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MASTER THESIS

Biomechanical Analysis of the Static Balance in Taekwondo Training Methodologies

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"To Italy, the country that welcomed me and in exchange it gave me its culture, traditions, and above all, its persons."

Acknowledgments

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Abstract

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by Álvaro GONZÁLEZ MEJÍA

Developmental Coordination Disorder (DCD) is one of the most common motor disorder with a prevalence of approximately 6% in typical children of primary school age. This disorder is characterized by marked impairments in motor functions, however it is the poor capacity for balance and coordination which makes it a serious problem. This can not only affect the attainment of academic achievements and daily activities, but requires extra attention for the high risk of falls, limits physical activity and affects the development of other motor skills. Due to the importance of solving this disorder or at least reducing some of its consequences, there have been numerous studies with children affected by either DCD or other diseases that have similar symptons in which participants follow a training protocol based on Taekwondo training methodologies. The results were optimal, improving different aspects such as coordination and balance. Therefore, it has been demonstrated that Taekwondo could be an effective tool with which to improve these abilities and skills of children with DCD. The problem arises from the fact that these studies have not identified the primary causes of this improvement, which would be directly related to Taekwondo. Since the results are not still enough precise, this makes difficult to find the solution to the problem. The aim of this work is mainly to determine which are the possible causes that make children's psychomotor abilities improve based on the Taekwondo methodologies of training. Afterwards, these causes are analyzed using OpenSim in order to better understand how the muscular system of the human body behaves. A final step will be try to analyze the reproduction of the results in a robotic system so that they have the same effect as a complete Taekwondo training. To do this, it has made use of a free software developed by Stanford University called OpenSim, which have simulated characteristic movements of Taekwondo in a static way by a musculoskeletal model with standard man measurements. In addition, the model has been subjected to various external forces of imbalance in order to study the static balance. The muscles which react to these perturbations are those that try to maintain the posture, and consequently the static balance, so that analyzing the way in which they react will offer important results about the muscles related to the balance and how they behave. After analyzing the results obtained, it was concluded with a list of muscles in charge of maintaining balance in a static way and how their patterns of activation are. This is very important, since it offers the possibility of knowing not only the muscles that are activated, but also how they do it and the relationships between them. Finally, a possible integration of these results in a robotic solution has been proposed. In this way, by means of electrical stimuli, the activation patterns of each muscle observed in the simulations are faithfully reproduced as if they were Taekwondo training. The possibility of providing a solution that reproduces the conditions of Taekwondo training and thereby improves balance abilities in people affected by DCD and other similar disorders, would greatly improve the quality of life of people and eliminate the enormous risks that such disorders entail, making their lives so much better.

Keywords: OpenSim, Taekwondo, Static Balance, DCD, Muscles, Front-Kick, Side-Kick, Robotics

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Chapter 1

Introduction

1.1 Motivations

This project arises from the observation of promising results in studies carried out on children with balance and coordination disorders, applying Taekwondo methodologies in them with the aim of improving their psychomotor abilities. These disorders are very serious, especially when those who suffer them are children, hinder their development and worsening not only their health, but their quality of social and educational life. Therefore, observing that the participants of these studies were improving, we wanted to delve further into the subject and investigate what could be the possible causes of these improvements, which have not been discovered yet. Identifying these causes in isolation could be of great importance, being a fundamental element in future studies to address the problem at its root. In addition, the possibility of a future integration in a robotic solution that allows an adapted training that reproduces the same training methodology, having an equal or very similar effect in the psychomotor capacities, was considered.

1.2 Context of the Study

This study takes place in a context in which the sport of Taekwondo is gaining strength and recognition. So much so that in recent years numerous studies have been carried out on children with psychomotor problems, generally diagnosed with Developmental Coordination Disorder (DCD), with the aim of evaluating its possible benefits and its possible use as therapy.

In addition, technology is increasingly advanced and is already part of our lives in one way or another, can be a tool of great importance to solve problems which years ago was unthinkable.

1.3 Objectives and Contributions

The objectives could be summarized basically in two:

1. Identifying the possible causes that make children's psychomotor abilities improve based on the Taekwondo methodologies
2. Analyzing with Opensim the specific Taekwondo movements which were identifies as possible causes

This will provide important and valuable results that will help to solve the multiple psychomotor problems affecting millions of children, improving their quality of life. In addition, it will allow to establish the bases in the search for robotic solutions that reproduce the methodologies of Taekwondo training.

1.4 Overview of the Thesis

In this master thesis the numerous studies that have been carried out on children with psychomotor disorders in which a training methodology based on Taekwondo is applied have been analysed in order to discover the effects that this can have on balance and coordination abilities. The participants are children generally between the ages of 9 and 16 who suffer from Developmental Coordination Disorder (DCD), Autism Spectrum Disorder (ASD) and Down Syndrome (DS), diseases that cause disorders with notable consequences in the daily lives of those who suffer them. These studies obtained important results, demonstrating that after following a protocol based on Taekwondo methodologies, the participants improved their psychomotor abilities. However, these results did not identify with a minimum of certainty which were the primary causes of such improvement, these being of utmost importance for later use in which they can be useful. Once these studies had been analyzed, some characteristic movements used in these studies were simulated that could in some way represent the training methodologies tested based on Taekwondo, so that the results could be applied to all the studies. These simulations have been made in a free software for biomechanical study and designed by Stanford University called OpenSim. The movements simulated were 2, divided into two static phases each: front kick and side kick. In addition, the aim was also to dynamically simulate a complete movement, in this case the front kick. In this way, and subjecting these movements to various tests in which unbalancing external forces have been added, it has been identified which muscles are activated and which are therefore in charge of maintaining the static balance. Finally, after analysing the results of the simulations, the bases for a possible future use of this knowledge have been laid so that it is possible to reproduce a Taekwondo training protocol in a robotic solution. This solution would allow to continue obtaining the benefits of Taekwondo without the need to perform this sport as such.

Chapter 2

Overview on Sport and Disabilities

Summary

Here is described the state of the art of the research that has been carried out. This chapter contains all the relevant publications in the area with the corresponding citations, briefly described and critically assesssed.

2.1 Technology in Sports

Since technology as we know it today emerged, it has become a fundamental part of our lives, repeatedly observed in our daily routine. We can find it when we wake up every morning with the mobile alarm, or with the first coffee of the day freshly made with our Nespresso tactile coffee maker while we are reading the news on our latest generation iPad. Our life today would not be understood without technology, and technology is improving by leaps and bounds to make it even better.

One of those aspects of our life in which technology has been firmly established is in the sport. Today technology and sport are inseparable, both advance hand in hand and there is constant improvement. It is true that there are always some sports that benefit more from technology than others, in which more money is researched and invested, normally driven basically by different interests, among which the economic one stands out. The more popular a sport is, the more money it generates and the more attractive it is to investors.

In the United States, for example, one of the most important and popular sports is the NFL, and because of this, an investment of $60 million was made in a program called Engineering Roadmap. This arose from just the inclusion of a new edict against players lowering their head to initiate contact, which looks for avoiding brain concussions, in addition to other injuries. This triggered other numerous investments of large sums of money in studies and researches into safer equipment, putting the focus on the helmet [1]. Two of the main objectives in terms of helmet use were two: the short-term development of a better performing all-purpose helmet, and a subsequent move toward position-specific helmets. Players at each position were enduring a different frequency, severity, or type of impact. For example, while the cornerbacks and wide receivers were the players who received the greatest number of concussions, the quarterbacks suffered the fewest among non-kickers. The difficulty is that there are no impact sensors currently permitted on the field, so researchers had to find a way in order to connect what they saw on video and what was physically happening. To do that, they used impactors that could launch heavily-instrumented crash-test dummies in a laboratory-grade, motion-tracking system to identify the exact motion [2]. These studies ended up obtaining different results that were offered as a solution to the problem of concussions so that the NFL, aided by technology, would become a safer sport. On the one hand, one of the most disruptive invent was a helmet with several layers which were designed using different methods: from foam to liquid crystalline elastomers and energy-absorbent textile fibers as helmet liners. On the other hand, a medical technology company succeeded at identify minute protein biomarkers in the blood that could be used to make an objective concussion diagnosis, discerning their severity and even helping determine a safe return-to-play time, and to identify early stage chronic traumatic encephalopathy (CTE), a degenerative brain disease linked with repetitive blows to the head [3]. Furthermore, there were other different invents related to other types of equipment, such as the mouthguard. A sensorized mouthguard was designed to allow not only coaches but also doctors to collect data of interest in real time during the game and a subsequent analysis.

But it is not only the NFL that is benefiting from the enormous benefits of technology. Another example might be tennis, a sport known internationally and which arouses so many passions, especially in Europe. There is nothing new in the use of technology in this great racquet sport, but what is new is the use of technology in training and improving performance in a more interactive way. For example, in 2009 was presented the design of a use-cooperative rope robot. This robot serves as a large-scale haptic interface in a multi-modal cave environment used for sport simulation, already tested experimentally in two applications: a rowing simulator and a tennis application. However, this adaptability and the high dynamics in sports lead to challenging requirements and specific design criteria of the hardware components in terms of user-cooperativity and versatility. It includes sensors to measure the position with a high resolution and the rope forces. Furthermore, an algorithm running in real-time is introduced, which calculates the distance between the single ropes and the user in order to avoid collisions. Both, the hardware and the algorithm, are being improved but it is already a first step for what may be a totally different training methodology [4]. Besides, due to its evolution in a high physical demand sport, its need of being quantified in order to do it safer and to protect players in the training environment has increased. That is the reason why in [5] is presented the big necessity of measuring physical parameters and data collection in tennis, given the example of Catapult, a company which works in this field and is currently well stablished in sports such as football and rugby.

And it was taking time for football to emerge as the star sport par excellence in Europe. It is one of the sports in which the most money is invested, and consequently much of it goes to technology. A good example is the niche sector which is called SportsTech. It aims to change the way sports events gather event data which is then analyzed to improve fan experiences. Startups that operate within this industry have developed technological solutions to improve the ability to measure and track sports performance and progress. The sports tech sector has three core pillars:

fan engagement, sports analytics, and smart stadiums. One of the companies dedicated to fan engagement is Konnecto, which analyzes fans by collecting both past and present data about their interactions and thus allows them to have sponsorships that best suit their fans' preferences. Another example is the use of the technology in the creation of smart stadiums, with projects which will enable fans to have easier access to events through the use of e-tickets, to find their seats easily, and even order a snack to their seat without getting up or missing a moment of the match [6].

In addition, one of the best-known advances in football today is the use of VAR (video assistant referee). Already in 2002 a system of detection of goal and out of band was presented. This system is formed by the sensorized football ball, a device that would wear the referee (most probably a wrist watch), and the detectors placed along the lines. Besides, they were presented also other ideas. The first one, the figure of the fourth referee, who would be placed in an electronic cabin outside where he would be able to review all the actions helped by video cameras placed in strategic locations along the pitch. On the other hand, a countermeasure to adversarial weather conditions like fog and snow: the configuration of the football ground with red light dots, which not also would permit a better sight but also would melt the snow falling on the line [7].

But not only is investment being made in these sectors. Although the football still has its limitations, there are some researches also into improving the skills of the players. This could be divided into the two main types of players according to their intended role: goalkeepers and field players. In relation to the former, there was a study that evaluated how adding spins to the ball in a direct free kick situation affected the goalkeeper's perception of the ball's trajectory [8]. As a consequence, a specific training was obtained for these in which this visual limitation of the human being was worked.

On the other hand, it is already well known the use of GPS for data collection and subsequent study, which allows quantifying the distance traveled, possible accumulated fatigue and other parameters. But over the years other sensors have been incorporated allowing much more complete readings of parameters until now not contemplated. For example, in [9] a patent presents sensorized balls, athletic equipment or sport accessories that allow players in general to interact with them using a variety of computing functions. Some of them are sensors, displays, cameras, recording and sharing of images and video, speakers and microphones, and even a functionality to determine if the user has sustained an impact that may cause a concussion or sunstroke. However, in a more football-specific way, in [10] another patent presents a sensor that can be integrated both in the shoes and in the ball and gives information about the players. It uses pressure, acceleration and magnetic field sensors. In relation to the information acquired, it can be used to measure accelerations, shot powers, paths and distances covered by the players as the relation among them and the ball.

Another example could be that presented in [11], which is a sport sensor that utilizes different technologies: accelerometer, gyro sensor to sense angular displacement, a GPS unit to senses position and velocity, a magnetometer to sense direction of movement, a heart rate monitor, and a controller programmed to manipulate the data and provide a display of the heartrate, speed, and other sport parameters. In addition, it can measure other parameters: respiratory rate (sensing the stretching of a chest band) and arterial oxygen saturation (pulse oximetry sensor place on an earlobe).

As it can be seen, most technological advances have enough flexibility to adapt to different sports, especially if they focus on physical parameters. Sensors integrated in sneakers or sports tops that do not hinder the practice of sport are normally used for this purpose. However, other sensors are somewhat newer, such as the sensors presented in [12], which are textile based sensors fully integrated within a garment that can be used in sport activities in a straightforward and comfortable way. Some of the sensors presented are: pH sensor intended to collects and analyses sweat in real-time in order to improve hydration strategies, piezoresistive sensor to measure breathing patterns, and a combination of those previously mentioned to measure body kinematics and dynamic postural alignments as joint movements and foot plantar pressures.

But obviously, it's not all football. More and more other minority sports are gaining strength and visibility, resulting in more monetary investments in studies that improve sports conditions. One of those sports that has grown a lot in recent years is athletics. Driven by the fever of the movement already well-known as "running", athletics is a sport that has become fashionable and many people without even having a strong base are becoming fond of it. This of course has encouraged also the investment of large amounts of money by major brands that have driven this phenomenon and many studies have been consistently carried out. The fact that this sport has penetrated so deeply into society, in which the vast majority of people do not have as many means as a person with a good base, has created the need for tools that allow interaction with the athlete so that without the need for a coach, he can improve and do training as if he were a professional, at least on equal terms.

These tools allow the collection of data and interaction with the athlete through different information technologies so that the athlete can improve something as important as for example the technique. Usually this information and data are collected by sensors; and after analyzing this data, a feedback is offered to the user using visual, auditory or proprioceptive feedback. Some of these information technologies can be video information, three-dimensional virtual environments, intrinsic feedback under vibration conditions, temporal feedback, feedback about team performance, feedback in aiming sports, force platforms and force transducers, eye movement, and the combination of feedback technologies [13].

One of the most influential sports scientists in society is Carlos Balsalobre-Fernández. This Spanish researcher is a pioneer in the development of mobile applications that are easy to use but of great scientific value, certified as valid measurement methods [14], which analyze data collected by just the smartphone. He has developed the following apps:

- MyJump2: to measure the jump height, force, power and velocity
- MySprint: to measure sprint force, power and velocity profiles
- Runmatic: to measure running mechanics and leg assymetric
- Powerlift: to measure bar velocity and maximal strength
- Dorsiflex: to measure ankle dorsiflexion

In the case of athletics, normally this data is collected by sensors built into the shoes or wearable as a smartwatch. In recent years the methods have evolved substantially, incorporating increasingly complex techniques and technologies such as Artificial Intelligence. The use of AI together with statistics allow us to identify non-linear and complex relationships such as the relationship between the accumulated fatigue in the athlete and his running technique, which changes as the time of training advances and can only be understood individually to each athlete. Here the AI allows the enrichment of the data as the amount of data collected increases and the individual adjustment for each athlete [15].

This type of data, which provides important information about the running technique, is usually collected by inertial sensors or IMU (Inertial Measurement Units). These have become very small and light, like the one presented in [16], a small and lightweight IMU optimized for long-term out-of-the-lab measurements. It extracts kinematic features from the sensors to assess three application areas: skill level assessment, fatigue monitoring, and training assistance. It was found that these areas can be covered sufficiently by two sensors located on the foot and on the shin. Besides, with the extracted data from the sensors in this study, it was carried out an analysis of them in terms of Normalized Foot Contact (NFC) duration, foot strike types, and heel lift.

Running foot strike patterns are very important in athletics, they have been studied many times and they can generally be divided into four types: rear-foot, mid-foot, fore-foot, and asymmetries. Rear-foot striking is more common in recreational distance runners. But as the distance increases, a large percentage of runners switches from mid-foot and fore-foot foot strikes to rear-foot and the frequency of discrete foot strike asymmetry declines. Obviously this is due to a relationship between the foot strike pattern and the fatigue and also the footwear [17]. Besides, It is true that one strike pattern may be better than another depending on different points of view such as energy expenditure or injury prevention, but there are no congruent results that show which one assures you victory. This does not mean that it should stop getting better. There are systems that also using IMU seek to evaluate the performance of different kinematic features measured by these foot-worn inertial sensors for detecting running gait temporal events to estimate inner-stride phases duration. Then, carrying out an statistical analysis and error estimation, and considering the most performant kinematic features, an accurate and precise estimation of inner-stride temporal parameters is possible, doing a good functional calibration of the inertial sensors and taking into account that running speed may affect the measures [18].

But not only are Inertial Measurement Units used to collect data, there are also other types of sensors that allow, for example, to quantify the state of fatigue through measurements and analysis of biomechanical and physiological parameters such as heart rate, heart rate variability, running speed, stride frequency and other other data. For example, in [19] was observed that a heart rate variability feature and two biomechanical features were best suited for classification of the perceived fatigue level, implementing the classifier on an embedded microcontroller.

Finally, in athletics, sensors located on the soles of the feet are used too. These are insoles with integrated force sensors that permit measuring the accumulation of impact force over a given session. This not only allows data to be obtained on accumulated load and fatigue, but also allows strike patterns to be studied by measuring ground contact and flight times and thus finding relationships between all of this [20]. But the measurement of flight times is not only applicable to the running, but also to sports in which this is precisely a way of scoring. There are measurement systems used in these types of sports with which performance can be measured, monitoring and gauging airtime, altitude and spin ratios. For example, in the ski aerial competitions where the team jumps off a ramp and lands in water, it is so useful [21].

And not only you can measure athletes, you can also measure vehicles. It is the example of the patent described in [22], in which it exposes an invention that it relates generally to monitoring and quantifying sport movement associated either with the person or with the vehicle used or ridden by the person. These measures include also parameters of "air time", power, speed, and drop distance. This invention is particularly useful in sporting activities in which sporting persons expend energy, move at varying speeds, and perform jumps; but it has also gaming aspects for connecting users across the Internet that it is so interesting.

As you can see, sport today cannot be understood without technology. Both have grown in parallel, and this being the era in which technology is presented in all aspects of our daily lives, sport obviously had to be affected as well. As I have mentioned before, there are also other minor sports that have a smaller number of fans and move fewer amounts of money which are also benefiting from this phenomenon. For example, sports such as golf, table tennis or swimming also enjoy these advances too. Advances such as the use of Artificial Intelligence and Internet of Things in golf, allowing an improvement in performance in the case of the athlete with data on his posture or hitting power, for example, and offering greater enjoyment to the viewer with better broadcasts of tournaments [23]. Or in table tennis, in which there have also been researches on how to improve training methodologies so that sports performance is higher. In 2005 a method was proposed that would allow a robot to play table tennis efficiently against a real person, returning all hits by calculating the ball flight duration and the necessary hitting forces for an optimum precision. This method consisted of three input-output maps which enable predicting the impact time of the ball hit by the paddle and the ball position and velocity at that moment, a change in ball velocities before and after the impact, and the bouncing point and time of the returned ball [24]. And finally in swimming, with an example such as the design of an innovative swimsuit made with materials that reduce friction with the water and improve the performance of the swimmer, being able to reach higher speeds [25].

2.2 Disabilities, and the Sport as Therapy: TKD

As we can see, no sport is foreign to technology and its irrepressible incursion into our society. But this union has also gone even further, making use of the innumerable benefits of sport to apply them as curative therapy in diseases, specifically in diseases that cause psychomotor disorders that have as consequences disabilities.

However, although numerous sports are used for this purpose, I would like to make special mention of a sport that is gradually making its way and is gaining importance internationally, being declared an Olympic sport in 1994 and that since its debut in Sydney 2000 has not missed in any of the Olympics. In addition, it is also one of the world's most popular sports among children and teenagers [26]. All of this has made it a sport in which a lot of research is currently being done, allowing it to continue growing and to be increasingly considered a sport of great expectations. Being still a rather unknown sport, the study fronts are diverse. These can focus on the training methodology as well as its benefits on the health of those who practice it. For example, in 2017 one of its most characteristic movements was studied: the roundhouse kick. It was carried out a multibody analysis on Taekwondo athlete movements during execution of the roundhouse kick using a virtual reference model with the standard human measurements (age: 30; height: 1720 mm; weight: 70 kg) [27]. In addition, driven by the boom in robotics, it has also been researched the use of robots in Taekwondo. It is interesting to study the possibility of designing robots that assist the athlete in his training, allowing more personalized training and without the need of any other person. Some ideas have already come to light, such as the prototype for the T.P.T. (Taekwondo Personal Trainer) robot, whose conceptual and functional design is already presented in [28]. Furthermore, this novel robotic platform can be integrated also in the context of other combat sports training. Or even better, these studies can be also integrated or used in other contexts with the foundations of Taekwondo, because this sport can offer some benefits to other aspects of our lives just only analyzing its methodologies. An example is the research done in [29], in which was used Taekwondo to design and develop humanoid robots with predictive behaviors that could be used in real life. Based on this martial art where anticipation and adaptation are key, we sought to design robots with approaches strongly based on the symbiotic interaction between the concepts of the embodied intelligence and simplicity that enables to reproduce the artificial body in symbiosis with its intelligence.

On the other hand, returning to the diseases in which sport training protocols are applied, these diseases have consequences that are reflected in a poor quality of life of the subjects who suffer from them, and there is a real necessity of reverting that situation. Some of the these studied disorders are Down Syndrome (DS), Autism Spectrum Disorder (ASD), and Developmental Coordination Disorder (DCD).

DS is the most recognizable genetic condition associated with intellectual disabilities. All cases demonstrate mental and physical changes to the body with adjoining affects regarding growth and physical development, medical problems and intellectual ability [30].

On the other hand, Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by deficits in social communication and interaction, restricted interests, and repetitive behaviors. Children with ASD often experience difficulties performing fundamental motor skills, such as walking, running, and jumping [31].

However, due to its spread and also being present in the other diseases, I am going to focus exclusively on DCD.

DCD is one of the most common motor disorder with a prevalence of approximately 6% in typical children of primary school age. They are characterized by marked impairments in motor functions, such as the following ones [32]:

- Lower maximal knee muscle strength and power
- Increased knee flexor and extensor co-activation
- Less steady force production
- Inconsistent timing of postural muscle activation
- Proximal to distal muscle activation patterns
- Increased and prolonged activation or co-contraction of the ankle muscles in standing

However, among the many sensorimotor problems found in children with DCD, one of the most serious and widespread is the poor balance capacity (previous studies have reported that 73% to 87% of children with DCD have postural control problems [32]). This not only interferes with their academic achievements and daily activities but also requires special attention because suboptimal balance ability may increase the risk of falls, limit activity participation, and affect motor skill development [33]. In addition, postural control relies on the central nervous system (CNS) to select and integrate sensory inputs from visual, somatosensory and vestibular systems and then generate appropriate motor outputs [26]. Analyzing these functions has an enormous difficulty, but due to its importance in the balance ability, it should not be overlooked.

That is why the maturation process plays an important role in this type of problems, so it has to be taken into account when the results are analyzed. Depending on each function, there are different maturation speeds and age ranges in which each of them develops. However, its precision it is not clear enough and it can differ depending on which source you consult. In [34] was investigated the development of sensory organization according to each sensory component in relation to age and sex, and it concluded that these are the ages in which an adult level is reached:

- Somatosensory function: 3-4 years old
- Visual function: 15-16 years old
- Vestibular function: 15-16 years old

Nevertheless, in [26] are mentioned different results that confirm the difficulty of the analysis:

- Somatosensory function: 9-12 years old
- Visual function: 7-10 years old
- Vestibular function: 7 years old

In order to fight against these problems and try to find a solution related to the sport, different methodologies of training have been tested aim to observe if they can be useful and applied on subjects suffering from these types of diseases, so that they can improve their quality of life.

