EFFECTS OF HAMSTRING LENGTHENING SURGERY ON MUSCLE–TENDON VELOCITIES OF PATIENTS WITH CEREBRAL PALSY

by

Fatma Turan

B.S., in Physical Therapy and Rehabilitation, Marmara University, 2018

Submitted to the Institute of Biomedical Engineering
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Biomedical Engineering

Boğaziçi University
2022

ACKNOWLEDGMENTS

First of all, I would like to thank my family who has supported me throughout my life and made me feel their love.

My advisor, who introduced me to biomechanical studies, benefited from his unique knowledge, and took him as an example so I would like to thank Prof. Dr., Can Yücesoy.

In addition, I would like to thank all Biomechanics Laboratory members, especially my friend Eda Biricik, for their cooperation and support for their help and guidance in my graduate studies.

The data of this study were obtained from the Gait Analysis Laboratory of the Department of Orthopedics and Traumatology, Istanbul University, and this thesis was completed thanks to their valuable efforts. Thanks to the whole team for their help.

I would like to thank Gülcan, Şahselen, Zeynep, Şehed, Fidan and Merve, who have supported me with their friendship since the very beginning of my master's process.

I would like to thank my dear Ayşe Aydınlı for her support and guidance throughout my university life.

I would also like to thank my teacher Zeliha Gülçat, whom I have been lucky to know since my university preparation period.

I would like to thank TUBITAK for supporting me financially with the 2210-A general domestic graduate scholarship during my master's period.

ACADEMIC ETHICS AND INTEGRITY STATEMENT

I, Fatma Turan, hereby certify that I am aware of the Academic Ethics and Integrity Policy issued by the Council of Higher Education (YÖK) and I fully acknowledge all the consequences due to its violation by plagiarism or any other way.

Name : ______________________ Signature: ______________________

Date: ______________________

ABSTRACT

EFFECTS OF HAMSTRING LENGTHENING SURGERY ON MUSCLE–TENDON VELOCITIES OF PATIENTS WITH CEREBRAL PALSY

Cerebral Palsy (CP) is a permanent movement disorder seen in early childhood, consisting of muscle spasticity and/or contracture, and difficulty in walking due to poor selective control. In CP patients, crouch gait with excessive knee flexion is usually corrected by hamstring lengthening surgery, which is believed to improve gait, by increasing the length or velocity of the spastic muscle. However, hamstring muscles that may not be not short and slow before the surgery can also be operated on. The thesis aims to assess whether the gait of CP patients improved after the surgery by testing the following hypotheses: (i) knee joint movement does not improve post-surgery, (ii) the hip joint movement was impaired pre-surgery, (iii) the gait deviation index (GDI) increases post-surgery, (iv) the muscle lenghtening velocity remains unchanged in postsurgery, and (v) the pre-surgery psoas lenghtening velocity is slower than post-surgery. 8 limbs of 4 CP patients who had undergone hamstring lengthening surgery were included in the study. Pre-and post-surgery muscle lengthening velocity changes of patients were compared with reference to age-matched TD children (14 limbs of 7 participants) based on gait analysis data and using musculoskeletal modeling (OpenSim). Our results showed that post-surgery, mean knee angular velocity did not change significantly. No significant effect of surgery was shown in hip angular velocity or GDI. Moreover, no significant changes were shown in hamstring muscle lenghtening velocities. Only two of the preoperative patients had slow psoas muscle lenghtening velocity. As a result, post-surgery improvement in knee movement was achieved without a significant change in hamstring muscle lenghtening velocity.

Keywords: Muscle Shortness, Cerebral Palsy, Contracture, OpenSim, Hamstring Lengthening Surgery, Spasticity, Psoas, Lengthening Velocity.

ÖZET

HAMSTRING UZATMA CERRAHİSİNİN SEREBRAL PALSİ HASTALARINDA KAS-TENDON HIZLARINA ETKİSİ

Serebral Palsi (SP), erken çocukluk döneminde görülen, kas spastisitesi ve/veya kontraktür ve yetersiz seçici kontrol nedeniyle yürümede güçlükten oluşan kalıcı bir hareket bozukluğudur. SP hastalarında aşırı diz fleksiyonlu çömelme yürüyüşü, genellikle spastik kasın uzunluğunu veya hızını artırarak yürüyüşü iyileştirdiğine inanılan hamstring uzatma ameliyatı ile düzeltilir. Ancak ameliyat öncesi kısa ve yavaş olmayan hamstring kasları da ameliyat edilebilir. Tez, aşağıdaki hipotezleri test ederek SP'li hastaların ameliyattan sonra yürüyüşlerinin düzelip düzelmediğini değerlendirmeyi amaçlamaktadır: (i) diz eklemi hareketi ameliyat sonrası düzelmez, (ii) kalça eklemi hareketi ameliyat öncesi bozulmuştur, (iii) yürüyüş sapma indeksi (GDI) ameliyat sonrası artar, (iv) kas uzama hızı ameliyat sonrası değişmeden kalır ve (v) ameliyat öncesi psoas uzatma hızı ameliyat sonrasına göre daha yavaştır. Hamstring uzatma ameliyatı geçirmiş 4 SP'li hastanın 8 uzuvları çalışmaya dahil edildi. Hastaların ameliyat öncesi ve sonrası kas uzama hızı değişiklikleri, yürüme analizi verilerine dayalı olarak ve kas-iskelet sistemi modellemesi (OpenSim) kullanılarak, yaş uyumlu TD çocuklarına (7 katılımcının 14 uzuvları) referansla karşılaştırıldı. Sonuçlarımız, ameliyat sonrası ortalama diz açısal hızının önemli ölçüde değişmediğini gösterdi. Kalça açısal hızında veya GDI'de ameliyatın önemli bir etkisi gösterilmedi. Ayrıca, hamstring kası uzama hızlarında önemli bir değişiklik gösterilmedi. Preoperatif hastaların sadece ikisinde yavaş psoas kası uzama hızı vardı. Sonuç olarak, hamstring kas uzama hızında önemli bir değişiklik olmaksızın diz hareketinde ameliyat sonrası iyileşme sağlandı.

Anahtar Sözcükler: Kas Kısalığı, Serebral Palsi, Kontraktür, OpenSim, Hamstring Uzatma Ameliyatı, Spastisite, Psoas, Uzama Hızı.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CP	Cerebral Palsy
CNS	Central Nervous System
GGI	Gillette Gait Index
GDI	Gait Deviation Index
UMN	Upper Motor Neuron
ECM	Extracellular Matrix
MFT	Myofascial Force Transmission
MTU	Muscle-tendon Unit
EDL	Extensor Digitorum Longus
SM	Semimembranosus
Ps	Psoas
GC	Gait Cycle
EMFT	Epimuscular Myofascial Force Transmission

1. INTRODUCTION

1.1 Cerebral palsy

Cerebral palsy is a childhood-onset static brain injury known as a lifelong disability that affects 1 in 500 newborns, with an estimated prevalence of 17 million people worldwide [1]. The motor impairments that individuals with CP have are complex and symptoms vary from patient to patient. There are primary and secondary symptoms that occur in CP, the first of which is muscle spasticity, loss of selective motor control, and muscle weakness, while the second is muscle contractures and bone deformities. All CP children are not bedridden, and approximately 75% of them can walk. Among the main dysfunctions of CP, posture and movement disorders that occur during walking can be observed in general. When clinical classifications are made, patients are classified according to the extremity that is affected from the CP and the symptoms of their disorders. For example (hemiplegia, diplegia, and quadriplegia status is a classification according to motor disorders such as abnormal extremities, while motor disorders (spastic, athetotic, dystonic, hypotonic, ataxic, and mixed group) is based on the existing neurological disorders [2].

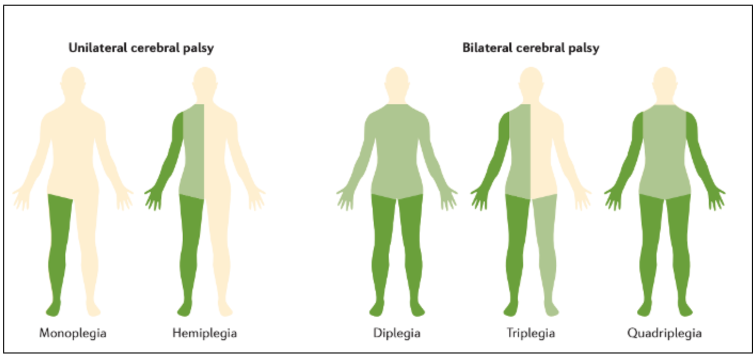

Figure 1.1 A topographical description of cerebral palsy: unilateral and bilateral cerebral palsy [1].

According to SCPE terminology, cerebral palsy is covered by the bilateral term, which is compatible with the extremity involvements of cerebral palsy. The topographic definition of cerebral palsy is divided into unilateral and bilateral cerebral palsy. While one side of the body is affected in hemiplegia, which usually affects the upper extremity more, in diplegia the lower or upper extremity is affected. In quadriplegia, all four extremities and the trunk are involved. synonyms for quadriplegia include tetraplegia or 'whole body involvement.

Early diagnosis of children with CP is important. Clinically, it is known that the majority of patients with CP have two risk factors, premature birth and difficult delivery with neonatal asphyxia (or oxygen deprivation). However, it turns out that it may be in its earlier stages today. High risk of cerebral palsy may also be caused by the following factors: placental abnormalities and fetal growth retardation, neonatal hyperbilirubinemia (excessive bilirubin levels in the blood due to breakdown of red blood cells. About 10-15% of children with cerebral palsy may have a brain malformation other than a brain lesion, thus neuroimaging is required to detect it [1].

There is a system called the Gross Motor Function Classification System (GMFCS), which has become the gold standard for classifying motor function in children with cerebral palsy [1]. Gross Motor Function Classification System (GMFCS), together with Gross Motor Function Measurement, can also determine the prognosis for future gross motor function so, it is important to see the rate of the progression of the CP [3].

1.2 Upper Motor Neuron Syndrome

A unique feature of Upper Motor Neuron Syndrome is that it affects certain muscle groups. The symptoms of UMN syndrome are divided into negative and positive symptoms. Negative symptoms include weakness, decreased motor control, and easy fatigue. Positive symptoms include increased muscle activity, while negative symptoms include decreased motor control and weakness [4].

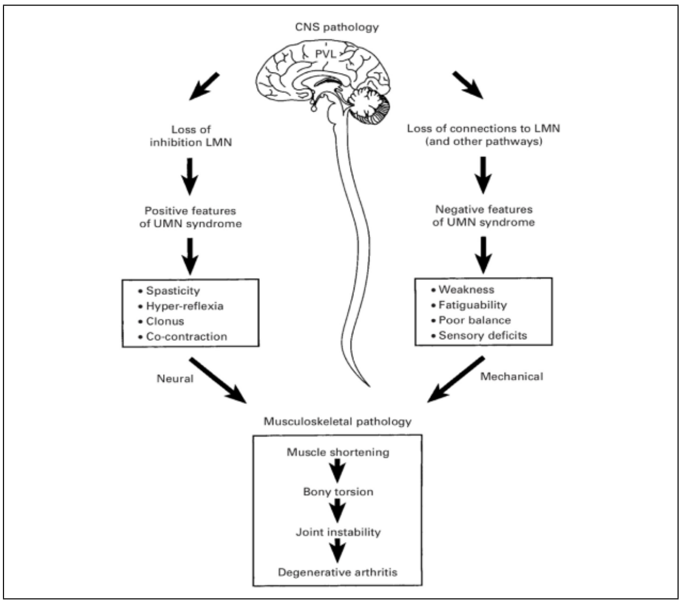

Figure 1.2 Positive and negative features of the upper motor neuron syndrome in cerebral palsy(CP) [4].

