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BAHCESEHIR UNIVERSITY

GRADUATE SCHOOL

DEPARTMENT OF BIOMEDICAL ENGINEERING

IMMEDIATE BIOMECHANICAL AND NEUROMUSCULAR ADAPTATIONS TO TARGETED EXERCISES AND THEIR IMPLICATIONS FOR MEDIAL TIBIAL STRESS SYNDROME PREVENTION

MASTER'S THESIS

AYMAN HACHEM BOUAMAMA

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ABSTRACT

IMMEDIATE BIOMECHANICAL AND NEUROMUSCULAR ADAPTATIONS TO TARGETED EXERCISES AND THEIR IMPLICATIONS FOR MEDIAL TIBIAL STRESS SYNDROME PREVENTION

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Master's Program in Biomedical Engineering
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In sports medicine and military settings, preventing medial tibial stress syndrome (MTSS), a common overuse injury affecting the lower limbs, is crucial. This study evaluates if controlled step-downs (CSD) and single-leg side hops (SLLH) effectively prevent MTSS by examining their immediate biomechanical and neuromuscular effects. Modern data acquisition techniques, including electromyography, motion capture, and force plates, were utilized to assess muscle activation, joint kinematics, and ground reaction forces.

Both targeted exercises were hypothesized to induce immediate biomechanical adaptations, such as altered muscle activity, enhanced kinematics, and reduced loading rate. These hypotheses were partially supported, with data showing a significant decrease in loading rate for the dominant leg after SLLH. Both exercises showed unique neuromuscular and kinematic adaptations, potentially affecting MTSS-related factors.

The results highlight the benefits of SLLH in reducing tibial loading, a key factor in MTSS development. The observed decrease in loading rate, alongside reduced muscle contraction and improved kinematics, suggests an all-encompassing strategy for MTSS prevention. While CSD also influenced joint kinematics and muscle activity, it did not significantly affect the loading rate.

These findings underscore the potential of targeted exercises like SLLH in modifying biomechanical and neuromuscular parameters linked to MTSS risk factors. The results offer a foundation for creating research-based exercise programs to prevent MTSS.

Key Words: Medial Tibial Stress Syndrome (MTSS), Exercise Interventions, Neuromuscular Adaptations, Loading Rate, Joint kinematics.

ÖZ

HEDEFLENEN EGZERSIZLERE ANLIK BIYOMEKANIK VE NÖROMÜSKÜLER ADAPTASYONLAR VE BUNLARIN MEDIAL TIBIAL STRES SENDROMUNUN ÖNLENMESINE ETKILERI

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Spor hekimliği ve askeri ortamlarda, alt uzuvları etkileyen yaygın bir aşırı kullanım yaralanması olan medial tibial stres sendromunun (MTSS) önlenmesi çok önemlidir. Bu çalışma, kontrollü adım inişlerinin (CSD) ve tek bacak yan sıçramalarının (SLLH) anlık biyomekanik ve nöromüsküler etkilerini inceleyerek MTSS'yi etkili bir şekilde önleyip önlemediğini değerlendirmektedir. Kas aktivasyonunu, eklem kinematiğini ve yer reaksiyon kuvvetlerini değerlendirmek için elektromiyografi, hareket yakalama ve kuvvet plakaları dahil olmak üzere modern veri toplama teknikleri kullanılmıştır.

Hedeflenen her iki egzersizin de değişen kas aktivitesi, artan kinematik ve azalan yüklenme oranı gibi ani biyomekanik adaptasyonları tetiklediği varsayılmıştır. Bu hipotezler, SLLH sonrasında baskın bacak için yüklenme oranında önemli bir düşüş olduğunu gösteren verilerle kısmen desteklenmiştir. Her iki egzersiz de MTSS ile ilgili faktörleri potansiyel olarak etkileyen benzersiz nöromüsküler ve kinematik adaptasyonlar göstermiştir.

Sonuçlar, SLLH'nin MTSS gelişiminde kilit bir faktör olan tibial yüklenmeyi azaltmadaki faydalarını vurgulamaktadır. Kas kasılmasının azalması ve kinematiğin iyileşmesinin yanı sıra yüklenme oranında gözlenen azalma, MTSS'nin önlenmesi için her şeyi kapsayan bir strateji önermektedir. CSD eklem kinematiğini ve kas aktivitesini de etkilerken, yüklenme oranını önemli ölçüde etkilememiştir.

Bu bulgular, MTSS risk faktörleriyle bağlantılı biyomekanik ve nöromüsküler parametrelerin değiştirilmesinde SLLH gibi hedefe yönelik egzersizlerin potansiyelinin altını çizmektedir. Sonuçlar, MTSS'yi önlemek için araştırmaya dayalı egzersiz programları oluşturmak için bir temel sunmaktadır.

Anahtar Kelimeler: Medial Tibial Stres Sendromu (MTSS), Egzersiz Müdahaleleri, Nöromüsküler Adaptasyonlar, Yükleme Hızı, Eklem Kinematiği.

In loving memory of my father who always told me:
“The path to success is filled with hard work but don’t forget to enjoy the journey because the pride you feel in your efforts is just as valuable as any prize at the end if not more…”

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I wish to express my deepest gratitude to my advisor Asst. Prof. Bora Büyüksaraç for his unwavering guidance and mentorship throughout the research. His trust and belief in me pushed me towards new heights I never thought I could reach.

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I would also like to thank my friends and comrades, whose companionship made this challenging journey enjoyable.

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LIST OF ABBREVIATIONS

ABD/AD	Abduction/Adduction
AUC	Area Under the Curve
BMD	Bone Mineral Density
BMI	Body Mass Index
BW	Body Weight
COP	Center of Pressure
CSD	Controlled Step Downs
DF/PF	Dorsiflexion/Plantarflexion
DL	Dominant Leg
FDL	Flexor Digitorum Longus
Flex/Ext	Flexion/Extension
GM	Gastrocnemius Medialis
GRF	Ground Reaction Forces
GUI	Graphical User Interface
IR/ER	Internal/External Rotation
MRI	Magnetic Resonance Imaging
MTSS	Medial Tibial Stress Syndrome
MVF	Maximal Vertical Force
NDL	Non-Dominant Leg
P1NP	Procollagen Type 1 N-Terminal Pro-peptide
PB	Peroneus Brevis
RF	Rectus Femoris
RMS	Root Mean Square
ROM	Range of Motion
SLLH	Single Leg Lateral Hops
SOL	Soleus
TA	Tibialis Anterior
TSF	Tibial Stress Fracture
TTVF	Time to Maximal Vertical Force

Chapter 1
Introduction

1.1 Background

Medial tibial stress syndrome (MTSS), frequently referred to as Shin splints, is a frequent overuse injury that mostly affects runners, jumpers, and newly recruited military personnel. Due to inflammation of the impacted muscles, tendons, and bone tissue, this syndrome is identifiable by exertional leg discomfort along the posteromedial border of the tibia. Between 13.6% and 20% of recreational runners suffer from MTSS (Hashim et al., 2024).

The causes of Medial tibial stress syndrome (MTSS) are complex and include overtraining, improper shoe selection, muscle imbalances, and other biomechanical abnormalities (Bhusari & Deshmukh, 2023). According to recent studies, MTSS could be predominantly caused by bone overload damage. Research suggests that individuals diagnosed with MTSS exhibit lower tibial bone mineral density and decreased bone repair function (Winters, 2019). The concept of MTSS has changed as a result of this discovery, moving from straightforward soft tissue damage to a more intricate bone-related illness.

A major contributing aspect to the development of MTSS is biomechanical factors. The effect of excessive pronation during gait, recognized as a major risk factor (Tweed, Campbell, & Avil, 2008), is of particular relevance. An excessive amount of tension on the leg's medial tissues as a result of this aberrant pronation causes the leg to rotate internally for a longer period, the calcaneus to eject and also the midtarsal joint to abduct (Tweed et al., 2008). These changes in biomechanics have a major role in the development and evolution of MTSS.

A combination of strategies, such as rest, ice treatment, and a gradual return to activity, are usually used in the rehabilitation of shin splints. The use of targeted exercises and running retraining in the management and prevention of MTSS is, nonetheless, gaining attention. To decrease tibial stresses and perhaps lower the incidence

of MTSS, running retraining techniques such as reducing overstrides, increasing step rate, and switching to a midfoot strike have been suggested (Anderson et al., 2024).

1.2 Purpose of the Study

Even with the increasing frequency and severity of shin splints, views on the most efficient methods to prevent this injury are still divided. The effect of targeted exercise interventions on MTSS-related parameters has not been deeply investigated in present studies, nor have their biomechanical alterations and implications

The main objective of this research is to investigate exactly how two different targeted exercise interventions, which are controlled step-downs (CSD) and single-leg side hops (SLLH), influence MTSS-related risk factors. Through the use of advanced data acquisition devices such as electromyography (EMG), force plate, and motion capture system which will provide a thorough examination of the ground reaction forces and kinematic metrics coupled with muscle activation profiles.

The goal of this preliminary study is to effectively collect data about the efficacy of these targeted exercises and provide information for future, larger-scale research on the prevention and treatment of MTSS. The results could substantially advance our knowledge of MTSS and open the door to more successful preventative and therapeutic approaches.

1.3 Hypothesis

It is hypothesized that applying controlled step-downs or single-leg lateral hops will cause instantaneous biomechanical alterations in the lower limbs. It is particularly expected that

- There will be a significant change in muscle activity in the post-assessment test compared to the pre-assessment baseline.
- kinematic metrics of the ankle, knee, and hip joint angles will demonstrate a significant increase in the post-assessment test compared to the pre-assessment baseline.

- A notable decrease in the loading rate will be observed in the post-assessment test compared to the pre-assessment baseline.

1.4 Significance of the Study

The outcomes of this research have the potential to significantly impact the fields of sports medicine and injury prevention by providing important insights into the processes by which such targeted exercises could potentially reduce the incidence of MTSS via the assessment of biomechanical and neuromuscular alterations generated by these particular interventions.

The findings can lay the ground for the creation of more complete preventative plans and rehabilitation plans for individuals who are at risk of or already experiencing MTSS which will enable the possibility of providing evidence-based recommendations for adding specific exercises to training plans and therapeutic strategies.

This thesis intends to add to the expanding and growing knowledge of MTSS by bridging the gap between theoretical biomechanics and practical application which will have an impact on injury prevention strategies and training methodologies in sports and military settings.

Chapter 2

Literature Review

2.1 Overview of Medial Tibial Stress Syndrome

2.1.1 Definition. The posteromedial border of the tibia, frequently in the middle to distal third, is the site of prevalent, perceptible discomfort that is characteristic of medial tibial stress syndrome (MTSS), often known as shin splints. MTSS is a frequent lower limb injury that is especially common in runners, gymnasts, dancers, and military personnel (Bhusari & Deshmukh, 2023).

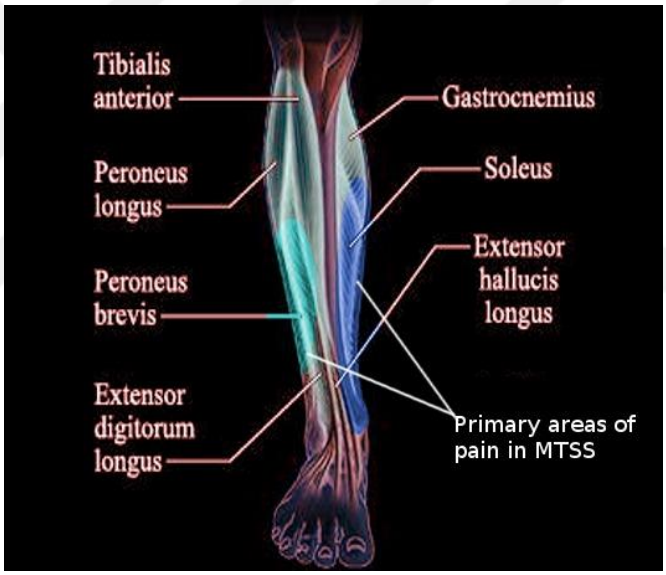

Figure 1. Primary pain regions and muscle anatomy in MTSS (Mcclure & oh, 2023).

2.1.2 Etymology. It is possible to understand the nature of "Medial Tibial Stress Syndrome" (MTSS) by dividing the phrase itself. "Tibial" refers to the shinbone, whereas "medial" indicates the inside surface of the shinbone. "Syndrome" represents a group of symptoms, while "stress" denotes the load applied on this bone. As a result, MTSS defines "shin splints," as a condition that causes pain and discomfort along the inner shinbone as a result of repetitive stress. As early as 1913, runners were reported to have this condition, which was previously referred to as "spike soreness" and misdiagnosed as a tibial stress fracture (Franklyn, 2015).

2.1.3 Epidemiology. MTSS is a common lower limb ailment that affects a large percentage of sportsmen and runners. Its frequency among runners ranges from 13.6% to 20%, which shows that it is frequent among active groups. It accounts for a significant share of lower limb injuries (Kakouris, Yener, & Fong, 2021).

2.1.4 Etiology. Running and military drills are two examples of repetitive pressure exercises that put a lot of load on the tibia and are the main causes of medial tibial stress syndrome (MTSS). Traction from the muscles, especially the flexor digitorum longus (FDL) and soleus, is another factor that contributes to traction-induced periostitis. Moreover, MTSS development is also influenced by bone microtrauma, which appears as edema and microcracks in the cortical bone as a result of repeated impact. (Franklyn, 2015)

MTSS is classified into four grades based on MRI findings. Grades 1 and 2 represent diffuse injuries consistent with MTSS which are characterized by general pain and inflammation. Grades 3 and 4 indicate localized injuries classified as tibial stress fractures (TSFs), with increasing bone involvement.

Low bone mineral density and abnormal tibial cortical bone geometry, such as a smaller cross-sectional area, are common in MTSS patients, indicating that both internal and external causes may play a role in the syndrome's progression. (Franklyn, 2015)

2.1.5 Physiopathology. The pathophysiological causes include traction-induced periostitis, which is brought on by the pulling of muscles on the periosteum, such as the flexor digitorum longus (FDL) and soleus. Subcutaneous periostitis is further exacerbated by microtrauma to the cortical bone, which appears as edema and microcracks. (Franklyn, 2015)

In reaction to physical stress, the cortical bone adjusts its geometric characteristics and bone mineral density (BMD). Individuals diagnosed with MTSS are more likely to have low BMD and lower tibial cortical bone geometric characteristics, which suggest an impaired bone response and put them at risk for stress injuries. (Franklyn, 2015)

2.1.6 Risk factors. In physically active individuals, MTSS has been linked to multiple risk factors. Greater BMI, altered bone geometry, abnormal gait kinematics, differences in leg length, increased navicular drop, restricted or excessive ROM in specific joints, and prior training history are some of these risk factors (Reinking, Austin, Richter, & Krieger, 2016).