In 2.1 can be observed a resume of the main studies that I have analyzed, organized by type of disorder and sport methodology applied. In general, the results that have been obtained are positive, with the following improvements:

- Balance performance improvement
- Somatosensory function improvement
- Isokinetic knee muscle strength at 180^{o}/s improvement
- Static single-leg standing balance control improvement
- Eye-Hand Coordination movement time improvement

It is possible to divide these studies into two basic types depending on the type of training: functional and non-functional training. The latter focuses on the muscle, stimulating it to obtain hypertrophy. It involves all the specific training that are normally performed using a machine to activate one or more muscles with a specific movement repeated over time. For example, isokinetic training is a type of strength training and it uses specialized exercise machines that produce a constant speed no matter how much effort you expend. These machines control the pace of an exercise by fluctuating resistance throughout your range of motion. It helps to control muscle development, increase muscle flexibility, and improve balance and coordination. In [35] 2 groups of people with Down Syndrome were tested: one group of DS-affected children with conventional physical therapy (control group), an other one who performed an isokinetic training (DS-iso). The results were the following:

- Both groups showed improvements in postural balance (static and dynamic), but DS-iso improved more.
- Both groups showed a higher peak torque of knee flexors and extensors, but DS-iso improved more.

On the other hand, functional training focuses on the movement, training a specific task which is desired to improve. This training not only improves the performance of that specific task, but also the muscles that are involved in the execution of it. Putting the focus on this last type of training, I am going to analyze in detail the studies that tested the Taekwondo training because it is an interesting sport in which many kicking techniques are used that involve unilateral standing postures, in which balance is crucial.

In general, the studies that used Taekwondo methodologies as method of training confirmed the sport as an important tool to improve the balance ability in children.

In [36] were studied 3 groups of people with DCD that showed isokinetic peak torque improvements and a lower Centre Of Pressure (COP) sway velocity at single-leg stance using the Unilateral Stance Test (UST). Static single-leg standing balance control is inferior in children with DCD, this could be attributed to the fact that DCD-affected children are less reliant on visual and vestibular inputs to maintain balance [36], and may be over-reliant on the hip strategy to achieve balance. Some possible explanation could be: **(1)** TKD training can improve the vestibular function that provides the most reliable sensory information for postural control; **(2)** similar to karate-trained athletes, TKD-trained children might have more effective cerebral mechanisms for integrating somatosensory, visual and vestibular inputs; therefore, they experience slower body sway while standing; **(3)** TKD-trained children might have developed better postural adjustment strategies and body alignment while practicing kicking or single-leg standing; and **(4)** their improved postural stability in a unilateral stance is associated with improved isokinetic knee extensor muscle strength (at 180º/s only, but not at 60º/s or 240º/s due to the specificity of TKD muscle training) as demonstrated in [36]. However, there were not important changes in Motor Control Test (MCT) composite scores. MCT represents the total reaction time between the onset of platform translation and the initiation of force response in the legs. It can be divided into two time periods: premotor reaction time and electromechanical delay.

Premotor reaction time represents latency between the start of platform translation and the onset of lower limb muscle reflex contraction (which can be detected by electromyography). It denotes the speed of neural transmission and information processing in the central nervous system. In contrast, electromechanical delay (i.e., the interval between the onset of electromyographic signals and force production in the legs) reflects the neuromechanical properties of muscles. It is mentioned that premotor reaction time in children with DCD is as short as that in typically developing children. Therefore, electromechanical delay should also be similar between children with and without DCD, giving them similar total reaction times. In other words, DCD itself may not affect the neuro-mechanical properties of children's muscles.

Besides, the Taekwondo protocol that was tested in [37] demonstrated that DCD-affected children who had followed it had a better skeletal development, higher Movement Assessment Battery for Children (MABC) scores (overall motor performance), and a better Eye-Hand Coordination (EHC) in terms of movement time. However, EHC reaction time and accuracy did not experiment changes. EHC movement time is a measure of the biomechanical delay required to generate sufficient muscle force to complete a finger-pointing task. Thus, this result reveals that training in TKD could probably shorten the biomechanical delay in generating muscle forces in the upper limbs. On the other hand, no changes were observed in static bipedal standing balance performance (mCTSIB test). This could be attributable to the fact that testing static balance in a bipedal stance on a force platform was not sufficiently challenging to reflect the participants' actual balance ability.

As I mentioned before, the consequences of the DCD are presented also in some other diseases, such as Down Syndrome and Autism Spectrum Disorder. Because of that, other studies in which a Taekwondo protocol has been applied have been carried out. On the one hand, DS children have experimented great improvements in lower body strength and in static (mCTSIB test) and dynamic balance (LOS test) [38].

These good results can be confirmed also in ASD-affected children, in which the Taekwondo protocol has demonstrated to improve their single leg stance balance both with eyes closed and opened, and their double leg stance balance and step-quick-turn over the long-term [31].

Paper	Type of disorder	Age of Refer-ence	Assessment	Sport	Results
[32]	DCD	6-9	Standing balance; Sensory organization; Motor control strategy	-	Low composite equilibrium scores; Low visual and vestibular ratios; Rely on vestibular signal primarily -> Tend to use hip strategy excessively; No changes in somatosensory functions; Small external perturbation -> ankle strategy; Larger and faster perturbation -> hip strategy
[33]	DCD	6-11	Postural control strategies; Sensory organization of balance control; Lower limb muscle performance	-	Bad postural control strategy; Low speed of muscle force production; Bad sensory organization; Slowness to generate knee flexor muscle torque and poor visual and vestibular function -> High use of hip strategy in sensory challenging environment
[36]	DCD	6-9	Isokinetic knee muscle strength; Reactive and static balance control	TKD (12 weeks, 1 session/week + daily exercises at home)	Improvements in isokinetic knee muscle strength 180^o/s; Improvements in static single-leg standing balance control; Non changes in reactive balance control
[39]	DCD	6-9	Sensory organization; Balance and motor proficiency	FMT (12 weeks, 1 session/week)	Improvements in somatosensory; Improvements in balance performance: balance and motor proficiency, and static single-leg standing

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Paper	Type of disorder	Age of Reference	Assessment	Sport	Results
[37]	DCD	6-9	Skeletal development; Motor performance	TKD (12 weeks, 1 session/week + daily exercises at home)	Better skeletal development; Improvements in Eye-Hand-Coordination movement time; Improvements in overall motor performance; No changes in static bipedal standing balance
[40]	DCD	7-9	Static and dynamic balance	Strength training (12 weeks, 2 sessions/week)	Improvements in muscle strength; Improvements in static balance; No changes in dynamic balance
[41]	DCD	6-10	Balance strategies; Neuromuscular performance: Sensory organization; Knee muscle peak force; Time to peak force	Functional Movement-Power Training (FMPT); Functional Movement Training (FMT) (12 weeks, 2 sessions/week)	FMPT: Better balance strategies; Higher knee extensor peak force; More time to peak force in knee flexors / FMT too, but less
[38]	DS	21-30	Lower body strength; Balance	TKD (10 weeks, 2 sessions/week)	Improvements in lower body strength; Better static/dynamic balance
[30]	DS	5-21	Different training interventions and their effectiveness	Dance, virtual reality games, two-wheel bicycles, strength and agility, balance and stability	Better quality of life; They need modifications and adaptations

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Paper	Type of disorder	Age of Reference	Assessment	Sport	Results
[42]	DS	14-17	Muscle strength; Physical functions (upper and lower limbs)	Resistance training (10 weeks, 2 sessions/week)	Improvements in lower limb strength; No changes in upper limb muscle strength; No changes in physical functions
[35]	DS	9-12	Muscle strength; Postural balance	Isokinetic training (12 weeks, 3 sessions/week)	Better postural balance; Higher peak torque of knee flexors and extensors
[43]	DS	14-22	Work task performance; Physical activity level	Resistance training (10 weeks, 2 sessions/week)	Improvements in upper and lower limb muscle strength; No changes in work task performance
[44]	DS	Group 1: 7-13; Group 2: 17-20	Balance; Coordination; Agility	Vestibular stimulation (6 weeks, 2 sessions/week)	Both groups: Better upper limb coordination and agility; No changes in overall balance; No changes in bilateral coordination / Group 2: Long-term balance improvements
[31]	ASD	8-13	Static balance (double/single leg stance); Functional balance (step-quick-turn)	TKD (8 weeks, 2 sessions/week)	Better single leg stance balance; Long-term balance improvements in double leg stance (unstable surface, eyes closed); Long-term step-quick-turn improvements

TABLE 2.1: Top studies

2.3 Methodology of Training: TKD

But not all Taekwondo protocols tested were the same. They differed in duration, intensity, and the type of movements that are trained. However, the structure uses to be the same: there is a first phase of warm-up in which the participants perform light aerobic exercises and joint movements, so that the body is prepared to perform more demanding and specific exercises. This part often lasts about 10-15 minutes.

Afterwards, the main part of the training begins, in which basically the exercises that are carried out encompass punches, blocks and kicks. These different movements can be combined in different ways, such as single and double punches. Besides, pads and blockers can also be added and used with a colleague. It may also contain other different calisthenics exercises such as push-ups, sit-ups and planks. This part does not have a fixed duration, it can vary, occupying always the main part of the training.

Finally, a cool-down part in which heart rate drops is carried out, with low-rate jogging and strechings. This part usually lasts about 5-10 minutes.

In 2.2 I have summarized all the Taekwondo protocols studied.

Paper	Sample	Duration	Exercise	Intensity
[37]	36	12 weeks; 1*60 min/week + TKD home exercises (the same ones)	Warm-up	5 min
			Streching	5-10 min
			Body punch	5-10 min
			Blocking techniques	15-20 min
			Kicking techniques	5-10 min
			Body punch	15-20 min
			Cool-down and stretching	5 min
[38]	22	10 weeks; 2*60 min/week	Warm-up	10 min
			Line Drills	15 min
			Pad Drills	15 min
			Calisthenics	10 min
			Streching	5 min
			Cool-down	5 min
[31]	8	8 weeks; 2*50 min/week	Warm-up	10 min
			Blocks and Body Punch	10 min
			Kicking	10 min
			Poomse	10 min
			Streching	5 min
			Cool-down	5 min
[36]	21	12 weeks; 1*60 min/week + TKD home exercises (the same ones)	Warm-up	5 min
			Streching	5-10 min
			Body punch	5-10 min
			Blocking techniques	15-20 min
			Kicking techniques	5-10 min
			Body punch	15-20 min

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Paper	Sample	Duration	Exercise	Intensity
			Cool-down and stretching	5 min
[39]	47	12 weeks; 2*90 min/week	Two-leg balance on foam with electromyographic biofeedback	10 min
			One-leg balance on ground (alternate feet): Not beyond muscle fatigue	5 min
			Walking in a straight line with heels raised	5 min
			Double-leg hops	5 min
			Ball balance while walking	5 min

TABLE 2.2: Protocols of TKD training

So the interesting part of the protocols is the main one, in which the characteristic Taekwondo exercises are performed. In order to understand better what type of movements were done, I am going to explain them in detail.

2.3.1 Blocking Techniques

Blocking techniques can be split into four types:

- Rising block
- Outside/side block
- Inside block
- Down block

They can be done with a single arm or alternating them, with or without pads. Besides, some blocks are also done with kicks.

2.3.2 Kicking Techniques

Kicking techniques can be basically split into five types:

- Front kick

- Slide back front kick
- Roundhouse kick
- Side kick
- Back kick

They can be done with a single leg or alternating them, with or without kick pads.

2.3.3 Drills

They are conditioning exercises aimed to develop speed, agility and quickness. Since during play athletes are frequently required to start, stop, and change direction and speed, they simulate real situations to adapt the body to these possible future movements. They are also known by increasing body control and awareness.

- Line Drills: they were done in unison as a group, all lined up in a row
  - Punching: singles and doubles
  - Blocking: high, side and low
  - Kicking: front
- Pad Drills: in this case, they were done with pads held by the instructor, adding different forces and stimulus
  - Front kick with pads
  - Slide back front kick
  - Blocking drills with soft blockers
  - Blocking drills with front kick

High-impact striking techniques (e.g., punching and blocking) might stimulate bone growth, whereas the kicking and striking focus mitt practice might improve balance control and eye-hand coordination.

2.3.4 Calisthenics Techniques

Calisthenics is a form of exercise consisting of a variety of free body exercises performed with varying degrees of intensity and rhythm, which may or may not be done with light handheld apparatuses such as rings and wands. Calisthenics provide the benefits of muscular and aerobic conditioning, promoting strength, endurance, flexibility, and augment the body's general well-being by placing controllable, regular demands upon the cardiovascular system. Besides, it can improve psychomotor skills such as balance, agility and coordination [45]. The following exercises were those carried out in [38]:

- Sit-ups
- Push-ups
- Planks

2.3.5 Poomse

Also known by *Poomsae* or *Pumsae*, it is a defined pattern of pre-arranged defense-and-attack motions that consists of the various fundamental stances, blocks, punches and kicks logically arranged in a meaningful order in response to attacks from multiple imaginary assailants. A set of these movements is called *Taegeuk*, and each movement or Poomse is numbered. In [31] were trained in two sets of Poomse:

- Poomse 1-8
- Poomse 10-16

Chapter 3

Description of the Study

Summary

In this chapter will be described the design adopted by this research to achieve the aims and objectives stated in 1.

In particular, it is described in detail the procedure followed to firstly choose the movements that represent as faithfully as possible the Taekwondo training methodologies used in the studies, then the configuration of OpenSim that has been done, and finally the different analyses that have been performed.

3.1 Taekwondo Movements

It is clear that Taekwondo can offer important benefits to the people suffering from disabilities related to motor impairments, specially balance and coordination disorders. These people however have difficulties to practice this sport, not only because they usually depend on others to attempt to the lessons, but also because it may be convenient to practice it in a individualized way or in groups adapted to their needs. Because of that, I want to study the Taekwondo methodology of training in order to find out why practicing this sport, their balance and coordination capabilities improve. To do that, I am going to analyse which are the specific muscles that are activated when some specific Taekwondo movements are performed. Besides, it is also interesting to study the extent of each muscle's contribution, and the order of activation. In that way, it will be possible to reproduce a completely Taekwondo training and benefit from its advantages easily and without too effort.

However, it is difficult to say in a precise way which are the specific Taekwondo movements that truly cause an important improvement in the balance ability. Firstly, because balance ability is the result of a composition of different functions that depend on different inputs. Furthermore, the Taekwondo training is based on a vast variety of exercises which are not isolated, such as a specific kick, which is a result of different postures and movements. Nevertheless, it is possible to find some situations which are usually presented in the majority of movements. Taking into account the results of the studies that are more related to the balance ability and the description of the Taekwondo protocols that were tested in them, it is possible to find some common exercises that can be responsible of these positive results. The improvement of the ability of keeping in a single-leg stance over time, which is usually tested by the UST, it is a key result. It is highly related to an improvement in balance, and this was observed in [36] and [31]. In these both studies were used the following exercises:

- Punchs & Blocks
  - Upper
  - Down
  - Inside
  - Outside
- Kicks
  - Front
  - Side
  - Roundhouse

Between all these movements, the kicks are more likely to have more relation to the single-leg stance ability. These movements are not completely presented in every single study, but they are some of their postures. Since the more common positive result among the studies is related to the static balance (single-leg stance tested by UST) and these common poses among the studies could be represented by an static posture, it is reasonable to study the static balance within the Taekwondo methodology of training.

Due to its simplicity, I am going to test two main Taekwondo kicks that are presented in almost every single level of protocol: front kick and side kick. These movements are going to be studied in a static way, splitting them into two phases: the initial position in a single-leg stance and with the other leg raised and ready to execute the movement (phase 1); and the position in which the kick has just been executed, with the execution leg straight (phase 2). Besides, an analysis has been added which was carried out at the beginning on the front kick in a dynamic way, but which has resulted of the scope of the project and has not been further deepened in this.

In addition, in order to add more complexity to the study and thus allow the results to be less biased, I am going to add additional external forces. This will also create more realistic situations, since in the real world there are external forces that are beyond our control and they generate imbalances.

All these analyses have been performed using OpenSim, a free open-source software system aimed at developing musculoskeletal structure models and to create static and dynamic simulations of a wide variety of movements [46]. It offers different tools which I have been able to use to analysis these static postures and to obtain information about the muscles that are involved.

3.2 OpenSim inputs

These different analyses that I have performed require different inputs, depending on each one. In the following sections I am going to explain in detail every single input that I have used.

3.2.1 Model

First of all, I had to choose a proper musculoskeletal model in order to use it in the simulation. This one had to meet different requirements:

- Being a scientifically validated model
- Meeting the standard being human measurements
- Being enough complex in lower body extremities, i.e. enough number of significant muscles

Finally, taking into account these premises, I chose one model from the OpenSim catalog that is called *Gait 2354*, which can be observed in 3.1. It is a three-dimensional model with 23 degrees of freedom which features 54 musculotendon actuators to represent 54 muscles in the lower extremities and torso. It is a simplification of the *Gait 2392* model in order to improve simulation speed. For example, the patella is removed to avoid kinematic constraints, and insertions of the quadriceps are handled with moving points in the tibia frame [47].

By default, the unscaled version of the model is 1.8 m tall and it has a mass of 75.16 kg. In my opinion, this model is perfectly able to represent faithfully enough the reality and to offer a significant number of muscles, being possible to analyze accurately the results.

3.2.2 Inverse Kinematics

Inverse Kinematics (IK) is the mathematical process of recovering the movements of an object in the real world by capturing its angles and positions per each time frame. This is done using some other data, such as a film of those movements. In OpenSim this process is performed by the IK Tool, which uses experimental data as input and whose output is a *.mot* file with all the joint angles of the model per each time frame. To do that, the IK Tool determines the model generalized coordinate values (joint angles and translations) that best reproduce the raw marker data obtained from motion capture [47].

Since I did not carry out this initial process, I have recreated these poses and movements by using one default IK's output *.mot* file. To do that, I have changed its values per each joint angle and time frame until reaching the desired pose, being that a realistic recreation of the real movements.

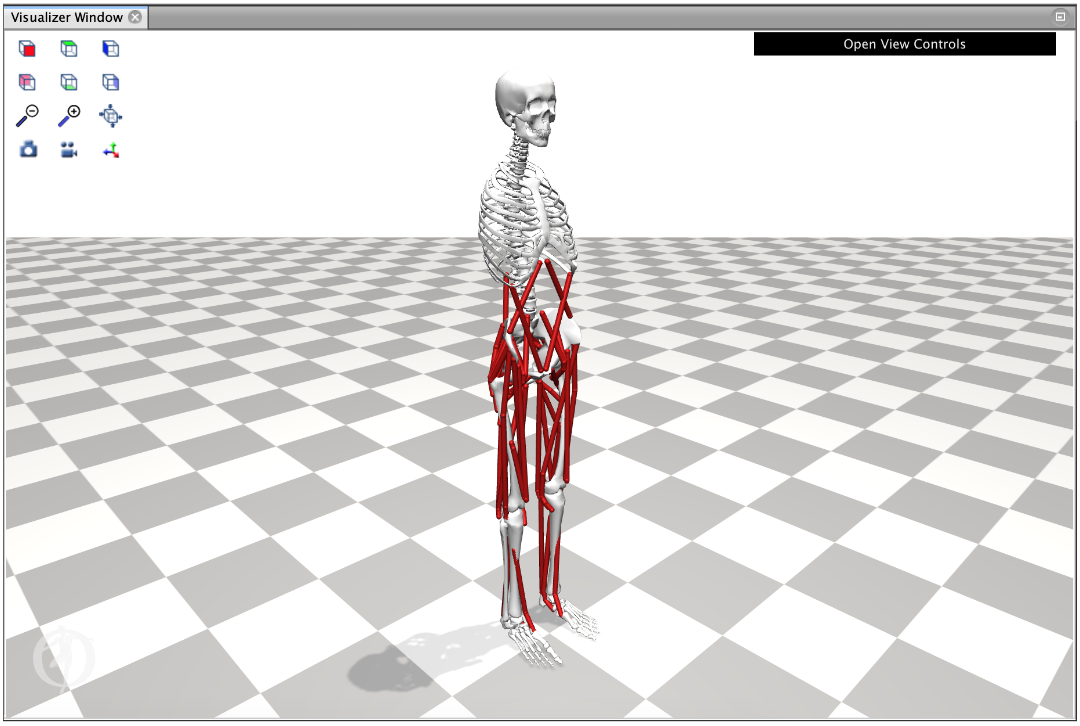


FIGURE 3.1: OpenSim Gait2354 Model

Consequently, different *.mot* IK files have been created, each of which representing one of the analyzed movements: front kick in phase 1, front kick in phase 2, side kick in phase 1, side kick in phase 2, and dynamic front kick. These files will belong to the inputs of the analyses to be performed. The movement sequence of the front kick dynamic can be seen in A.

3.2.3 External Forces

In addition to the IK *.mot* file, it is also important to provide the external forces that are involved in the real movement. One of the most important are the different forces that arise in the ground as a consequence of the weight of the model itself, as well as other torques due to the rotational movements. As it can be observed in 3.6, the forces are modelled as vectors and will be applied to the Center of Mass of the soles of the feet. In this type of file, they are labelled following this pattern (for the right foot):

- *ground_force_v* : Magnitude in N of the forces per each coordinate axis. For example, for the axis X: *ground_force_vx*
- *ground_force_p* : Position of the forces per each coordinate axis. For example, for the axis X: *ground_force_px*
- *ground_torque_* : Magnitude in Nm of the torques per each coordinate axis. For example, for the axis X: *ground_force_x*

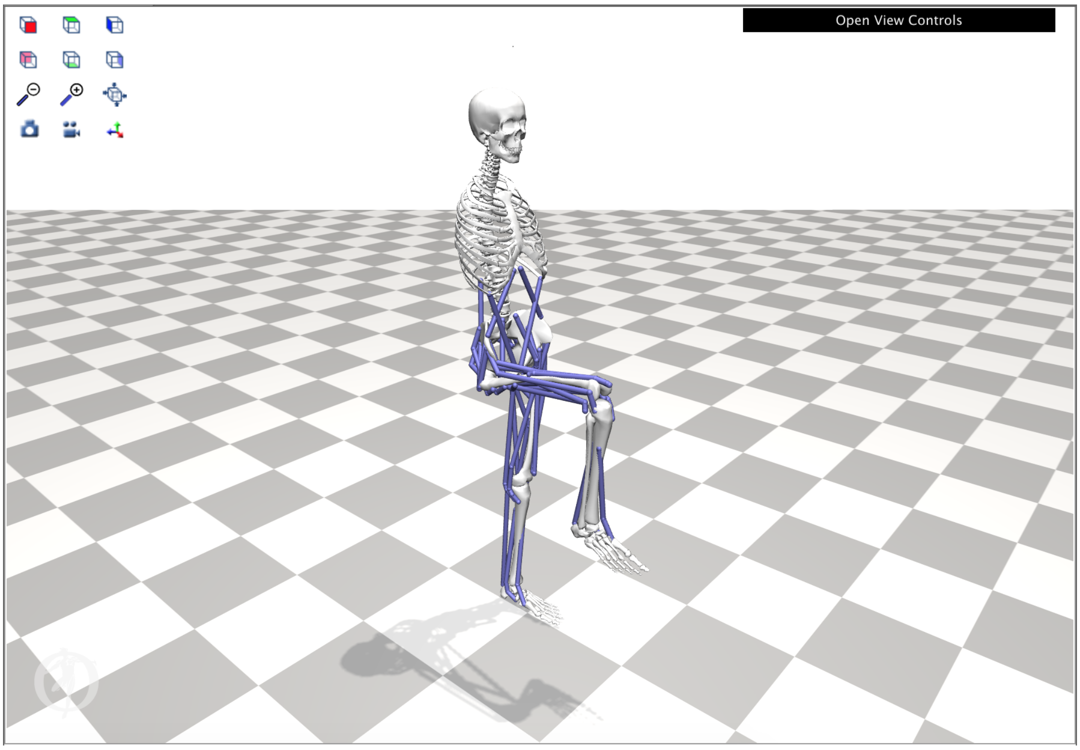


FIGURE 3.2: Front Kick pose in phase 1

Besides, in order to add to my analyses different situations that may enrich it, I have added other disturbing external forces that recreate a situation of greater imbalance on the subject. These are pushing forces applied to the head of the left femur (supporting leg) from four different points. Their force vectors are located on the XZ plane and follow the orientation of these axes, with both positive and negative senses. They thus generate forces that follow a symmetrical pattern: it starts to be generated in the second 0.2 until reaching its maximum in 0.5 seconds. Then it gradually decreases until 0.8 seconds. In the file, they are labelled following this pattern (for the force following the Z axis, in positive sense):

- *push_Zpositive_v* : Magnitude in N of the forces per each coordinate axis. For example, for the axis X: *push_Zpositive_vx*
- *push_Zpositive_p* : Position of the forces per each coordinate axis. For example, for the axis X: *push_Zpositive_px*

In 3.7 and 3.8 are represented these pushing forces in a two-leg stance pose of the model at two different points: at the beginning when the forces have not been applied yet and at an advanced point.