1.3 Skeletal muscle basics

The function of the muscles in our body is just like the engines in machines, thanks to them we can breathe, move and continue our daily life activities. Properly trained and coordinated skeletal muscles give people incredible records in different sports. The most basic contractile unit of skeletal muscle is the intricately repeating sarcomere. It is bounded by the sarcomere Z-band and consists of aligned contractile and structural proteins. A set of structural proteins including actin and myosin has contractile proteins titin, nebulin, desmin, and dystrophin. Composed of sarcomeres arranged in series in order, myofibrils are contractile organelles in a muscle fiber. In typically developing human muscle, sarcomeres produce force most optimally at a length of 2.6µm [5],[6]. Therefore, each 1 mm (=1,000µm) myofibril contains approximately 400 sarcomeres that are neatly aligned in series with each other. Myofibrils can be several centimeters long. A myofibril can contain thousands of sarcomeres. Myofibrils are approximately 0.5 to 1.0µm in diameter. Muscle fibers are multinucleated long and thin skeletal muscle cells. They may contain thousands of myofibrils running parallel to each other.

The muscle fibers are surrounded by the sarcolemma, known as the cell membrane, and are surrounded by the endomysium, a connective tissue which connects neighboring muscle fibers. The next larger structure is called the muscle fascicle, which consists of more than one muscle fiber. And these multiple muscle fibers are contained within a connective tissue called the perimysium. Muscle, the most major structure, consists of muscle fascicles. There are also connective tissues that connect the muscles to other muscles in the same group.

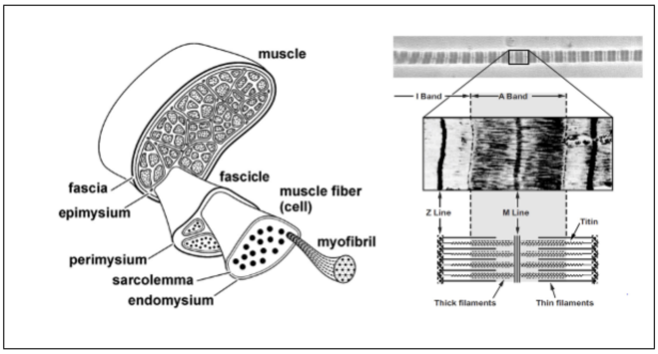

Figure 1.3 Microscopic view of muscle layers and filaments in sequence [1].

One of the important considerations in the amount of force that a sarcomere (or muscle) can exert depends on the length of the muscle, depending on the length of the sarcomere turn, the actin and myosin filaments overlap to varying degrees.

The "sliding filament" theory should be mentioned when looking at the mechanisms of contraction of a skeletal muscle. In 1954, two different scientists, Andrew Huxley and Hugh Huxley concluded that muscle shortening and lengthening are not caused by myosin shortening, but by the relative sliding of actin to myosin filaments, and the theory they found was called the sliding filament theory. Three years later, Andrew Huxley produced the first mathematical model of the sliding of these two myofilaments and it was called the cross-bridge theory [4].

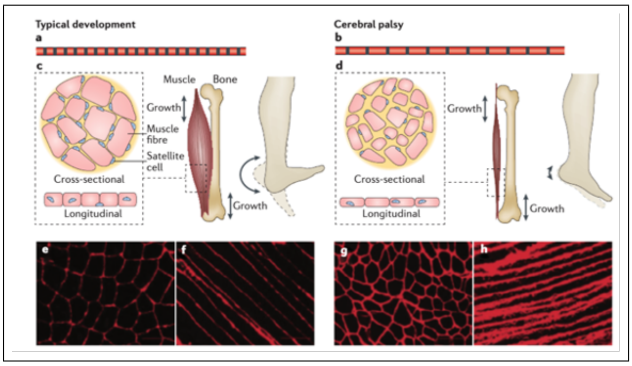

Figure 1.4 Beautifully depicts the structural changes observed in the muscles of children with cerebral palsy compared to typically developing children [4].

1.4 The structural changes between CP and TD children in terms of muscles

Although the total fascicle lengths of both muscles of both CP and TD children are almost the same, the sarcomere length of the children with cerebral palsy is longer than the sarcomere length of the typically developing children. Section c.d show the growth in the muscles of typically developing children. As the bone length increases, it adapts to the bone, and its sarcomeres are added in series as the bone grows, thus maintaining the full range of motion of the joint. It is assumed that it is forced into flexion, that is, unable to maintain the range of motion (section d, right image). A microscopic view of the muscle is shown in the left panels. In cross-sections, the muscle fibers of children with cerebral palsy are smaller than those of typically developing children. Additionally, in longitudinal sections, fibers from children with cerebral palsy typically have fewer satellite cells than normally developing children. e-h sections show immunohistochemical staining of human muscle for laminin, one of the components of the extracellular matrix (ECM). Section e and section g are cross sections whereas section f and section h are longitudinal sections. Attention should be paid to the increased amount of ECM in the muscles of children with cerebral palsy. (section g and section h) [1].

1.5 Mechanism of spasticity

Spasticity is the increase in the resistance of a muscle to a passive stretch with velocity. Slow passive movements of the extremities do not elicit increased resistance. Rapid stretches of the muscles cause an immediate increase in tone followed by a decrease in muscle resistance with continued stretching. This phenomenon is called clasp-knife rigidity stiffness. The antigravity muscles of the arms and legs are most affected, such as the arm flexors and extensors of the leg [7].

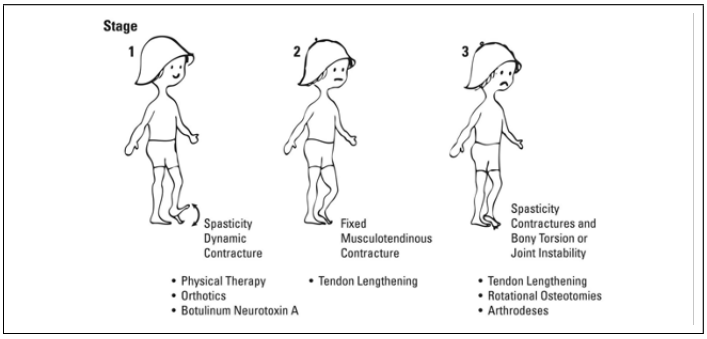

Figure 1.5 It shows that there are some different stages in CP [4].

According to the “Traditional View”, skeletal muscle in CP is only one end organ in CP and its abnormal activation leads to fixed contracture as a result of prolonged stay in the same position. However, recent advances in our understanding of CP muscle reveal the inadequacy of this view. Intrinsic changes in CP muscle path morphology, including decreased satellite cell number and function, abnormalities in sarcomerogenesis, increased connective tissue and fat, ribosomal dysfunction, and highly elastic myofibrils, are more than just one end organ suggesting a more localized role in its development. According to Rang’s Traditional View, it has been widely accepted that spastic muscles exert abnormal forces on growing bone and cause bone deformities [4].

1.6 Muscle lengthening surgery

Since the muscles of patients with CP may have contracture, they are considered short compared to normal muscles and this condition is considered to reduce the range of motion. It can be said that the decrease in the range of motion of a muscle can cause static contracture or dynamic contracture by spasticity. While the length change of the muscle may be a result of shortness, the lengthening velocity of the muscle is an indicator of spasticity, which is resistance due to velocity [8]. There are various treatment methods to reduce contracture, one of them is muscle lengthening surgery. Muscle lengthening surgeries, also known as remedial surgery [9], muscle relaxation [10], and aponeurotomy [11], are frequently used to reduce contracture. Crouch gait is one of the most common gait disorders that patients with CP suffer from. Also, Crouch gait or, excessive knee flexion during the gait is often known as the shortness of hamstrings, and hamstring lengthening surgery intends to reduce the effect of shortness by increasing the muscle-tendon unit (MTU) length [5].

1.7 Gait cycle

Gait is the most important activity of human beings, even though the number of steps has decreased today. The analysis of gait is important for detecting and treating existing pathologies. Thanks to the gait analysis technologies available today, the invisible data such as; moment, power, ground reaction force, muscle force, etc have become measurable. The gait cycle is the sequence of phases from the moment one-foot touch to the ground and ends with the same foot touching the ground again. In these phases, the foot does not have to be on the ground completely and the best example of this is idiopathic toe walking, which can be observed in CP. According to the old terminology, the walking phases were classified as heel strike-heel off, while the new gait terms were used as initial contact-terminal stances [12].

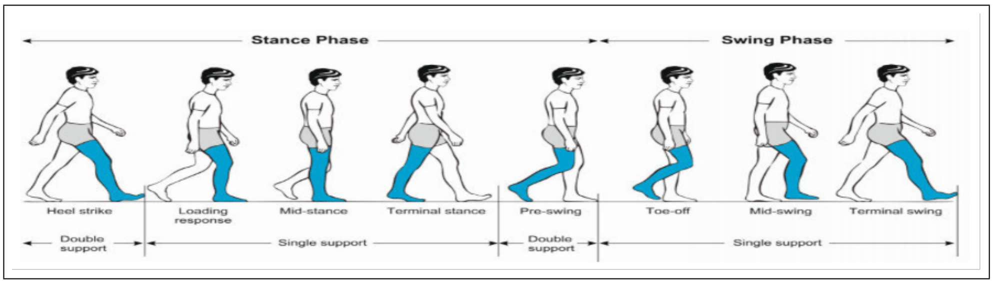

Figure 1.6 It shows the gait phases of the gait cycle [12].

1.8 Epimuscular myofascial force transmission(EMFT)

Although the classical definition of the muscle-tendon complex is the opinion that the muscle generates force and the tendon transmits the force, recent studies have shown that force transmission is not limited to the tendon, but is also transmitted by the connective tissue known as the intramuscular fasciae (endo-, peri- and epimysium) [13],[14],[15]. Even though the tendon is accepted as the most important structure in terms of force transmission, it is not the only structure: these connective tissues that affect the sarcomere length are also important mechanisms. Therefore, muscular force transmission is an inadequate term while myofascial force transmission is a more comprehensive term. Yucesoy et al. tested in an animal experiment the three muscles extensor digitorum longus (EDL), tibialis anterior (TA), and the extensor hallucis longus (EHL) although they do not share a common tendon, and it is reported that transmission is transmitted through connective tissues [16]. When we look at the structures in a muscle, it is seen that each of them is connected to each other with connective tissues [14]. Endomysium, perimysium, and epimysium wrap around muscles from the smallest unit of muscle to the largest muscle, respectively, but the epimysium also connects the muscle with other structures. Along with these, structures such as neurovascular pathways, muscles in the same compartment, and antagonistic muscles in other compartments are also interconnected. Synergistic and antagonistic muscles are mechanically integrated because of several different structural continuities as explained above.

A study by Yucesoy et al. show that differential changes in length between limb muscles, for example between mono- and bi-articular muscles, or between agonist and antagonistic, differences in moment arms, and these relative position changes cause the muscle's epimuscular myofascial connections to stretch, which explains the epimuscular myofascial force transmission [17]. In Yucesoy et al. study , for example, inter-antagonistic mechanical interactions may affect the entire lower leg of the rat [14]. It is thought that the peak strength of spastic muscles is observed in shorter muscle lengths compared to normal muscles and they cannot produce active force in longer muscle lengths. The increase in knee flexion seen in the gait phases of patients with CP is not known yet. However, for limited knee extension: simultaneous activation of the knee flexor [18] and extensor muscles [19] with the increase of spastic semitendinosus forces makes it easier to understand the changes in the surrounding tissues. A study by Ateş et al.shows that it has been shown that muscle lengthening surgery also affects other muscles that are not intervened due to their mutual mechanical interactions [20].

1.9 Musculoskeletal Modeling: OpenSim

OpenSim is an open-source software program for modeling and simulating the musculoskeletal system. It should be in track row column (TRC) file format [21] [22]. These file format conversions are done thanks to Mokka [23]. There are generic models in OpenSim that represent the human musculoskeletal system. One of them is the OpenSim Gait_2392 model. The Gait_2392 model includes 92 muscle-tendon actuating units so that 76 different muscles in the lower extremities and torso are represented with 23 degrees of freedom.

