during a standing calf raise (Kinugasa, Kawakami, & Fukunaga, 2005). Strengthening the soleus would increase its pull on the tibia which would pull the tibia rearward, reducing leg dorsiflexion range of motion. This makes the standing calf raise an unsuitable exercise for this investigation. The gastrocnemius may be active during knee flexion exercises, such as the seated leg curl (Gallucci & Challis, 2002). Mechanically, leg curl exercise may not be ideal for training the gastrocnemius as the leg flexes relative to the thigh which is the resultant action of the hamstring muscles. In contrast to leg curl exercise, the glute-ham-gastroc raise requires the thigh to flex relative to the leg, an action that can be accomplished by the gastrocnemius (Chiu et al., 2017).

However, no research has examined if this is the ideal method of strengthening this gastrocnemius. There are some shortcomings to this exercise. Notably, this exercise relies on the body weight of the individual as resistance. It is not known if simply increasing the number of sets and repetitions performed is sufficient to increase the exercise difficulty. There is the potential to add weight to the exercise by instructing an individual to hold weight. This modification, may change the exercise by shifting muscle effort to other joints, such as the hip. A shift in muscle effort distribution has been observed in other exercises. For example, research has examined the effect of barbell load and range of motion on relative muscular effort of the ankle plantar flexors, knee extensors, and hip extensor muscle groups during a barbell back squat (Bryanton et al., 2012). The results show that the ankle plantar flexor relative muscular effort is impacted more by barbell load whereas the knee extensors are impacted by barbell load, and the hip extensors are impacted by both load and range of motion (Bryanton et al., 2012). Further biomechanical analyses are required to determine how the glute-ham-gastroc raise should be performed to maximize the training stimulus exerted on the gastrocnemius. Alternately, other exercises may be identified that could more effectively train the gastrocnemius.

The final, and perhaps most important, limitation of the study was the assumption that the plantar aponeurosis and plantar intrinsic muscles could be considered as one unit. The self-massage and stretching were expected to increase the inextensibility of both structures. Although the passive tension of these structures may have decreased, our methods did not consider the active tension that the plantar intrinsic muscles could exert. The effectiveness of our methods could increase if the plantar intrinsic muscles were considered separately and their change in activation levels between the lunge and the partial squat were examined.

Recommendations for Future Research

Previous research conducted on methods used for increasing leg dorsiflexion range of motion has shown varying degrees of improvements. This suggests that the cause of poor range of motion is multifaceted. Future research will need to examine if the methods used in this investigation could be used in conjunction with stretching ankle plantar flexor musculature to result in magnified improvements.

Even though our results show increases in leg dorsiflexion range of motion it is not known how this relates to performance and injury risk. Future research will need to examine if these increases are practically meaningful in terms of improved movement mechanics and if they are associated with lower incidents of lower extremity injuries.

Future research will need to examine the plantar intrinsic muscles. It is not known if the change in activation level of these muscles is responsible for the difference in leg dorsiflexion between the weight bearing lunge and the squat. Future research should examine the activity levels of the plantar intrinsic muscles during different static tasks as well as during various dynamic activities such as varying intensities of squats and landing from a jump. This will be able to provide information on whether the activation levels are directly proportional to the difficulty of the dynamic task performed or not. Future research will also need to examine if all individuals experience similar changes in activation levels or if structural and functional foot arch types contribute. If the plantar intrinsic muscles do impact the position of the calcaneus, research needs to examine if it is from the muscles being too weak resulting in muscle spasm, if they are too strong, or if the length-tension relationship contributes.

Recommendations for Practitioners

The results from our study show that self-massage and stretching of the plantar structures of the foot and the glute-ham-gastroc raise can be used as an alternative method for increasing leg dorsiflexion range of motion. Practitioners in the field of human movement such as, strength and conditioning coach, physiotherapist, or athletic therapist can easily employ these interventions with individuals that have decreased range of motion. They are easy to incorporate into a program and may elicit greater increases than solely relying on stretching and rolling out techniques.

Conclusions

The results from our study suggest that trying to increase calcaneal plantar flexion through a self-massage and stretching of the plantar structures in addition to the glute-ham-gastroc raise exercise can potentially serve as an alternative way to increase leg dorsiflexion range of motion.

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Appendix A:

	Day 1	Day 2	Day 3
Week 1	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 5 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 5 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 5 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch
Week 2	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 8 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 8 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 8 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch
Week 3	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 10 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 10 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch	**Group 2:** 10 x 3/ GHG-1 2 min self-massage 2 x 30 sec stretch
Week 4	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 8 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 8 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 8 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch
Week 5	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 10 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 10 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 10 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch
Week 6	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch	**Group 1:** 2 min self-massage 2 x 30 sec stretch
	Group 2: 12 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 12 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch	**Group 2:** 12 x 3/ GHG-2 2 min self-massage 2 x 30 sec stretch

Table 2: 6-week intervention program overview