In addition, I used different magnitudes to observe how the activation patterns behave depending on it. To do that, I selected three different intensities:

- 50N: a force less than the mass of the model (~70 kg)
- 100N: a force slightly superior to the mass of the model (~70 kg)
- 150N: a force almost twice as great as the mass of the model (~70 kg)

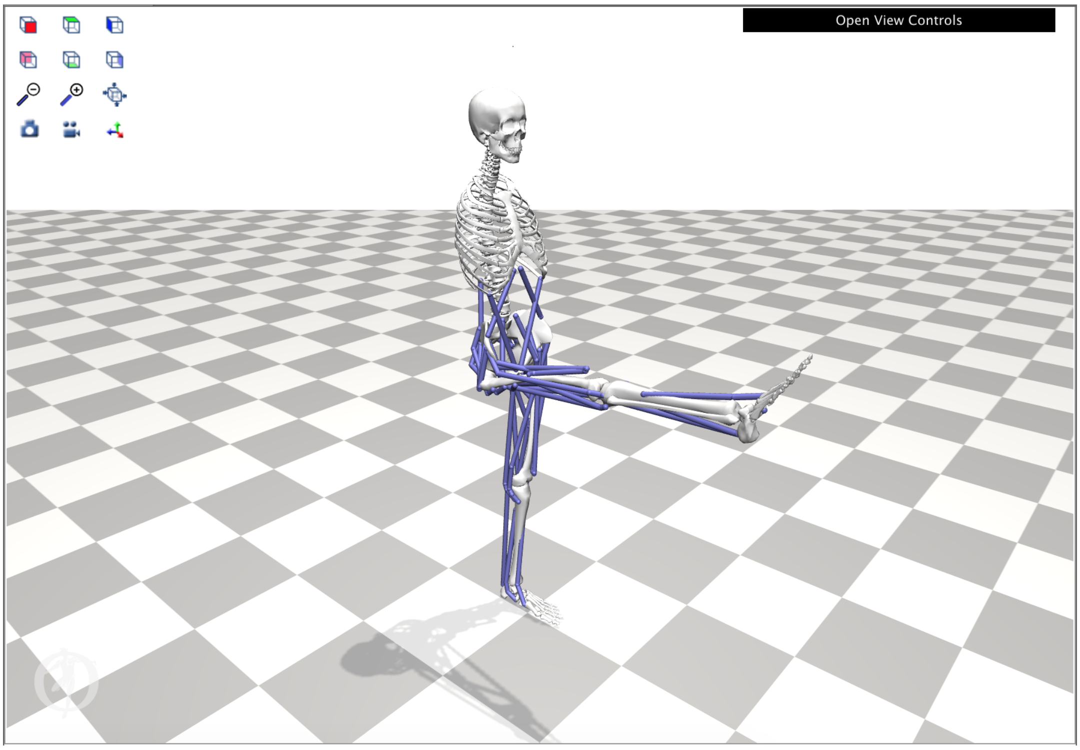


FIGURE 3.3: Front Kick pose in phase 2

These three components (model, kinematics and external forces) are going to be the main inputs of the analyses to be carried out.

3.3 Inverse Dynamics (ID)

Inverse Dynamics is the OpenSim tool which solves the problem of determining the net forces and torques in each joint responsible for a given movement by inversely resolving the classical expressions of movement and the relationship between force and acceleration [48]. It helps me to figure out the magnitudes of the ground forces which are necessary to satisfy the Newton's 3^{rd} Law: for every action there is an equal and opposite reaction. The output forces and torques of the pelvis joint account for discrepancies between the model, experimental motions and external forces (for example, *pelvis_tx_force* and *pelvis_tilt_moment* respectively), so these values should be around zero. To achieve that, I perform firstly the Inverse Dynamics analysis without adding external forces, then I observe what are the magnitudes of the forces and moments that create discrepancies, and finally I edit the external forces file to adjust these differences and perform again the ID analysis with the external forces files to check it.

3.4 Static Optimization (SO)

This tool is an extension of the Inverse Dynamics one that takes into account the position of the model, its velocities and accelerations to obtain individual muscular

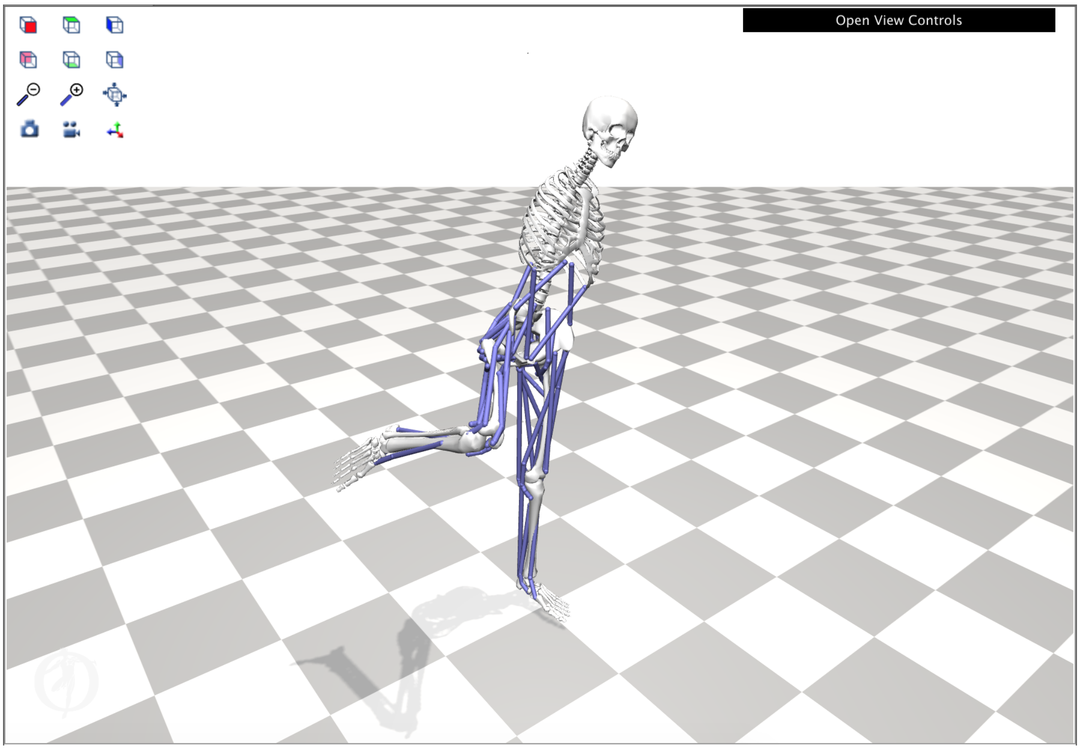


FIGURE 3.4: Side Kick pose in phase 1

forces for each time instant, which are obtained by minimizing the energy of muscular activations [48]. Since its function is to analyze different kinematics through a discrete process in time and our simulations are performed on static poses, it perfectly meets the requirements of our study and it will be used to carry out the analyses of the static postures.

3.5 Residual Reduction Algorithm (RRA)

The RRA tool is applied to make the model's generalized coordinates (joint angles and translations) computed with the IK tool more dynamically consistent with the measured ground reaction forces and moments analysis [46], resulting in the reduction of the residual forces. In order to do that, I followed the following process:

1. Making a first RRA analysis with default inputs
2. If RRA analysis is failing, trying to increase the maximum excitation for residuals by orders of magnitude until the simulation runs, then trying working the way back down
3. Checking tracking errors and residuals forces
4. Either decreasing or increasing tracking weights on coordinates with low or high errors, respectively. Tracking weights are relative
5. Decreasing the actuator optimal force as close as possible to 1 without making RRA analysis fail

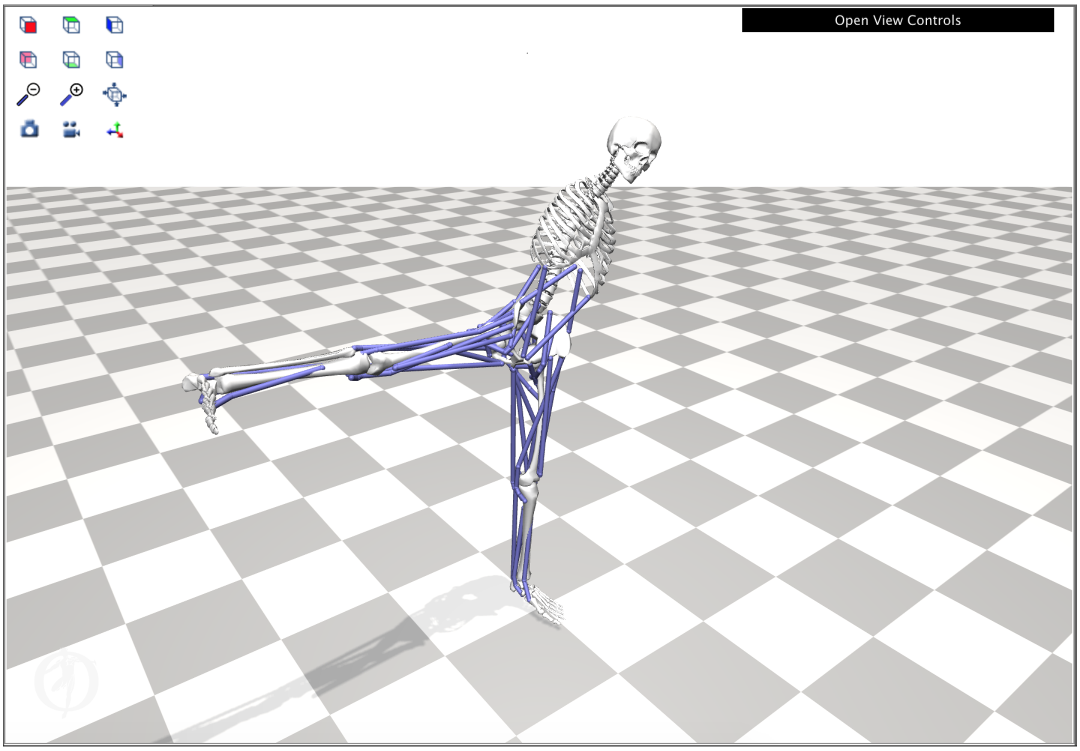


FIGURE 3.5: Side Kick pose in phase 2

3.6 Computed Muscle Control (CMC)

The CMC tool is intended to calculate a set of muscle excitations (or, more generally, actuator controls) that will drive a dynamic musculoskeletal model to track a set of kinematic positions in the presence of applied external forces (if applicable) [48].

It uses a static optimization criterion to distribute forces across synergistic muscles and proportional-derivative control to generate a forward dynamic simulation that closely tracks the kinematics derived in the RRA analysis. Although a static performance criterion is used, the full state equations representing the activation and contraction dynamics of the muscles are incorporated into the forward dynamic simulation [47]. That is why CMC will be used only in the dynamic front kick movement, since it doesn't make sense to use it in a static analysis.

In order to do the CMC analysis, different setting files have to be added to the input flow in addition to the three ones already mentioned before.

3.6.1 Tracking Tasks

The tracking tasks file specifies which coordinates to track and the corresponding tracking weight (weights are relative and determine how "well" a joint angle will track the specified joint angle from RRA or kinematics) [47]. Assuming that every single coordinate of each joint are equally well designed, I have assigned the same tracking weight to all of the joints: 1.

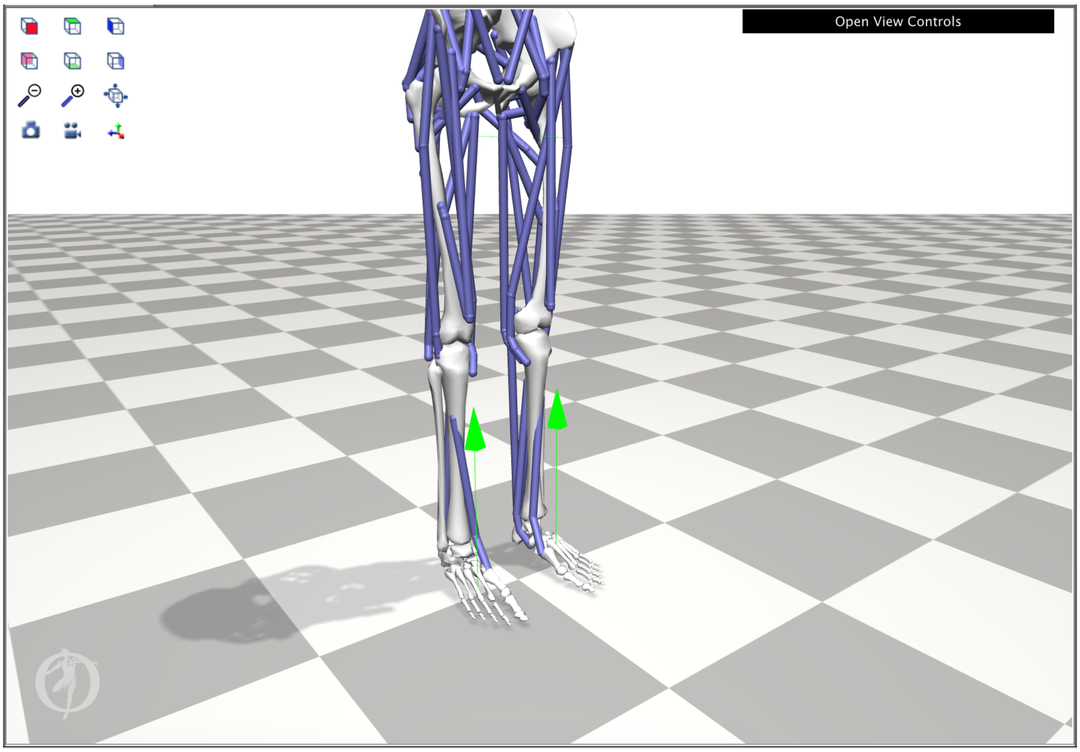


FIGURE 3.6: External Ground Forces

3.6.2 Actuators

The actuators file contains the residual and reserve actuators as well as torque actuators. Reserve actuators, which are the actuators on the coordinates, can add extra actuation during portions of the movement where muscles are not able to generate sufficient accelerations (e.g., during a spike in acceleration) [46]. It is mandatory to add one reserve actuator per each joint that is represented by the model.

On the other hand, residual actuators are "hand of God" forces that account for (what should be small) discrepancies between the model, experimental motions, and external forces; in other words, these actuators ensure that Newton's 2^{nd} law, F=ma, is satisfied throughout the analysis [46]. In this case, there are three actuators, each one per axis, directly applied to the Center Of Mass of the pelvis.

Finally, since in this particular model there are no muscles that control lumbar flexion/extension (trunk motion in general) and consequently all the other lower limb muscles have to take care of it, torque actuators have to be added, each one per axis, at the lumbar joint in order to support this function and avoiding in this way biased results [46]. Since the model is designed hierarchically, its first free joint is the ground-pelvis joint, which these torque actuators are applied to.

These actuators have different parameters that have to be taken into account, but the most important is the labelled *optimal_force*, which is in charge of indicating what is the optimal force of each actuator. This parameter will be multiplied by the activation number to obtain the applied force. If the optimal force value is big, when trying to minimize the sum of activations squared, the optimizer can use small activation values to generate large forces. However, if it is small, the optimizer must

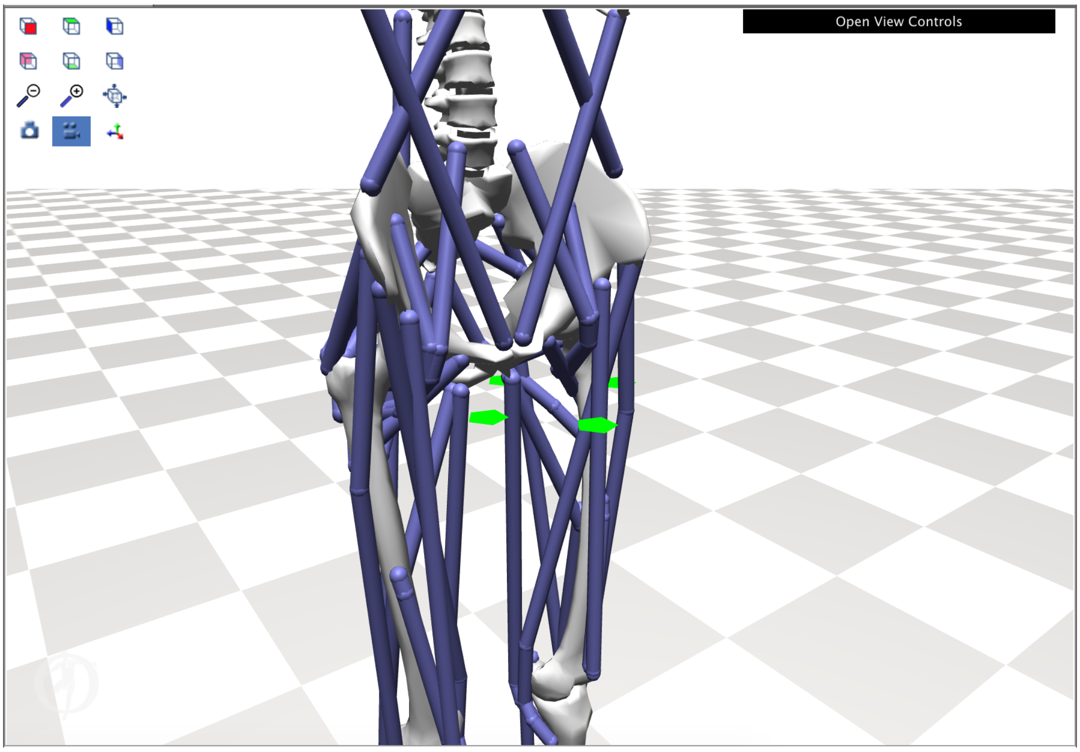


FIGURE 3.7: External Pushing Forces at the initial point

use very high activations to produce any meaningful forces. So when the optimal force is very low (~1 N) the optimizer can still choose to use the actuators, but the cost is so high that it will only use them when needed [47]. The smaller the optimal force parameter is, the more significant will be the activation value, so I assigned the value 1 N to every single actuator.

3.6.3 Actuators Constraints

This file contains limits on muscles, reserves and residuals actuators that will act on the model. These limits are expressed as the maximum and minimum excitation or control signal that can be applied on each actuator. They expressed basically the range in which they can operate.

3.7 Comparison between SO and CMC

These two methods have been applied in 4.6 to the same kinematics with exact conditions in order to analysis the same: muscle activations. However, the results differ between them, so I am going to try to explain it and give some reasons about why this can be possible.

We have to take into account that both methods are built based on different assumptions. CMC sacrifices execution time and complexity, both of which are far greater, at the expense of offering a solution with both smooth activations and state

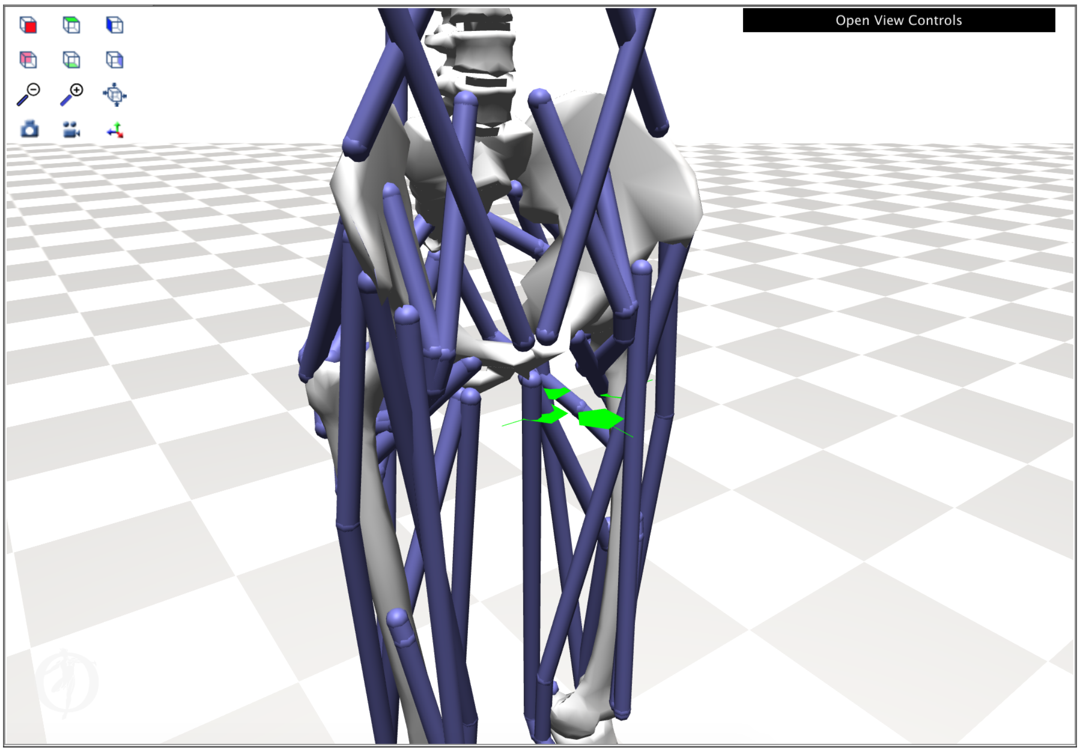


FIGURE 3.8: External Pushing Forces at an advanced point

profiles. This is done performing integration to advance the system through time, using the "look ahead window" parameter and allowing to anticipate the activation of the muscles before the event happens as long as it falls within the "look-ahead window".

On the other hand, SO performs its algorithm frame-by-frame, obtaining the muscle activations and forces that produce the Inverse Dynamics solution per each time instant. It is much faster in terms of execution time, but has the disadvantage of being the solution not as much smooth as CMC, neither are states and the sampling is much sparser than CMC (only computed for specified frames rather than from integration). It is usually used to figure out general trends and/or bounds on activation/forces in a quasi-static sense.

Therefore, both analyses are valid and can offer a great deal of help to the researcher, but it has to be him who decides which one better fits the purpose of the research.

Chapter 4

Simulation on OpenSim

Summary

Here in this chapter are presented the different results that have been obtained after performing the analyses using OpenSim. These results are organized in different sections which each [ht]one corresponds to one of the different postures that have been analysed. Besides, as I said before, the results about the analyses of the Front Kick Dynamic are also added.