This model, which is assumed not to scale with any patient, represents an individual 180 centimeters tall and 75160 grams in weight [24]. OpenSim allows multiple model access, in which the spasticity model includes models that show changes in the geometry of the musculoskeletal systems after physiotherapy or surgical operation. OpenSim scaling tool means changing the size and dimensions of the generic model following the patient. This scaling process helps to compare the markers placed on the patient and the markers seen on the model. This calculation was implemented using the setup file, which contains the weights given and gives an output file, as it is important that the reference for the static experimental data in TRC format, the length and weight of the patients in markers with the same name in the experimental data.

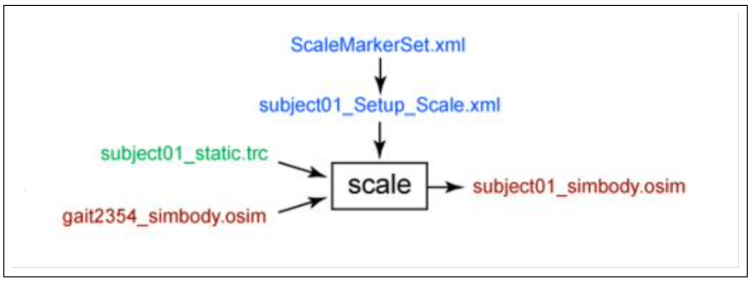

Figure 1.7 Input and output factors of the scaling tool [25].

After the personal model was obtained by scaling, inverse kinematics tool muscle-tendon complex length, knee and hip angles were calculated in each period of the experimental data, and the positions of the model were determined. Then, setup files should be created for the inverse kinematics process. These setup files must contain the same tokens (with the same token names and weights for recalculation) for consistency. was used to calculate muscle-tendon complex length, and knee and hip angle correspondingly as it steps through each time frame of experimental data and arranges the positions of the model again in a pose that 'best matches' the experimental marker and coordinates data for that time step.

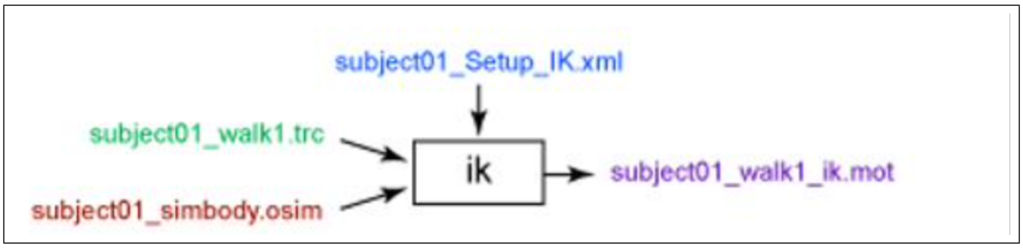

Figure 1.8 It represents input and output factors for inverse kinematics [26].

1.10 Importance of classification

"Single event multilevel surgeries" means more than one surgery combined in a single procedure and is one of the most commonly performed surgeries in CP patients. It is an operation that usually involves hip and calf [6] muscles, and the osteotomy is also performed when needed. Although hamstring muscles cover more than one joint and its pathology is similar to other pathologies, the underlying causes such as crouch gait may be different [5]. In these studies, we can see how important the classification is to understand the effects of muscle lengthening surgery.

1.11 Gait improvement parameters

In this thesis, the MTU lengthening velocity was calculated using the semimembranosus muscle to represent the hamstring muscles, and it was also calculated for the psoas muscle. Muscle angular velocities were calculated in the sagittal plane. The angular velocity changes in the sagittal plane of the knee and hip joints due to surgery were investigated one by one and a gait score was used to stand for the change in the total gait.

1.11.1 Knee angular velocity in the sagittal plane

In this study, the change in knee joint angular velocity reflects the severity of the gait pathology at initial contact during walking.

1.11.2 Hip angular velocity in the sagittal plane

According to a study, although muscle-tendon lengthening changed the muscle-tendon angles in the sagittal plane during gait, the joint angular velocities in the hip and knee did not change in the sagittal plane. Although such a result is obtained, it is important that the angular velocity of the hip can also be an example of how spasticity changes the angular velocity just like the knee [27]. Joint angular velocity in spastic gait and the influence of muscle-tendon lengthening tended to exhibit worsened anterior pelvic tilt ($p < 0.05$) because of crossing two joints [28].

1.11.2.1 The psoas muscle. It starts from the biarticular muscle Psoas the vertebraes (T12-L4) and ends at the lesser trochanter of the femur. Its main function is hip flexion, but it also determines the position of the pelvis on the trunk. In a study, patients whose gait improved after hamstring lengthening surgery and it stated that they had shorter preoperative psoas muscles but not shorter hamstrings [5]. The article claims that increased anterior pelvic tilt is the main problem causing crouch gait, due to the larger moment arm of the hamstrings at the hip joint compared to the knee joint [29]. Examination of muscle-tendon lengths and velocities, and both the knee and hip joint was performed to understand satisfactory or unsatisfactory post-surgical changes in knee extension or anterior pelvic tilt [24].

1.11.3 Gait scores and pathology in general context

Thanks to Gillette Gait Index (GGI), the deviation in gait can be shown with a single number, thus making an objective assessment. The following values are the gait characteristics represented: Time to foot off as a percent of the total gait cycle time, walking speed normalized by leg length, cadence, mean pelvic tilt, pelvic range of motion in the sagittal plane, mean pelvic rotation, minimum hip flexion, total range of hip flexion-extension, peak abduction in swing, mean hip rotation in stance, knee flexion at initial contact, time to peak knee flexion, total range of knee flexion-extension, peak dorsiflexion in stance, peak dorsiflexion in swing and mean foot progression angle in stance [30]. In children with CP, their gait is most affected due to motor impairments. Some of these children walk with abnormally excessive knee flexion during the terminal swing and stance phases of the gait cycle [5]. Some studies have shown that not all CP patients with a crouch gait have shorter hamstrings, in fact, they usually have the normal length or longer hamstrings compared to typically developing children [8]. Another study showed that hamstring lengthening surgery improved the patient's gait by different mechanisms. According to a classification study, patients with short hamstrings had increased postoperative MTU length, while patients with low hamstring lengthening velocity had increased postoperative velocity. However, in this study, patients who did not have short or slow hamstrings also had surgery and they benefited from it [5]. These findings indicate that it is not fully understood whether muscle lengthening surgery lengthens the short muscle or accelerates the slow muscle, and it is thought that studies on the subject should continue and different mechanisms may be effective. The reason for increased knee flexion in the knee may be clarified when some understanding of exactly how hamstring lengthening surgery provides recovery. Although the main goal in muscle lengthening surgery is to lengthen the MTU, a partial fasciotomy (ie preparatory dissection) is performed to expose the target muscle [31]. An in situ animal study of muscle lengthening surgery has shown that surgery has significant effects on target and non-targeted muscles attributable to EMFT [Muscle lengthening surgery causes differential acute mechanical effects in both targeted and non-targeted synergistic muscles].

1.12 Aim of the Thesis

The thesis aims to assess whether the gait of CP patients improved after the surgery by testing the following hypotheses: (i) knee joint movement does not improve post-surgery, (ii) the hip joint movement was impaired pre-surgery, (iii) the gait deviation index (GDI) increases post-surgery, (iv) the muscle lenghtening velocity remains unchanged in postsurgery, and (v) the pre-surgery psoas lenghtening velocity is slower than post-surgery.

2. METHODS

2.1 Subjects

A retrospective study was conducted to evaluate muscle–tendon velocity and angular velocities of the preoperative and postoperative gait analysis data of patients with those of CP patients who underwent hamstring lengthening surgery. One of the patients was excluded because he could not complete a gait cycle in the gait analysis data obtained from him. The remaining 4 patients had 8 limbs and the data of 8 limbs of CP patients (mean age:13.75, sd:1.707) was used in the study and obtained from Istanbul University, Gait Analysis Laboratory Database. All participants with CP, have Gross Motor Functional Classification System (GMFCS) scores of 1 or 2. In addition, gait analysis data for 14 limbs of 7 age-matched TD children were obtained as reference. Among the exclusion criteria of the patients, the condition of not undergoing operations that change the skeletal geometry such as osteotomy was considered because the musculoskeletal geometry of OpenSim's generic model was prepared according to healthy individuals.

2.2 Gait Analysis

BTX (ELITE 2002, BTX Bioengineering, Milan, Italy), a motion analysis system in Istanbul University Gait Analysis Laboratory contains six infrared cameras and two force plates (Kistler Instrumente AG, Winterthur, Switzerland). Helen Hayes Marker Placement Protocol [REF]. Bilateral markers were located on the crista intertrochanterica and anterior superior iliac spine (ASIS), femur lateral epicondyle, metatarsal head, heel, lateral malleolus, tibial tuberositas. Three gait analysis trials of each patient generally were obtained pre-operatively and post-operatively. The results of the gait analysis were used to determine the angular velocity of the hip and knee with the joint angle data obtained during the walking of the patients [18].

2.3 Musculoskeletal Modeling

2.3.1 OpenSim

Maintained on simtk.org, OpenSim which was used in our study is an open-source platform for simulating, modeling, and analyzing the neuromusculoskeletal system. The graphical user interface is written in Java and the software is ANSI C++. Developed by experts working on musculoskeletal structures, Simtk.org serves as a public repertory for data, models, and computational tools related to physics-based simulation of biological structures, which can be easily accessed through Simtk.org.

2.3.1.1 Data Preparation. OpenSim requires input in TRC format to simulate and model musculoskeletal structures in motion. Data obtained through gait analysis are in c3d format and contain a few gait cycles. Mokka converts c3d files into files with trc extension and provides compatable data for Opensim initiated by the participants' contact with the force plate and if the markers are entirely detected by the cameras. For the five patients one by one, personalized musculoskeletal models were developed by modifying the OpenSim Gait_2392 model. The Gait_2392 model contains 92 muscle-tendon actuating units so that 76 different muscles in the lower extremities and torso are represented with 23 degrees of freedom. Instead of the typical weight and height values accepted in the healthy human model that OpenSim uses for models, it was scaled according to the physical characteristics of each of the patients. OpenSim Gait_2392 was required to be modified and this goal was reached with the scaling operation. After the scaling, the inverse kinematics tool was used to calculate muscle-tendon complex length. Setup files should be created for inverse kinematics operation with a similar method of scaling setup files. These setup files need to include the same markers (with the same marker names and weights for calculation) for consistency. When the inverse kinematics operation is applied and executed, the ik. motion file is obtained. After the appropriate steps, it has been converted to be usable in Excel.

2.3.1.2 MTU Length and Velocity Calculations. Muscle–tendon length was calculated as the distance along the modeled path of the hamstring muscles and psoas muscle between the muscle's origin and insertion in Opensim. After applying the inverse kinematic tool to the personalized scaled generic model, the start and end of the gait cycles of the data with the .sto extension taken from Opensim are marked in Excel. Muscle–tendon velocity was calculated by computing the numerical derivative of the muscle-tendon length data depending on time and using a zero-phase digital filter with a cutoff frequency of 8 Hz (2nd-order Butterworth filter, MATLAB, The Math- Works, Natick, MA).

2.4 Gait Improvement Parameters

Several gait improvement parameters were chosen to be used instead of a single one since the hamstrings (knee flexors) are biarticular muscles that affect both knee and hip angle and the psoas muscle affects hip angle during gait. Due to the nature of the hamstrings, gait improvement should be focused on knee angle and hip angle whereas it should be evaluated according to total gait as well for completeness. By understanding such relationship: (1) we can develop a better understanding of the nature of the gait impairment in CP patients. (2) Muscle lengthening surgeries can be improved and planned to be more target specific.

2.4.1 Knee Angular velocity in sagittal plane

Knee angular velocity is the rate of change of knee joint angular displacement (in degrees) occurring during the gait cycle. The knee angle in the sagittal plane obtained from the text files of the patients taken was transformed into 101 data points in order. Time derivatives of this data were calculated in Matlab.