2.1.7 Clinical presentation. Physical examination observations and patient-reported symptoms are what define the clinical presentation of MTSS. Patients usually report the sensation of pain along the medial tibial border brought due to physical activity, which frequently gets worse during or after exercising. Additional signs of chronic exertional compartment syndrome (CECS) might be pressure-like, burning, or cramping feelings in the calf. For some individuals exercising may cause pins and needles or a cold foot (Winters, 2019).

It is necessary to palpate the posteromedial tibial boundary during a physical examination (Figure 2). The diagnosis of MTSS is confirmed by palpable discomfort across a distance of five cm or more. If there is no discernible pain or if the discomfort is localized to fewer than five centimeters, other lower limb injuries, such as stress fractures, could be the cause. (Winters, 2019).

Figure 2. Shin palpation test (Newman, Adams, & Waddington, 2012).

2.1.8 Positive diagnosis. If the patient's history, symptoms, and physical examination are all positive for MTSS suspicion, a thorough clinical evaluation is required. A decisive tool for this examination is magnetic resonance imaging (MRI), which helps confirm the diagnosis by displaying typical abnormalities including periosteal inflammation and cortical bone edema. It is important to distinguish MTSS from other injuries, especially tibial stress fractures (TSFs). To determine the precise nature of the injury, the diagnosis should also take into account the patient's activity history, clinical symptoms, and other risk factors. For the purpose of promoting recovery and averting recurrences in the future, accurate diagnosis is essential. (Franklyn, 2015)

2.1.9 Differential diagnosis. A variety of injuries are included in the differential diagnosis of tibial stress injuries in athletes and military personnel. Particular injuries include tendon and muscle injuries that could hold a similarity to the symptoms of MTSS, as well as chronic compartment syndrome, which appears as comparable leg discomfort. It is important to rule out non-specific illnesses such as bone tumors that can manifest as tibial discomfort. Leg discomfort can also be caused by nerve entrapment diseases, like neuropathy. thus, these should be taken into account in the differential diagnosis. (Lefebvre et al., 2017)

2.1.10 Treatment. Conservative care is the cornerstone of treatment for MTSS. This includes exercise therapy targeted at training and strengthening the lower leg muscles as well as a graduated loading program designed to progressively increase the load on the impacted region. Although several treatments including gait retraining, rest, ice massage, shockwave therapy, strengthening and stretching exercises, bracing for the lower legs, and injectable therapies have been proposed, however, their efficacy has not yet been shown. (Craig, 2008)

Because there is no clear etiology for MTSS, surgical intervention such as fasciotomy or periosteal stripping is typically not advised as a first-line therapy. Moreover, there is little data to support the efficacy of surgery, and the results are not well documented. (Lefebvre et al., 2017)

2.1.11 Prevention. Based on the information that is currently available in the literature, a number of preventative strategies have been proposed for MTSS, yet the success rate varies wildly. One prevention technique was the use of shock-absorbent insoles, which are intended to lessen impact forces exhibited to the tibia; nevertheless, the ideal level of shock absorption is yet unknown. While there is conflicting data to support their effectiveness, pronation-control insoles, which are designed to reduce excessive foot pronation, may also provide some advantages. (Craig, 2008)

Other preventive methods have proposed running programs that involve a gradual increase in training load and changes to footwear, such as choosing appropriate running shoes and providing enough support and cushioning. However, it is unclear which particular adjustments or shoe styles are best for preventing MTSS. Changes to the distance, frequency, and duration of running are among other training program modifications to try to prevent training mistakes that lead to the development of MTSS. Although it is frequently advised, research indicates that stretching the muscles in the lower legs may not be a direct preventive measure for MTSS.

2.2 Current Research on MTSS

An in-depth overview of medial tibial stress syndrome (MTSS) is given by Franklyn and Oakes (2015), who concentrate on the condition's etiology, mechanisms, and preventative implications. They suggest that MTSS is a limiting overuse injury that's common among people who participate in repetitive impact activities. It is distinguished by widespread subcutaneous periostitis of the tibial anteromedial or posteromedial surface accompanied by cortical bone microtrauma beneath the skin. Two key risk factors for MTSS are identified by the authors: low bone mineral density and certain geometric characteristics of the tibial cortical bone. The authors emphasized the importance of accurate evaluation by utilizing thorough clinical tests and imaging methods, and they propose that finite element analysis would be a useful tool in deciphering the processes behind tibial stress injuries. The authors stress the importance of further investigation to pinpoint the precise pathways causing damage and provide focused therapies to reduce the chance of MTSS.

An evidence-based overview of the diagnosis and treatment of MTSS is given by Winters (2019), who highlights the significance of an accurate assessment and successful management techniques to avoid recurrence. The author stated that MTSS can be accurately identified using a systematic history and physical examination technique, and it's critical to distinguish it from other injuries like chronic exertional compartment syndrome. As these interventions target the affected tibial bone and crural fascia, the author dictated that surgery is not advised for MTSS and suggested moderate treatment options such as education on training loads, graded tibial loading programs, and ankle plantar flexor strengthening exercises.

The association between dynamic and static foot position and the occurrence of MTSS in distance runners was investigated by Tweed, Campbell, and Avil (2008). They reported that MTSS progression is influenced by several biomechanical parameters, such as excessive pronation and foot position, highlighting the need to evaluate both static and dynamic components. The authors explained how MTSS symptoms may develop in runners due to unusual pronation of the subtalar joint, particularly in the late stance phase of running. Apropulsive gait, early heel lift, abductory twist throughout gait, and the difference between neutral and relaxed calcaneal stance postures are among the key indicators of MTSS that the study discovered. The authors suggest that dynamic screening for incorrect or mistimed pronation might help in MTSS prevention and symptom reduction.

In long-distance runners with MTSS, specific characteristics of lower leg muscle structure and function are examined in this research by Mattock, Steele, and Mickle (2021). They suggest that the understanding of these variations will help design effective rehabilitation plans. They stated that tibial stress during running is influenced by variables related to the structure and functioning of the lower leg muscles. The authors compared asymptomatic controls and symptomatic runners to see if any notable variations in muscle properties might be connected with the development of MTSS. The flexor hallucis longus cross-sectional area and soleus thickness were considerably less in MTSS symptomatic limbs than in control limbs, whereas the lateral gastrocnemius thickness was higher. Significant reductions in the maximum voluntary isometric contraction strength of the flexor hallucis longus, soleus, tibialis anterior, and peroneal muscles, as well as decreased

ankle plantar flexor endurance, were seen in the limbs exhibiting symptoms. From the mentioned results the authors concluded that people with MTSS have functional and structural weaknesses in the muscles of their lower legs, which would weaken their capacity for withstanding running stresses leading to aggravated MTSS.

Ampomah Brown (2016) investigated the connection between the muscles located in the area where MTSS-related discomfort is felt. The author stated that the soleus and flexor digitorum longus muscles are likely responsible for the symptoms of MTSS when traction is a contributing component to the condition as opposed to the tibialis posterior muscle, which has historically been connected to the injury. This study's findings proved that the posteromedial border of the tibia is directly attached to the soleus and flexor digitorum longus muscles and not to the tibialis posterior muscle. The author finally stated that more evidence from further studies showcased that these muscles are decisive factors in the origin of MTSS because those studies revealed that the bulk of the fiber linkages for the flexor digitorum longus and soleus were found in the middle part of the tibia.

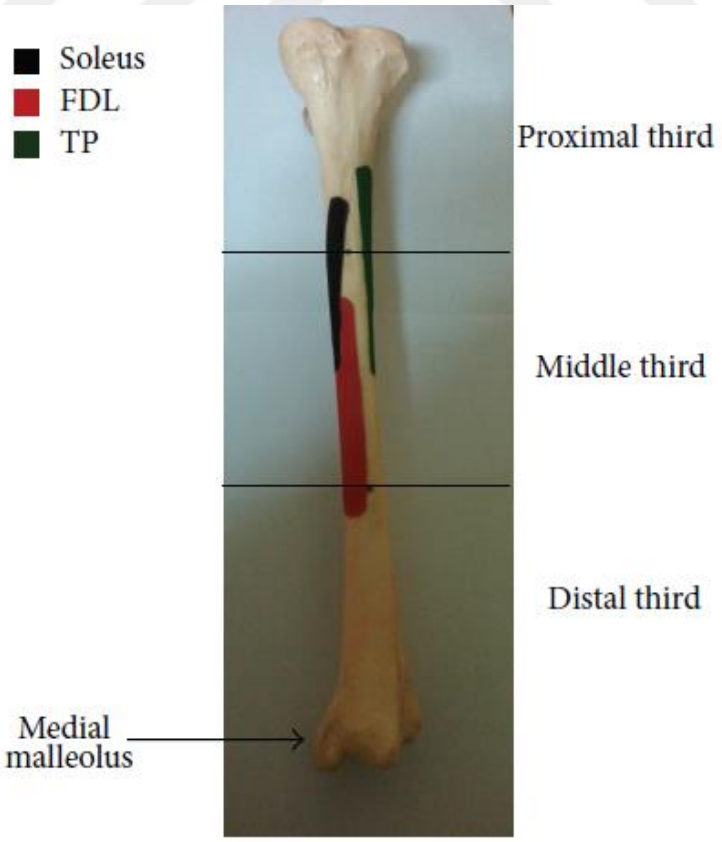

Figure 3. Muscle attachments on the posterior side of the left tibia (Brown, 2016).

Rathleff et al. (2011) investigated the connection between midfoot kinematics and SEMG signals in patients diagnosed with MTSS In comparison to healthy controls, the authors anticipated that MTSS patients would show lesser complexity in midfoot kinematics and increased complexity in SEMG signals from the tibialis anterior and soleus muscles. However, the results of this study interestingly demonstrated that midfoot kinematics had lesser structural complexity in MTSS patients' SEMG signals than in the controls. The author deduced that this inverse association raises the possibility that gait variability is governed by independent regulatory systems. Based on these findings the authors concluded that evaluating the intricacy of midfoot kinematics and muscle activation can shed light on the gait traits of individuals diagnosed with MTSS which in return will lead to the development of therapies that improve kinematic variability and muscle function to avoid MTSS.

In their study of MTSS, Lefebvre et al. (2017) offer a thorough assessment of the physiological causes, clinical presentation, imaging methods, and available treatments. The authors emphasized some risk factors linked to MTSS, such as taking part in highly competitive sports, military training, excessive or repeated exertion, and postural problems. The authors acknowledged that prevention is essential and should concentrate on resolving postural problems and treating risk factors which include an imbalance between the tibia's natural processes of healing and remodeling and recurrent submaximal micro-traumatic stresses. The authors stated that the best imaging modality for MTSS is determined to be MRI as it facilitates lesion identification and categorization.

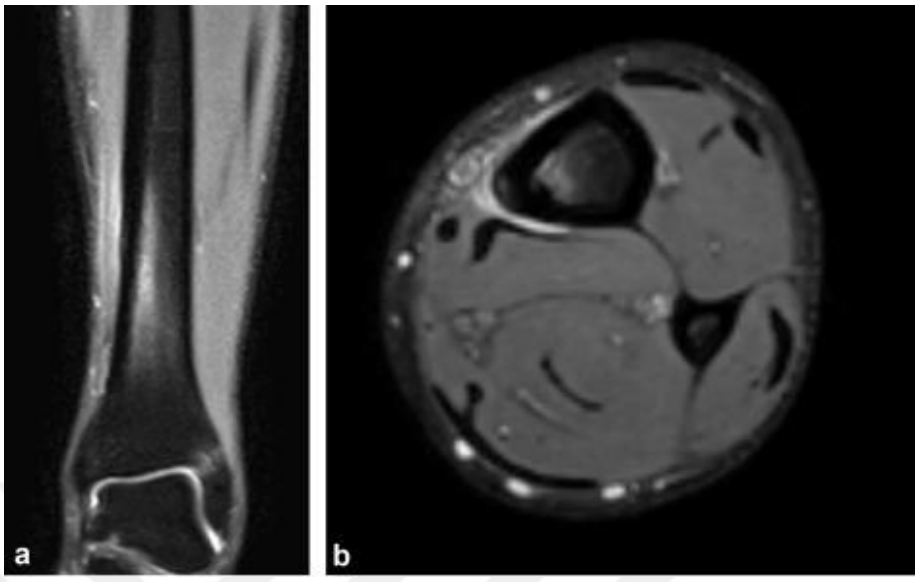

Figure 4. Fat sat t2-weighted mri slices, axial (a), and coronal (b) (Lefebvre Et Al., 2017).

The influence of a full physical therapy strategy on a patient diagnosed with MTSS is examined in the case report by Deshmukh, Phansopkar, and Wanjari (2022). The authors stated that poor running mechanics and repeated stress are common causes of MTSS and that early detection and focused treatment are essential to preventing the disease's development. They emphasize the necessity for individualized treatment regimens by highlighting the impact that susceptible risk factors such as training intensity and footwear have in worsening MTSS. This research's findings showed a notable decrease in pain as well as enhancements in strength, range of motion, and functional ability. These results highlight the effectiveness of individualized treatment regimens and the possible benefits of physical therapy measures like cupping therapy, stretching, and strengthening exercises, to improve athletic performance and help prevent related injuries such as MTSS.

2.3 Targeted Joints

2.3.1 Hip. From the first heel contact of the stance phase and until the completion of that phase, hip flexion occurs. This is due to the reduction of the angle between the pelvis and the femur bringing the thigh closer to the abdomen. The opposite motion, known as hip extension, begins after the initial flexion during the stance phase of walking and entails raising the angle between the femur and pelvis as well as extending the thigh away from the abdomen. (Lunn, Lampropoulos, & Stewart, 2016)

During the gait cycle, the thighs of an individual move away from the midline of the body from midstance until the completion of the stance phase, a motion known as abduction. After abduction, adduction—the thigh's return to the midline—continues until the end of the gait cycle

The thigh's inward and outward rotations are referred to as hip internal and external rotation, which take place in the transverse plane. (Lunn et al., 2016)

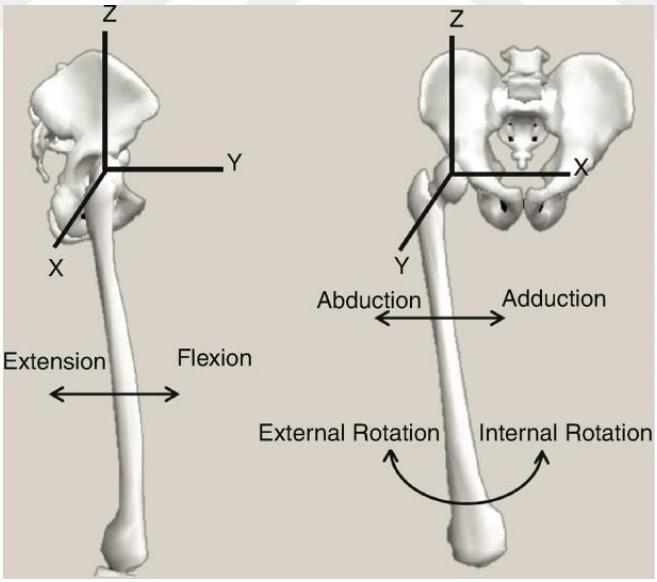

Figure 5. Hip joint axes and movement directions (Liu, Hua, & Cheng, 2020).