4.1 Two-Leg Stance

First of all, in order to know which are the specific muscles that are activated due to the Taekwondo posture, I am going to analyse a static two-leg stance posture. In this way, I will be able to compare this normal pose to those specific of the Taekwondo and observe the differences. In 4.1 can be observed how the vast majority of the muscles are below the value 0.1 of activation, the 10% of the normal ratio, which in my opinion their activation is almost negligible in this posture. Just only four set of muscles are above this threshold (from highest to lowest activation value order):

- Left/right medial gastrocnemius (*med_gas_l/r*)
- Left/right bicep femoris long head (*bifemlh_l/r*)
- Left/right gluteus medius 1 (*glut_med1_l/r*)
- Left/right bicep femoris short head (*bifemsh_l/r*)

Although their activation values are not too high, they are enough to be considered and this information may be useful in the next analyses.

4.2 Front-Kick phase 1

I am going to study the front kick in its initial phase, in which, with a single-leg stance, the right knee reaches its highest point and its flexion is maximum.

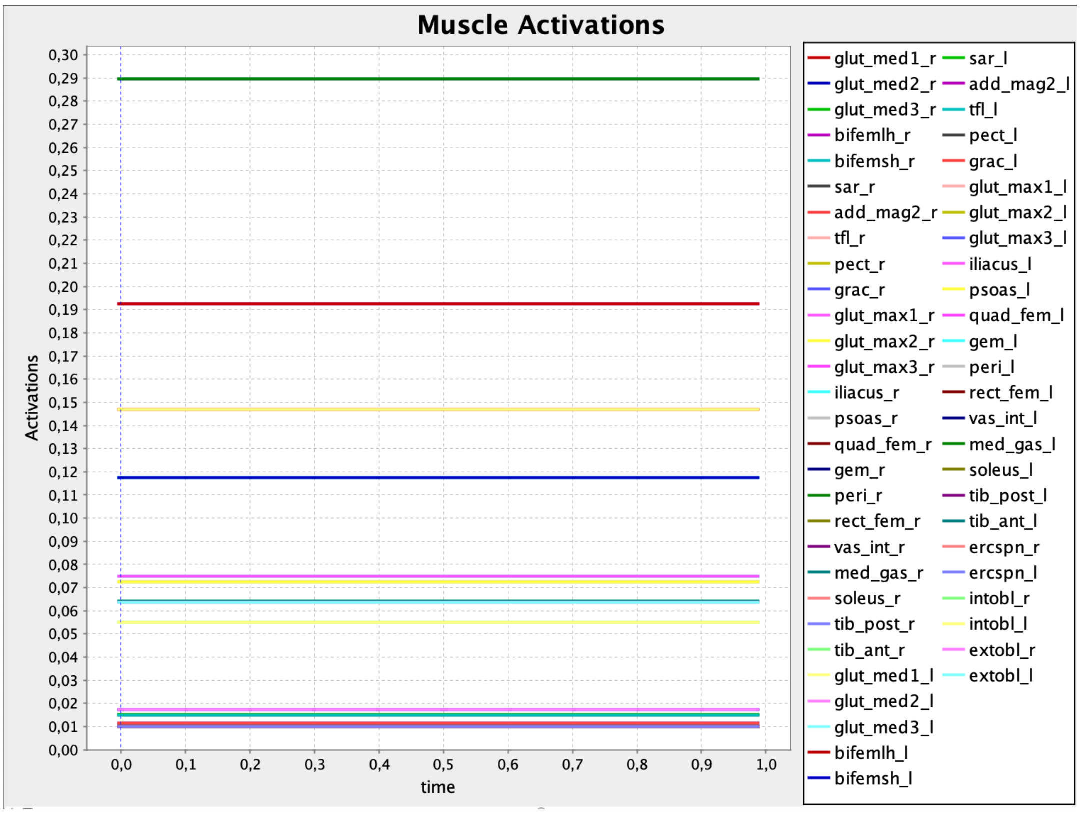


FIGURE 4.1: Two-Leg Stance with ground forces, SO analysis, Muscle Activations

4.2.1 Inverse Dynamics

Once the Inverse Dynamics analysis without adding external forces is done, ground forces can be adjusted properly. In 4.2 can be observed the forces and the moments that account for discrepancies between the model, experimental motions, and external forces. For example, *pelvis_ty_force* has a value of 737.113 N, which is the magnitude that I have to adjust in the external forces file, specifically in the component Y of the ground force vector for the left foot. Once the external forces file is edited with the rest of the values, I can perform again the ID analysis adding now the file, and the output that I obtain can be observed in 4.3, in which the values are closer to zero, which is ideal.

4.2.2 Static Optimization

Without perturbations

First, it is important to describe the muscles which are activated because of only the Taekwondo posture. I consider an activation value of 0.30 a good threshold, not only because it is a low value if it is compared to the values in 4.1 in which 0.29 is the maximum activation in a low-demand posture, but also because below it the activated muscles are more concentrated and they lose significance, as it can be observed in 4.4.

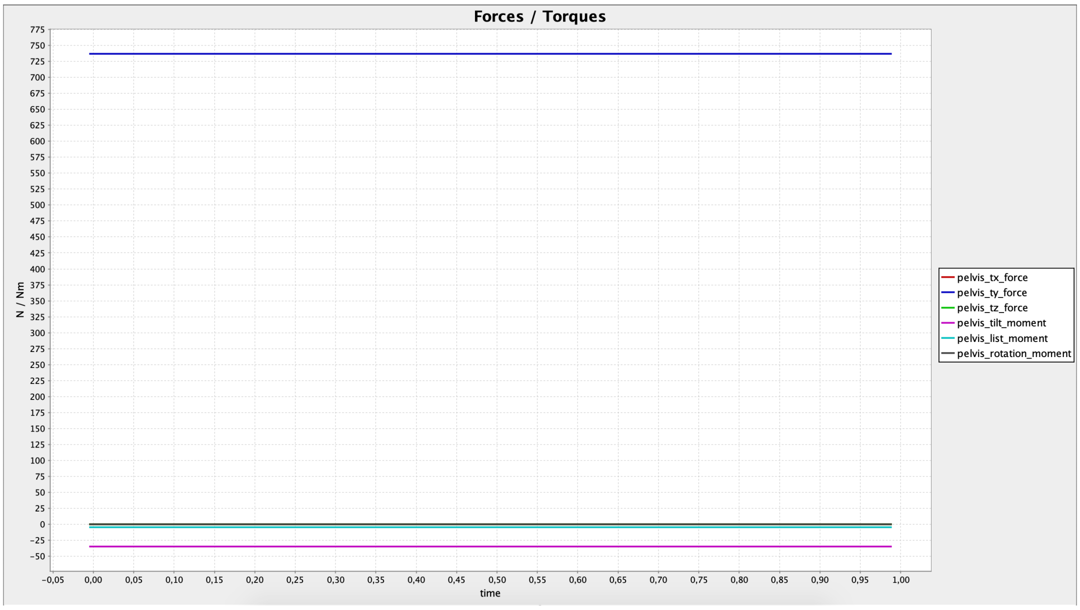


FIGURE 4.2: Front Kick phase 1 without ground forces, ID analysis

In this case, the following muscles have an important activation value (from highest to lowest activation value order):

- Right sartorius (*sar_r*)
- Right bicep femoris short head (*bifemsh_r*)
- Right iliacus (*iliacus_r*)
- Right rectus femoris (*rect_fem_r*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)

On the other hand, I am going to study also the muscles which are intended to maintain the posture, and consequently the balance, when some extra external forces come into play. These forces will be generated from four different points and with different intensities, as it is explained in 3.2.3. First, I am going to do these analyses with a pushing force of 100 N.

Z+ perturbation

When this extra force is added, there are some muscles that try to maintain the posture, thus these ones have a special importance in terms of balance. Some muscles increase their activation values, others instead decrease them, and there are even some of them that have both reactions: they decrease and increase their activation

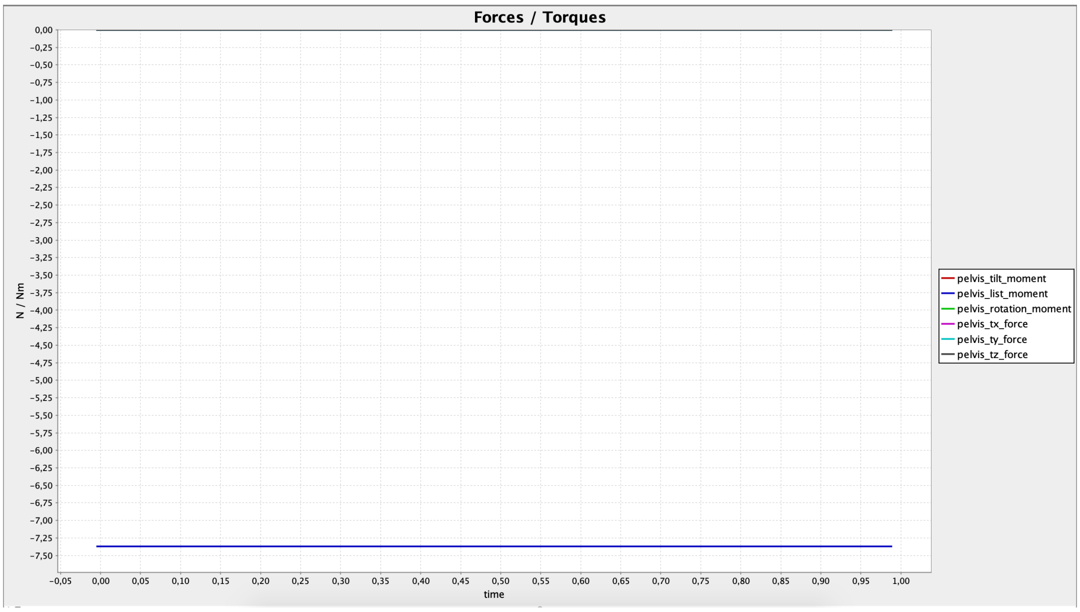


FIGURE 4.3: Front Kick phase 1 with ground forces added, ID analysis

values depending on the intensity of the pushing force, as it can be observed in 4.5. In order to make it easier, I am going to differentiate them.

These are the muscles with a significant influence that are activated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left adductor magnus (*add_mag2_l*)
- Left pectineus (*pect_l*)
- Left gracilis (*grac_l*)

And these ones which are deactivated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)

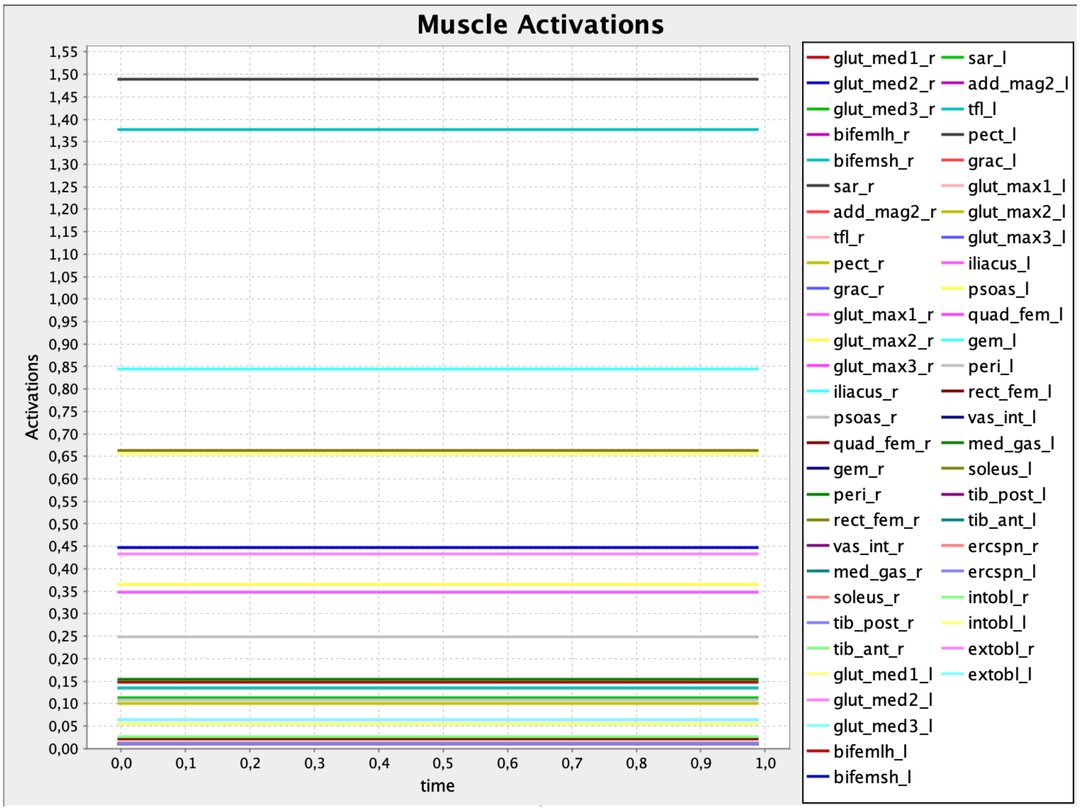


FIGURE 4.4: Front Kick phase 1 without perturbations, SO analysis, Muscle Activations

- Left periformis (*peri_l*)

It is important to highlight that there are some muscles which are presented in both lists. These are those that have different stretches in which are either activated or deactivated. This depends on the intensity of the pushing force. For example, in 4.5 is possible to see how the left gluteus medius 1 (*glut_med1_l*) is deactivated at the beginning and when it reaches a specific activation value too low (0.264 in the second 0.38), it has to be reactivated again since the pushing force is too high.

Z- perturbation

In this case, these are the muscles with a significant influence that are activated, and are graphically shown in 4.6:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)

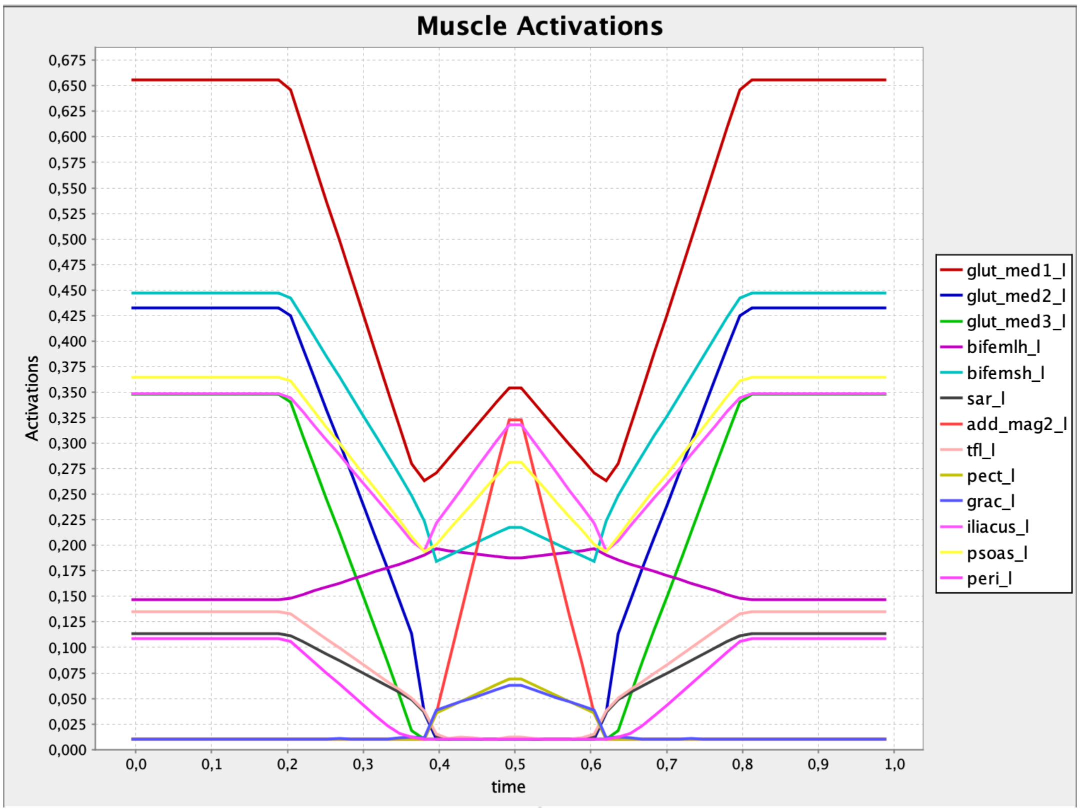


FIGURE 4.5: Front Kick phase 1 with Z+ perturbations, SO analysis, Muscle Activations

- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)
- Left gluteus maximus 1 (*glut_max1_l*)

On the other hand, just only the left bicep femoris long head (*bifemlh_l*) is deactivated.

X+ perturbation

In the analysis with this X+ perturbation, these are the muscles with a significant influence that are activated:

- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left periformis (*peri_l*)
- Left sartorius (*sar_l*)

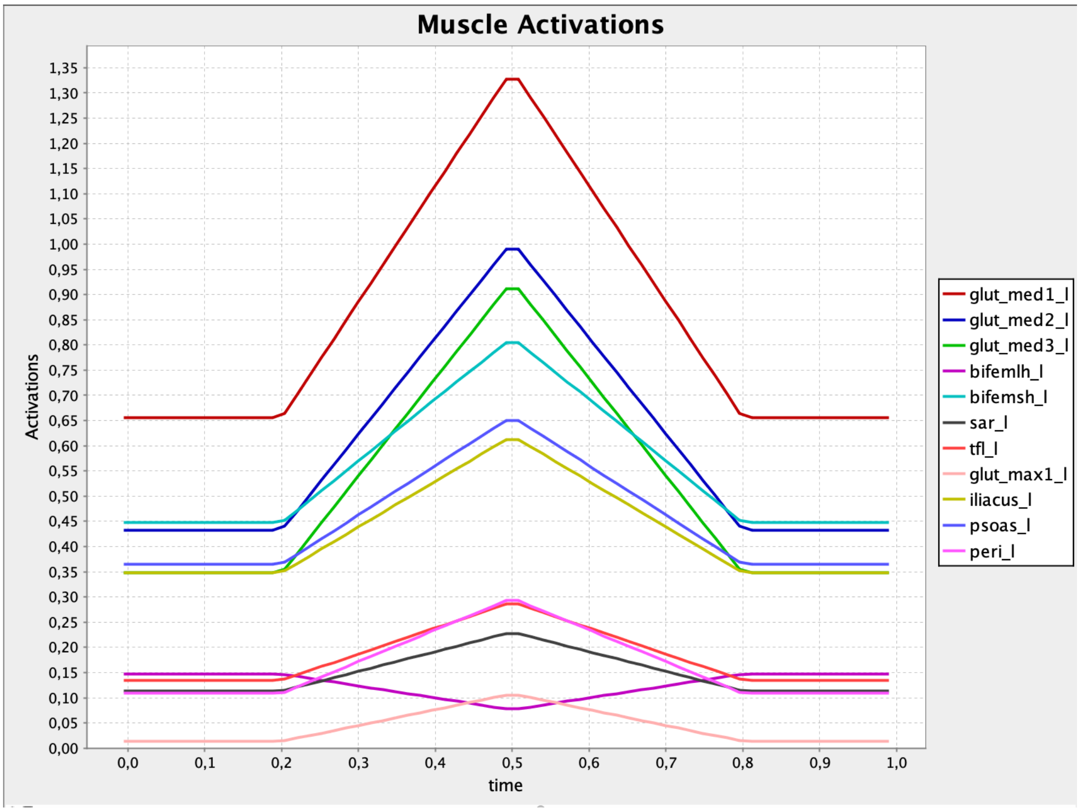


FIGURE 4.6: Front Kick phase 1 with Z- perturbations, SO analysis, Muscle Activations

- Left gemellus (*gem_l*)
- Left gracilis (*grac_l*)

And these ones which are deactivated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris long head (*bifemlh_l*)

The complete graph with all muscles activated and deactivated can be seen at 4.7.

X- perturbation

Finally in this case, these are the muscles with a significant influence that are activated, and which are represented in 4.8:

- Left gluteus medius 1 (*glut_med1_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left gluteus maximus 1 (*glut_max1_l*)

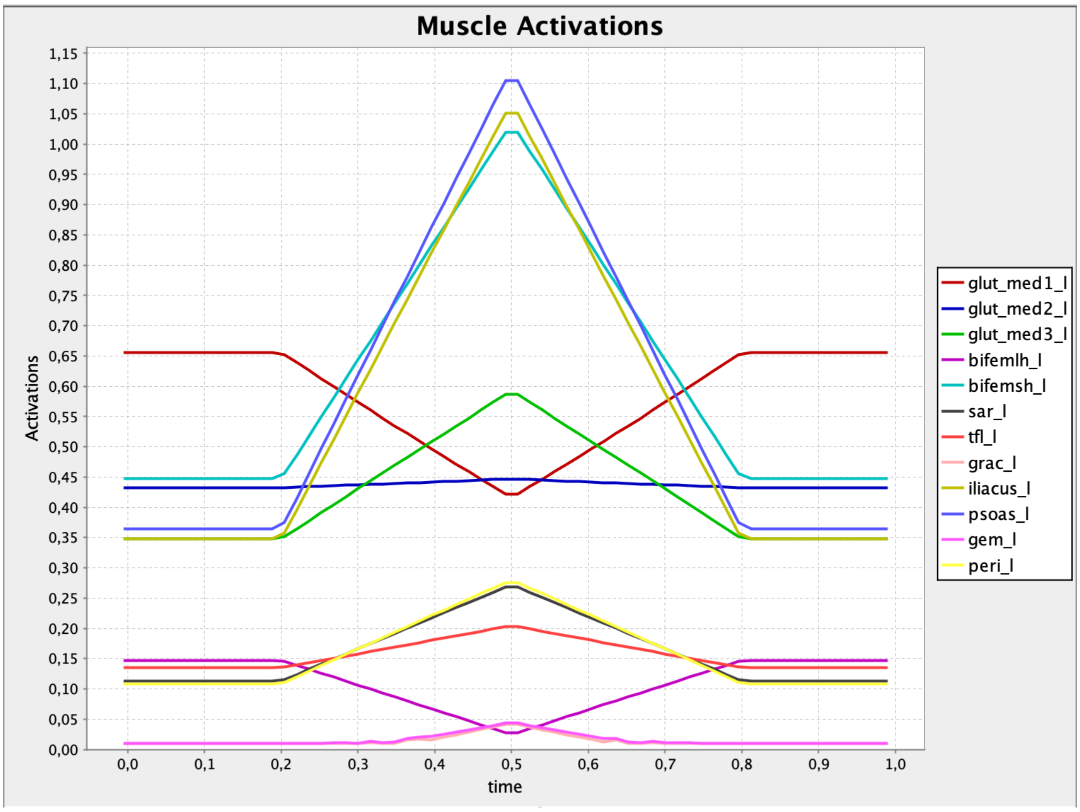


FIGURE 4.7: Front Kick phase 1 with X+ perturbations, SO analysis, Muscle Activations

- Left gluteus maximus 2 (*glut_max2_l*)
- Left vastus internus (*vast_int_l*)

And these ones which are deactivated:

- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)

4.3 Front-Kick phase 2

Now, I am going to study the final hitting phase of the front kick, in which the knee maintains its highest point, and it is completely stiff.