2.4.2 Hip Angular velocity in sagittal plane

As with the knee angular velocity, The Hip Angle in the sagittal plane was obtained from the text files of the patients. The obtained joint angles were polarized sequentially, and then the velocity value was obtained by taking the first derivative in Matlab. The filter was used due to the distortions in the velocity graph.

2.4.3 Gait Scores

Gillette Gait Index, (GGI) was developed as a method to calculate the deviation of a subject's gait from the mean normal values and to display this deviation as a single number. GGI is the representation of the general gait model with numerical values. They are kinematic data consisting of the pelvis, hip, knee, ankle, and foot progression angles in sagittal, frontal, and transversal planes, respectively. High or low GGI values are related to lower extremity movement quality during walking. The kinetic kinematic data of patients with CP were calculated in Excel by the GDI formula, and the gait score was obtained as a result.

2.5 The Statistical Analyses

A correlation analysis was performed to assess the relationship between muscle lengthening velocity and other gait improvement parameters obtained from the gait analysis data. It was also aimed at characterising whether there is a significant difference between knee and hip angular velocity and muscle lengthening velocity in the initial contact phase of walking between postoperative and preoperative.

2.5.1 Subject Validation

When classifying the patients, the hamstrings were defined as 'short' if muscle-tendon complex length values for the semimembranosus and psoas muscles were less than two standard deviations than corresponding TD mean data during walking. Similarly, muscle lengthening velocity values which are two standard deviations smaller than corresponding TD mean data were defined as slower.

2.5.2 Preoperative and postoperative comparison of CP patients

Preoperative and postoperative data, which were selected from 8 limbs as reference data were first tested for normal distribution using the Shapiro-Wilk normality test. The Pearson product-moment correlation or Spearman's rank correlation was calculated based on the normality of the data sets.

2.5.3 Correlation Analyses

The correlation analyses were performed to examine if the changes in the MTU lengthening velocity of the mentioned muscles had significant relation with the knee and the hip angular velocities in the sagittal plane at the initial contact phase of the gait cycle and/or the gait scores. The normality of the data sets was tested by the Shapiro-Wilk normality test. The Pearson product-moment correlation or Spearman's rank correlation was calculated based on the normality of the datasets.

3. RESULTS

3.1 Subject Validation

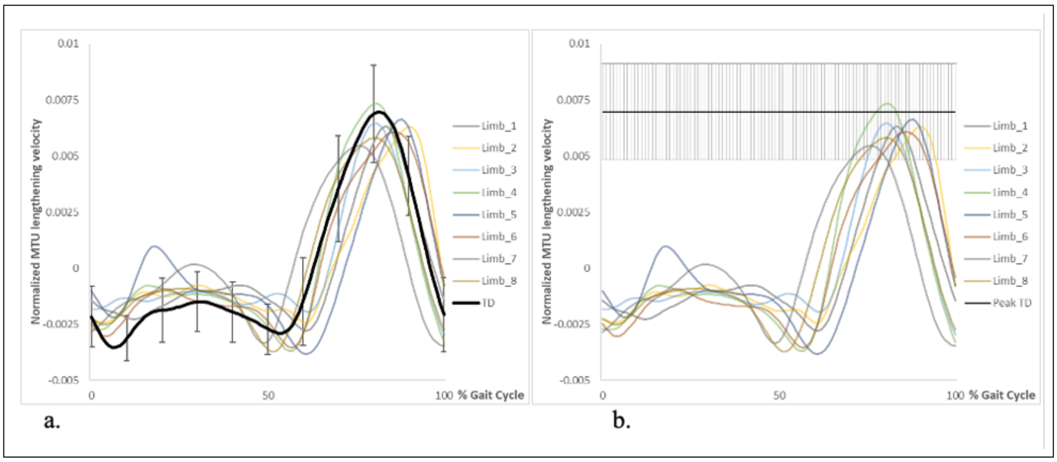

Figure 3.1 Pre-operative normalized semimembranosus MTU lengthening velocity of participants for a gait cycle a. compared to mean lengthening velocity of TD with 2 SD b. compared to peak of the mean MTU lengthening velocity of TD participants.

Figure 3.1.a and b. show that pre-operative semimembranosus MTU velocity of all patients were not below more than 2 SD of the peak mean velocity of the TD participants in at least one time point of a gait cycle. Therefore, semimembranosus muscles of the patients were determined as “not slow”.

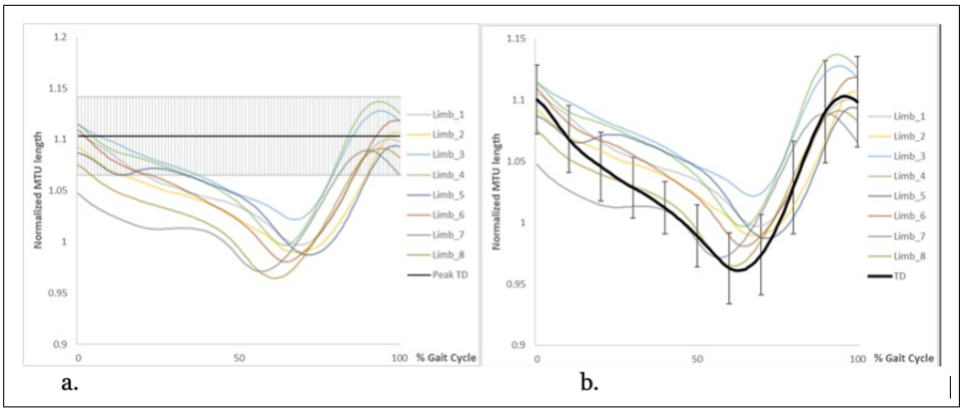

Figure 3.2 Pre-operative normalized semimembranosus MTU length of participants for a gait cycle a. compared to mean length of TD with 2 SD. b. compared to peak of the mean MTU length of TD participants.

Figure 3.2 a. and b. show for one gait cycle that, the patients' preoperative mean semimembranosus MTU lengths were not less than the mean minus 2 SD of peak semimembranosus MTU lengths of TD. Therefore, the semimembranosus muscles of all patients were classified as "not short".

3.2 Gait Improvement Parameters

3.2.1 Knee Angular velocity in sagittal plane

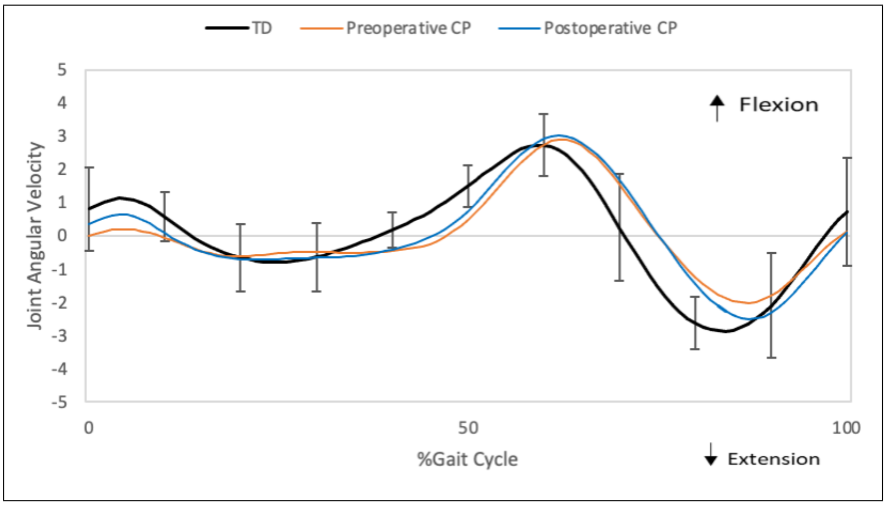

Figure 3.3 This figure shows the preoperative and postoperative mean knee angular velocities of patients with CP compared to TD for a gait cycle.

The mean knee angular velocity preoperative and postoperative data do not show normal distribution. Wilcoxon signed rank test showed that there is not significant difference. As can be seen, the preoperative knee angular velocities do not exceed the mean angular velocity of the TD by more than 2 SD except for some part of gait cycle. We find that the mean knee angular velocity after surgery does not change much more than 2 SD of the mean knee angular velocity of the TD. This confirms the first hypothesis that there is no significant change in knee angular velocity in patients with CP whose hamstrings are not "short" and " slow", especially in the first contact phase of gait, although their knee movements are improved.

3.2.2 Hip Angular velocity in sagittal plane

Figure 3.2.2 shows that neither preoperative nor postoperative mean hip angle-GC curves exceed those for TD ± 2 SD. Pre- and post-operative hip angular velocities data per GC do not show a normal distribution. Wilcoxon signed-rank test showed no significant difference in gait analysis data between preoperative and postoperative. As can be seen from the graph, the mean value of hip angular velocities of CP patienst in sagittal plane at initial contact is lower than postoperative mean and TD, which confirms the second hypothesis.

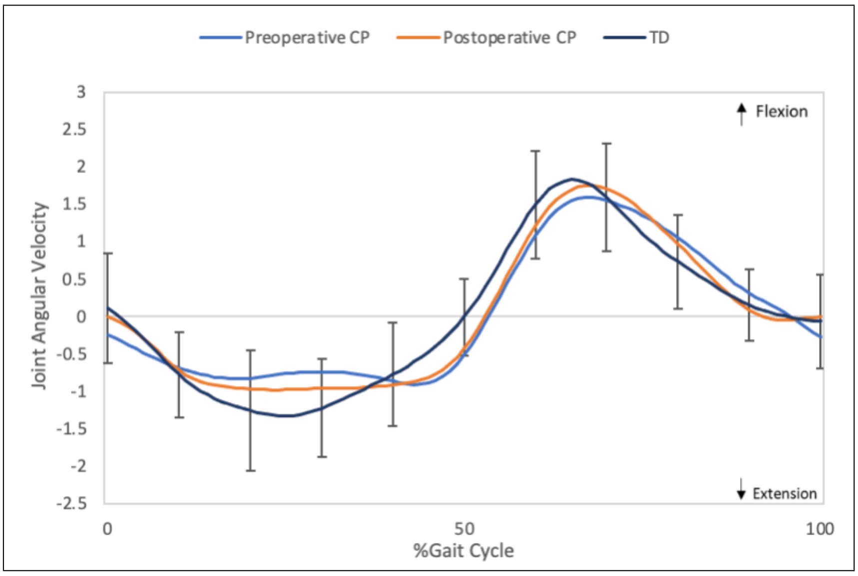

Figure 3.4 3.2.2 Figure 3.2.2 Preoperative and postoperative mean hip angular velocities of patients for a gait cycle compared with TD. The mean hip angular velocities after surgery do not deviate much at the initial contact i.e., they fall within the 2 SD range.

3.2.3 Gait Score

Table 3.1 shows the GDI's of each CP patients calculated. The pre- and the post-operative GDI data conforms with the normal distribution. However, Paired t-Test showed no significant difference between preoperative and postoperative GDI values. This result rejects the third hypothesis.

Table 3.1
GDI values calculated per each limb studied, pre- vs. post-operatively

Subjects	Pre-operative	Post-operative
Limb_1	76.1	71.3
Limb_2	61.8	75.9
Limb_3	72.5	93.4
Limb_4	78.1	89.4
Limb_5	77.5	75.1
Limb_6	82.4	75.4
Limb_7	84.8	86.0
Limb_8	77.6	90.0

3.3 MTU Lengthtening Velocity Change of Hamstrings

The pre- and the post-operative SM MTU lengthtening velocity curves do not show a normal distribution. Wilcoxon signed-rank test showed no significant difference in gait analysis data between preoperative and postoperative. Compared to TD, pre- and post-operative SM MTU lengthtening velocities are more than the range of 2 SD from the mean MTU lengthtening velocities of TD, especially in the initial contact that children suffer from crouch gait. This result confirms the fourth hypothesis.