2.3.2 Knee. The sagittal plane is where knee flexion in where the calf moves towards the posterior thigh and extension is when the leg straightening occurs. The full flexion movement's range of motion is 140° whereas the complete extension's is 0°. To achieve the large range of rotation, the technique entails a combination of rolling and sliding of the femoral condyles across the tibial plate, known as rollback. Because of its asymmetry, the internal condyle starts sliding before the external condyle does, with rolling predominating from maximal extension (0°–10°/15°) to sliding (10°/15°–140°). (Affatato, 2015)

The inner and outward motions of the foot are described by internal and external rotation, which takes place in the transverse plane. The degree of rotation is impacted by the location of the joint in the sagittal plane. Because the femoral condyles pivot internally on the tibial plate during flexion, there is a slight exterior rotation, and there is a slight internal rotation during complete extension. Surprisingly, there is more rotation on the lateral condyle than the medial condyle.

Leg's motion towards the midline -leg adduction- and leg's motion away from the midline -leg abduction- both take place in the frontal plane. Knee flexion causes these passive motions to increase by about 30°. However, because of the limitations placed on them by the surrounding soft tissue, which prevent excessive movement, they only entail a small range of motion. (Affatato, 2015)

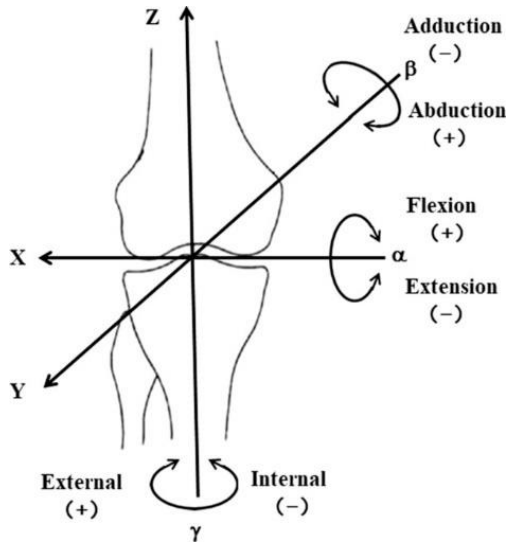

Figure 6. Knee joint axes and movement directions (Wang Et Al., 2021).

2.3.3 Ankle. Dorsiflexion is the upward movement of the foot towards the shin in the sagittal plane. This action is essential for getting the foot off the ground during the swing phase of gait. On the other hand, plantarflexion, the opposite motion, is the foot pointing downhill away from the shin. The beginning of the swing phase needs power generation. It occurs with the help of the opposite motion, known as plantar flexion which assists in extending the foot forward during the walking's push-off phase and achieves maximum peak during toe-off. (Brockett & Chapman, 2016)

The ankle joint, despite being frequently regarded as uniaxial, displays simultaneous internal and exterior rotation because of its slant axis of motion. The foot's internal rotation occurs when the foot rotates inward. This is known as Ankle dorsiflexion. Contrariwise, the foot's external rotation occurs when the foot rotates outward. This is known as Ankle plantarflexion.

To maintain adaptation to uneven surfaces and maintain balance during motion, several movements are required. These movements mostly take place in the transverse plane. One of which is abduction, which is the movement of the foot away from the body's midline. It usually occurs during the supination action and includes adduction, inversion, and plantarflexion. In contrast, pronation includes dorsiflexion, eversion, and abduction, which is linked to adduction, or the movement of the foot towards the midline. (Brockett & Chapman, 2016)

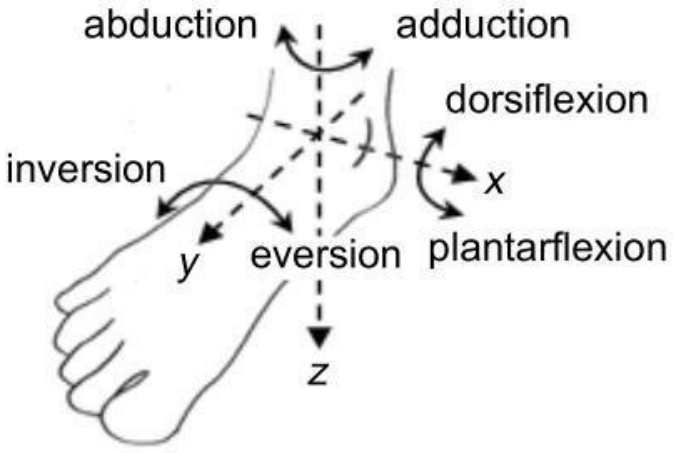

Figure 7. Ankle joint axes and movement directions (Chin Et Al., 2017).

2.4 Targeted Muscles

2.4.1 Tibialis anterior. The primary muscle located in the anterior compartment of the lower leg, the tibialis anterior, emerges from the lateral tibia and inserts on the medial cuneiform and base of the first metatarsal via its tendon. To clear the foot during the swing phase of gait, this muscle functions as the main dorsiflexor of the foot. In addition, the tibialis anterior helps elevate the medial arch during foot inversion by working in coordination with the tibialis posterior. The plantar flexors of the posterior compartment counter the movements of the tibialis anterior, which is a muscle in the anterior compartment that is perfused by the anterior tibial artery and innervated by the deep peroneal nerve. Together, these muscles allow for dorsiflexion and inversion. (Juneja & Hubbard, 2023)

2.4.2 Peroneus brevis. Originating from the lower two-thirds of the lateral fibula, the peroneus brevis is a muscle found in the lateral area of the lower leg. It attaches to the styloid process of the proximal fifth metatarsal. The peroneus brevis, working in coordination with the peroneus longus, helps in plantarflexion at the ankle joint and foot eversion. This muscle, which is vulnerable to dislocation and is fed by the peroneal artery and innervated by the superficial peroneal nerve, is often involved in lateral ankle sprains. (Basit, Shah, & Siccardi, 2023)

2.4.3 Soleus. the soleus, which is an important part of the triceps surae. Its fibers originate from the proximal fibula and the tibia's soleal line, and they unite to enter into the Achilles tendon or calcaneal tendon. The function of this muscle is vital for plantar flexion of the foot, especially when the knee is bent, which helps in running, and walking. To help with venous return from the lower limbs, the soleus also serves as a peripheral vascular pump. (Dalmau-Pastor et al., 2014)

2.4.4 Gastrocnemius medialis. The gastrocnemius medialis implants distally on the posterosuperior area of the adjacent femoral condyle after emerging from the popliteal face of the distal femur. This muscle, which is a component of the triceps surae, plays a major role in knee flexion as well as plantar flexion of the foot. Interestingly, the medial head is more tense than the lateral head, highlighting its importance in these motions. (Dalmau-Pastor et al., 2014)

2.4.5 Rectus femoris. The most prominent muscle in the front of the thigh area, the rectus femoris, is a bipennate muscle that is a component of the quadriceps complex. It originates from the direct head of the anterior inferior iliac spine and the indirect head of the superior acetabular ridge. It enters on the patellar base through the quadriceps tendon and ends up joining it with the tibial tuberosity. This muscle is essential for exercises demanding strong knee extension since it acts as both an extensor and a hip flexor. (Murdock, Mudreac, & Agyeman, 2023)

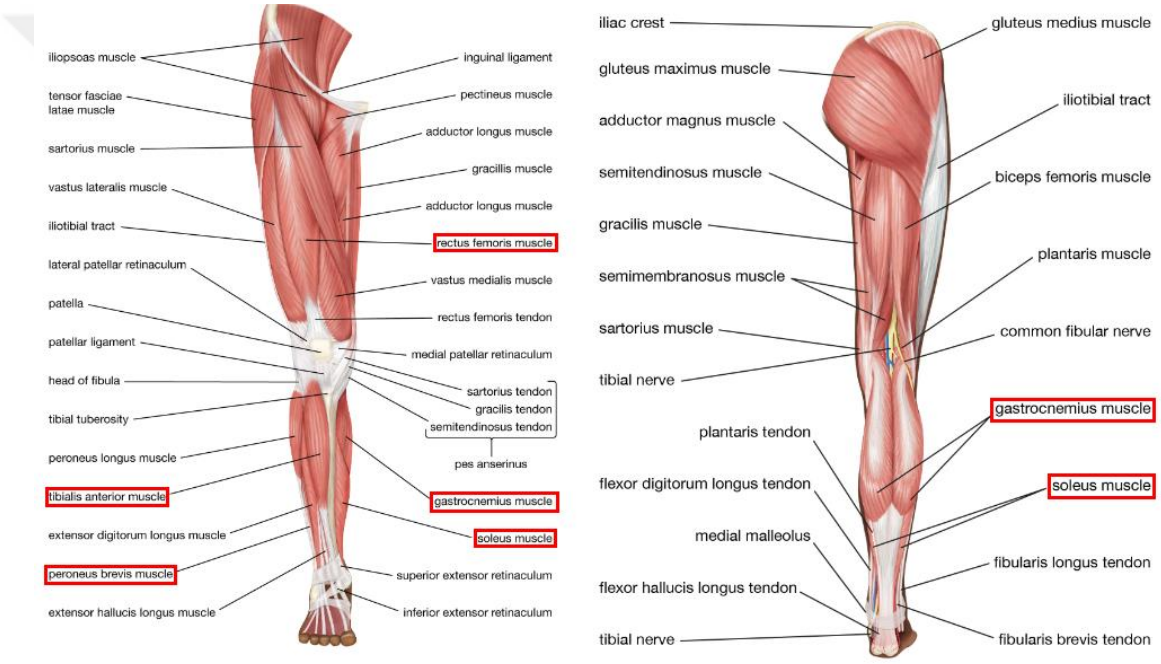

Figure 8. Anterior and posterior views of lower leg muscles ("Leg | Definition, Bones, Muscles, & Facts," 2024).

2.5 Rational for Exercise Selection

There isn't a direct link in the literature that connects MTSS to SLLH or CSD exercises. however, several studies offer strong evidence about the importance of those exercises and their influence on lower-extremities strength, stability of the ankle, and postural control which all are important factors in minimizing injuries in athletes

2.5.1 Single-leg lateral hops. The multiplanar aspect of human movement is highlighted by Meylan et al. (2009), especially in sports requiring quickness and agility, highlighting the need for training in all three planes of motion. Frequently overlooked in conventional training regimens, lateral hops concentrate on the lateral movement capacities of the body, activating distinct muscle groups and movement patterns that are not sufficiently addressed by other exercises.

Lateral hops are an orthopedic test used by Johnson and Stoneman (2007) to evaluate the strength and stability of the ankle after lateral ankle sprains. This indicates that the exercise efficiently works the surrounding muscles, especially the peroneal muscles, as well as the ankle joint. Tibial stress may be decreased and excessive pronation may be mitigated by strengthening these muscles, which are essential for regulating pronation, a biomechanical aspect linked to MTSS.

The knee mechanics of the standardized rebound side hop (SRSH), which is similar to lateral hops, were explored by Markström, Tengman, and Häger (2021). The SRSH engages the peroneals and soleus, two muscles that regulate the ankle and lower leg, by eliciting increased frontal and transversal plane motions at the knee. By making these muscles stronger, you may improve the stability of your lower legs and maybe reduce tibial stress. Moreover, beneficial changes in muscles, tendons, and bones may be stimulated by the intense demands of the SRSH, enhancing their resistance to the recurrent loading linked to MTSS.

Although the research does not clearly show a direct correlation between lateral hops and MTSS prevention, the gathered information from these studies strongly suggests that lateral hops should be included in a focused MTSS preventive program. Lateral hops can be a useful technique in reducing the risk factors linked to MTSS because they address the multiplanar character of the movement, target particular muscle groups, improve ankle function and stability, and perhaps promote favorable changes in tissues.

Figure 9. Single leg lateral hop exercise representation ("Andy Murray's Strength Workout," 2018).

2.5.2 Controlled step-downs. The importance of lower-extremities strength and control in preserving the kinetic chain and minimizing injuries in athletes is highlighted by Zipser et al. (2021). Like controlled step-downs, the single-leg step-down task assesses lower extremity stability and control in a weight-bearing, single-leg stance, which is essential for improving running mechanics and minimizing tibial stress. Lower extremity injuries may be prevented by strengthening the hip abductors and enhancing general control of the lower extremities. One such risk factor is greater knee valgus.

Bell-Jenje et al. (2016) emphasize the significance of ankle dorsiflexion in preserving the appropriate alignment of the lower limbs. Restricted ankle dorsiflexion might end in compensatory motions that put more strain on the tibia. Proper lower limb alignment and good ankle dorsiflexion can be promoted by controlled step-downs, which may result in more uniformly distributed forces and less stress on the tibia. In addition to strengthening and enhancing coordination, the exercise might assist the muscles surrounding the ankle joint, which are crucial for preserving appropriate lower limb mechanics.

The connection between foot position, lower extremity mechanics, and injury risk is emphasized by Kim, Yoo, Hwang, and Kwon (2021). Dynamic knee bending, a risk factor for several lower limb injuries, can result from pronated foot position. Appropriate foot assignment, knee alignment, and hip control are necessary for controlled step-downs, which may reduce these risk factors. Additionally, the exercise requires the contraction and synchronization of lower leg muscles which are important for ankle stability and foot pronation control, improving overall resilience and stability of the lower extremities.

Although the particular impact of controlled step-downs on MTSS has not been investigated, the majority of data from these studies indicates that this exercise may be beneficial in treating the underlying reasons for MTSS. Controlled step-downs can be an effective approach to minimize the risk of this injury.