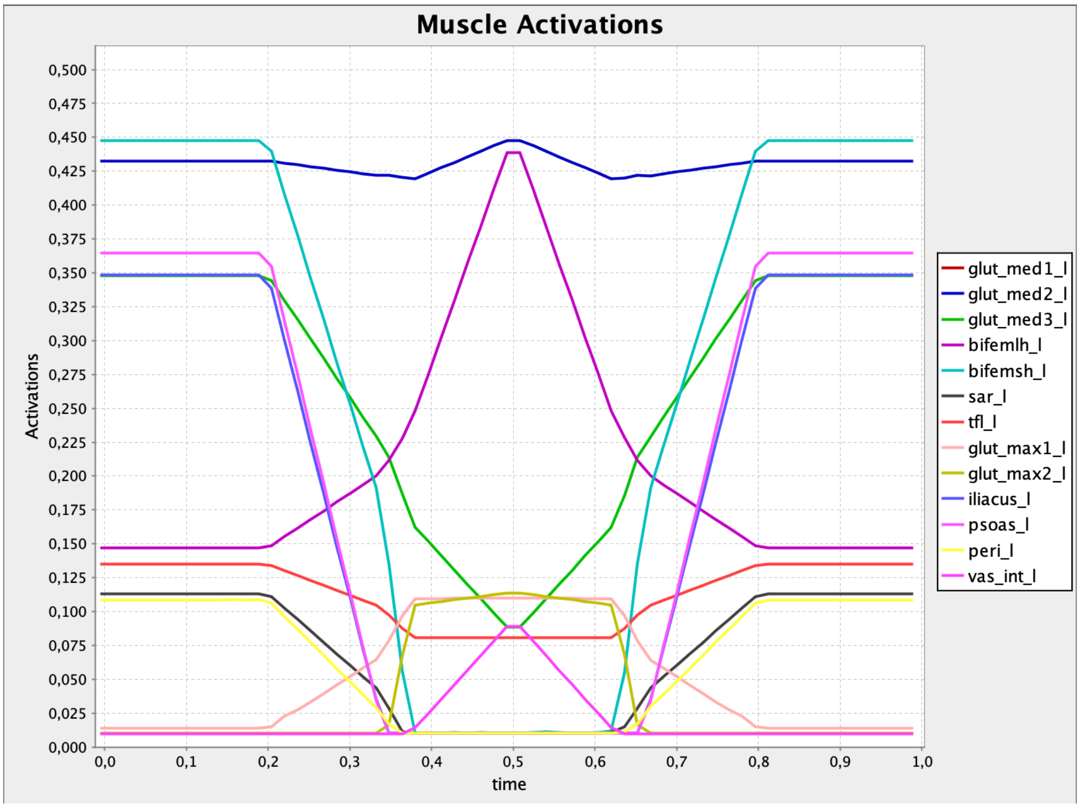


FIGURE 4.8: Front Kick phase 1 with X- perturbations, SO analysis, Muscle Activations

4.3.1 Inverse Dynamics

Since it is a different posture, first I have to repeat the Inverse Dynamics analysis in order to adjust the ground external forces, following the same process that in 4.2.1: first I perform the ID analysis without adding external forces to know the ground forces that I need to add to the external forces file. Once I know them, I repeat the analysis with now the external forces to check that the residual forces and moments are now close to zero.

4.3.2 Static Optimization

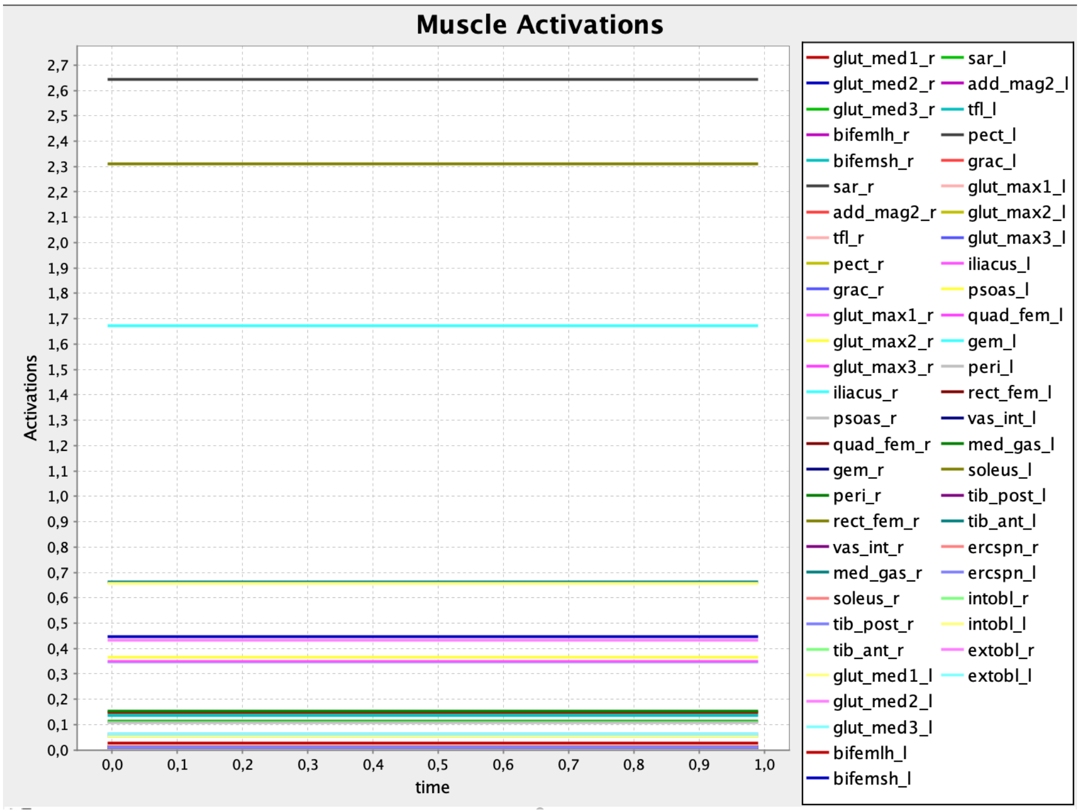
Without perturbation

Again, I am going to study first which are the muscles that are activated just because of the posture, that they are represented in 4.9.

Considering an activation value of 0.30 a good threshold, the following muscles have an important incidence in the front kick phase 2 pose (from highest to lowest activation value order):

- Right sartorius (*sar_r*)

- Right rectus femoris (*rect_fem_r*)
- Right iliacus (*iliacus_r*)
- Right medial gastrocnemius (*med_gas_r*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l)*
- *Left gluteus medius 2 (glut_med2_l)*
- *Left psoas (psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)



[ht]

FIGURE 4.9: Front Kick phase 2 without perturbations, SO analysis, Muscle Activations

Afterwards, I am going to add the pushing forces which are already explained in 3.2.3 with first just only 100 N. In this way, I will be able to find out which are the muscles intended to maintain the posture.

Z+ perturbation

When this extra force is added, the changes in the activation values of the muscles are represented in 4.10. These muscles try to maintain the posture fighting against the pushing force, compensating it. The muscles that increase their activation values are the following:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left adductor magnus (*add_mag2_l*)
- Left pectineus (*pect_l*)
- Left gracilis (*grac_l*)

And these ones are those which are deactivated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)

Again, there some muscle which are listed twice because they have different stretches in which are either activated or deactivated.

Z- perturbation

In this case, the following list shows the muscles graphically represented in 4.11 that are activated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)
- Left gluteus maximus 1 (*glut_max1_l*)

On the other hand, just only the left bicep femoris long head (*bifemlh_l*) is deactivated.

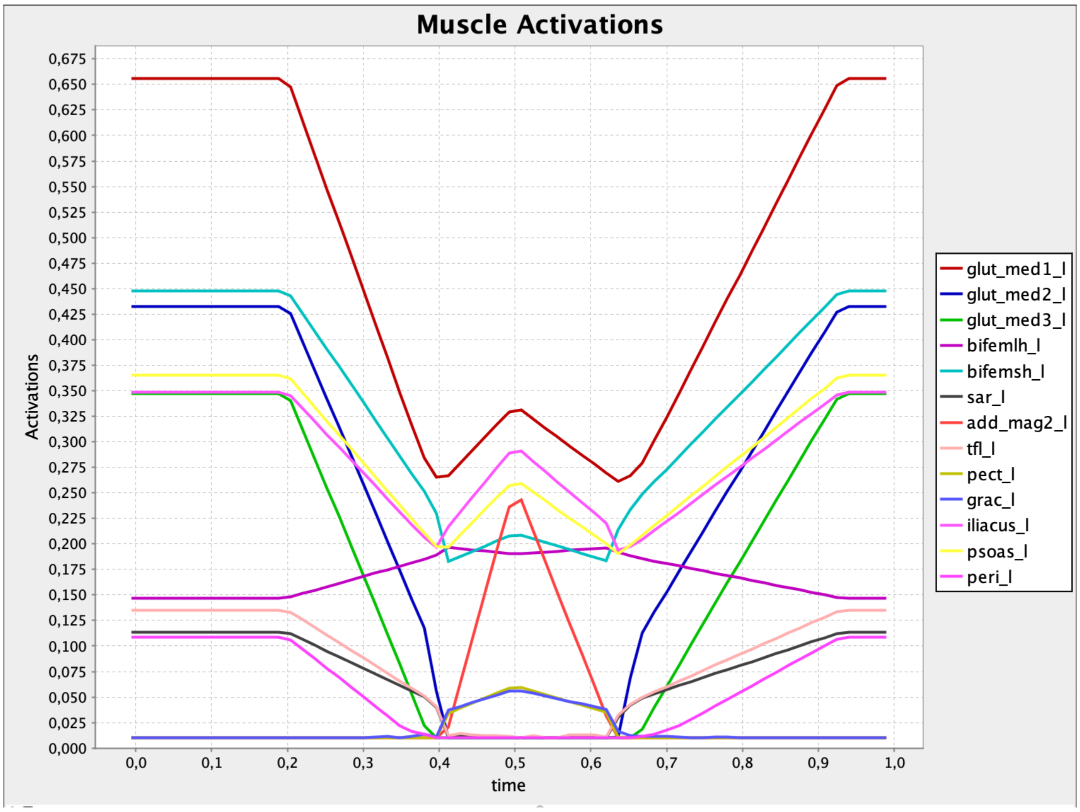


FIGURE 4.10: Front Kick phase 2 with Z+ perturbations, SO analysis, Muscle Activations

X+ perturbation

In this analysis, these are the muscles which are represented in 4.12 that are activated with a X+ perturbation:

- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)
- Left gemellus (*gem_l*)
- Left gracilis (*grac_l*)

And these ones which are deactivated:

- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris long head (*bifemlh_l*)

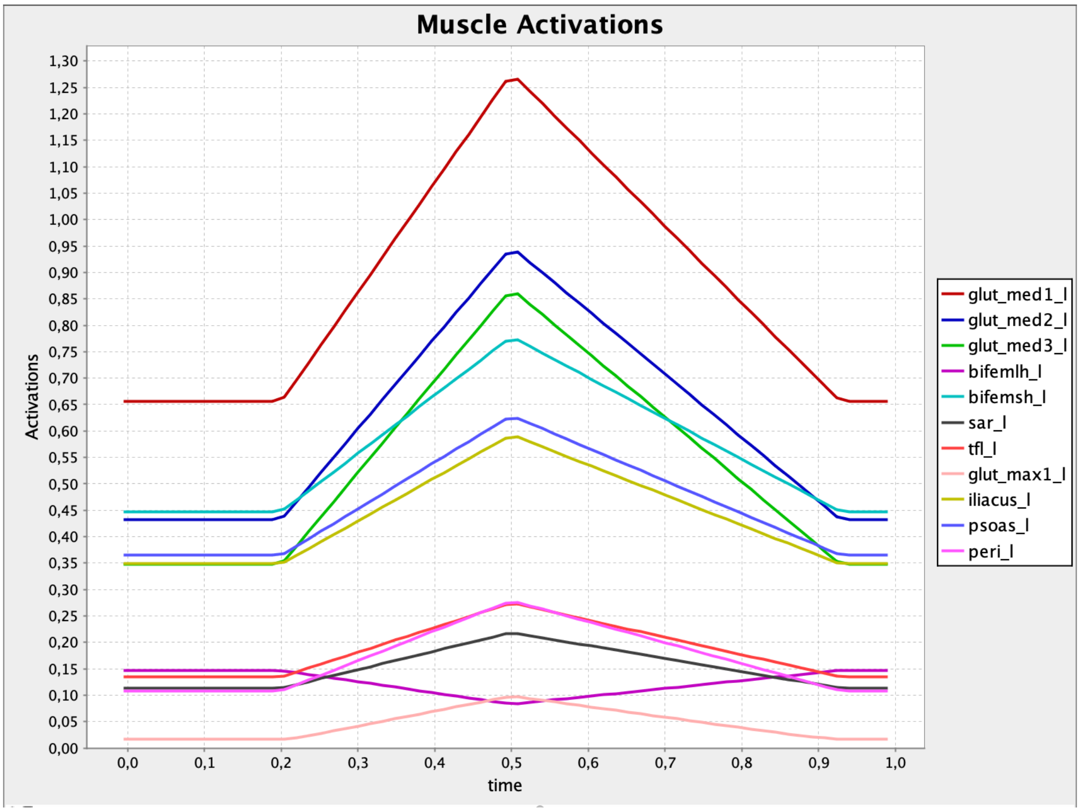


FIGURE 4.11: Front Kick phase 2 with Z- perturbations, SO analysis, Muscle Activations

X- perturbation

Finally for this type of perturbation, these are the muscles with a significant influence that are activated, and which are represented in 4.13:

- Left gluteus medius 1 (*glut_med1_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left vastus internus (*vast_int_l*)

And these ones which are deactivated:

- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left tensor fasciae latae (*tfl_l*)

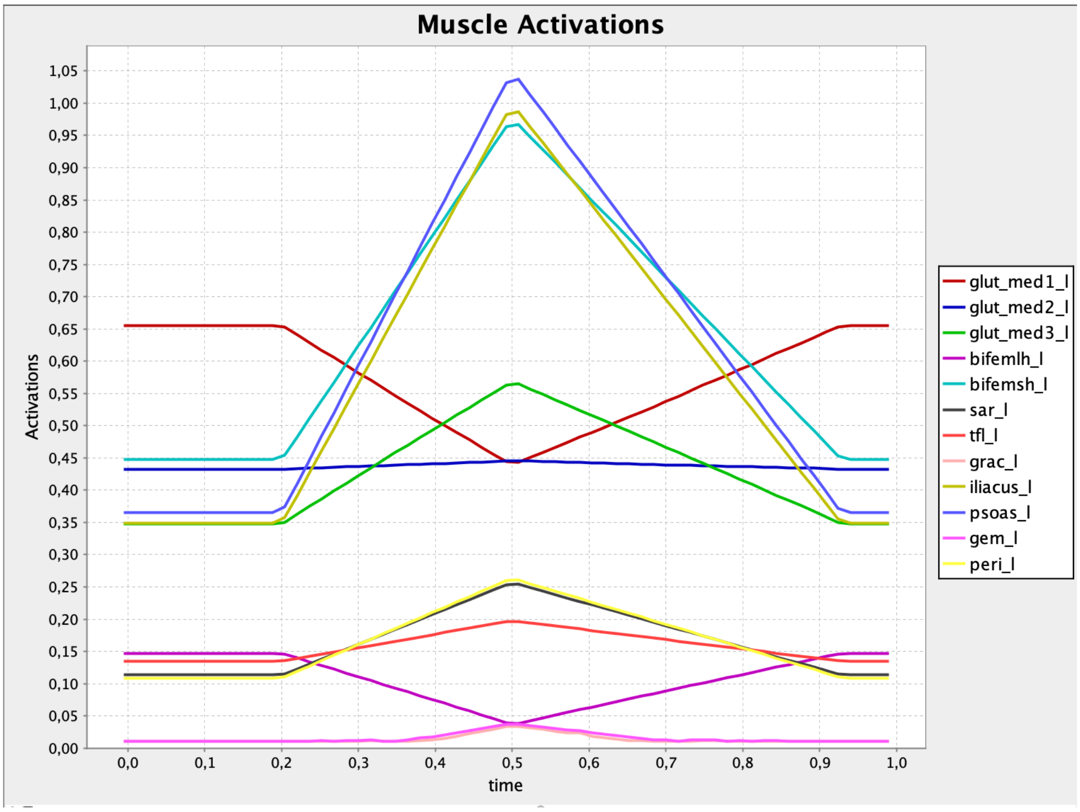


FIGURE 4.12: Front Kick phase 2 with X+ perturbations, SO analysis, Muscle Activations

- Left sartorius (*sar_l*)
- Left periformis (*peri_l*)

As it can be observed, in both phases of this front kick the muscles activated and deactivated per each pushing force are the same, following the same pattern. The main difference between the phases is the magnitude of the change in the activation level of each muscle. Since the phase 2 of the front kick may be a posture with a greater imbalance level, the level of either activation or deactivation of the muscles are greater too.

4.4 Side-Kick phase 1

In this section, I am going to study another type of posture of a different Taekwondo movement, the side kick in an initial phase, in which the knee reaches its highest point, as well as knee flexion is maximum.

4.4.1 Inverse Dynamics

Like I have been doing with the other postures, first I have to perform the Inverse Dynamics analysis in order to adjust the ground external forces following the same

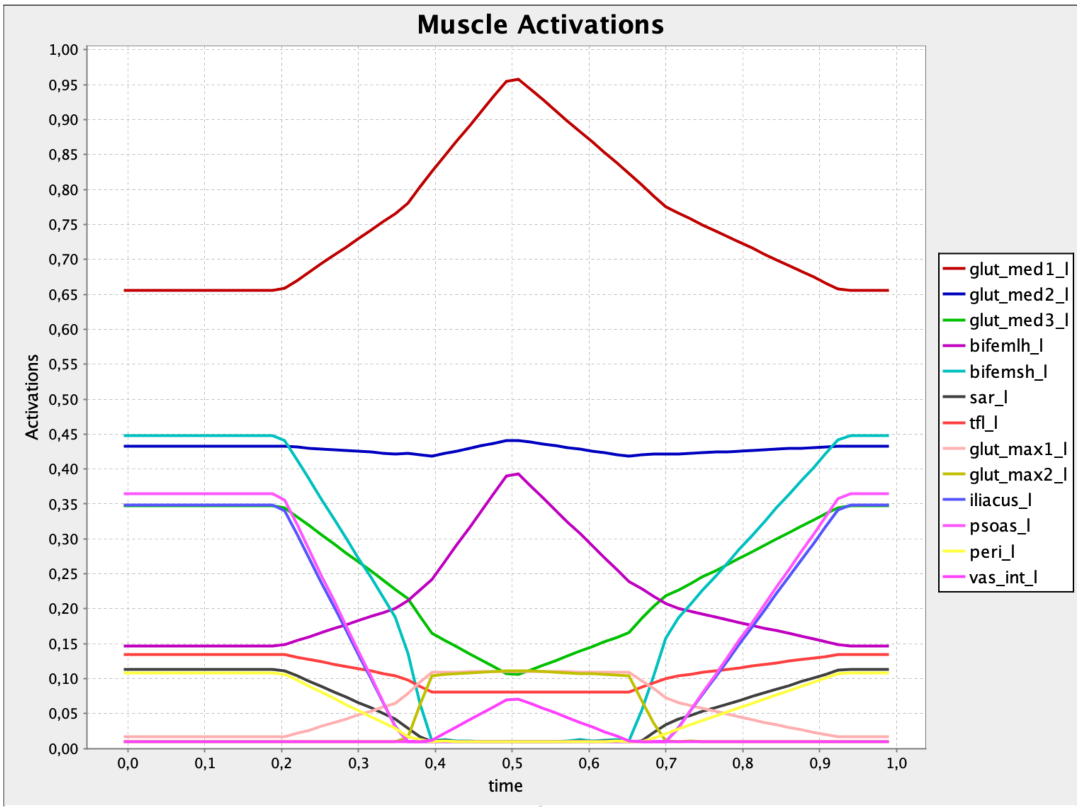


FIGURE 4.13: Front Kick phase 2 with X- perturbations, SO analysis, Muscle Activations

process already explained in 4.2.1. Once I have done this, I can start with the following analyses.

4.4.2 Static Optimization

Without perturbations

First of all, I perform the Static Optimization analysis in order to study which are the muscles which are activated just only because of the posture. These muscles are represented in 4.14. However, I only highlight the muscles whose activation value is above 0.30, following the same reasoning explained in 4.2.2. This is the list of these muscles (from highest to lowest activation value order):

- Right sartorius (*sar_r*)
- Right bicep femoris short head (*bifemsh_r*)
- Right tensor fasciae latae (*tfl_r*)
- Right periformis (*peri_r*)
- Right iliacus (*iliacus_r*)
- Right gluteus medius 3 (*glut_med3_r*)
- Right gemellus (*gem_r*)

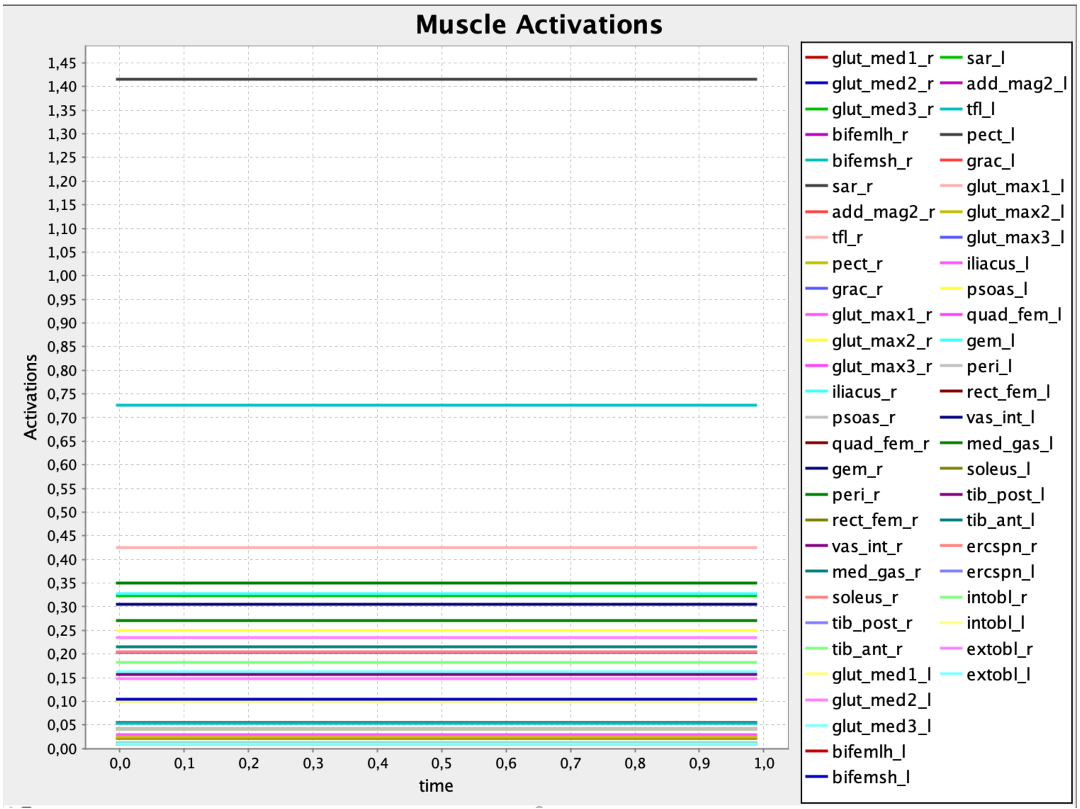


FIGURE 4.14: Side Kick phase 1 without perturbations, SO analysis, Muscle Activations

Z+ perturbation

Once this pushing force is added, some muscles change their activation values in different ways, as it can be observed in 4.15: some increasing it, some decreasing it, and others both. These are those which are activated when this Z+ perturbation comes into play:

- Left medial gastrocnemius (*med_gas_l*)
- Left tibialis anterior (*tib_ant_l*)
- Left tibialis posterior (*tib_post_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left adductor magnus (*add_mag2_l*)
- Left iliacus (*iliacus_l*)
- Left psoas (*psoas_l*)