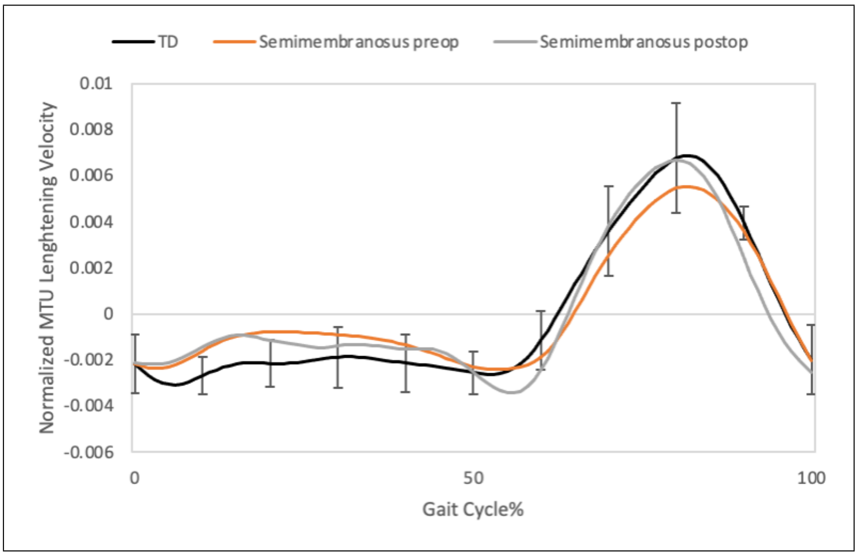

Figure 3.5 The pre-operative and post-operative means of the semimembranosus muscle which was selected to represent the hamstring group muscles, normalized MTU lengthening velocities were compared with the TD mean for a gait cycle.

3.4 Psoas

3.4.1 Pre-operative MTU lengthtening velocity

Figure 3.4.1 a. and b. show that preoperative psoas MTU lenghtening velocity of CP patients were mostly within the normal range of 2 SD. Although the psoas muscle appears to be inactive between 0% and 30% of the gait cycle, it must lengthen to allow the gluteus muscles to contract concentrically in this interval.

However, limb_6 and limb_3 MTU lenghtening velocity were less than 2 SD from the peak MTU lenghtening velocity of TD and were classified as “slow”, while limb_1, limb_2, limb_4, limb_5, limb_7 and the psoas lenghtening velocity of extremity_8 were classified as “not slow”. These results partially reject the fifth hypothesis.

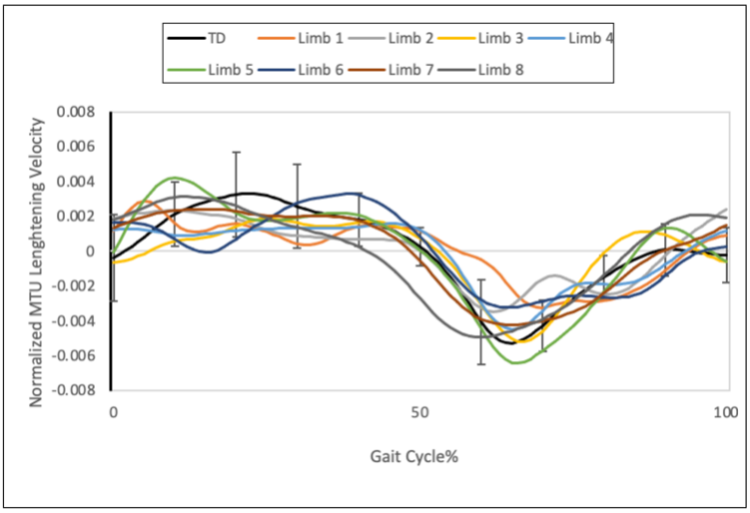

Figure 3.6 Pre-operative normalized psoas MTU lengthtening velocity of CP patients for a gait cycle compared to mean lengthtening velocity of TD with 2 SD.

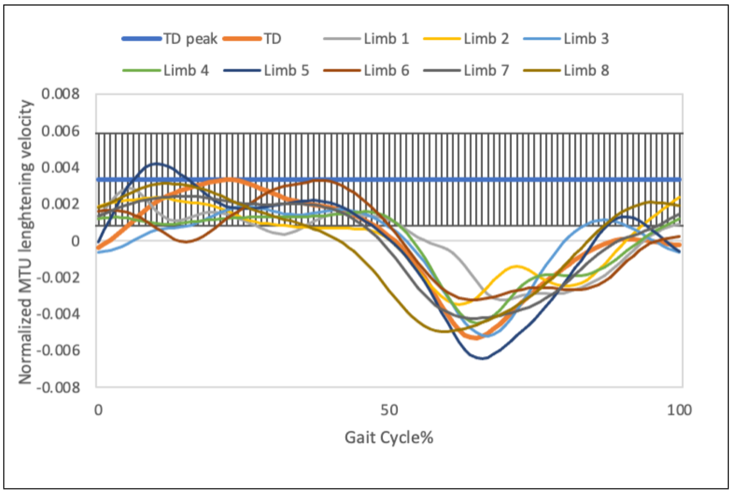

Figure 3.7 The preoperative normalized psoas MTU lenghtening velocity of CP patients for one gait cycle compared to the peak of the mean MTU lenghtening velocity of TD participants.

3.4.2 MTU lengthtening velocity change

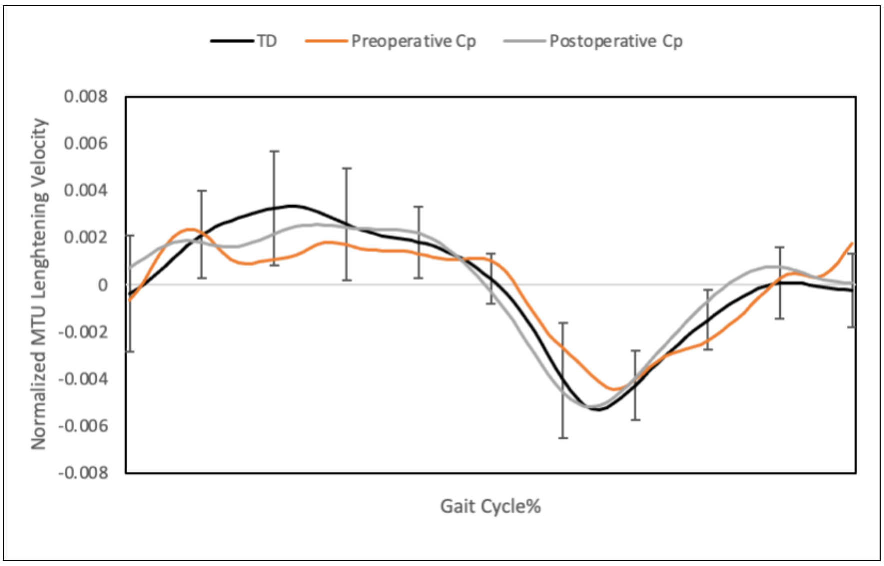

Figure 3.8 shows the mean MTU lengthening velocities of the psoas of CP patients before and after surgery compared to TD for a gait cycle.

The data do not show a normal distribution. Wilcoxon signed-rank test showed no significant difference in gait analysis data between Psoas preoperative and postoperative lengthening velocities. In conclusion, although the surgical intervention targets the hamstring muscles and does not involve the psoas, MTU lengthening velocity of the psoas was also looked at. The inclusion of the psoas is because the hamstring also crosses the hip joint. However, no significant change was observed on the MTU lengthening velocity of the psoas.

3.5 Correlation Analyses

Table 3.2
Person product-moment correlations

	Knee Angular V	Hip Angular V	GDI	SM MTU LV	Ps MTU LV
Knee Angular V	1	.672	.415	-.438	.479
Hip Angular V	.672	1	.519	-.588	.272
GDI	.415	.519	1	.131	.323
SM MTU LV	-.438	-.588	.131	1	.794*
Ps MTU LV	.298	.272	.323	.794*	1

(* Correlations with $p<0.05$, L: Lenghtening, LV: Lenghtening Velocity.)

Table 3.3
Normalized MTU lengthening velocity changes at initial contact (0% gait cycle) per subject

Subjects	Semimembranosus	Psoas
Limb_1	-0.0010	0.0007
Limb_2	0.0010	-0.0008
Limb_3	-0.0028	0.0051
Limb_4	0.0003	-0.0009
Limb_5	-0.0018	1.3605
Limb_6	0.0005	-0.0016
Limb_7	0.0028	-0.0012
Limb_8	0.0014	-0.0037

Each column represents the difference between the pre- and post-operative normalized MTU lengthening velocity changes data.

Table 3.4
Gait improvement parameters per subject

Subjects	Knee angular velocity	Hip angular velocity	Gait Score
Limb_1	1.327°	0.523°	-4.8
Limb_2	-0.391°	0.091°	14.1
Limb_3	0.616°	0.232°	20.9
Limb_4	-0.584°	-0.305°	11.2
Limb_5	0.904°	1.102°	-2.3
Limb_6	0.135°	0.321°	-7.0
Limb_7	0.447°	-0.028°	1.3
Limb_8	0.477°	-0.051°	12.4

Each column represents the difference between the pre- operative and post-operative angular velocity data.

4. Discussion & Conclusion

4.1 Conclusion

Although CP is a pathology arising from upper motor neuron involvement, the Peripheral Nervous System (PNS) is also affected. The complexity of the pathology complicates the understanding of the mechanism and finding the appropriate treatment methods becomes difficult. Symptoms such as spasticity, which are abnormal discharges from the upper tracts added to the picture of CP, also make the mechanism more difficult to understand.

Muscle lengthening surgery is widely used in CP. Although the surgery is used to correct muscle shortness that causes crouch gait, it is not known exactly which mechanisms actually improves the gait of the patient. There may be other mechanisms behind the gait impairment other than muscle shortness. In the present study, the gait analysis data of patients who underwent hamstring lengthening surgery were taken and it was examined how much specific surgery performed with different parameters corrected walking. Eight limbs of 4 patients were included in the study and MTU lengthening velocities were calculated using a musculoskeletal model by choosing non-short and not slow hamstrings preoperatively. The kinematic gait analysis data modeled by OpenSim helps us to understand the changes in the limbs of the body and the results obtained are useful for patients' activities of daily living. The study initially performed graphs comparing TD's to show that CP patients did not have short and slow hamstrings. Delp et al. revealed that most subjects' psoas muscles were shorter during walking, and showed that spasticity or other dynamic factors—not just static muscle contracture contributed to the abnormal movement patterns in subjects with a crouch gait. Delp et al showed that it is usually treated with surgical lengthening of the hamstrings. Although hamstring lengthening surgery is generally known to reduce stance phase knee flexion, it can also cause other problems, such as decreased knee flexion during swing or increased hip flexion during stance [29].

When we look at the correlations in this thesis , it is observed that there is a significant, yet very small negative relationship between semimembranosus and psoas MTU lengthening velocity. There is a non significant positive relationship between psoas lengthening velocity and gait score. Also, there is a non significant large positive relationship between knee angular velocity and hip angular velocity.

According to Arnold et al., [5] the motive for hamstring lengthening surgery is due to either tight hamstrings or static contracture. With the velocity information, they could reach not only musculoskeletal information but also the neuromusculoskeletal system information. As in the present study, the authors chose to study semimembranosus muscle as the representative of hamstring muscles because its length changes are similar to the semitendinosus. Also, according to the study, four of the 18 subjects walked at different velocities that were significantly slower after surgery than before surgery. It has been stated that the patients walking slower after the surgery, the difference in the walking speeds of the patients in the study, and the heterogeneity of the patient data undergoing various procedures may be the cause. Damiano et al., [32] when examining muscle responses to spasticity, showed that increased stiffness in both agonist and antagonist muscles was negatively related to angular velocity. Previous work had shown that "patients with CP who do not demonstrate heightened stretch responses may still have increased passive muscle stiffness and weakness that can also contribute negatively to muscle performance.These arguments combined show that spasticity negatively affects muscle performance even though it may not cause increased stretch responses [32]. In this thesis, preoperative hamstring MTU lengths and lengthening velocities of CP patients were compared with TD children's to show that all CP patients in the study did not have short and slow hamstrings prior to the operation. Then, the success of the lengthening surgery was evaluated with the five hypotheses. Postoperative knee movements during walking were used as a success indicator [28].