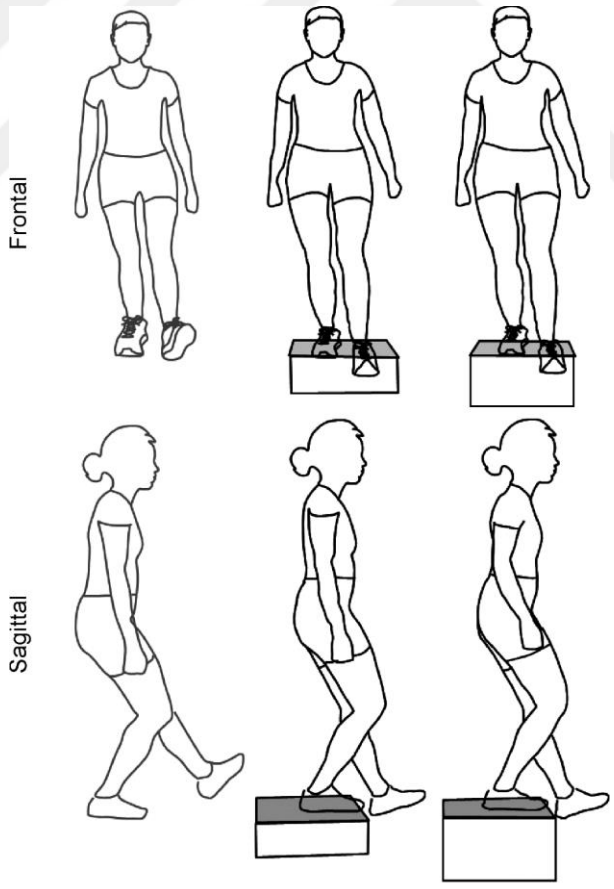

Figure 10. Controlled step-down exercise representation (Lewis Et Al., 2015).

2.6 Single Leg Jumps Assessment Test Used for the Pre-Post Phases

An increasing amount of study data supports the use of the single-leg jump-landing test, however, it hasn't been specifically used in relation to MTSS.

According to Ross, Guskiewicz, and Yu (2005), the test's capacity to disrupt the kinetic chain of the lower extremities and collect information on ground response forces makes it possible to compute factors like loading rates that are connected to stress fractures and MTSS. Because of the test's sensitivity in identifying variations in lower limb function, it may be able to identify minute modifications brought about by training programs, capturing crucial elements of neuromuscular control and coordination that are pertinent to the prevention of injuries.

Mendes et al. (2021) draw attention to the high-impact character of single-leg jump landings, which put a strain on the tibia and other lower extremities. Since MTSS is frequently linked to impact and repeated stress, this test has practical importance. The study supports the test's utility in MTSS prevention by highlighting the significance of neuromuscular control and muscle activation patterns in preserving joint stability and avoiding injuries. Exercise treatments may be evaluated for their effect on tibial stress by using a force plate to collect objective data on factors such as loading rate and peak vertical force.

The need to comprehend lower limb kinematics during dynamic tasks for evaluating injury processes and risk factors is emphasized by Kawahara et al. (2022). The single-leg jump-landing task is a useful tool for identifying possible MTSS contributors because it captures lower limb movement patterns and forces accurately. The test's capacity to identify millisecond movement differences indicating of deeper causes, even in the absence of overt damage, is shown by its sensitivity in distinguishing between healthy persons and those with chronic ankle instability.

Although the research does not directly show a connection between single-leg jump-landing mechanics and MTSS, the availability of data does support the test's capacity to evaluate dynamic foot mechanics, muscle activation, and its applicability to

lower limb injuries. These results support its inclusion in assessing how exercise programs affect MTSS-related parameters.

Chapter 3

Materials and Methods

3.1 Participant Selection and Study Design

This randomized controlled experiment aims to investigate the biomechanical and neuromuscular effects of two distinct targeted exercise interventions, in the form of single-leg lateral hops, and controlled step downs, that aim to prevent medial tibial stress syndrome (MTSS). A total of 20 participants between the ages of 23-28 were recruited for this study (Table 1).

3.1.1 Exclusion criteria. The following exclusion criteria were used to ensure the validity and safety of this study:

- History of lower limb injuries.
- Neurological disorders affecting motor control, balance, or muscle function
- Cardiovascular or respiratory conditions limiting exercise capacity
- Orthopedic or musculoskeletal disorders influencing gait or movement
- Current or recent pregnancy
- Use of medications that affect muscle function, coordination, or pain perception

Table 1

Participant Demographics and Group Allocation

Subject NO	Dominant leg	Allocated Group	Gender	Age	Height	weight
001	R	SLLH	M	28	177.5	70
002	L	SLLH	M	27	176	76
003	R	CSD	M	24	181	83
004	R	SLLH	M	24	173	76
005	R	CSD	F	23	172	77
006	R	SLLH	M	25	182	78
007	R	SLLH	M	24	177	76
008	R	SLLH	M	26	180	83
009	R	CSD	M	24	178.5	78
010	R	SLLH	M	23	188	70
011	R	SLLH	M	28	177	81
012	R	CSD	M	25	176	76
013	R	CSD	F	27	157	59

Table 1 (cont'd)

014	R	SLLH	M	27	180	78
015	R	CSD	M	24	173	73
016	L	SLLH	F	27	158	51
017	R	CSD	M	25	184.5	87
018	R	CSD	M	26	181	79
019	R	CSD	M	25	176	81
020	R	CSD	M	25	175	87

3.1.2 Participant randomization. The recruited participants were randomly allocated into one of two intervention groups CSD or SLLH. To enable a randomized yet equal distribution of participants a MATLAB-based subject allocation code with a graphical user interface (GUI) was developed and used (Figure 11). The code basically allowed an asymptotic convergence towards balanced group distributions by dynamically adjusting the allocation probability for each group based on the existing group sizes.

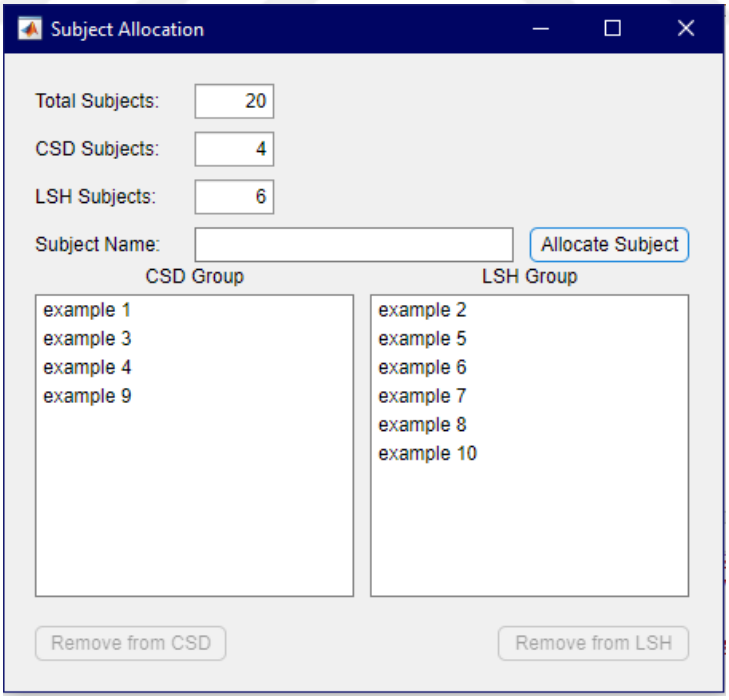

Figure 11. Subject allocation interface.

This allocation method's fundamental idea was based on probability theory, where the chances of being assigned to a certain group are based on how much capacity that

group has left in relation to the overall amount of space that both groups have left. This self-correcting mechanism ensured the reduction probability of uneven group assignments while maintaining the advantages of randomization.

A Monte Carlo simulation was used to test and confirm the allocation algorithm's probabilistic unbiased. In this simulation, the allocation process was carried out 10000 times for a total number of 20 subjects. The results of this simulation made it clear that the distribution of group sizes converged towards a binomial distribution centered around half the total number of individuals which in our case is 10 subjects (Figure 12). A visual inspection of the allocation patterns was used to validate the systemic unbiased in the participant distribution process which strengthened the validity of the randomization algorithm (Figure 13).

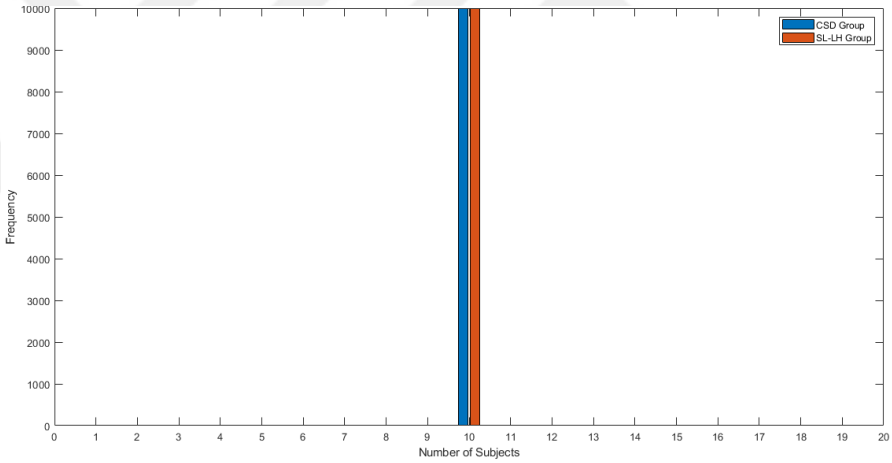

Figure 12. Frequency distribution of subjects in CSD and SLLH groups across 10,000 simulations.

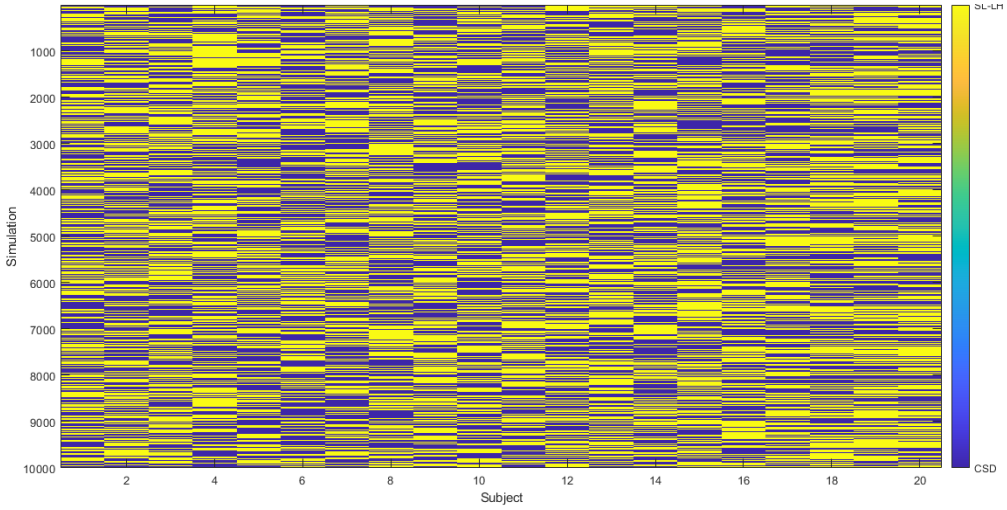

Figure 13. Subject allocation visualization across 10,000 Monte Carlo simulations.

3.2 Instrumentation and Devices

3.2.1 EMG. The surface electromyography (sEMG) signals were recorded using the Trigno® Wireless Biofeedback (SN: SP-W02C-1357) System, which is considered the golden standard for sEMG signal detection (Jayaraman et al., 2024). This system's sensors each contain a three-axis accelerometer and an electromyography electrode, allowing for wireless data transmission across a 40-meter range. With a 7-hour battery life and a 2148 Hz sampling rate, the device provides usage of Delsys' exclusive EMGworks Acquisition software for data handling and makes it easier to gather high-quality biological signals. The Trigno system's capacity to provide precise and consistent sEMG data is further improved with the addition of noise-resistant sensors and unique parallel-bar technology. (Nair, Rajapriya, & Rajeswari, 2021)

Figure 14. Trigno wireless sEMG system (gage, 2023).

3.2.2 Xsens. The XSENS Awinda system (XSENS Technologies B.V., Enschede, The Netherlands) was utilized to measure joint angles. It is a wireless motion capture solution composed of 17 inertial measurement units (IMUs). This system wirelessly transfers data to a Wi-Fi router that is linked to a computer device. It operates at a sampling frequency of 60 Hz. The IMUs' raw data is processed using the MVN Analyze program to provide a thorough 23-segment biomechanical model with 22 joints, each represented by 3D angles showcasing the 3 axes. In compliance with the International Society of Biomechanics (ISB) guidelines for standardizing kinematic data reporting. (Wu et al., 2002)

3.2.3 Force plate. The BERTEC FP-4060-05-PT force platform (Bertec Corp.; Columbus, OH, USA) was used to measure the ground reaction forces. This 600 mm x 400 mm horizontal platform collects three force components (Fx, Fy, and Fz) and three-moment components around the x, y, and z axes at a 1000 Hz sample frequency using six-component load transducers. The center of pressure (CoP) is then automatically calculated using these six outputs. (Ferreira, Castro, & Esteves, 2023)

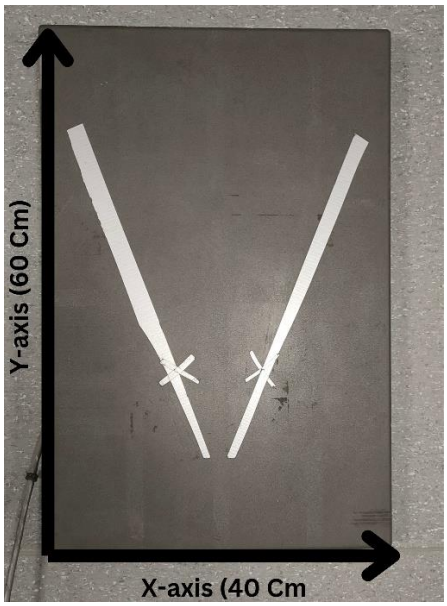

Figure 15. BERTEC FP-4060-05-PT force platform.

To synchronize the data recording of XSENS, the Bertec force plate, and the Trigno® Wireless Biofeedback (SN: SP-W02C-1357) System, an extra device was

utilized: the Delsys Trigger Module. This device receives the incoming pulse from the XSENS base and sends it to the AM6800 amplifier and EMG base station (SP-W02) with the aid of the EMG works Acquisition software.

Figure 16. Trigno® wireless biofeedback (SN: SP-W02C-1357) System (Gage, 2020).