And these ones are those which are deactivated:

- Left medial gastrocnemius (*med_gas_l*)
- Left tibialis anterior (*tib_ant_l*)

- Left gluteus medius 3 (*glut_med3_l*)
- Left tibialis posterior (*tib_post_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left periformis (*peri_l*)
- Left sartorius (*sar_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left bicep femoris long head (*bifemlh_l*)

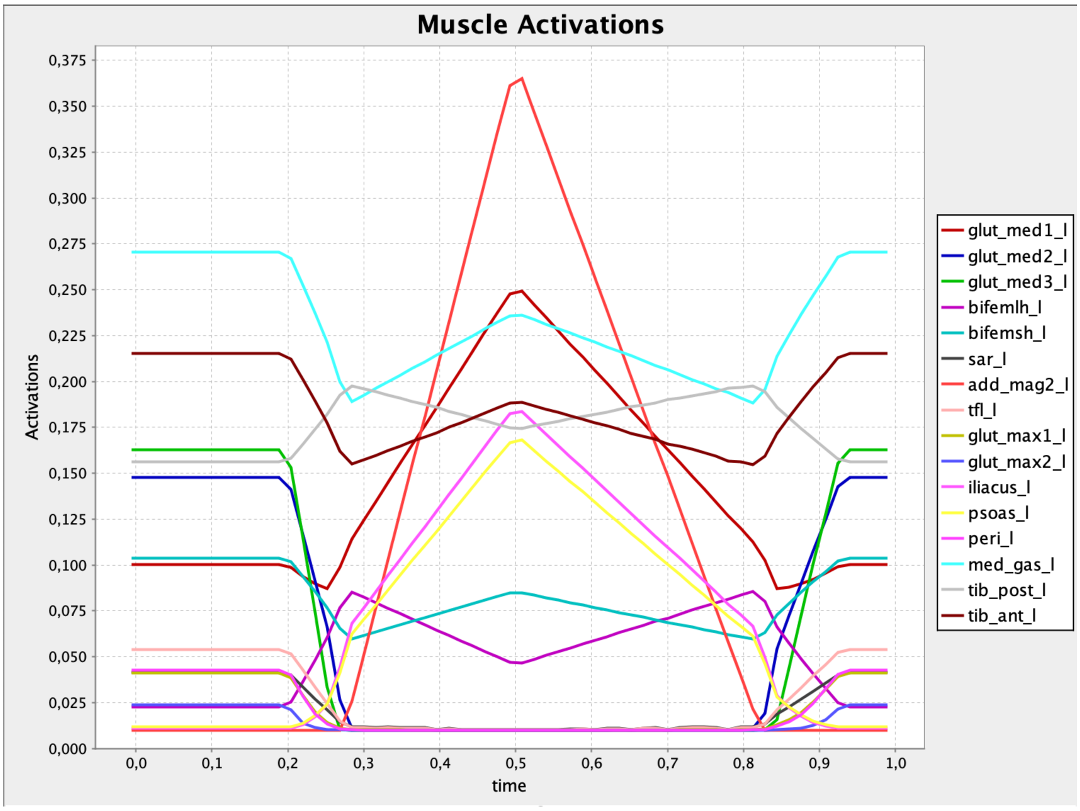


FIGURE 4.15: Side Kick phase 1 with Z+ perturbations, SO analysis, Muscle Activations

Z- perturbation

In this case, the following list shows the muscles graphically represented in 4.16 that are activated:

- Left medial gastrocnemius (*med_gas_l*)
- Left tibialis anterior (*tib_ant_l*)
- Left gluteus medius 3 (*glut_med3_l*)

- Left gluteus medius 2 (*glut_med2_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left periformis (*peri_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left sartorius (*sar_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left rectus femoris (*rect_fem_l*)
- Left gemellus (*gem_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)

On the other hand, just only the left tibialis posterior (*tib_post_l*) is deactivated.

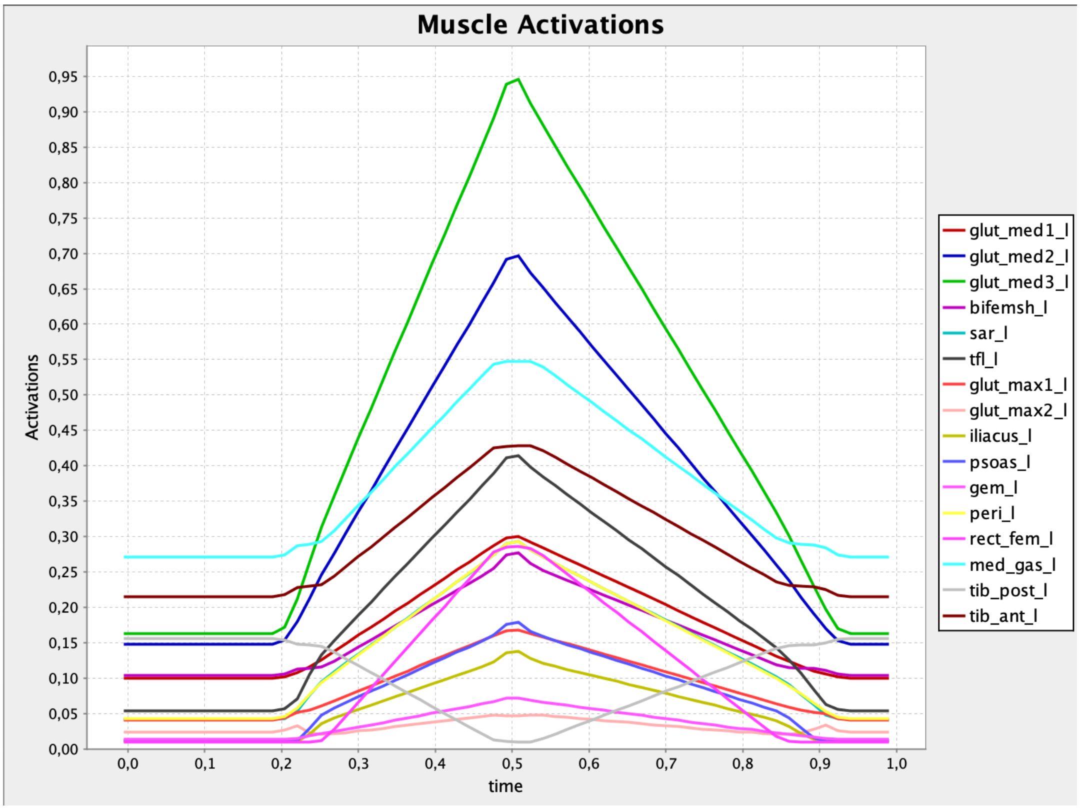


FIGURE 4.16: Side Kick phase 1 with Z- perturbations, SO analysis, Muscle Activations

X+ perturbation

On the other hand, when the X- pushing force is added, these are the muscles that are activated, which also can be observed graphically represented in 4.17:

- Left medial gastrocnemius (*med_gas_l*)

- Left tibialis anterior (*tib_ant_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left periformis (*peri_l*)
- Left sartorius (*sar_l*)
- Left iliacus (*iliacus_l*)
- Left psoas (*psoas_l*)
- Left gemellus (*gem_l*)
- Left quadratus femoris (*quad_fem_l*)
- Left rectus femoris (*rect_fem_l*)

And these ones are those which are deactivated:

- Left tibialis posterior (*tib_post_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left bicep femoris long head (*bifemlh_l*)

X- perturbation

Finally, when this pushing force comes into play, these are the muscles with a significant influence that are activated, and which are represented in 4.18:

- Left gluteus medius 3 (*glut_med3_l*)
- Left tibialis posterior (*tib_post_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left soleus (*soleus_l*)
- Left vastus internus (*vast_int_l*)

And these ones which are deactivated:

- Left medial gastrocnemius (*med_gas_l*)

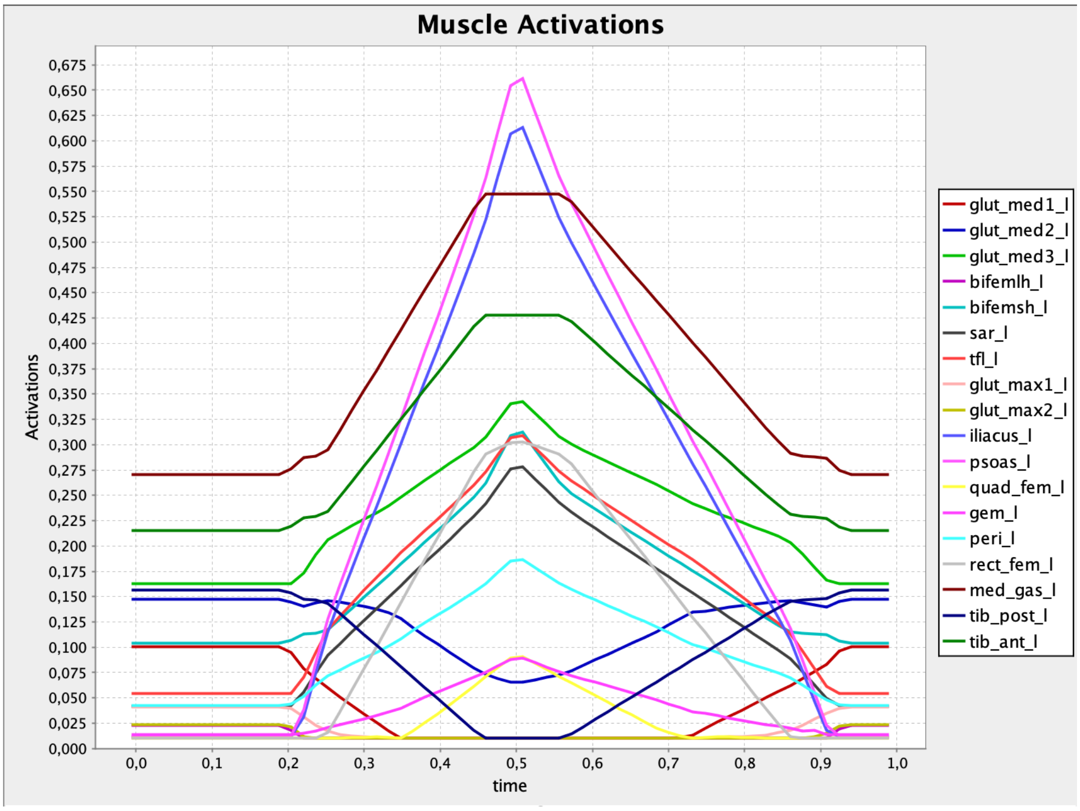


FIGURE 4.17: Side Kick phase 1 with X+ perturbations, SO analysis, Muscle Activations

- Left tibialis anterior (*tib_ant_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left periformis (*peri_l*)
- Left sartorius (*sar_l*)
- Left gemellus (*gem_l*)

4.5 Side-Kick phase 2

I am going to study the side kick in the final hitting phase, in which the knee maintains its highest point, and it is completely stiff.

4.5.1 Inverse Dynamics

Again, since it is a different posture of the side kick movement, I have to repeat the Inverse Dynamics analysis in order to adjust the ground external forces, as I have been doing in the previous analyses of the other postures, following the same process explained in detail in 4.2.1.

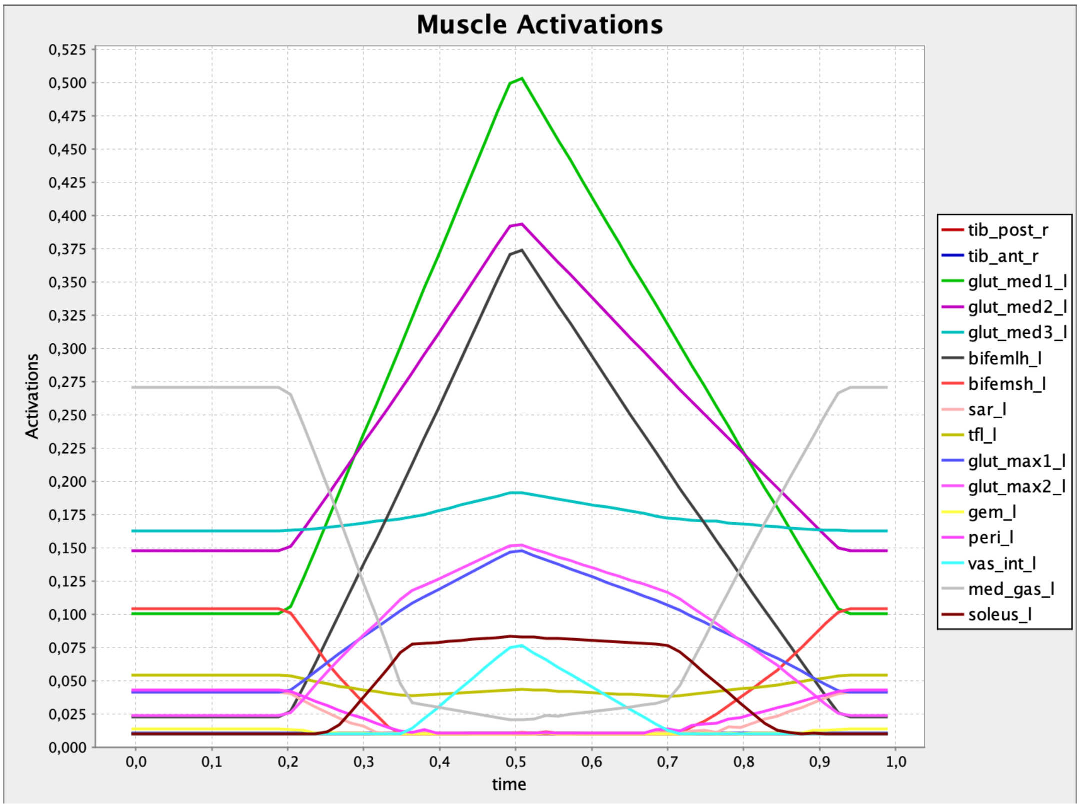


FIGURE 4.18: Side Kick phase 1 with X- perturbations, SO analysis, Muscle Activations

4.5.2 Static Optimization

Without perturbations

First of all, I study the muscles that are activated due to just the posture, which are represented in 4.19. Considering again a threshold of 0.30 following the reasoning that can be read in 4.2.2, these are the muscles that have a meaningful activation value (from highest to lowest activation value order):

- Right bicep femoris short head (*bifemsh_r*)
- Right gluteus medius 2 (*glut_med2_r*)
- Right sartorius (*sar_r*)
- Right tensor fasciae latae (*tfl_r*)
- Right gluteus medius 3 (*glut_med3_r*)
- Right gluteus maximus 1 (*glut_max1_r*)
- Right external oblique (*extobl_r*)
- Right gluteus maximus 2 (*glut_max2_r*)

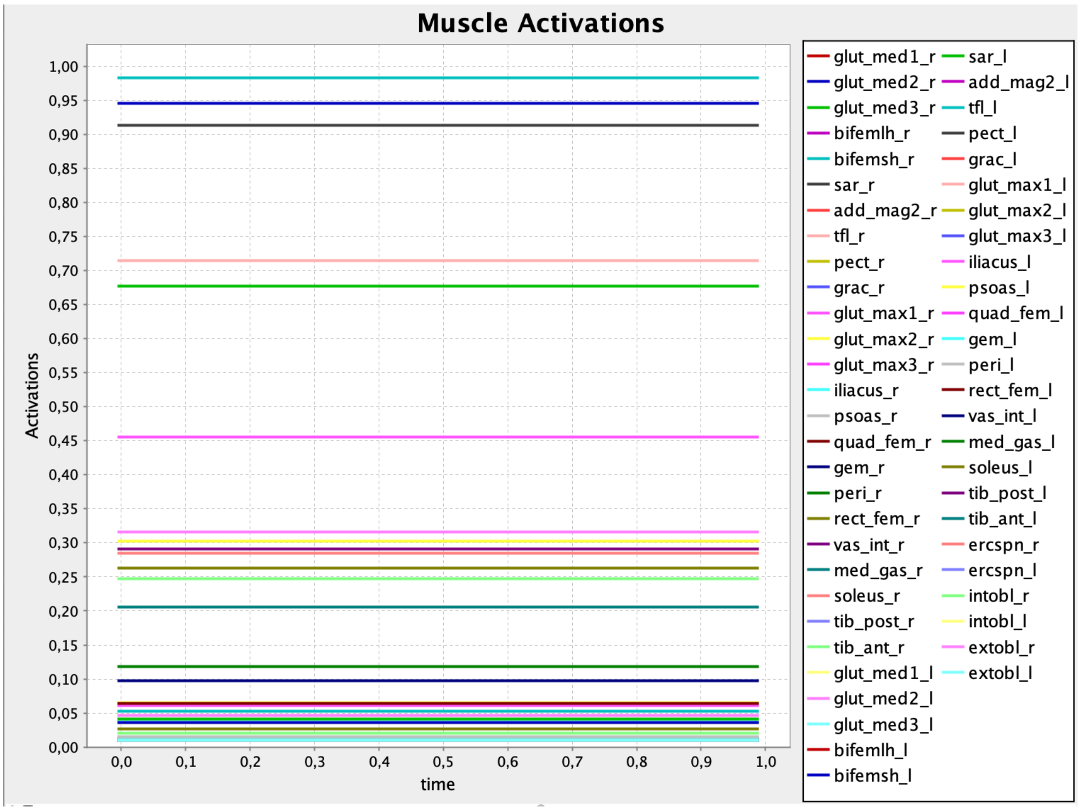


FIGURE 4.19: Side Kick phase 2 without perturbations, SO analysis, Muscle Activations

Z+ perturbation

In 4.20 are represented the muscles that change their activation values when the Z+ pushing force is added to the analysis. Some of these muscles increase their activation values, and they are the following:

- Left tibialis posterior (*tib_post_l*)
- Left psoas (*psoas_l*)
- Left iliacus (*iliacus_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left soleus (*soleus_l*)
- Left pectineus (*pect_l*)
- Left adductor magnus (*add_mag2_l*)
- Left gracilis (*grac_l*)

On the contrary, these are which decrease their activation value:

- Left tibialis anterior (*tib_ant_l*)
- Left medial gastrocnemius (*med_gas_l*)
- Left rectus femoris (*rect_fem_l*)
- Left tensor fasciae latae (*tfl_l*)

- Left gluteus medius 2 (*glut_med2_l*)
- Left sartorius (*sar_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left periformis (*peri_l*)

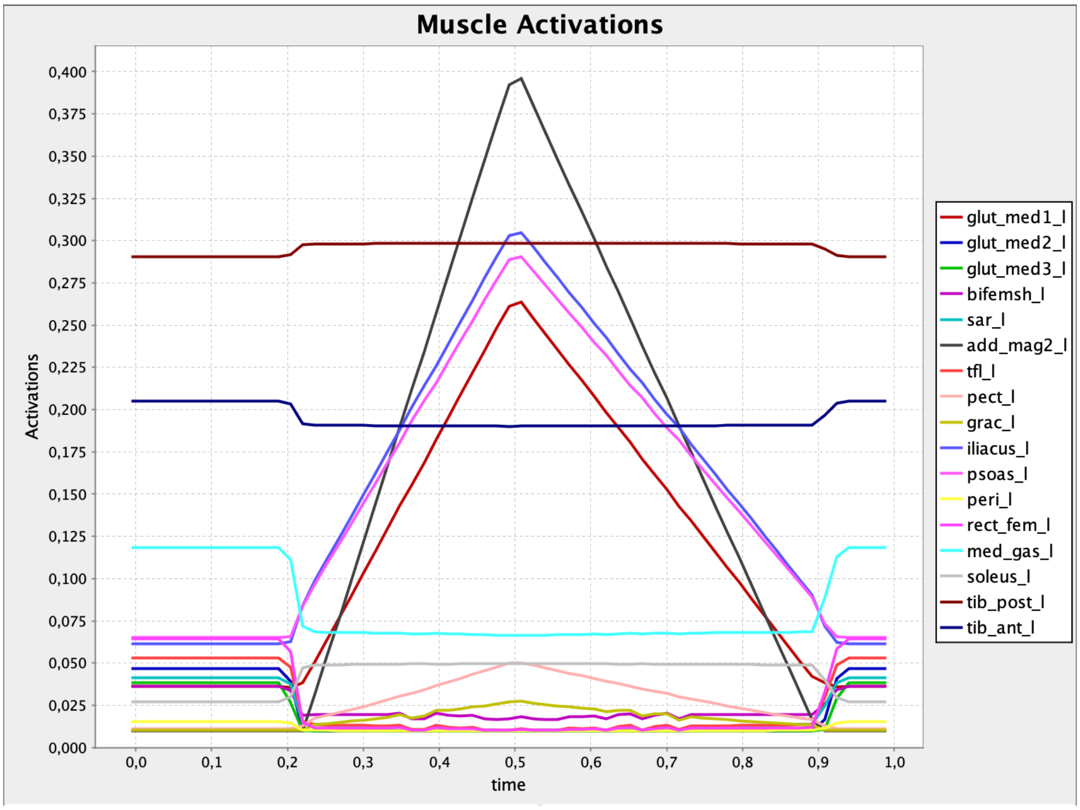


FIGURE 4.20: Side Kick phase 2 with Z+ perturbations, SO analysis, Muscle Activations

Z- perturbation

On the other hand, when this pushing force is added, the following muscles are activated:

- Left tibialis anterior (*tib_ant_l*)
- Left medial gastrocnemius (*med_gas_l*)
- Left psoas (*psoas_l*)
- Left rectus femoris (*rect_fem_l*)
- Left iliacus (*iliacus_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left sartorius (*sar_l*)
- Left gluteus medius 3 (*glut_med3_l*)

- Left bicep femoris short head (*bifemsh_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left periformis (*peri_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left gemellus (*gem_l*)
- Left gluteus maximus 2 (*glut_max2_l*)

And just only the left tibialis posterior (*tib_post_l*) and the left iliacus (iliacus_l) are deactivated.