In this thesis, there was no significant difference between the knee angular velocities at the initial contact preoperatively and postoperatively. Likewise, there was no significant difference in hip angular velocities between preoperative and postoperative but it can be said that the angular velocity of the hip was also slower preoperatively. These results show that knee and hip joint movement velocities do not improve after surgery. The insufficient preoperative hip motion may be related to the slow psoas because some patients had slower psoas preoperatively. However, according to the results, only two of the patients had slower psoas than others preoperatively. This shows us that the change of the hip joint movement cannot be understood with the psoas alone. Velocity is known to be an indicator of spasticity, but even if the muscle lengthening velocity values do not change, when there is an improvement in total walking, it can be said that this is due to a mechanism other than velocity change.

In conclusion, no significant correlation was observed between any of the values, and it cannot be interpreted that the hamstring lengthening surgery provided an improvement by increasing the muscle lengthening velocity of the target muscle. When all the results are combined, it was observed that there was no significant increase in the MTU lengthening velocity change, which is an indicator of spasticity. When a physical result is obtained, there is a positive correlation between the angular velocities of the hip and knee, and since the hamstring muscle passes two joints, an improvement in total gait is observed after the surgery by the release of the overly tight epimuscular structures caused by during the surgery. The abnormal cross-linking of the collagen fibers are the reasons for stiffness in the connective tissue [33], this abnormality may cause joint contracture through EMFT. The CP patients suffering from crouched gait with not short or slow hamstrings can be experiencing stiffness in the epimuscular structures that leads their hamstrings to operate at more proximal positions whereas they should operate at more distal positions.

4.1.1 Limitations

Gait features a complex mechanism consisting of different synchronized phases in which many muscles work actively. While gait is so complex, it is a pathology that results from upper motor neuron damage such as CP and causes many secondary problems in the periphery, but also seriously affects the patient's walking. At the same time, CP that seriously affects the patient's gait, which is difficult to understand, becomes even more difficult. Crouch gait is frequently observed in CP patients and hamstring muscles are lengthened to treat such pathological condition. Although lengthening these muscles is beneficial for short-term total walking, it brings some unknowns. Mostly, these surgeries involve more than one intervention instead of a single application which makes it more difficult to review. Although the required number of patients was initially calculated to be 28 it was possible to reach data for 4 patients for the reasons stated above. An increase in the number of patients could yield stronger statistical results. Secondly, the ground reaction force which is the force exerted by the ground on muscles ,data during the gait analyses were not available in the database. However, recent studies have shown that muscle lengthening surgery significantly affects force exertion [9],[34]. The changes in the force exertion should be studied to better understand the mechanism behind the healing. Nevertheless, the ground reaction force does not exist in the OpenSim database. The musculoskeletal model OpenSim cannot separate the changes in MFT and EMFT, but it allows an approximation of the force exerted on a single muscle during walking. Since it cannot distinguish these changes, it does not take into account the epimuscular connections and ignores the interactions around the muscles.

4.1.2 Future Studies

In future studies, the number of patients should be increased in order to obtain statistically significant results. The patient data included in a prospective study should have undergone similar practices, such as receiving similar conservative treatments. In addition, the necessary scales for spasticity should be used in the evaluation of patients and should be recorded in the reports.

APPENDIX A. PRE- AND POST-OPERATIVE JOINT ANGULAR VELOCITIES AND MTU LENGTHTENING VELOCITY PER LIMB

A.1 Limb_1

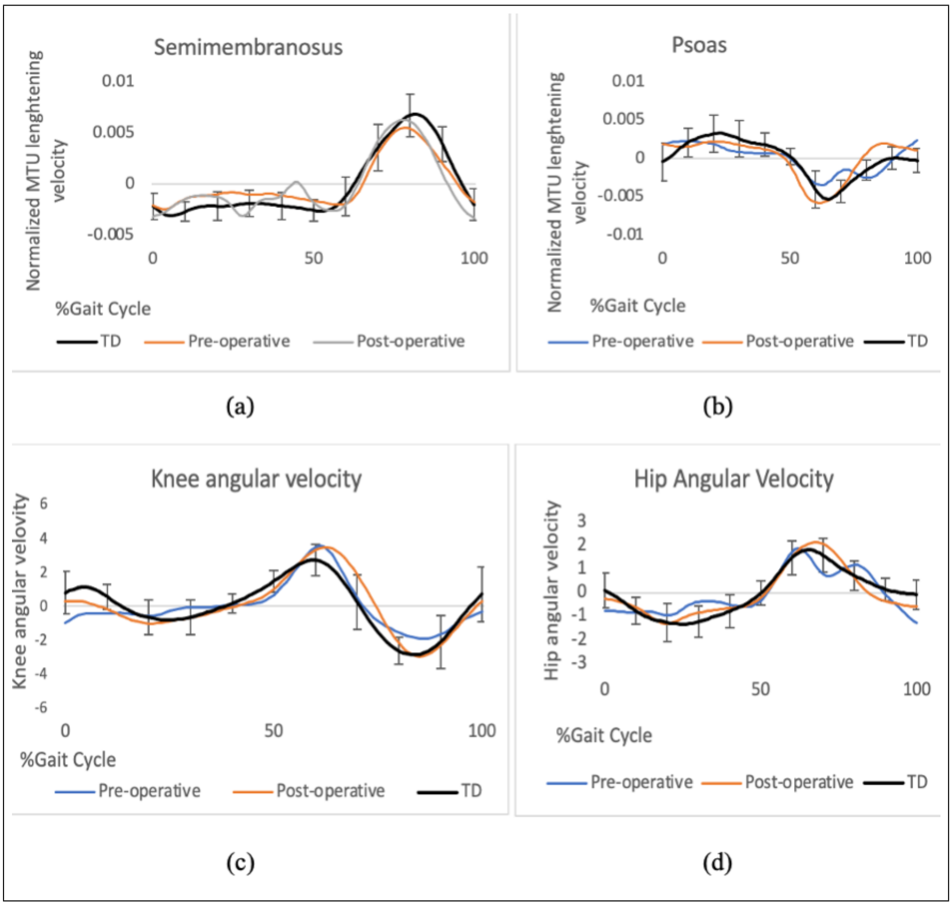

Figure A.1 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_1 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.2 Limb_2

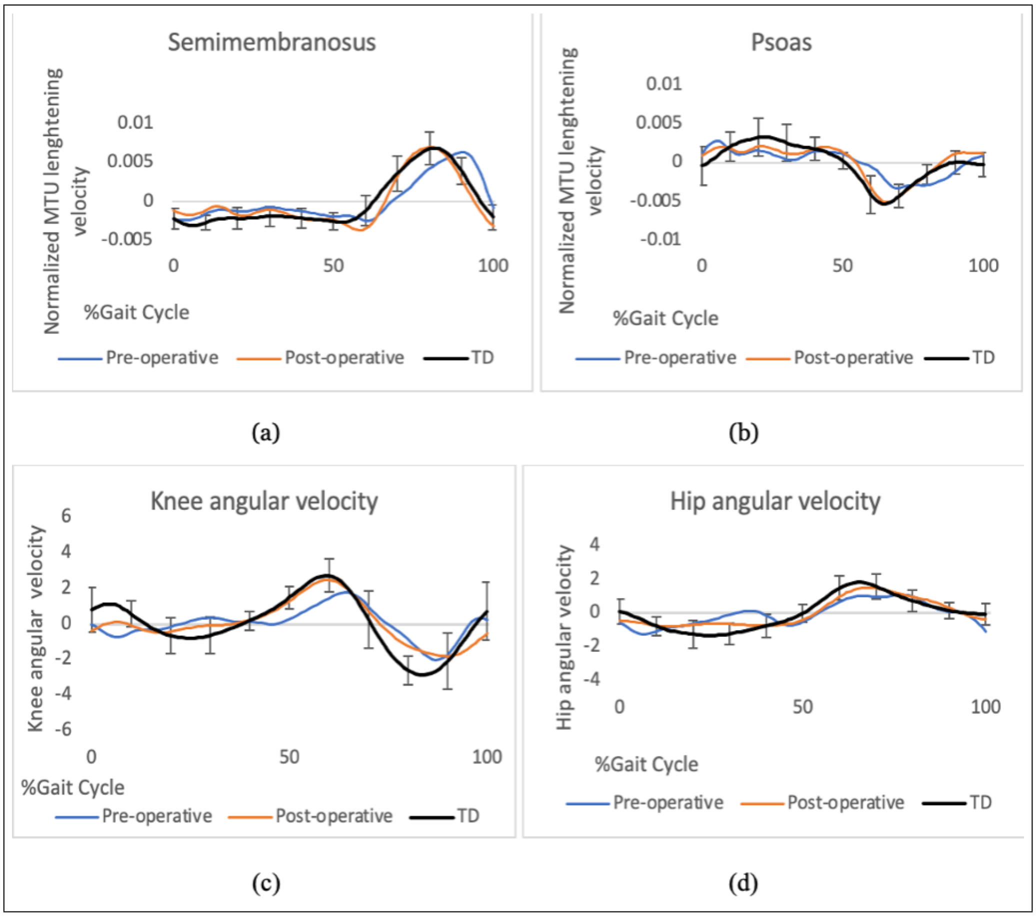

Figure A.2 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_2 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.3 Limb_3

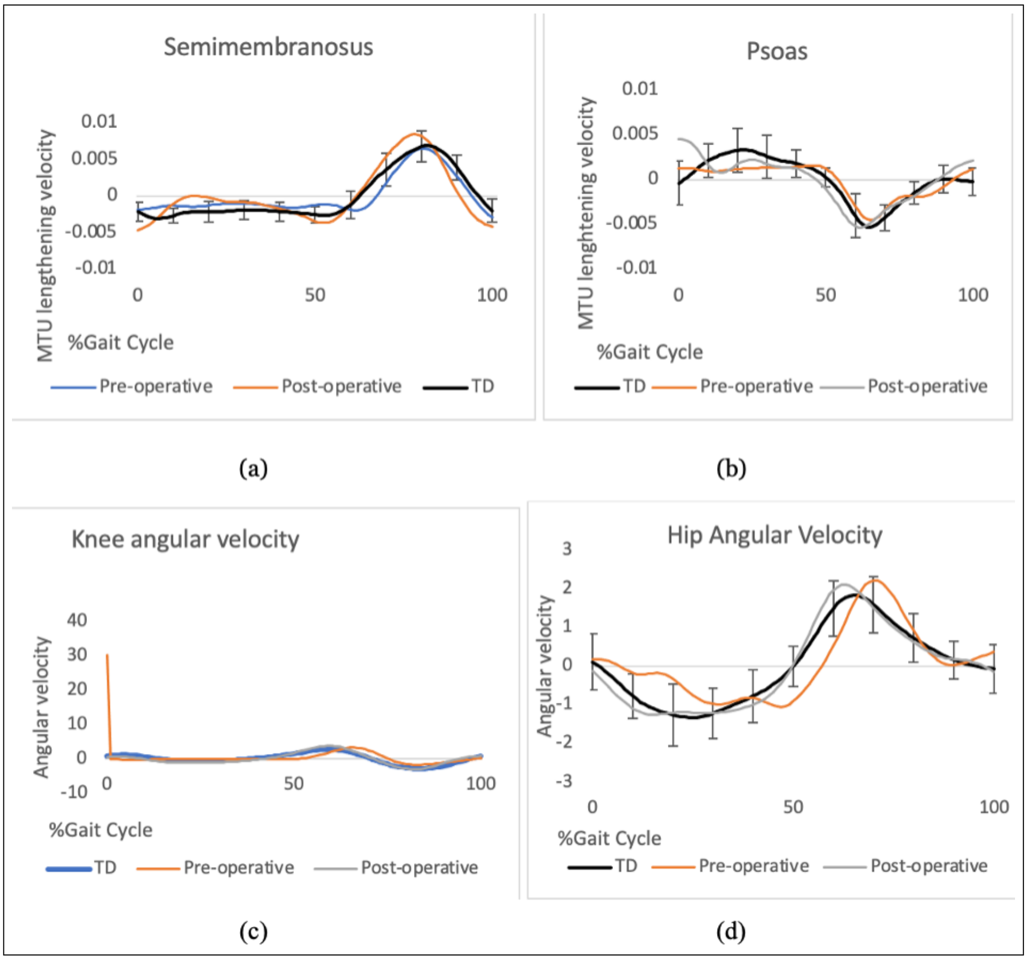

Figure A.3 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_3 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.4 Limb_4