3.3 Data Acquisition

3.3.1 EMG. Surface electromyography (sEMG) electrodes were attached to the targeted muscles (Figure 17) in compliance with SENIAM.org guidelines before the start of the experimental trials. To get the best possible signal quality, the regions of skin that were designated for sEMG measurements were carefully cleaned with alcohol and shaved (Konrad, P., 2005). The sensors were then firmly positioned using adhesive tape to reduce motion artifacts and preserve stability during the data-gathering process.

Figure 17. Lower limb EMG sensors placement.

3.3.2 Xsens. Participants were outfitted with the XSENS Awinda system using the included headband, Velcro straps, and Lycra T-shirt before data collection (Figure 18). The instructions provided by XSENS movella guidelines and instructions were carefully followed while placing the sensors to ensure an accurate connection and reduce motion artifacts. Several body segment measurements were then taken, including head height, shoulder height, shoulder width, elbow span, wrist span, arm span, hip height, hip width, knee height, ankle height, foot length, and sole thickness.

Afterward, participants engaged in a 16-second walk to and from the starting point after assuming a static upright N-pose for 3 seconds during the calibration phase. Until the MVN software declared the calibration procedure successful, it was repeated as needed.

3.3.3 Force plate. After the motion capture device was calibrated, participants were instructed to take a position on the force plate. This stage made it possible to weigh each participant, guaranteeing that the ground reaction force data in later analysis would be properly normalized according to body weight.

Figure 18. Experimental setup featuring a subject equipped with 17 XSENS AWINDA sensors, standing on the BERTEC force platform.

3.4 Experimental Protocol

The experimental protocol for this thesis was structured into three phases: pre-assessment, exercise intervention, and post-assessment.

3.4.1 Pre-Assessment phase. This phase consisted of four single-leg forward jumps (two per leg) executed from a designated distance of 45 cm onto the force plate (Figure 19). The designated distance was determined through a pilot study involving 15 individuals, ensuring a comfortable yet challenging jumping position.

Figure 19. Experimental setup for single-leg jump test.

3.4.2 Exercise intervention. In this phase, the participants engaged in their assigned exercise intervention groups. Group 1 performed single-leg lateral hops covering a distance of 45 cm per repetition, while Group 2 executed controlled step-downs from a height of 18 cm.

Both groups completed 3 sets of 6 repetitions per leg. A 5-minute rest period was interposed between the pre-and post-assessment.

3.4.3 Post-Assessment phase. This phase mirrored the pre-assessment protocol. Participants repeated the single-leg forward jump test from the same 45 cm distance (Figure 19). This approach will facilitate a direct comparison of biomechanical and neuromuscular parameters before and after the intervention which will allow a comprehensive assessment of the intervention's effects.

3.5 Data Analysis and Preprocessing

3.5.1 Preprocessing. To eliminate the baseline drift, EMG data from the pre/post-test phases and exercise interventions were detrended and then filtered by using a fourth-order Butterworth bandpass filter with cutoff frequencies of 500 Hz and 15 Hz. A notch filter at 50 Hz was used to reduce power line interference. After the signals were rectified for additional analysis.

As for the motion data markers were placed manually on specific frames indicating the beginning and end of each set and each repetition of both exercises within the XSENS software interface to allow segmentation of exercise phase data before loading XSENS data into MATLAB (MathWorks (MATLAB_R2023)) for analysis. Data relevant to the particular joints of interest were extracted for additional processing.

A fourth-order Butterworth low-pass filter with a 15 Hz cutoff frequency was used to filter force plate data, which was used only during the pre/post-evaluation phase.

3.5.2 Exercise phase data analysis. To extract relevant features, further analysis was performed on the data collected during the targeted exercise phase, which included EMG signals sampled at 2148 Hz and XSENS motion capture data sampled at 60 Hz.

Initially, the EMG data were down-sampled to 60 Hz to match the XSENS data's sampling frequency. Markers that had been previously placed into the XSENS program were used to segment the data for each individual into 18 repetitions.

For each of those repetitions, features were extracted and calculated from both EMG and XSENS data. EMG features included mean amplitude, AUC, RMS, and MAX value, as for motion data, the features extracted were ROM, RMS, and MAX angle value.

Each repetition was then plotted individually but overlaid on each other to simplify the observation of patterns or trends in muscle activation and joint kinematics throughout the exercise interventions (Figure 23,24).

3.5.3 Pre/post assessment phase data analysis. To extract relevant parameters, such as mean EMG, AUC, RMS, the maximum value for EMG data and ROM, RMS for motion data, loading rate, COP displacement, impulse, TTVF, and MVF for the force plate, a thorough analysis and detection process was conducted on data gathered from EMG, XSENS, and force plate systems during the pre/post assessment phase.

Alterations in the center of pressure (CoP) in both the x and y axes were tracked to segment the data. The landing on the force plate was indicated by a transition from zero to a non-zero CoP value; the take-off was marked by the opposite change. These markers allowed for accurate segmentation by indicating the beginning and end of each of the four jump landings during the pre/post-evaluation phase.

Force plate markers were up-sampled to 2148 Hz to line them with the EMG sampling frequency and frame length. To ensure a single temporal framework for analysis, those same markers were then down-sampled to 60 Hz to match the XSENS data frame length. This method allowed for the synchronization of the markers with the lower-frequency XSENS data while maintaining the high-frequency EMG and force plate data.

The synchronized markers facilitated the data segmentation process by simplifying the calculation of desired parameters for each device/signal. From the segmented EMG data, the mean EMG, AUC, RMS, and maximum value were calculated. While loading rate, CoP displacement, and greatest vertical peak were computed from the segmented force plate data, ROM and RMS were obtained from the segmented joint angle data.

All data streams (EMG, XSENS, force plate) were resampled to a single frame rate for trend evaluation and visualization. Plot comparisons and pattern identification across several data streams were synchronized by using the same CoP markers for segmentation following resampling. During the pre/post evaluations, this unified illustration made it easier to see patterns and correlations between ground reaction forces, joint kinematics, and muscle activation.

3.6 Statistical Analysis

Statistical analysis was performed using MedCalc® Statistical Software (MedCalc Software Ltd, Ostend, Belgium 2023) to evaluate the pre/post phases results within each exercise group. Given the distinct motion differences of the two targeted exercises, a direct comparison between the two groups during the intervention phase was not feasible.

The Shapiro-Wilk test was used to assess the normality of the data distribution. For data exhibiting normality, paired t-tests were implemented to compare pre-and post-intervention measurements within each group. In cases of non-normality, the non-parametric Wilcoxon signed-rank test was applied for pre/post comparisons. The predefined significance level for those statistical tests was set at $p < 0.05$.

Chapter 4

Results

4.1 Primary Outcome: Loading Rate Changes Following Interventions

Loading rate decreased significantly only in the single leg lateral hops exercise group for the dominant leg (DL) (pre: 77.7011(BW/s) ± 24.2272, post: 61.0806(BW/s) ± 22.7453, p = 0.0039). no significant changes were observed in the non-dominant leg (NDL) or either leg for the controlled step-down group.

Table 2

Effect of SLLH And CSD Interventions on Loading Rate

Exercise	Leg	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
SLLH*	DL	7.77E+01 (2.42E+01)	6.11E+01 (2.27E+01)	0.0039	0.0092
SLLH	NDL	6.33E+01 (2.88E+01)	5.79E+01 (1.76E+01)	0.4079	0.4525
CSD	DL	5.25E+01 (1.66E+01)	4.75E+01 (1.39E+01)	0.2522	0.4656
CSD	NDL	5.10E+01 (2.42E+01)	5.18E+01 (2.70E+01)	0.9116	0.9237

* Indicates statistically significant parameter (p < 0.05).

4.2 Secondary Outcome: Neuromuscular and Kinematic Adaptation

4.2.1 EMG: muscle activation changes during pre/post assessment. A significant decrease was observed in the peroneus brevis muscle activity, as evidenced by reductions in AUC (p = 0.0422) for the dominant leg of the SLLH group (Table 3).

Table 3

Effect of SLLH Intervention on the Dominant Leg's EMG Parameters

Muscle Name	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
TA	Mean EMG	3.49E-05 (9.36E-06)	3.73E-05 (1.55E-05)	0.4877	0.3405
TA	MAX	8.01E-04 (5.76E-04)	6.39E-04 (2.86E-04)	0.2324	0.0002
TA	RMS	6.91E-05 (2.72E-05)	6.75E-05 (2.85E-05)	0.8136	0.3174
TA	AUC	3.33E-01 (8.24E-02)	2.86E-01 (1.14E-01)	0.1538	0.6042
PB	Mean EMG	4.67E-05 (2.17E-05)	4.41E-05 (1.89E-05)	0.7025	0.2459
PB	MAX	1.75E-03 (1.98E-03)	1.60E-03 (2.01E-03)	0.1309	0.7395
PB	RMS	1.27E-04 (1.22E-04)	1.17E-04 (1.09E-04)	0.2324	0.0137
PB*	AUC	4.43E-01 (1.79E-01)	3.31E-01 (1.01E-01)	0.0422	0.9539
SOL	Mean EMG	4.08E-05 (1.70E-05)	3.99E-05 (1.74E-05)	0.4316	0.0027
SOL	MAX	1.54E-03 (2.01E-03)	1.09E-03 (1.57E-03)	0.6953	<0.0001
SOL	RMS	1.06E-04 (1.04E-04)	8.65E-05 (8.93E-05)	0.6953	0.0001
SOL	AUC	4.05E-01 (1.82E-01)	3.36E-01 (1.74E-01)	0.1020	0.0629
GAS	Mean EMG	3.84E-05 (4.77E-05)	3.93E-05 (5.49E-05)	0.8082	0.9959
GAS	MAX	1.03E-03 (1.77E-03)	9.42E-04 (1.74E-03)	0.1055	0.0044
GAS	RMS	1.01E-04 (1.86E-04)	9.34E-05 (1.71E-04)	0.3740	0.9928
GAS	AUC	3.74E-01 (4.52E-01)	3.38E-01 (5.11E-01)	0.2466	0.9698
RF	Mean EMG	1.53E-05 (7.36E-06)	1.70E-05 (7.78E-06)	0.1064	0.0896

Table 3 (cont.d)

RF	MAX	4.91E-04 (2.55E-04)	4.54E-04 (2.74E-04)	0.5375	0.4456
RF	RMS	3.22E-05 (1.22E-05)	3.39E-05 (1.56E-05)	0.5099	0.3289
RF	AUC	1.54E-01 (9.67E-02)	1.41E-01 (8.26E-02)	0.3156	0.4381

* Indicates statistically significant parameter ($p < 0.05$).

In the non-dominant leg of the SLLH group, the tibialis anterior muscle showed a significant decrease in mean EMG, RMS, and AUC (all $p < 0.05$). Additionally, the peroneus brevis and rectus femoris muscles exhibited decreased activity, with significant reductions in AUC for the former and mean EMG, RMS, and AUC for the latter (all $p < 0.05$) (Table 4).

Table 4

Effect of SLLH Intervention on the Non-Dominant Leg's EMG Parameters

Muscle Name	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
TA*	Mean EMG	4.20E-05 (2.11E-05)	2.76E-05 (8.88E-06)	0.0201	0.2078
TA	MAX	1.26E-03 (1.32E-03)	8.59E-04 (7.09E-04)	0.0840	0.0016
TA*	RMS	9.90E-05 (8.46E-05)	5.98E-05 (2.84E-05)	0.0137	0.0005
TA*	AUC	3.88E-01 (1.61E-01)	2.49E-01 (8.65E-02)	0.0036	0.6732
PB	Mean EMG	3.13E-05 (1.28E-05)	2.38E-05 (8.67E-06)	0.1170	0.2099
PB	MAX	6.86E-04 (4.49E-04)	5.11E-04 (2.22E-04)	0.2754	0.0233
PB	RMS	5.76E-05 (2.11E-05)	4.52E-05 (1.39E-05)	0.0981	0.7205
PB*	AUC	2.89E-01 (1.06E-01)	2.11E-01 (7.04E-02)	0.0446	0.6253
SOL	Mean EMG	3.33E-05 (1.57E-05)	3.00E-05 (1.75E-05)	0.3664	0.9929

Table 4 (cont.d)

SOL	MAX	7.78E-04 (8.76E-04)	1.05E-03 (1.81E-03)	0.8457	<0.0001
SOL	RMS	6.13E-05 (3.79E-05)	7.07E-05 (9.19E-05)	0.3223	<0.0001
SOL	AUC	3.28E-01 (1.71E-01)	2.75E-01 (1.77E-01)	0.2501	0.8162
GAS	Mean EMG	2.92E-05 (2.56E-05)	2.45E-05 (1.61E-05)	0.2624	0.2798
GAS	MAX	1.08E-03 (1.87E-03)	8.10E-04 (1.40E-03)	0.0645	0.0013
GAS	RMS	8.58E-05 (1.47E-04)	6.61E-05 (1.03E-04)	0.1934	0.0002
GAS	AUC	2.82E-01 (2.36E-01)	2.22E-01 (1.44E-01)	0.1507	0.8032
RF*	Mean EMG	1.44E-05 (5.75E-06)	9.63E-06 (2.80E-06)	0.0058	0.5447
RF	MAX	4.39E-04 (2.78E-04)	3.95E-04 (2.21E-04)	0.3129	0.1686
RF*	RMS	3.19E-05 (1.48E-05)	2.52E-05 (9.07E-06)	0.0245	0.5376
RF*	AUC	1.42E-01 (6.98E-02)	8.68E-02 (2.59E-02)	0.0113	0.9174

* Indicates statistically significant parameter ($p < 0.05$).

A significant decrease was found in the MAX parameter of the peroneus brevis muscle (pre: 3.14E-03 ± 2.17E-03, post: 2.17E-03 ± 2.04E-03, $p = 0.0183$) for the dominant leg of the CSD group (Table 5).