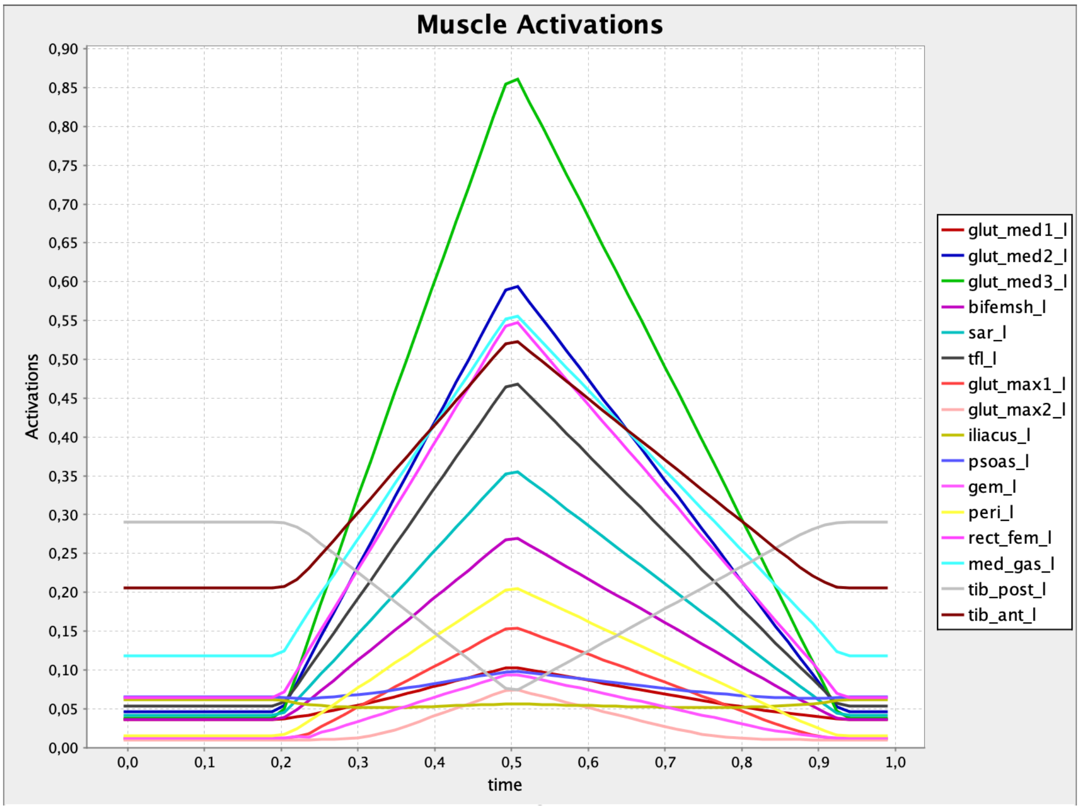


FIGURE 4.21: Side Kick phase 2 with Z- perturbations, SO analysis, Muscle Activations

X+ perturbation

When the X+ pushing forces is added, other different muscles are either activated or deactivated, as it can be observed in 4.22. The muscles that are activated are the following:

- Left tibialis anterior (*tib_ant_l*)
- Left medial gastrocnemius (*med_gas_l*)
- Left psoas (*psoas_l)*
- *Left rectus femoris (rect_fem_l*)
- Left iliacus (*iliacus_l*)

- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left periformis (*peri_l*)
- Left gemellus (*gem_l*)
- Left quadratus femoris (*quad_fem_l*)
- Left pectineus (*pect_l*)

And these ones are those which are deactivated:

- Left tibialis posterior (*tib_post_l*)
- Left gluteus medius 2 (*glut_med2_l*)
- Left soleus (*soleus_l*)

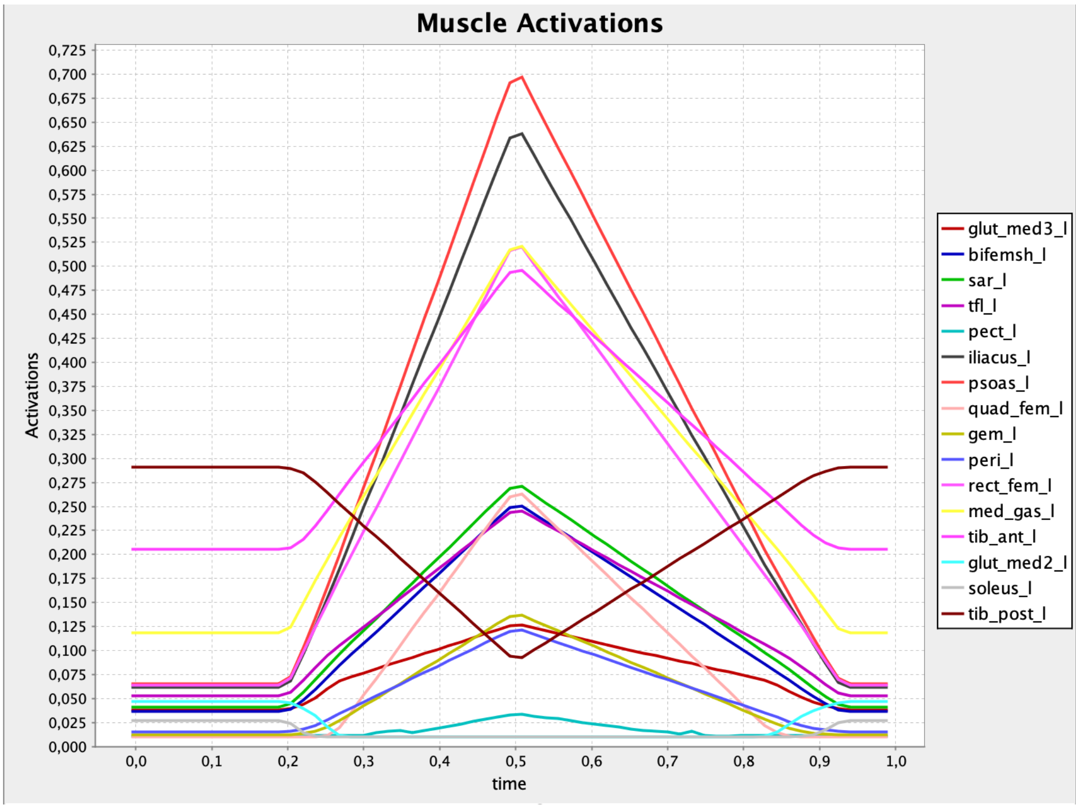


FIGURE 4.22: Side Kick phase 2 with X+ perturbations, SO analysis, Muscle Activations

X- perturbation

Finally, in this analysis in which the X- pushing force comes into play, these are the muscles that are activated:

- Left tibialis posterior (*tib_post_l*)

- Left gluteus medius 2 (*glut_med2_l*)
- Left gluteus medius 1 (*glut_med1_l*)
- Left soleus (*soleus_l*)
- Left gluteus maximus 1 (*glut_max1_l*)
- Left bicep femoris long head (*bifemlh_l*)
- Left gluteus maximus 2 (*glut_max2_l*)
- Left vastus internus (*vast_int_l*)
- Left tensor fasciae latae (*tfl_l*)

And these ones which are deactivated:

- Left tibialis anterior (*tib_ant_l*)
- Left medial gastrocnemius (*med_gas_l*)
- Left psoas (*psoas_l*)
- Left rectus femoris (*rect_fem_l*)
- Left iliacus (*iliacus_l*)
- Left tensor fasciae latae (*tfl_l*)
- Left sartorius (*sar_l*)
- Left gluteus medius 3 (*glut_med3_l*)
- Left bicep femoris short head (*bifemsh_l*)
- Left periformis (*peri_l*)
- Left gemellus (*gem_l*)

In 4.23 are represented all the muscles that change their activation value when this pushing force comes into play.

In these two phases of the side kick movement there are more differences between them when the same pushing force is applied. Although in general the muscles that are intended to maintain the posture are almost always the same, the pattern changes and in some analyses with a specific pushing force a muscle appears that it does not often do it.

Furthermore, as it happened also in the front kick movement, there are muscles that their activation pattern changes: in some stretches it increases and in others, decreases. This depends on the intensity of the pushing force, and it is characteristic of the pushing force Z+.

4.6 Front-Kick dynamic

In this section, I am going to study the full front kick movement dynamically, from its initial phase with both feet resting on the ground to the moment when the knee is at its highest point and completely bent after hitting.

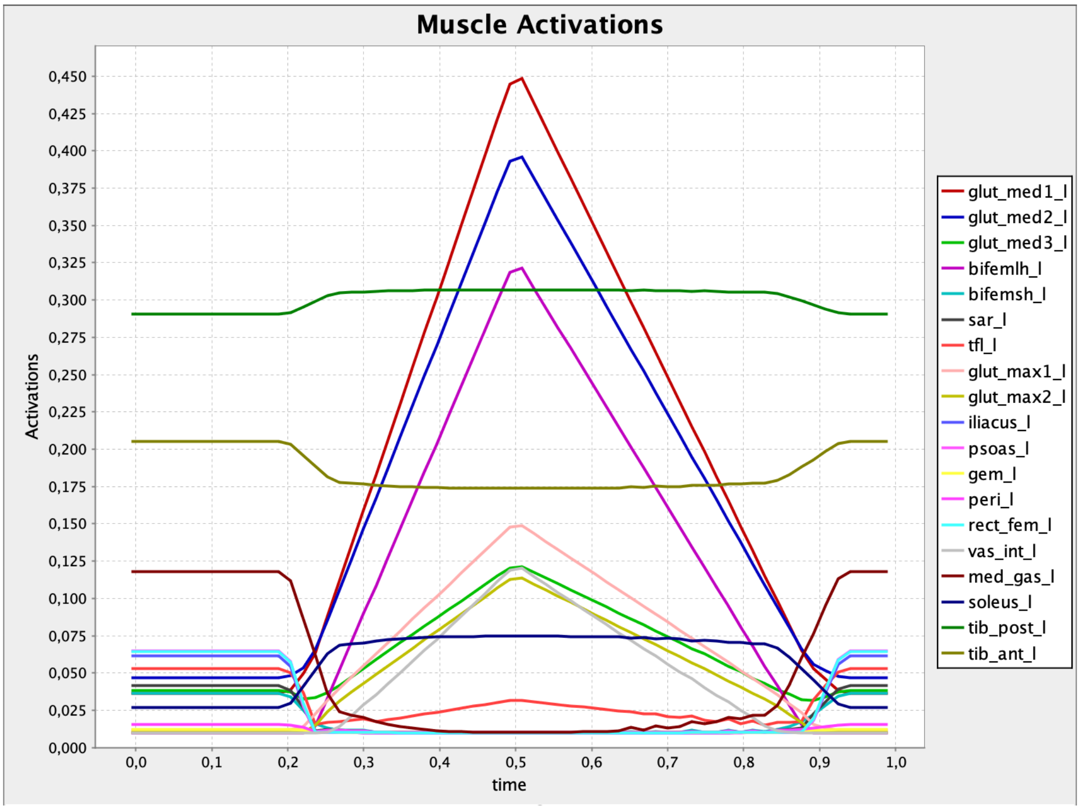


FIGURE 4.23: Side Kick phase 2 with X- perturbations, SO analysis, Muscle Activations

This analysis was carried out at the beginning of the study, before focusing on the static balance, with the objective of observing the activation patterns of the muscles in a complete movement of Taekwondo, in this case the Front Kick. To do that, were performed two types of analysis offered by OpenSim, allowing also to observe the differences between them: Static Optimization and Computed Muscle Control. However, in this case the pushing forces which were used in the previous postures were not added here. The comparison between these two analyses and why the results differ can be found in 3.7.

I present below the results of these studies, without going into depth to analyze the results as they fall outside the scope of the study. It is important to point out that the CMC analysis does not offer muscle activations as an output, so I will use the muscle forces as an output of both analyses and this will allow us to compare them correctly. As explained in 3.6.2, there is a proportional relationship between forces and activation values closely linked to the parameter *optimal_force*.

In addition, to simplify the results and show them more clearly, I present only the outputs of the iliacus and psoas muscles of both legs: Left/Right iliacus (*iliacus_l/r*) and left/right psoas (*psoas_l/r*). In B you can observe the output for the whole set of muscles for both SO and CMC analysis.

4.6.1 Inverse Dynamics

Again, following the same process that I have done with the other postures, first I have to perform the ID analysis in order to adjust the ground external forces. This is explained in detail in 4.2.1.

First, in 4.24 is presented the pelvis forces and torques before adjusting the ground external forces.

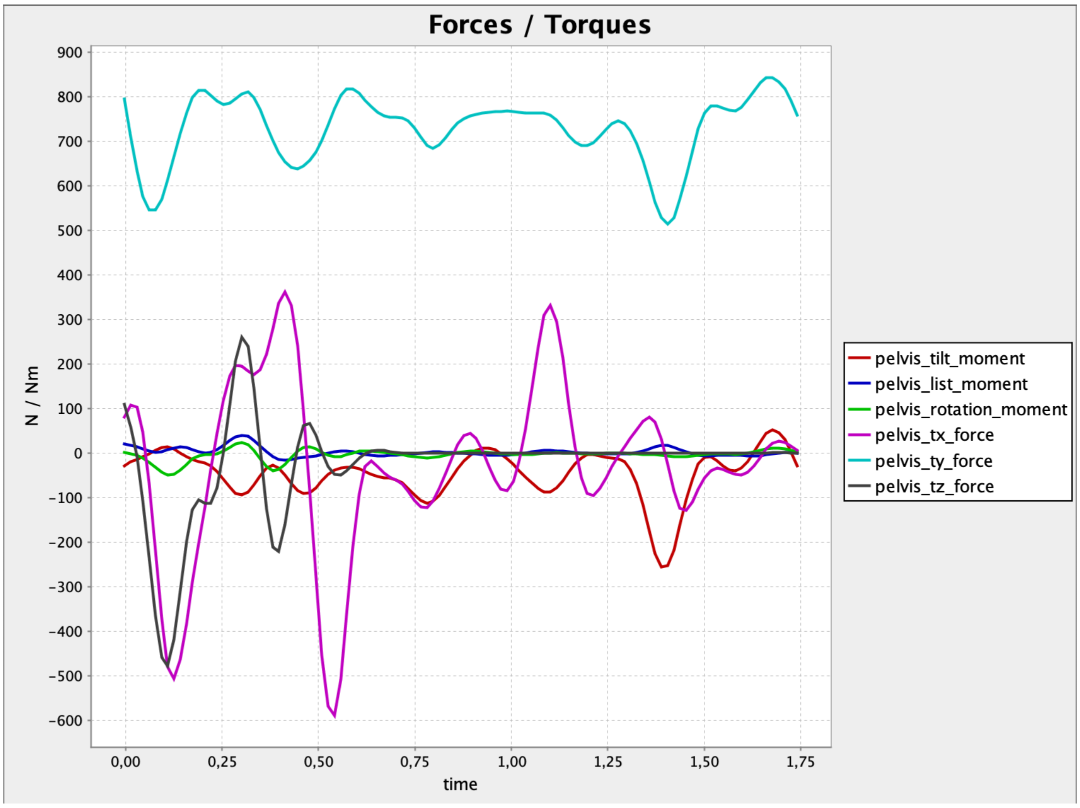


FIGURE 4.24: Front Kick Dynamic without ground forces added, ID analysis

Once these ground forces have been adjusted, the SO and CMC analyses can start. In 4.25 is presented how the pelvis forces and torques result.

4.6.2 Static Optimization

As I explained above, no perturbations forces will be added to these analyses. It will only be analyzed how the activation patterns and muscular forces behave when a Taekwondo front kick is executed.

In 4.26 and 4.27 are presented both results. It can be observed how the patterns are almost the same due to the proportional relationship between the activation and force values.

FIGURE 4.25: Front Kick Dynamic with ground forces added, ID analysis

4.6.3 Computed Muscle Control

In 4.28 can be observed how now the patterns draw smoother curves, with exponential slopes, due to the nature of the algorithm behind the CMC analysis.

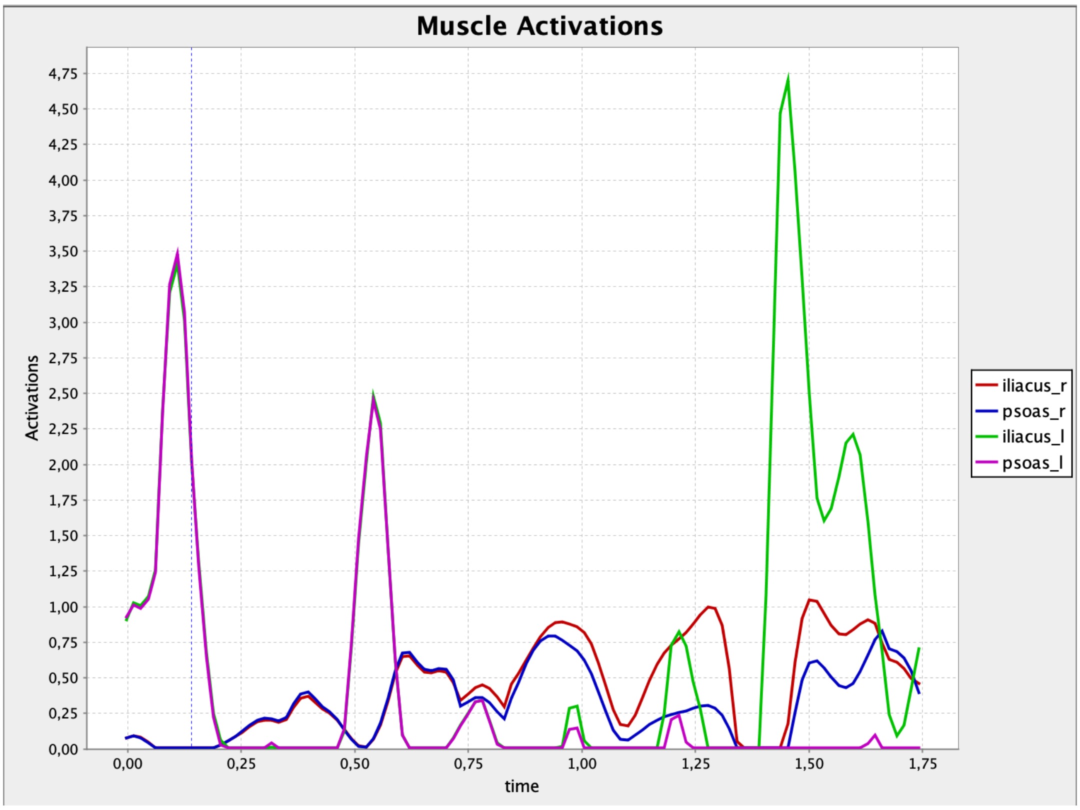


FIGURE 4.26: Front Kick Dynamic without perturbations, SO analysis, Left/Right iliacus and Left/Right psoas Activations

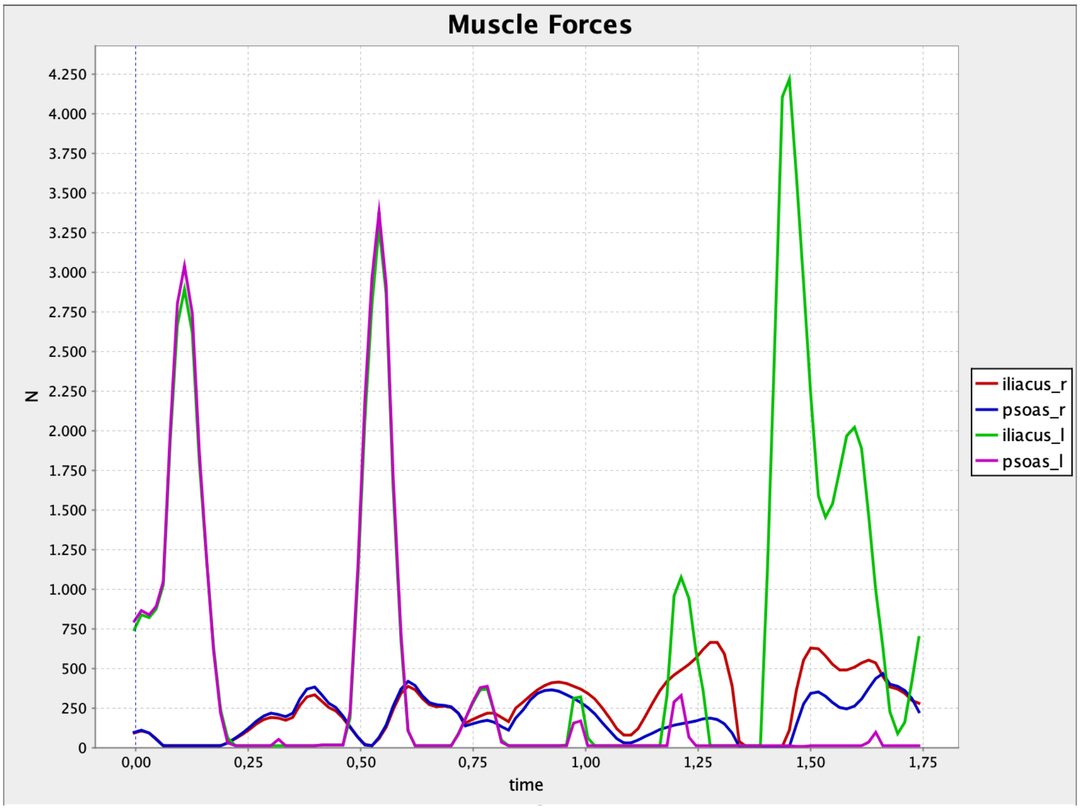


FIGURE 4.27: Front Kick Dynamic without perturbations, SO analysis, Left/Right iliacus and Left/Right psoas Forces

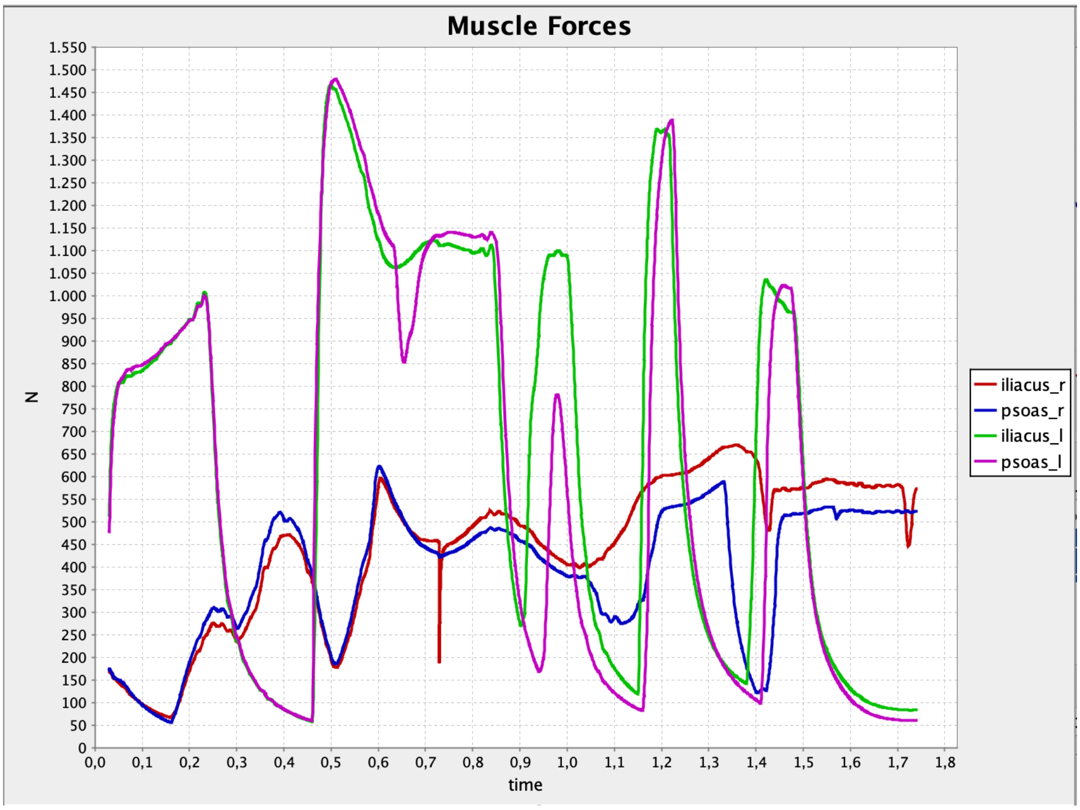


FIGURE 4.28: Front Kick Dynamic without perturbations, CMC analysis, Left/Right iliacus and Left/Right psoas Forces

Chapter 5

Experimental Results

Summary

In this chapter are analyzed in detail all the results previously presented such as the graphics, and theirs interpretations with a full discussion of them. In addition, the use of these results in a possible future line of work has been evaluated as next steps of study.

5.1 Analysis of the results

Once I have presented all the results that I have obtained performing the proper analyses with OpenSim, I would like to make a few comments about them.

It is important to point out that in the muscular system of the human body, there are agonist and antagonist muscles. While the former are responsible for executing muscle contraction, the latter relax, allowing movement. This causes synergies between muscle groups that cause that when the activation levels of some muscles increase, other activation levels associated with other muscles decrease. This can be observed in the results obtained, when some muscles are activated for a certain pushing force, and in the force in the opposite direction the muscles which in the previous one acted as antagonists are now activated. Besides, this explains why there are some muscles which are activated while others are deactivated, showing agonist-antagonist relationships.

In addition, in some results it can be observed how some muscles have activation patterns in stretches, in which sometimes they present an increase of their activation level and others a decrease. This depends on the intensity of the pushing force, which when is greater, these activation patterns are more common. However, it is most emphasized in the pushing forces in the direction Z+. For example, in 4.5 you can see how the left gluteus medius 1 (*glut_med1_l*) is deactivated at the beginning and when it reaches a specific activation value too low, (0.264 in the second 0.38), it has to be reactivated again because the pushing force is too high.