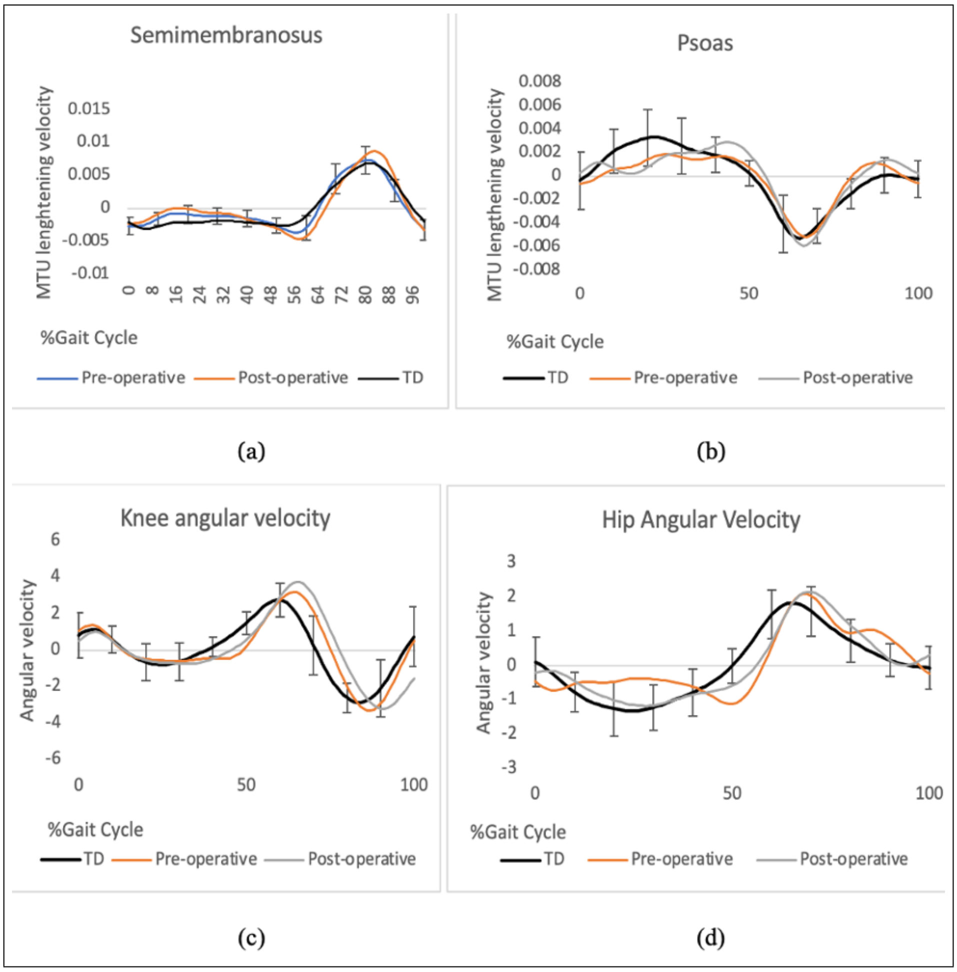

Figure A.4 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_4 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.5 Limb_5

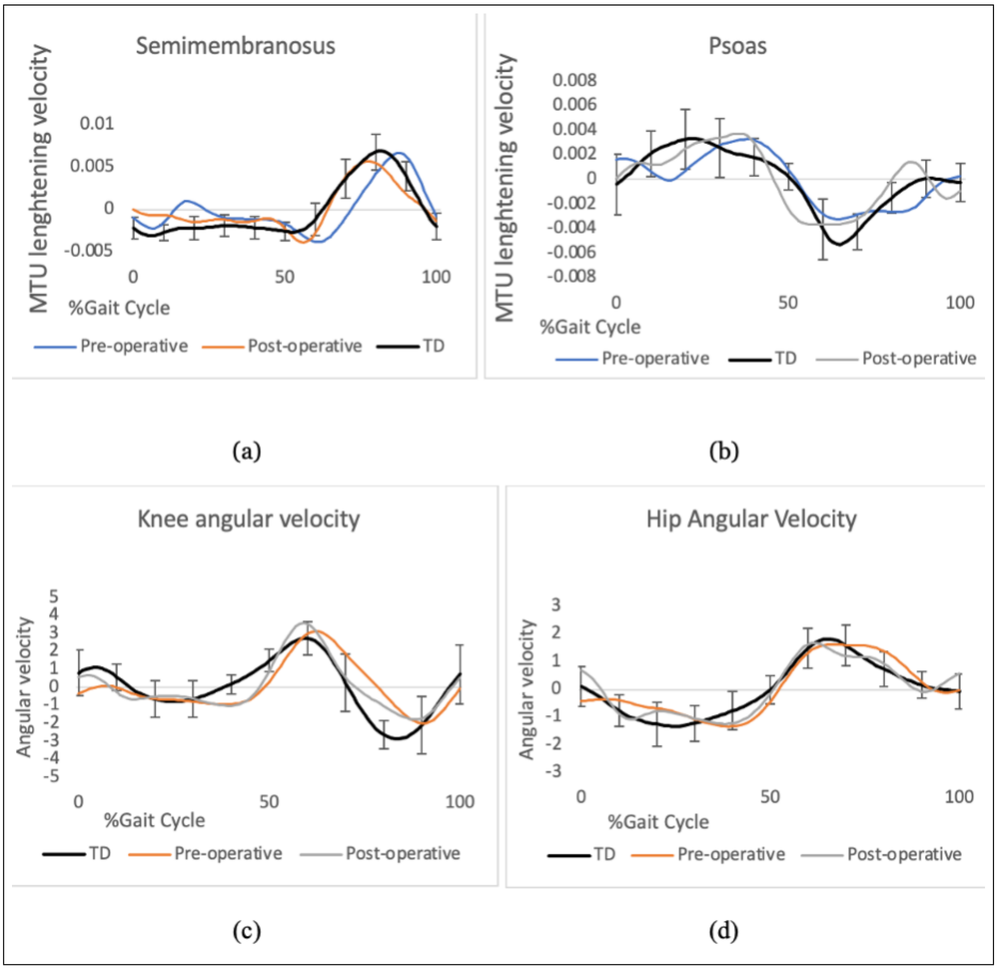

Figure A.5 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_5 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.6 Limb_6

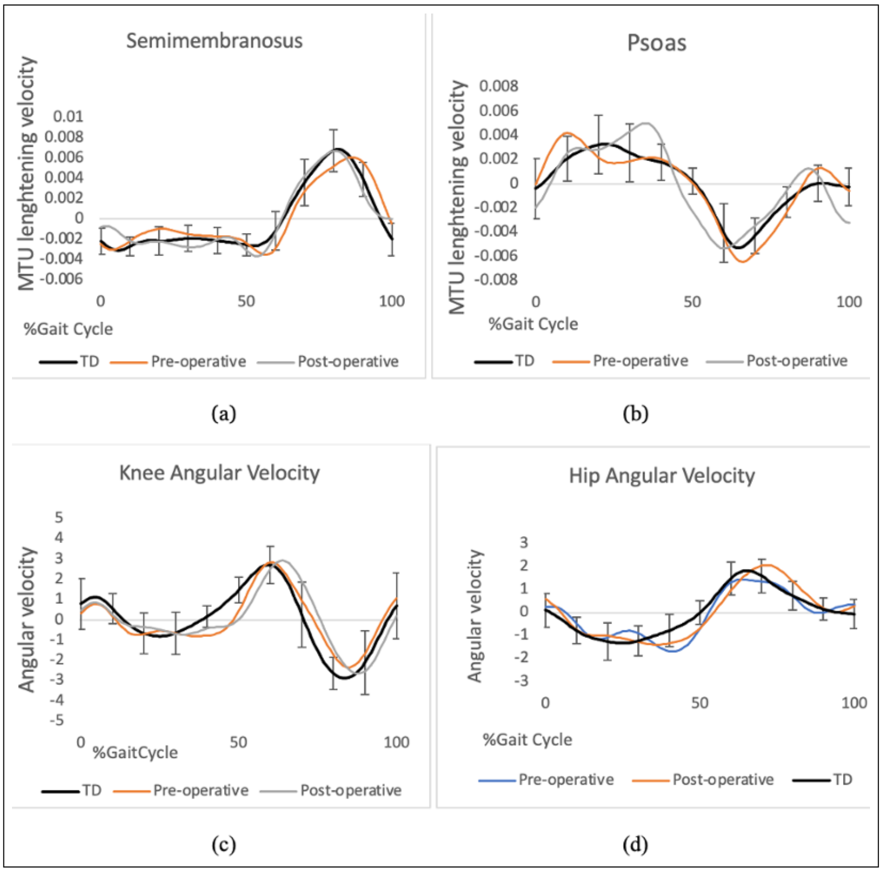

Figure A.6 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_6 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.7 Limb_7

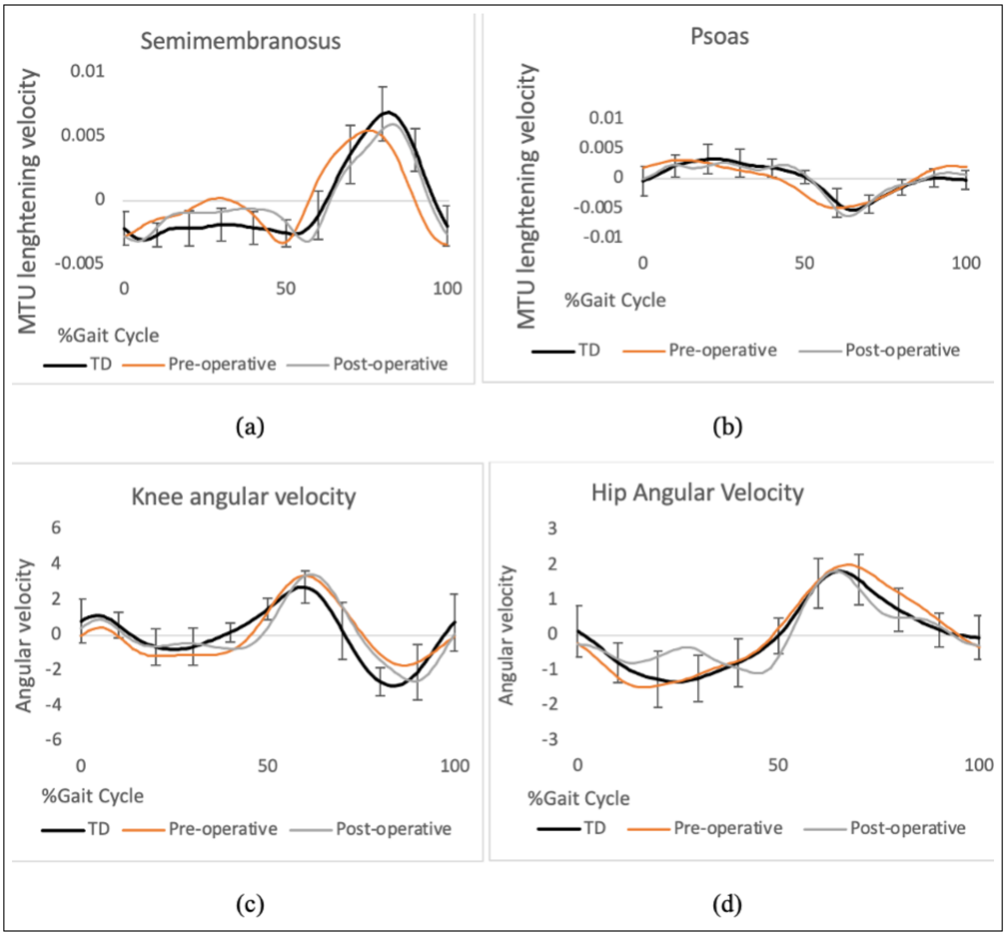

Figure A.7 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_7 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