Table 5

Effect of CSD Intervention on the Dominant Leg's EMG Parameters

Muscle Name	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
TA	Mean EMG	3.97E-05 (2.02E-05)	2.02E-05 (2.08E-05)	0.3934	0.4604
TA	MAX	7.79E-04 (5.09E-04)	5.09E-04 (4.09E-04)	0.3223	0.0431
TA	RMS	7.19E-05 (3.53E-05)	3.53E-05 (3.06E-05)	0.2554	0.9882

Table 5 (cont.d)

TA	AUC	3.46E-01	1.45E-01	0.1405	0.5308
		(1.45E-01)	(1.01E-01)		
PB	Mean EMG	5.20E-05	3.64E-05	0.4316	0.018
		(3.64E-05)	(5.77E-05)		
PB*	MAX	3.14E-03	2.17E-03	0.0183	0.1983
		(2.17E-03)	(2.04E-03)		
PB	RMS	1.83E-04	1.56E-04	0.1602	0.0408
		(1.56E-04)	(2.21E-04)		
PB	AUC	4.41E-01	2.13E-01	0.6655	0.4543
		(2.13E-01)	(2.92E-01)		
SOL	Mean EMG	3.33E-05	8.95E-06	0.6825	0.5321
		(8.95E-06)	(1.23E-05)		
SOL	MAX	9.85E-04	1.34E-03	0.0840	0.0001
		(1.34E-03)	(1.47E-03)		
SOL	RMS	7.27E-05	5.43E-05	0.7695	0.0001
		(5.43E-05)	(9.26E-05)		
SOL	AUC	3.16E-01	1.12E-01	0.8173	0.0561
		(1.12E-01)	(1.30E-01)		
GM	Mean EMG	3.05E-05	1.31E-05	0.1431	0.482
		(1.31E-05)	(7.57E-06)		
GM	MAX	5.29E-04	2.14E-04	0.4211	0.8738
		(2.14E-04)	(1.43E-04)		
GM	RMS	5.27E-05	2.14E-05	0.1732	0.8899
		(2.14E-05)	(1.32E-05)		
GM	AUC	2.76E-01	9.34E-02	0.0840	0.0009
		(9.34E-02)	(9.88E-02)		
RF	Mean EMG	1.45E-05	6.11E-06	0.4653	0.2739
		(6.11E-06)	(3.96E-06)		
RF	MAX	3.49E-04	1.26E-04	0.3963	0.5739
		(1.26E-04)	(1.42E-04)		
RF	RMS	2.75E-05	1.11E-05	0.5906	0.5279
		(1.11E-05)	(9.21E-06)		
RF	AUC	1.28E-01	3.32E-02	0.4694	0.6294
		(3.32E-02)	(4.38E-02)		

* Indicates statistically significant parameter ($p < 0.05$).

The tibialis anterior, peroneus brevis, and rectus femoris muscles all demonstrated a significant decrease in AUC (all $p < 0.05$) for the non-dominant leg of the CSD group (Table 6).

Table 6

Effect of CSD Intervention on the Non-Dominant Leg's EMG Parameters

Muscle Name	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
TA	Mean EMG	4.16E-05 (1.88E-05)	3.87E-05 (1.84E-05)	0.4552	0.1666
TA	MAX	1.18E-03 (1.08E-03)	8.63E-04 (7.55E-04)	0.0645	0.0001
TA	RMS	8.18E-05 (3.84E-05)	7.53E-05 (3.83E-05)	0.2494	0.2015
TA*	AUC	3.61E-01 (1.40E-01)	3.20E-01 (1.37E-01)	0.0341	0.4922
PB	Mean EMG	4.41E-05 (2.39E-05)	3.74E-05 (1.74E-05)	0.1778	0.8206
PB	MAX	1.32E-03 (1.07E-03)	9.90E-04 (1.02E-03)	0.4314	0.454
PB	RMS	1.01E-04 (7.39E-05)	7.79E-05 (4.99E-05)	0.3450	0.2503
PB*	AUC	3.67E-01 (1.25E-01)	3.09E-01 (1.43E-01)	0.0209	0.4762
SOL	Mean EMG	3.00E-05 (8.94E-06)	2.71E-05 (1.11E-05)	0.4703	0.7167
SOL	MAX	1.15E-03 (1.54E-03)	6.38E-04 (5.03E-04)	0.4922	0.0002
SOL	RMS	7.19E-05 (5.86E-05)	5.10E-05 (2.29E-05)	0.4316	0.7507
SOL	AUC	2.80E-01 (1.00E-01)	2.39E-01 (1.21E-01)	0.1121	0.0036
GM	Mean EMG	3.43E-05 (1.71E-05)	3.36E-05 (8.96E-06)	0.8910	0.5548
GM	MAX	1.32E-03 (1.76E-03)	1.08E-03 (1.17E-03)	0.4922	0.2452
GM	RMS	9.45E-05 (1.06E-04)	8.20E-05 (5.94E-05)	0.3223	0.0001

Table 6 (cont.d)

GM	AUC	3.05E-01 (1.10E-01)	2.87E-01 (8.51E-02)	0.6319	0.0001
RF	Mean EMG	1.41E-05 (6.13E-06)	1.18E-05 (4.79E-06)	0.2298	0.1962
RF	MAX	4.52E-04 (2.77E-04)	3.62E-04 (1.89E-04)	0.1952	0.7922
RF	RMS	3.32E-05 (1.70E-05)	2.67E-05 (1.04E-05)	0.1078	0.2168
RF*	AUC	1.25E-01 (4.29E-02)	9.44E-02 (3.57E-02)	0.0106	0.4744

* Indicates statistically significant parameter ($p < 0.05$).

4.2.2 Kinematics: joint angle changes during pre/post assessment. For the dominant leg of the single-leg lateral hops the Knee flexion/extension exhibited a significant increase in both MAX and ROM (all $p < 0.05$). Additionally, ankle internal/external rotation showed a significant increase in MAX ($p < 0.05$) (Table 7).

Table 7

Effect of SLLH Intervention on the Dominant Leg's Kinematic Parameters

Joint Angle	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
Hip Abd/Ad	MAX	12.69 (05.74)	10.53 (04.03)	0.2069	0.5143
Hip Abd/Ad	RMS	06.33 (02.30)	06.77 (01.66)	0.5811	0.3025
Hip Abd/Ad	ROM	18.73 (04.29)	18.40 (04.14)	0.8534	0.6898
Hip IR/ER	MAX	05.07 (04.37)	05.68 (09.23)	0.7695	0.0371
Hip IR/ER	RMS	06.87 (01.88)	07.27 (03.07)	0.7093	0.5262
Hip IR/ER	ROM	18.98 (08.40)	16.47 (07.40)	0.2500	0.4004
Hip Flex/Ext	MAX	39.77 (07.62)	41.51 (07.25)	0.2602	0.1311
Hip Flex/Ext	RMS	20.20 (06.65)	23.83 (08.01)	0.5566	0.0086
Hip Flex/Ext	ROM	30.28 (09.75)	27.74 (04.80)	0.2685	0.1641
Knee Abd/Ad	MAX	03.31 (01.64)	03.89 (01.88)	0.2598	0.2396
Knee Abd/Ad	RMS	01.36 (00.46)	01.73 (01.04)	0.2203	0.0652
Knee Abd/Ad	ROM	07.25 (02.34)	07.52 (02.60)	0.3223	0.0328
Knee IR/ER	MAX	06.61 (02.05)	08.22 (05.04)	0.4922	0.0301
Knee IR/ER	RMS	03.60 (00.92)	03.79 (01.46)	0.9219	0.0104
Knee IR/ER	ROM	16.27 (05.60)	14.67 (05.00)	0.3775	0.3775

Table 7 (cont.d)

Knee Flex/Ext*	MAX	45.39 (06.97)	48.93 (07.29)	0.0311	0.5848
Knee Flex/Ext	RMS	19.68 (06.32)	23.25 (08.01)	0.1188	0.0876
Knee Flex/Ext*	ROM	37.71 (04.20)	41.40 (04.26)	0.0262	0.9772
Ankle Abd/Ad	MAX	09.90 (01.09)	11.15 (02.05)	0.1172	0.4150
Ankle Abd/Ad	RMS	06.24 (00.91)	06.29 (01.12)	0.8674	0.5839
Ankle Abd/Ad	ROM	19.71 (06.62)	21.67 (07.27)	0.3230	0.6165
Ankle IR/ER*	MAX	07.89 (03.94)	17.11 (15.82)	0.0105	0.0028
Ankle IR/ER	RMS	06.16 (01.71)	07.50 (04.62)	0.7695	0.0011
Ankle IR/ER	ROM	19.62 (06.97)	26.69 (14.69)	0.1055	0.0012
Ankle DF/PF	MAX	16.52 (03.62)	16.39 (04.99)	0.9316	0.6007
Ankle DF/PF	RMS	09.39 (03.04)	09.96 (04.89)	0.5842	0.7932
Ankle DF/PF	ROM	21.76 (05.07)	24.31 (08.99)	0.4490	0.0986

* Indicates statistically significant parameter ($p < 0.05$).

For the non-dominant leg of the SLLH group, no significant changes in the kinematic parameter of the joint angles were observed (Table 8).

Table 8

Effect of SLLH Intervention on the Non-Dominant Leg's Kinematic Parameters

Joint Angle	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
Hip Abd/Ad	MAX	08.84 (06.70)	09.04 (05.98)	0.9088	0.0785
Hip Abd/Ad	RMS	06.49 (02.28)	05.78 (02.26)	0.2901	0.5902
Hip Abd/Ad	ROM	15.35 (02.66)	15.74 (05.03)	0.8258	0.7473
Hip IR/ER	MAX	05.65 (08.13)	05.03 (08.92)	0.8146	0.3264
Hip IR/ER	RMS	06.44 (02.72)	07.19 (03.14)	0.5091	0.4426
Hip IR/ER	ROM	15.51 (05.31)	14.01 (05.38)	0.1253	0.4019
Hip Flex/Ext	MAX	40.76 (07.64)	41.08 (07.67)	0.8457	0.0216
Hip Flex/Ext	RMS	22.76 (08.06)	20.27 (05.64)	0.1470	0.1806
Hip Flex/Ext	ROM	27.82 (05.43)	30.41 (06.74)	0.1941	0.6257
Knee Abd/Ad	MAX	03.27 (01.30)	03.71 (01.44)	0.1074	0.8240
Knee Abd/Ad	RMS	01.54 (00.38)	01.47 (00.50)	0.6842	0.9072
Knee Abd/Ad	ROM	07.26 (02.31)	06.87 (01.89)	0.3372	0.7923
Knee IR/ER	MAX	07.70 (02.33)	09.44 (04.31)	0.0645	0.0094
Knee IR/ER	RMS	03.81 (01.47)	04.57 (02.25)	0.1585	0.3788
Knee IR/ER	ROM	14.71 (06.17)	14.92 (06.55)	0.8873	0.9002
Knee Flex/Ext	MAX	47.06 (08.01)	46.28 (06.52)	0.6339	0.5271

Table 8 (cont.d)

Knee Flex/Ext	RMS	22.49 (10.91)	17.25 (03.35)	0.3710	0.0055
Knee Flex/Ext	ROM	38.98 (05.42)	41.00 (05.20)	0.1340	0.4971
Ankle Abd/Ad	MAX	10.14 (03.80)	09.63 (02.39)	0.4922	0.0313
Ankle Abd/Ad	RMS	07.65 (03.90)	05.52 (01.93)	0.3710	0.0001
Ankle Abd/Ad	ROM	19.26 (04.41)	19.24 (02.61)	0.4922	0.0178
Ankle IR/ER	MAX	10.16 (12.02)	14.11 (16.02)	0.6953	0.0284
Ankle IR/ER	RMS	08.28 (06.10)	07.85 (04.71)	0.7058	0.4697
Ankle IR/ER	ROM	23.35 (13.02)	21.80 (14.80)	0.6609	0.6363
Ankle DF/PF	MAX	15.79 (06.44)	15.67 (04.60)	0.6250	0.0224
Ankle DF/PF	RMS	09.77 (04.68)	07.51 (01.54)	0.1602	0.0035
Ankle DF/PF	ROM	23.36 (07.72)	27.21 (05.52)	0.1880	0.3646

For the dominant leg of the controlled step-downs the Hip flexion/extension demonstrated a significant increase in MAX ($p < 0.05$) (Table 9).

Table 9

Effect of CSD Intervention on the Dominant Leg's Kinematic Parameters

Joint Angle	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
Hip Abd/Ad	MAX	13.09 (05.85)	12.62 (06.29)	0.7658	0.2339
Hip Abd/Ad	RMS	06.17 (20.47)	05.92 (01.75)	0.7328	0.4476
Hip Abd/Ad	ROM	17.97 (60.26)	16.81 (05.94)	0.3951	0.8364
Hip IR/ER	MAX	01.05 (03.09)	00.86 (04.60)	0.8671	0.7163
Hip IR/ER	RMS	07.68 (02.70)	07.90 (03.46)	0.7560	0.8794
Hip IR/ER	ROM	15.57 (04.67)	15.82 (05.57)	0.8647	0.2575
Hip Flex/Ext*	MAX	35.88 (03.81)	39.49 (04.84)	0.0433	0.3673
Hip Flex/Ext	RMS	20.03 (04.10)	22.53 (04.41)	0.0853	0.3749
Hip Flex/Ext	ROM	23.65 (05.59)	25.48 (05.78)	0.3609	0.8305
knee Abd/Ad	MAX	03.55 (01.75)	03.81 (02.13)	0.5566	0.0371
knee Abd/Ad	RMS	01.55 (00.37)	01.85 (01.43)	0.9219	0.0007
knee Abd/Ad	ROM	07.53 (02.59)	06.23 (01.51)	0.0543	0.9929
knee IR/ER	MAX	05.88 (01.99)	05.89 (02.24)	0.9781	0.1748
knee IR/ER	RMS	03.32 (01.38)	03.28 (01.10)	0.8944	0.9731
knee IR/ER	ROM	14.08 (05.56)	13.14 (03.84)	0.5393	0.6838
Knee Flex/Ext	MAX	43.66 (04.78)	44.08 (04.90)	0.4316	0.0196

Table 9 (cont.d)

knee Flex/Ext	RMS	20.28 (04.21)	20.85 (04.78)	0.4605	0.1381
knee Flex/Ext	ROM	33.74 (06.18)	35.53 (06.04)	0.1369	0.1189
ankle Abd/Ad	MAX	10.62 (01.45)	10.37 (02.47)	0.6721	0.6541
ankle Abd/Ad	RMS	06.46 (01.09)	06.56 (01.55)	0.7406	0.3728
ankle Abd/Ad	ROM	21.32 (04.94)	21.23 (04.83)	0.3223	0.0167
ankle IR/ER	MAX	11.58 (06.19)	11.41 (06.48)	0.9455	0.6175
ankle IR/ER	RMS	06.55 (02.30)	06.42 (02.15)	0.7573	0.7522
ankle IR/ER	ROM	21.89 (05.31)	20.79 (04.89)	0.6194	0.4191
ankle DF/PF	MAX	14.68 (03.84)	16.43 (06.21)	0.3750	0.0052
ankle DF/PF	RMS	10.36 (02.71)	10.10 (02.59)	0.7047	0.4214
ankle DF/PF	ROM	28.02 (06.51)	32.71 (08.80)	0.1367	0.6625

* Indicates statistically significant parameter ($p < 0.05$).

For the non-dominant leg of the controlled step downs group no significant changes were observed in the kinematic parameters were observed (Table 10).

Table 10

Effect of CSD Intervention on the Non-Dominant Leg's Kinematic Parameters

Joint Angle	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
Hip Abd/Ad	MAX	09.89 (04.19)	09.57 (05.82)	0.8616	0.3097
Hip Abd/Ad	RMS	06.45 (02.04)	07.10 (03.05)	0.6377	0.3431
Hip Abd/Ad	ROM	16.56 (03.59)	16.32 (04.81)	0.8337	0.6438
Hip IR/ER	MAX	03.41 (06.97)	01.53 (04.84)	0.1806	0.4391
Hip IR/ER	RMS	07.38 (03.41)	06.83 (02.91)	0.3841	0.1998
Hip IR/ER	ROM	16.36 (05.72)	15.55 (06.13)	0.8457	0.0451
Hip Flex/Ext	MAX	37.63 (05.05)	39.66 (07.13)	0.1602	0.0426
Hip Flex/Ext	RMS	22.28 (06.54)	21.05 (05.81)	0.5831	0.6621
Hip Flex/Ext	ROM	24.36 (06.89)	27.34 (08.11)	0.2743	0.8362
knee Abd/Ad	MAX	03.55 (02.33)	03.25 (02.80)	0.5074	0.9027
knee Abd/Ad	RMS	01.59 (00.68)	01.70 (01.40)	0.7713	0.1532
knee Abd/Ad	ROM	07.78 (02.76)	06.76 (02.30)	0.2042	0.8922
knee IR/ER	MAX	06.96 (02.83)	06.04 (02.47)	0.1290	0.2572
knee IR/ER	RMS	03.68 (01.03)	03.32 (01.43)	0.3624	0.7718
knee IR/ER	ROM	15.40 (04.37)	14.77 (06.56)	0.6901	0.0725
Knee Flex/Ext	MAX	43.38 (03.29)	42.65 (05.25)	0.6856	0.9929

Table 10 (cont.d)

knee Flex/Ext	RMS	19.89 (05.52)	17.65 (03.98)	0.1627	0.7287
knee Flex/Ext	ROM	35.02 (04.43)	37.25 (06.80)	0.3561	0.2880
ankle Abd/Ad	MAX	11.23 (01.97)	09.94 (03.02)	0.2415	0.6674
ankle Abd/Ad	RMS	07.10 (01.74)	06.96 (01.45)	0.8157	0.3063
ankle Abd/Ad	ROM	21.98 (04.29)	20.68 (05.50)	0.0782	0.5316
ankle IR/ER	MAX	08.38 (06.71)	08.21 (08.06)	0.9476	0.3938
ankle IR/ER	RMS	07.92 (03.68)	07.43 (03.43)	0.6209	0.3899
ankle IR/ER	ROM	22.33 (05.73)	19.57 (09.21)	0.2830	0.0548
ankle DF/PF	MAX	13.29 (04.09)	13.71 (06.49)	0.6250	0.0027
ankle DF/PF	RMS	08.26 (03.03)	07.57 (02.21)	0.1541	0.0632
ankle DF/PF	ROM	23.94 (08.65)	27.50 (08.28)	0.3229	0.3294

4.2.3 Ground reaction forces (GRF) and center of pressure (CoP). The following sections will present the results of the GRF and CoP analysis, which provides key insights into the biomechanical responses observed during the SLLH and CSD groups.

4.2.3.1 Ground reaction force (GRF) metrics. The results obtained from the ground reaction force metrics show that Time to vertical force (TTVF) demonstrated a statistically significant increase and on the other hand impulse demonstrated a statistically significant decrease only in the dominant leg for the Single-leg lateral hops (SLLH) group (all, $p < 0.05$). No other significant changes were observed in GRF metrics (MVF, impulse, TTVF) for the non-dominant leg nor in both legs of the CSD group (Table 11).

Table 11

Effect of SLLH and CSD Interventions on Ground Reaction Force Metrics

Group	Leg	Parameters	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
SLLH	DL	MVF	2.66E+00 (2.74E-01)	2.42E+00 (3.41E-01)	0.0710	0.3141
SLLH *	DL	TTVF	3.89E-02 (1.76E-02)	4.80E-02 (2.15E-02)	0.0283	0.0010
SLLH *	DL	Impulse	4.49E+00 (7.39E-01)	3.99E+00 (5.64E-01)	0.0496	0.5312
SLLH	NDL	MVF	2.56E+00 (4.10E-01)	2.49E+00 (2.29E-01)	0.6230	0.4848

Table 11 (cont.d)

SLLH	NDL	TTVF	3.72E-01 (7.33E-01)	4.73E-02 (1.57E-02)	0.8384	<0.0001
SLLH	NDL	Impulse	4.47E+00 (6.69E-01)	4.28E+00 (4.11E-01)	0.4228	0.3533
CSD	DL	MVF	2.39E+00 (2.28E-01)	2.41E+00 (2.29E-01)	0.8457	0.0348
CSD	DL	TTVF	5.38E-02 (1.92E-02)	5.93E-02 (1.79E-02)	0.3535	0.7491
CSD	DL	Impulse	4.41E+00 (9.24E-01)	4.24E+00 (1.24E+00)	0.1934	0.0252
CSD	NDL	MVF	2.45E+00 (3.09E-01)	2.38E+00 (2.84E-01)	0.1652	0.4358
CSD	NDL	TTVF	6.22E-02 (2.82E-02)	5.88E-02 (2.71E-02)	0.6485	0.7927
CSD	NDL	Impulse	4.39E+00 (1.24E+00)	4.27E+00 (1.35E+00)	0.6503	0.4142

* Indicates statistically significant parameter ($p < 0.05$).

4.2.3.2 Center of pressure (CoP) displacement. The results obtained from the center of pressure displacement show a statistically significant decrease only in the non-dominant leg for the Single leg lateral hops (SLLH) group (pre: 0.8918± 0.2026, post: 0.7228± 0.1377, $p = 0.0321$), with no significant changes observed in the dominant leg of the SLLH group or either leg for the CSD group (Table 12).

Table 12

Effect of SLLH and CSD Interventions on CoP Displacement

Exercise	Leg	Pre-Assessment Mean (SD)	Post-Assessment Mean (SD)	P-value	Shapiro-Wilk Normality Test
SLLH	DL	8.79E-01 (2.19E-01)	8.28E-01 (2.44E-01)	0.4682	0.7564
SLLH*	NDL	8.92E-01 (2.03E-01)	7.23E-01 (1.38E-01)	0.0321	0.9039
CSD	DL	7.74E-01 (1.32E-01)	8.05E-01 (1.44E-01)	0.3920	0.9356
CSD	NDL	8.53E-01 (1.81E-01)	7.28E-01 (1.59E-01)	0.1376	0.6753

* Indicates statistically significant parameter ($p < 0.05$).

The box and whisker plots shown below will help to visualize all differences obtained for the significant parameters in each intervention and each leg.

Figure 20. Composite whisker-box plots of significant parameters for the dominant leg after the SLLH intervention.

Figure 21. Composite whisker-box plots of significant parameters for the non-dominant leg after the SLLH intervention.

Figure 22. Composite whisker-box plots of significant parameters for the dominant leg after the CSD intervention.

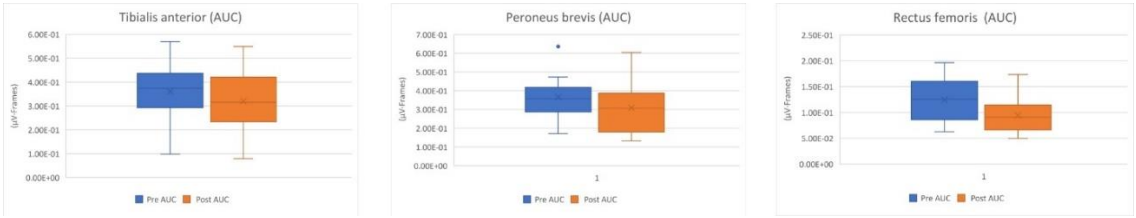

Figure 23. Composite whisker-box plots of significant parameters for the non-dominant leg after the CSD intervention.

4.3 Exercise-Specific Neuromuscular and Kinematic Patterns

4.3.1 Single leg lateral hops. Figure 24 showcases the patterns of the normalized muscle activation for the tibialis anterior, peroneus brevis, soleus, gastrocnemius medialis, and rectus femoris muscles alongside the joint angles of the hip, knee, and ankle in all 3-axis obtained during the single leg lateral hops exercise.

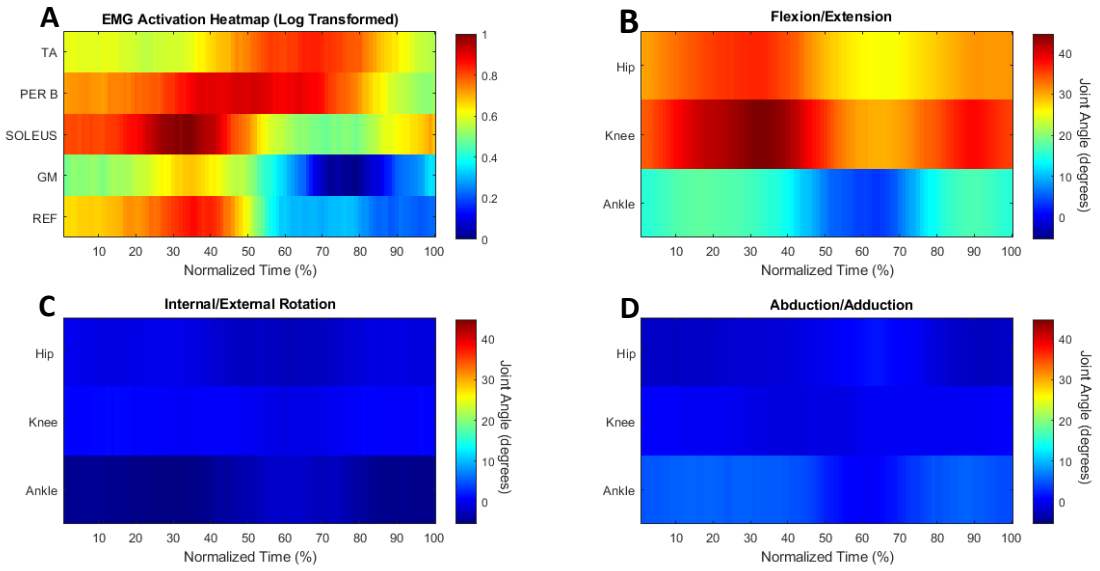

Figure 24. Muscle activation & joint angles pattern during SLLH exercise.

In Figure 24 (A) we can see that the tibialis anterior alongside the peroneus brevis muscle exhibits high levels of activation throughout the exercise in both the push-off and landing which indicates their role in the ankle stabilization in the lateral movement, the soleus muscle on the other hand shows moderate to high activity during the exercise especially in the propulsion phase since the soleus contributes to the plantar flexion of the ankle and also has a role in the shock absorption in the landing phase as opposed to gastrocnemius medialis which has a notable drop in the middle phase of the hop which indicates that the latter muscle is more involved in the initial push-off similarly to gastrocnemius, the rectus femoris has an active increase at the beginning of the exercise during the push-off phase which indicates it's involvement to generate the force needed to propel the body.

Figure 24 (B) presents the joint angle changes in the sagittal plane. the knee joint showed a substantial flexion specifically during the push-off phase to facilitate the take-off and a slight increase in flexion in the lading phase showing its critical role in shock absorption, on the other hand, the ankle joint exhibited pronounced plantar flexion peaking during the push-off phase which aligns with its role in generating the necessary force for the lateral hop. Lastly, the hip joint showed a relatively constant degree of flexion/extension except for a slight increase during the landing which is logical since the hip is involved in the absorption of impact.

Figure 24 (C) illustrates the internal/external rotation angles which is minimal particularly in the knee and hip since the movement is primarily involved in the sagittal and frontal plane.

Figure 24 (D) showcases the abduction/adduction angles with relatively small variations in all of them.

4.3.2 Controlled step-downs. Figure 25 illustrates the patterns of the normalized muscle activation for the tibialis anterior, peroneus brevis, soleus, gastrocnemius medialis, and rectus femoris muscles alongside the joint angles of the hip, knee, and ankle in all 3-axis obtained during the controlled step-down exercise.

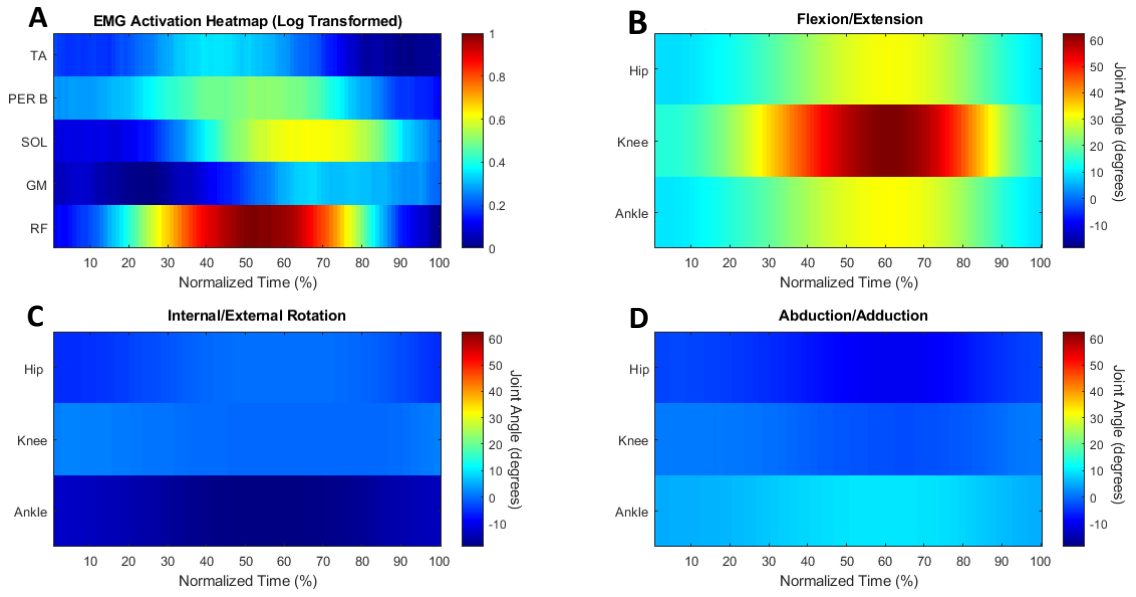

Figure 25. Muscle activation & joint angles pattern during CSD exercise.