A.8 Limb_8

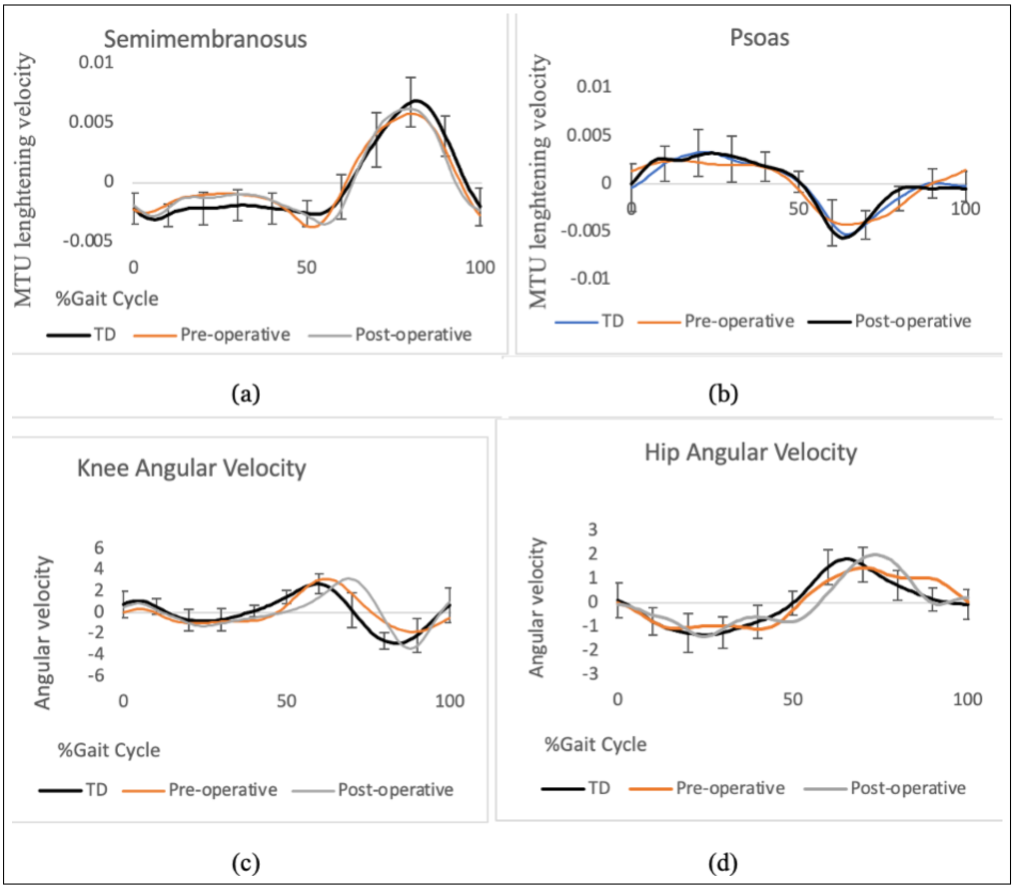

Figure A.8 Pre-operative and post-operative a. Semimembranosus MTU lengthtening velocity b. Psoas MTU lengthtening velocity of the Limb_8 compared to TD for a gait cycle. c. knee angular velocities d. hip angular velocities.

REFERENCES

1. Graham, H. K., P. Rosenbaum, N. Paneth, B. Dan, J.-P. Lin, D. L. Damiano, J. Becher, D. Gaebler-Spira, A. Colver, D. S. Reddihough, *et al.*, "Cerebral palsy (vol 2, 15082, 2016)," *Nature Reviews Disease Primers*, Vol. 2, 2016.

2. Armand, S., G. Decoulon, and A. Bonnefoy-Mazure, "Gait analysis in children with cerebral palsy," *EFORT Open Reviews*, Vol. 1, no. 12, pp. 448–460, 2016.

3. O'Neil, M. E., and N. Lennon, "Therapy management of the child with cerebral palsy: An overview," *Cerebral Palsy*, pp. 2395–2404, 2020.

4. Howard, J. J., and W. Herzog, "Skeletal muscle in cerebral palsy: from belly to myofibril," *Frontiers in Neurology*, Vol. 12, p. 620852, 2021.

5. Arnold, A. S., M. Q. Liu, M. H. Schwartz, S. Õunpuu, L. S. Dias, and S. L. Delp, "Do the hamstrings operate at increased muscle–tendon lengths and velocities after surgical lengthening?," *Journal of Biomechanics*, Vol. 39, no. 8, pp. 1498–1506, 2006.

6. Salami, F., J. Brosa, S. Van Drongelen, M. C. Klotz, T. Dreher, S. I. Wolf, and M. Thielen, "Long-term muscle changes after hamstring lengthening in children with bilateral cerebral palsy," *Developmental Medicine & Child Neurology*, Vol. 61, no. 7, pp. 791–797, 2019.

7. Emos, M. C., and S. Agarwal, "Neuroanatomy, upper motor neuron lesion," in *StatPearls [Internet]*, StatPearls Publishing, 2021.

8. Laracca, E., C. Stewart, N. Postans, and A. Roberts, "The effects of surgical lengthening of hamstring muscles in children with cerebral palsy–the consequences of pre-operative muscle length measurement," *Gait & Posture*, Vol. 39, no. 3, pp. 847–851, 2014.

9. Ateş, F., R. N. Özdeşlik, P. A. Huijing, and C. A. Yucesoy, "Muscle lengthening surgery causes differential acute mechanical effects in both targeted and non-targeted synergistic muscles," *Journal of Electromyography and Kinesiology*, Vol. 23, no. 5, pp. 1199–1205, 2013.

10. Khot, A., S. Sloan, S. Desai, A. Harvey, R. Wolfe, and H. K. Graham, "Adductor release and chemodenervation in children with cerebral palsy: a pilot study in 16 children," *Journal of Children's Orthopaedics*, Vol. 2, no. 4, pp. 293–299, 2008.

11. Baumann, J., and H. Koch, "Lengthening of the anterior aponeurosis of the gastrocnemius muscle," *Operat Orthop Traumatol*, Vol. 1, no. 1, pp. 254–8, 1989.

12. Pirker, W., and R. Katzenschlager, "Gait disorders in adults and the elderly," *Wiener Klinische Wochenschrift*, Vol. 129, no. 3, pp. 81–95, 2017.

13. Huijing, P. A., "Epimuscular myofascial force transmission: a historical review and implications for new research. international society of biomechanics muybridge award lecture, taipei, 2007," *Journal of Biomechanics*, Vol. 42, no. 1, pp. 9–21, 2009.

14. Yucesoy, C. A., "Epimuscular myofascial force transmission implies novel principles for muscular mechanics," *Exercise and Sport Sciences Reviews*, Vol. 38, no. 3, pp. 128–134, 2010.

15. Wilke, J., R. Schleip, C. A. Yucesoy, and W. Banzer, "Not merely a protective packing organ? a review of fascia and its force transmission capacity," *Journal of Applied Physiology*, Vol. 124, no. 1, pp. 234–244, 2018.

16. Yucesoy, C. A., B. Koopman, G. Baan, H. Grootenboer, and P. Huijing, "Extramuscular myofascial force transmission: experiments and finite element modeling," *Archives of Physiology and Biochemistry*, Vol. 111, no. 4, pp. 377–388, 2003.

17. Yucesoy, C. A., G. C. Baan, B. H. Koopman, H. J. Grootenboer, and P. A. Huijing, "Pre-strained epimuscular connections cause muscular myofascial force transmission to affect properties of synergistic ehl and edl muscles of the rat," 2005.

18. Kaya, C. S., Y. Temelli, F. Ates, and C. A. Yucesoy, "Effects of inter-synergistic mechanical interactions on the mechanical behaviour of activated spastic semitendinosus muscle of patients with cerebral palsy," *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 77, pp. 78–84, 2018.

19. Ateş, F., Y. Temelli, and C. A. Yucesoy, "Effects of antagonistic and synergistic muscles' co-activation on mechanics of activated spastic semitendinosus in children with cerebral palsy," *Human Movement Science*, Vol. 57, pp. 103–110, 2018.

20. Ateş, F., Y. Temelli, and C. A. Yucesoy, "Human spastic gracilis muscle isometric forces measured intraoperatively as a function of knee angle show no abnormal muscular mechanics," *Clinical Biomechanics*, Vol. 28, no. 1, pp. 48–54, 2013.

21. Delp, S. L., F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen, "Opensim: open-source software to create and analyze dynamic simulations of movement," *IEEE Transactions on Biomedical Engineering*, Vol. 54, no. 11, pp. 1940–1950, 2007.

22. Seth, A., J. L. Hicks, T. K. Uchida, A. Habib, C. L. Dembia, J. J. Dunne, C. F. Ong, M. S. DeMers, A. Rajagopal, M. Millard, *et al.*, "Opensim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement," *PLoS Computational Biology*, Vol. 14, no. 7, p. e1006223, 2018.

23. Barré, A., "Mokka-motion kinematic and kinetic analyzer," 2011.

24. John, C. T., F. C. Anderson, J. S. Higginson, and S. L. Delp, "Stabilisation of walking by intrinsic muscle properties revealed in a three-dimensional muscle-driven simulation," *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 16, no. 4, pp. 451–462, 2013.

25. Started Word Search, *China word search*, Independently Published, Apr. 2021.

26. Started Word Search, *China word search*, Independently Published, Apr. 2021.

27. Granata, K. P., M. F. Abel, and D. L. Damiano, "Joint angular velocity in spastic gait and the influence of muscle-tendon lengthening," *The Journal of Bone and Joint Surgery. American volume*, Vol. 82, no. 2, p. 174, 2000.

28. Arnold, A. S., M. Q. Liu, M. H. Schwartz, S. Ounpuu, and S. L. Delp, "The role of estimating muscle-tendon lengths and velocities of the hamstrings in the evaluation and treatment of crouch gait," *Gait & Posture*, Vol. 23, no. 3, pp. 273–281, 2006.

29. Delp, S. L., A. S. Arnold, R. A. Speers, and C. A. Moore, "Hamstrings and psoas lengths during normal and crouch gait: implications for muscle-tendon surgery," *Journal of Orthopaedic Research*, Vol. 14, no. 1, pp. 144–151, 1996.

30. Schutte, L., U. Narayanan, J. Stout, P. Selber, J. Gage, and M. Schwartz, "An index for quantifying deviations from normal gait," *Gait & Posture*, Vol. 11, no. 1, pp. 25–31, 2000.

31. Saraph, V., E. Zwick, C. Uitz, W. Linhart, and G. Steinwender, "The baumann procedure for fixed contracture of the gastrosoleus in cerebral palsy: evaluation of function of the ankle after multilevel surgery," *The Journal of Bone and Joint Surgery. British volume*, Vol. 82, no. 4, pp. 535–540, 2000.

32. Damiano, D. L., E. Laws, D. V. Carmines, and M. F. Abel, "Relationship of spasticity to knee angular velocity and motion during gait in cerebral palsy," *Gait & Posture*, Vol. 23, no. 1, pp. 1–8, 2006.

33. James, SE Farmer, M., "Contractures in orthopaedic and neurological conditions: a review of causes and treatment," *Disability and Rehabilitation*, Vol. 23, no. 13, pp. 549–558, 2001.

34. Yucesoy, C. A., and P. A. Huijing, "Substantial effects of epimuscular myofascial force transmission on muscular mechanics have major implications on spastic muscle and remedial surgery," *Journal of Electromyography and Kinesiology*, Vol. 17, no. 6, pp. 664–679, 2007.