In Figure 25 (A) the tibialis anterior and peroneus brevis demonstrate a low to moderate activation early on and then start increasing which indicates that that these muscles are engaged in leg descent. In contrast, the soleus and gastrocnemius medialis demonstrate are moderately active early on in the exercise with a significant increase in activation as the intervention progresses for the soleus muscles, this suggests that the latter muscle is crucial for stabilizing the leg as the body descends and then elevates. evidently, the rectus femoris has the highest activation in the second half of the exercise which is a reflation of its role in extending the knee to help lift the other leg.

Figure 25 (B) shows that the hip flexion/extension has relatively a moderate ROM throughout the intervention with a slight increase in flexion/extension as the leg is lifted back up. Alternatively, the knee flexion/extension is marked by an increase in the early stages of the exercise, then the knee extends back as the other leg is lifted. Ultimately the ankle flexion/extension showed moderate dorsiflexion at the beginning of the intervention then transitioned into slight plantarflexion when the leg is being lifted up

For Figure 25 (C) the hip and knee internal/external rotation joints showed minimal rotation all through the exercise which indicates that the exercise's primary motion occurs in the sagittal plane. As for the ankle joint, it maintains stability with minimal adaptations, as seen by the mild internal rotation that maintains stability when the leg is elevated

The hip joint showed a slight abduction in Figure 25 (D) during the intervention with limited changes which could be an indicator that the hip remains relatively stable in the frontal plane. Eventually, the knee and ankle joints showed very minimal adduction/adduction which concludes that the leg is primarily moving up and down without any significant lateral movement

4.4 Summary of Pre- and Post-Assessment Findings

The primary focus of this thesis was to investigate the immediate biomechanical and neuromuscular effects of single-leg lateral hops (LH) and controlled step-downs (CSD) as a potential targeted exercise for MTSS prevention.

The results obtained partially support the initial hypotheses. Specifically, the statistically significant decrease in loading rate observed in the dominant leg following the SLLH exercise ($p = 0.0039$). This aligns with the hypothesis that these interventions would induce changes that could potentially mitigate the risk of MTSS, as a reduced loading rate is commonly associated with decreased stress on the tibia. However, no significant changes in loading rate were found for the non-dominant leg in the SLLH group or both legs in the CSD group.

Both interventions promoted distinct neuromuscular and kinematic adaptations. The SLLH exercise led to decreased muscle activity in the peroneus brevis and tibialis anterior muscles. Additionally, the SLLH intervention resulted in increased knee flexion/extension range of motion (ROM) and MAX values in the dominant leg, along with an increased MAX value in ankle internal/external rotation. On the other hand, the CSD exercise intervention only induced a significant increase in hip flexion/extension MAX value in the dominant leg. As for muscle activity, the results show that the CSD intervention elicited a decrease in the activation of the peroneus brevis muscle for both legs and a decrease in the activation of the tibialis anterior and rectus femoris muscles for the non-dominant leg. Interestingly, CoP displacement decreased significantly in the non-dominant leg following the SLLH exercise intervention, suggesting potential improvements in dynamic balance.

Overall, these results suggest that both LH and CSD interventions may influence biomechanical and neuromuscular factors relevant to MTSS, even though the specific adaptations between the exercises are different. The observed decrease in loading rate following LH exercise is particularly promising, opening doors to further investigations into the potential of this specific exercise for MTSS prevention. The discussion chapter will further explore the implications and meaning of these findings and their potential clinical relevance regarding MTSS prevention.

Chapter 5

Discussion

5.1 Reduction in Loading Rate and its Significance

Our study revealed that Upon performing the single-leg lateral hop (SLLH) exercise a statistically significant decrease in loading rate in the dominant leg ($p = 0.0039$) which is crucial for preventing MTSS since previous research has shown a direct correlation between high-loading rates and the development of soft and hard tissue injuries in the lower limbs. On the other hand, the neuromuscular system's capacity to reduce impact forces is time-dependent with shock absorption within the first 50 ms of landing which mostly relies on muscle pre-activation. This means that damage to the musculoskeletal will result from an abrupt rise in loading rate as seen in landings with high vertical forces within this first interval of landing, which might overpower the neuromuscular system's mechanisms of defense. (Puddle & Maulder, 2013).

The loading rate value we obtained following SLLH (61.08 BW/s) was slightly higher than those reported in normal running patterns (60 BW/s) of healthy university students (Ruano et al., 2009). This suggests that the single leg side hop while still dynamic and challenging promotes a landing strategy that falls within a potentially safer interval zone in terms of loading rate, in other words, this decrease in loading rate has the potential of preventing or reducing the risk of excessive stress on the tibia and associated bone remodeling imbalances highlighted by (Gaeta et al., 2005)

5.2 Exploring the Mechanisms of Adaptation

The following sections will delve deeper into the potential mechanisms underlying the observed adaptations in neuromuscular control, proprioception, and biomechanics, which collectively contribute to injury prevention and performance enhancement.

5.2.1 Neuromuscular control. The reductions in muscle activity that occurred after both SLLH and CSD exercises point to possible enhancements in neuromuscular efficiency and control, which is an important aspect of preventing MTSS. The notable decrease in peroneus brevis activity in the SLLH intervention group correlates with the knowledge that imbalance and dysfunction in that muscle can trigger the development of MTSS (Galbraith & Lavallee, 2009). This mechanism of adaptation can help reduce stress on the medial part of the tibia by decreasing excessive pronation while stabilizing the subtalar joint after an impact. A reduction in excessive ankle dorsiflexion can be deducted due to the decreased tibialis anterior activity these factors would suggest that a more deliberate and controlled foot strike happened therefore reducing the resultant impact pressures applied to the tibia which was shown as a decrease in the loading rate.

Additionally, lower maximal activity in the rectus femoris and gastrocnemius medialis muscles points towards a possibility of an improved coordination mechanism and a decreased compensatory muscular activation pattern, which would, in theory, postpone the start of muscle fatigue and related changes in running mechanics (Galbraith & Lavallee, 2009). Even though the CSD group showed less notable alterations in muscle activity, there could be a possibility of better and improved neuromuscular control and efficiency as demonstrated by the reduction in activity of the rectus femoris, peroneus brevis, and tibialis anterior muscles.

The overall decrease in muscle activity points towards a high possibility of a potential shift towards a controlled and coordinated movement strategy, which can contribute to a reduced risk of MTSS, even though the relationship between muscle activation complexity and MTSS is still being investigated, as (Rathleff et al., 2011) highlighted.

5.2.2 Proprioceptive enhancement. The coupling of the observed improvement in the maximal ankle internal/external rotation angle with the decreased CoP displacement in the non-dominant leg after SLLH exercise points toward a possible improvement in proprioceptive function and dynamic balance, which is important because deficits in proprioception have been related to an increased risk of lower extremity injuries such as MTSS (Griebert et al., 2016).

The result we obtained for the increased maximal ankle internal/external rotation angle, although not definitive, could potentially improve and promote better control of foot and ankle mechanics during dynamic activities, which in itself may improve and strengthen proprioceptive feedback (Baltich et al., 2014). Improved dynamic balance and postural control are also strongly linked to proprioceptive sharpness (Galbraith & Lavallee, 2009), and this is further supported by the decreased CoP displacement we obtained in the non-dominant leg.

These adaptations can contribute to a more coordinated and improved controlled movement pattern, with the potential of reducing the likelihood of unnatural and uncomfortable landings or compensatory movements that transmit stress on the tibia, causing MTSS. Furthermore, these adaptations enhance the body's ability to sense and respond to changes in foot position and balance demands.

The lack of statistically significant alterations in ankle joints or CoP displacement in the CSD exercise group proves that the particular movement patterns associated with SLLH exercise could be more beneficial in inducing and enhancing proprioceptive adaptations. This underscores the potential specificity of the latter exercise interventions in addressing distinct aspects of neuromuscular control.

5.2.3 Biomechanical optimization. The observed increase in the maximal and ROM of knee flexion/extension in the dominant leg after the SLLH exercise is likely the result of a biomechanical adaptation to the load distribution and shock absorption during the landing phase. Research indicates that sufficient knee flexion is necessary for efficient shock attenuation and that the knee joint plays a key role in reducing impact forces while running (Aweid, Osmani, & Melton, 2019). As the knee flexes, it allows for a greater ROM, which in response weakens the peak loads and stress delivered to the tibia and distributes the pressure and impact more throughout the joint (Anderson et al., 2024). So, in conclusion, the observed enhanced knee flexion ROM in the dominant leg will help to create a more regulated and less stressful landing pattern, which will lower the risk of tibial overload and sequentially the development of MTSS.

The lack of significant kinematic changes in the CSD group may be due to the exercise's unique movement constraints not producing the same level of biomechanical optimization at the knee joint or maybe the body’s joint's response to it, which could be the reason for this group's lack of decrease in loading rate and CoP displacement.

5.3 Implications for Injury Risk Reduction

The results of this investigation show strong evidence that CSD and SLLH may be viable strategies for reducing key risk factors linked to MTSS. The significant role that excessive tibial loading plays in the development of MTSS is straightforwardly addressed by the decrease in the loading rate in the dominant leg following the SLLH intervention. The latter-mentioned intervention successfully reduced the stress on the tibia and surrounding structures by promoting a landing technique that resulted in a reduced loading rate. This could potentially prevent a series of events that lead to periostitis, bone marrow edema, and stress fractures

Additionally, the kinematic and neuromuscular changes shown in response to both exercises point towards possible avenues for treating and covering other known risk factors for MTSS. As shown by Tweed, Campbell, and Avil (2008) when they found a high correlation between the development of MTSS and excessive pronation, which is a biomechanical anomaly that can be alleviated by the combined effect of reduced peroneus brevis activity and enhanced ankle proprioception. These adaptations can decrease

aberrant loading patterns that put excessive strain on the medial tibial tissues by improving foot and ankle control and promoting a more neutral foot posture. On top of that, the increased ROM in the knee flexion/extension seen after the SLLH intervention, particularly in the dominant leg, assists in shock absorption and load distribution during landing, thereby offsetting the unfavorable impacts of early heel lift and restricted ankle dorsiflexion, which have both been linked to an increased risk of MTSS (Tweed, Campbell, & Avil, 2008; Moen et al., 2012)

The CSD intervention did not result in the same level of loading rate improvement, however, by improving lower limb stability and control, the changes in hip kinematics and muscle activation patterns that were obtained can still potentially play a role in preventing MTSS. These modifications can decrease the demand for compensatory motions and ineffective movement patterns, which causes more damage regarding tibial stress.

The results of this thesis emphasize the potential of the SLLH in particular as a preventative intervention for MTSS given that it incorporates biomechanical, neuromuscular, and proprioceptive adaptations to address and cover several risk factors. Collectively, the decreased loading rate, the ameliorated muscle activation patterns, increased proprioception, and optimal joint kinematics can render the lower limb more robust and injury-resistant. These primary results provide positive and encouraging evidence for the possibility of tailored exercise programs in decreasing the risk of MTSS, nevertheless, further studies are required to examine the long-term benefits of these interventions.

Chapter 6: General Conclusion, Limitations & Future Work

6.1 Conclusion

The immediate biomechanical and neuromuscular effects of SLLH and CSD as prospective strategies for MTSS prevention were effectively explored in this thesis. According to our investigations, these exercises induce different adaptations, with SLLH having a particularly enticing effect on the loading rate which is a crucial parameter in the development of MTSS.

The observed reduction in loading rate following SLLH, coupled with the associated neuromuscular and kinematic adaptations, suggests a multifaceted mechanism for mitigating tibial stress. The decreased muscle activity in key lower limb muscles may contribute to improved neuromuscular control and reduced fatigue, while enhanced ankle proprioception and optimized knee joint kinematics likely facilitate a more controlled and efficient landing pattern. These adaptations collectively point towards a reduced risk of bony overload and associated periosteal abnormalities, which have been implicated in the development of MTSS.

Although CSD triggered certain kinematic and neuromuscular alterations, its effect on loading rate was not as significant as that of SLLH. This implies that the latter exercise's unique movement patterns and biomechanical requirements could prove to be especially beneficial in addressing the vital component of tibial loading.

To sum up, this thesis highlights the possibility of specific exercise programs, especially single-leg lateral hops, to affect the biomechanical and neuromuscular aspects linked to the risk of MTSS. In an effort to preserve lower limb health and avoid overuse injuries, the observed results showed the intricate interactions between loading rate, muscle activation, proprioception, and joint kinematics. These preliminary results offer a solid stepping stone for creating evidence-based exercise programs targeted at preventing the risk of MTSS among individuals who are engaged in impact activities, nevertheless, additional studies are necessary to further investigate the long-term effects of these interventions and their applicability to diverse populations.

6.2 Limitations & Future Work

It's critical to recognize the study's inherent drawbacks even if it offers insightful information about the immediate biomechanical and neuromuscular changes triggered by the two targeted exercise interventions. First of all, the findings might not be as broadly applicable to a larger population due to the relatively small sample size (n=20). Furthermore, the study was limited to the immediate results from one exercise session. Although the changes that have been found are favorable, it is yet unclear how they will affect MTSS prevention in the long run.

These drawbacks, on the other hand, also open up exciting new possibilities for future study. A longitudinal study with a more varied and extensive sample size can document the long-term impacts of single-leg lateral hops on the prevalence of MTSS and related biomechanical and neuromuscular characteristics. We can obtain a more thorough grasp of these exercises' potential for prevention if we include them in participants' daily routines and do evaluations over a period of three to four months, which corresponds to the average bone remodeling cycle for the lower extremities. This longitudinal study would also enable the evaluation of other metrics, such as the time to stabilization, which would offer more information on how the treatments affect balance and postural control.

In conjunction with MRI imaging, the addition of objective measurements of bone health like the osteogenic index and P1NP blood tests will also yield important insights into how these targeted exercises affect tissue adaptability and bone remodeling. The creation of evidence-based exercise regimens that successfully address the underlying mechanisms of this common overuse injury may result from an all-encompassing approach, which would allow for a more thorough evaluation of the long-term effects of single-leg lateral hops and controlled step-downs for MTSS prevention.

The conclusion is that despite concentrating on the immediate effects of single-leg lateral hops and controlled step-downs, this study is an essential first step in comprehending their potential for MTSS prevention. Future longitudinal research would undoubtedly determine the effectiveness of these exercises in lowering the risk of MTSS and promoting optimal lower limb health in active individuals by incorporating additional

measures and a more diverse sample, as the findings set a solid foundation for future research.

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