Focusing on the Front Kick posture, it is easy to see how the muscles either activated and deactivated for each pushing force in both phase 1 and phase 2 are the same. There is also a set of muscles that are always activated or deactivated when one pushing force comes into play, but in some specific cases appear some muscles that they do not often do it, such as the left adductor magnus (*add_mag2_l*) in the Z+ pushing force, which can be observed in 4.2.2. In addition, both postures follow almost identical activation patterns. The main difference between these two postures is the intensity of the changes in the activation level of each muscle. Since the phase 2 of the front kick is a posture with a greater imbalance level, the changes in the activation and deactivation values of the muscles are greater too.

On the other hand, I am going to analyze the two postures related to the Side Kick. In this case, and contrary to the Front Kick, the muscles responsible for maintaining the posture, and therefore the balance, do not coincide in the two phases for each pushing force. However, with also a few exceptions where a muscle appears only with a specific pushing force, the set of muscles whose activation level changes when a pushing force is added is always the same. Furthermore, the activation patterns are different in both phases. In addition, it can be observed that as expected, due to the higher level of posture demand, the increases of the activation values are much higher in the second phase. Finally, in the Side Kick you can see how there are also muscles that follow a pattern of activation in stretches, that is, they are activated or deactivated depending on the intensity of the pushing force. As in the Front Kick, this activation pattern is more characteristic of the pushing force in the Z+ direction.

5.2 Next Steps

In the previous sections I have presented the different muscles that are in charge of maintaining a specific posture which is usually used in the training methodology of the Taekwondo. This is closely related to the static balance, so stimulating these muscles will mean an improvement in the balance capacity of the subjects who undergo this stimulation, as if it were a Taekwondo training. Once it is known which are the muscles that it is necessary to stimulate, the next step would be decide how to do it.

These muscles follow an activation pattern when a perturbation is added. This depends on the direction of the perturbation, and the intensity of it.

In order to reproduce faithfully in the best way a complete training methodology of Taekwondo, a solution could be calculating the proportion in which each muscle is activated per each posture and each perturbation, then obtaining the aggregate for each movement and stimulating the muscles in the same proportion. The different intensities of the perturbations will give the correspondence between the intensity of the stimulation and the proportion at which each muscle is activated.

To calculate the proportion in which each muscle is activated, it would be as simple as calculating the area of each positive change in the activation value of each muscle.

I going to do an example with three different muscles that are activated in the front kick phase 1 posture when a perturbation comes into play: Left gluteus medius 1 (*glut_med1_l*), left biceps femoris short head (*bifemsh_l*), and left psoas (*psoas_l*).

First of all, I calculate the covered areas by each positive change of the activation value for each pushing force and each intensity. These values are expressed in 5.1 and 5.2, as a consequence of a perturbation in the Z and X direction, respectively.

Front Kick phase 1

	Z+			Z-		
	50 N	100 N	150 N	50 N	100 N	150 N
glut_med1_l	0	0.0108	0.03956	0.1008	0.2019	0.3036
bifemsh_l	0	0.003536	0.014112	0.0537	0.1074	1.617
psoas_l	0	0.01056	0.037904	0.0426	0.0855	0.129

TABLE 5.1: Covered area by the positive changes in activation values of the muscles when Z-direction pushing forces (Units of area)

Front Kick phase 1

	X+			X-		
	50 N	100 N	150 N	50 N	100 N	150 N
glut_med1_l	0	0	0	0.0369	0.093688	0.49616
bifemsh_l	0.0858	0.1719	0.245544	0	0	0
psoas_l	0.111	0.222	0.3567	0	0	0

TABLE 5.2: Covered area by the positive changes in activation values of the muscles when X-direction pushing forces (Units of area)

Afterwards, these values are then added together to calculate the total area covered for each intensity of a perturbation force, obtaining an estimate of the amount of activation of each muscle in a given posture and subjected to certain perturbations evenly distributed in the four coordinates. These total amounts are expressed in 5.3 and they can be graphically observed in 5.1.

Front Kick phase 1

	Total		
	50 N	100 N	150 N
glut_med1_l	0.14	0.31	0.84
bifemsh_l	0.14	0.28	1.88
psoas_l	0.15	0.32	0.52

TABLE 5.3: Total covered area by the positive changes in activation values of the muscles in Front Kick phase 1 (Units of area)

Finally, these areas have to be expressed in proportion to the maximum value, so that values can be better managed and a relationship between them obtained. These proportional values are expressed in 5.4 and they can be graphically observed in 5.2.

Expressing these values in percentages provides a better arrangement of the data and makes it easier to understand and use. For example, assuming that this information is going to be used to stimulate the muscles with a stimulation device, the maximum value would be the maximum tension offered by the device, so that the

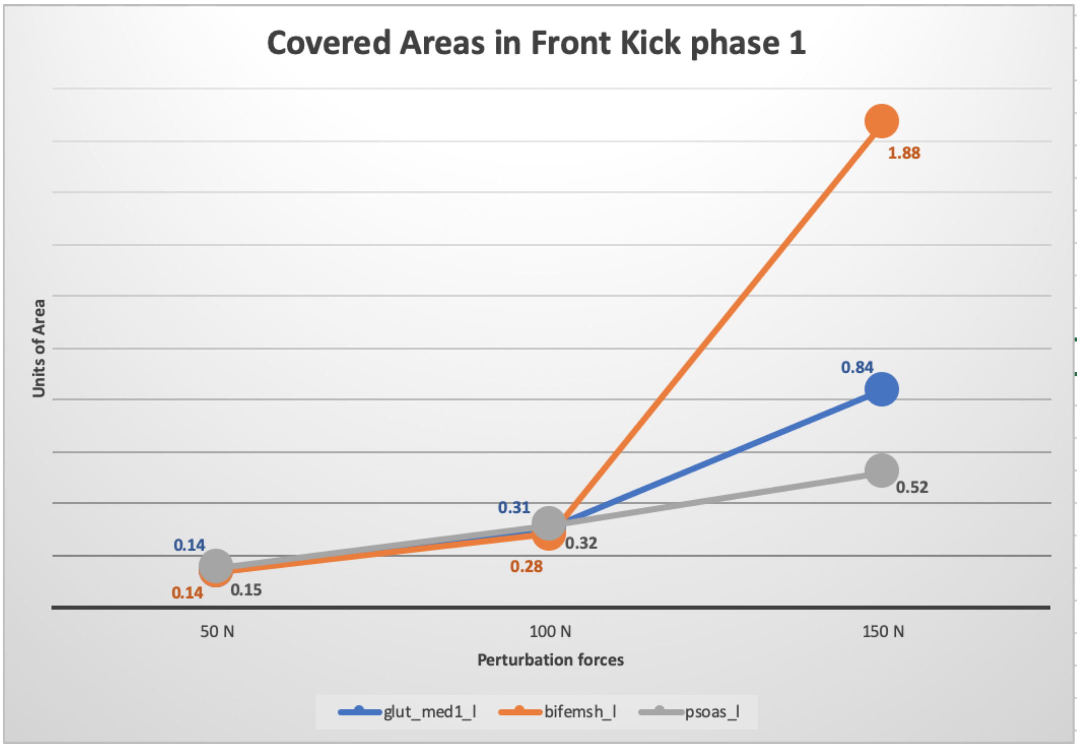


FIGURE 5.1: Total covered areas by the positive changes of activation values (Units of area)

Front Kick phase 1

	Total		
	50 N	100 N	150 N
glut_med1_l	7.34%	16.33%	44.72%
bifemsh_l	7.43%	15.07%	100%
psoas_l	8.18%	16.95%	27.90%

TABLE 5.4: Contribution ratio of each muscle proportional to the maximum value in Front Kick phase 1

stimulation level can be graduated and specific for each muscle, corresponding to the chosen intensity. This intensity will be related to the intensity of the pushing forces used in our simulations.

Assuming a stimulation device with a maximum voltage of 100 V and three levels of intensity, the proportional values of stimulation per each intensity level would be those expressed in 5.5.

This process should be done with all the muscles which are involved and with the other postures, so that it will possible to reproduce a taekwondo movement by stimulating the muscles in charge of maintaining the static balance and complete in that way a full taekwondo training just only with a electro-stimulation device.

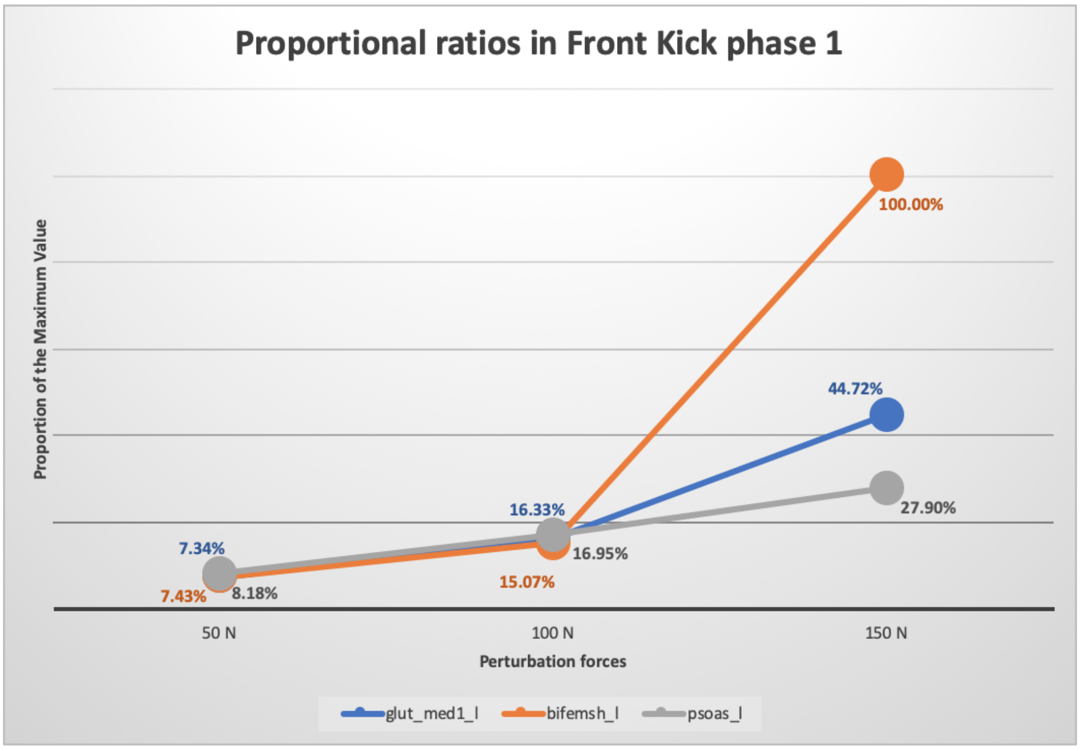


FIGURE 5.2: Contribution ratio of each muscle proportional to the maximum value in Front Kick phase 1

Front Kick phase 1

	Total		
	Intensity 1 N	Intensity 2	Intensity 3
glut_med1_l	7.34 V	16.33 V	44.72 V
bifemsh_l	7.43 V	15.07 V	100 V
psoas_l	8.18 V	16.95 V	27.90 V

TABLE 5.5: Stimulation values proportional to a maximum available voltage of 100 V

Chapter 6

Conclusions

This thesis has its origin in the promising results obtained in different studies carried out with children with psychomotor problems, in which training protocols based on Taekwondo methodologies were applied. The participants of these studies experienced great improvements in different psychomotor aspects, which can be highlighted those related to balance and coordination, serious causes that put at risk not only the correct development of children, but their safety, sociability and education.

It was therefore decided to investigate these studies with the intention of identifying what could be the causes responsible for such improvements, which may be key in the search for a definitive solution to these disorders. The use of OpenSim, free software developed by Stanford University for the biomechanical study, was of great help.

The analysis of the Taekwondo methodologies used in the different studies had several difficulties, among which I would highlight the following:

- Diversity in the parameters studied, and consequently, diversity of results.
- Diversity of samples subjected to the studies, both in age and sex.
- Diversity in Taekwondo training protocols used

In spite of this, it was possible to isolate two movements that were characteristic of Taekwondo and were present in most of the studies: Front Kick and Side Kick. However, due to the fact that the studies were carried out by means of generally static tests, it was decided to analyze these movements in a static way, deepening the study of static balance.

For this purpose, two phases of each movement were chosen, one initial and one final, and they were exposed to perturbation forces that simulated a destabilizing environment, thus being able to accurately analyze by OpenSim the muscle responses responsible for maintaining balance.

OpenSim has turned out to be a very powerful program that offers a great variety of tools that allow very advanced biomechanical analyses. For our study purposes, the full potential of OpenSim was not used, but it gave a clear idea of it. Because the inputs used were not measured in the laboratory, but generated by me through trial and error, it was difficult to achieve a good level of accuracy in faithfully reproducing the movements and postures used in the analyses. This made the analyses in OpenSim very difficult, having to invest a large part of the time in this task. In the process of simulation of the movements in OpenSim, a first experiment was made with the Front Kick in a dynamic way, which helped me to understand the muscular responses that were obtained and the different results that offered the different tools of OpenSim. In addition, I was able to lay the foundations of my knowledge about the use and handling of OpenSim. Finally, the results of this experiment did not add value to the static balance study but were added to the thesis.

Finally, the different results obtained from the OpenSim experiments offered a certain set of muscles that were activated when the perturbation forces were added. These muscles were therefore in charge of maintaining the postures, and therefore the static balance. It is true that for each disturbing force the muscles that were activated were different, with different activation patterns as well, but it was obtained that the set of muscles really involved in this task was always the same.

Thanks to these results, it was possible to identify the muscles responsible for the static balance that are closely related to Taekwondo, which suggests that the stimulation and strengthening of these muscles will improve balance capacities in children affected by psychomotor problems. This would represent an important step forward in the study of effective and minimally invasive treatments for children that would allow them to improve their psychomotor abilities with just only muscle stimulations, for example.

In addition, a possible continuation of the present work has been analyzed based on a robotic solution that allows to reproduce a training protocol based on Taekwondo by means of the electrical stimulation of the muscles identified as beneficial for the improvement of the static balance. A group of three muscles has been chosen for it, which were identified as keys in the muscular responses observed in the previous results, and the percentage of contribution that each muscle has in the tasks related to the static balance has been calculated.

To conclude, with the results obtained I would like to mention some other possible future lines of work, among which I could highlight:

- Study the forces generated by each muscle group
- Study movements dynamically, thus deepening coordination and dynamic balance.
- Study other characteristic movements of Taekwondo
- Implementation of a robotic solution based on electro stimulation that reproduces a training protocol based on Taekwondo
- Study in adult persons

Appendix A

Front Kick Dynamic movement

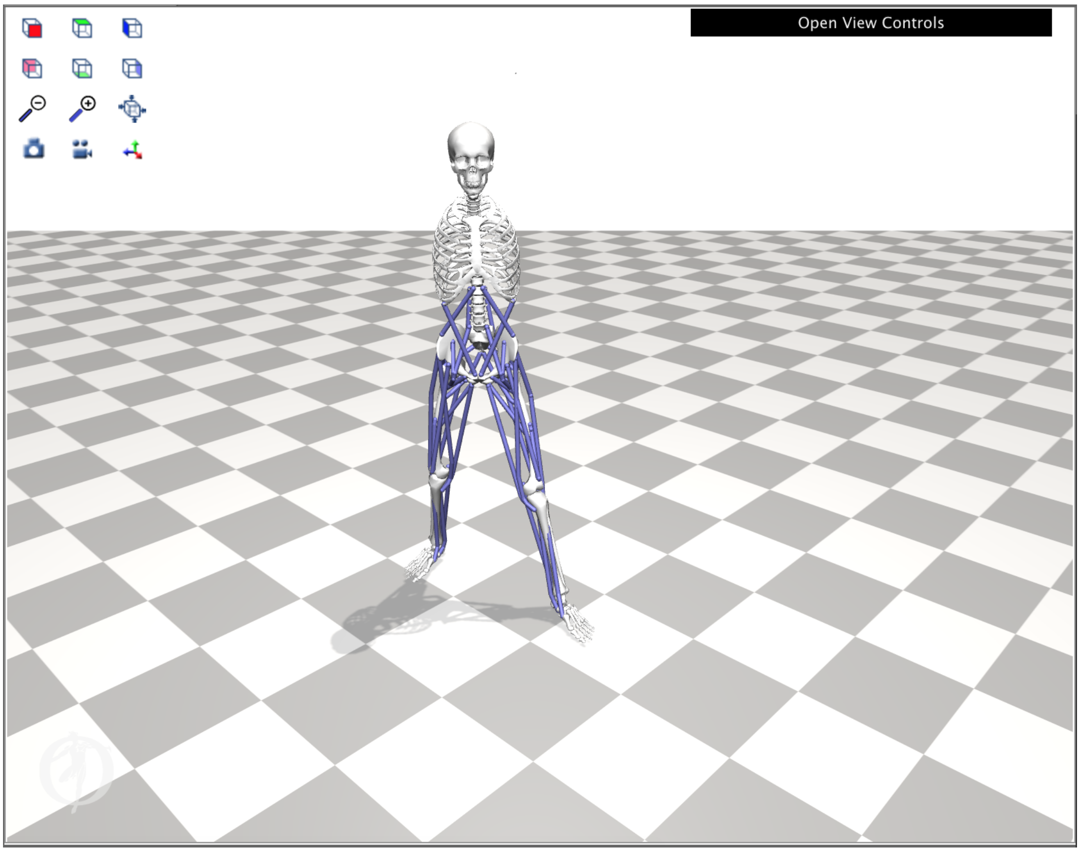


FIGURE A.1: Front Kick Dynamic sequence 1

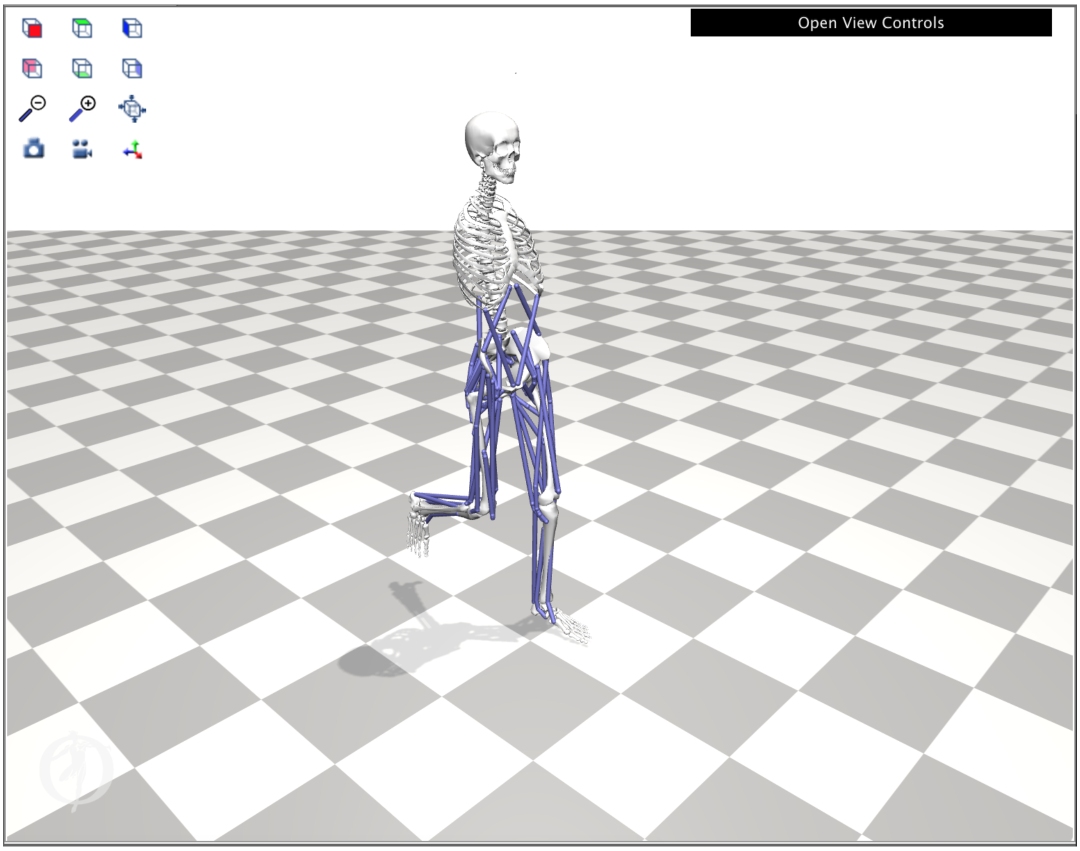


FIGURE A.2: Front Kick Dynamic sequence 2

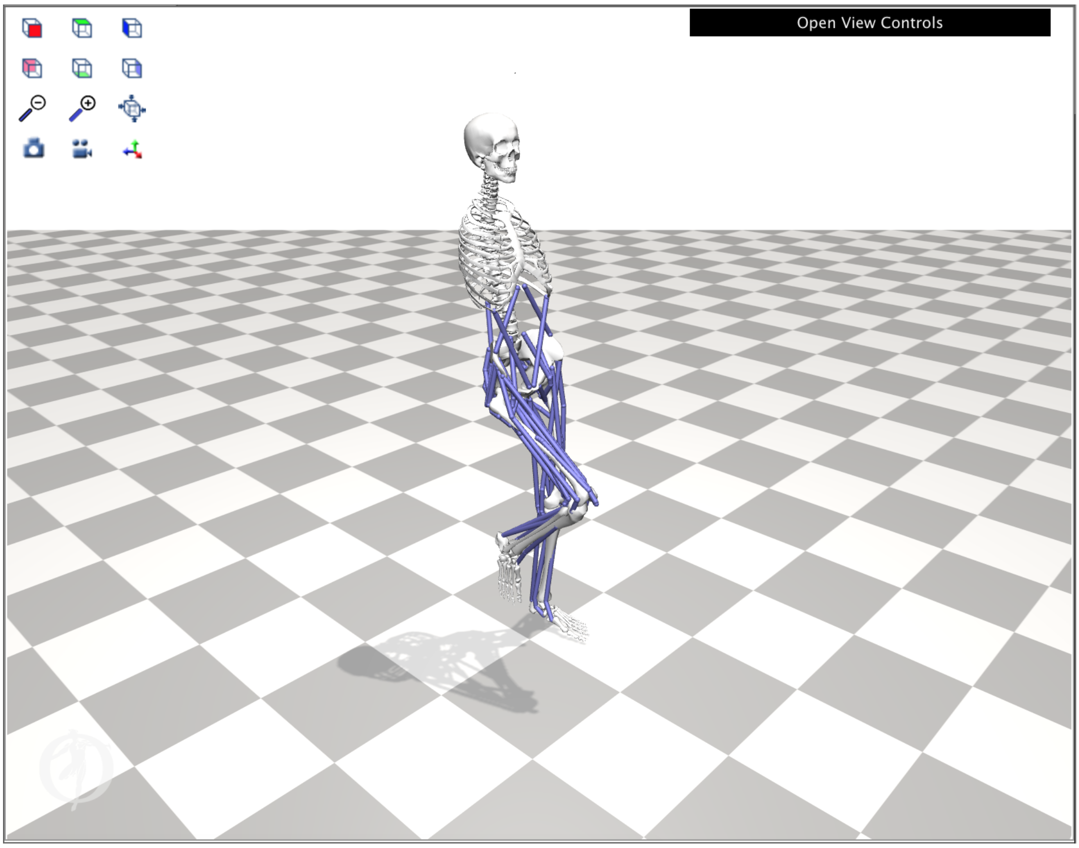


FIGURE A.3: Front Kick Dynamic sequence 3

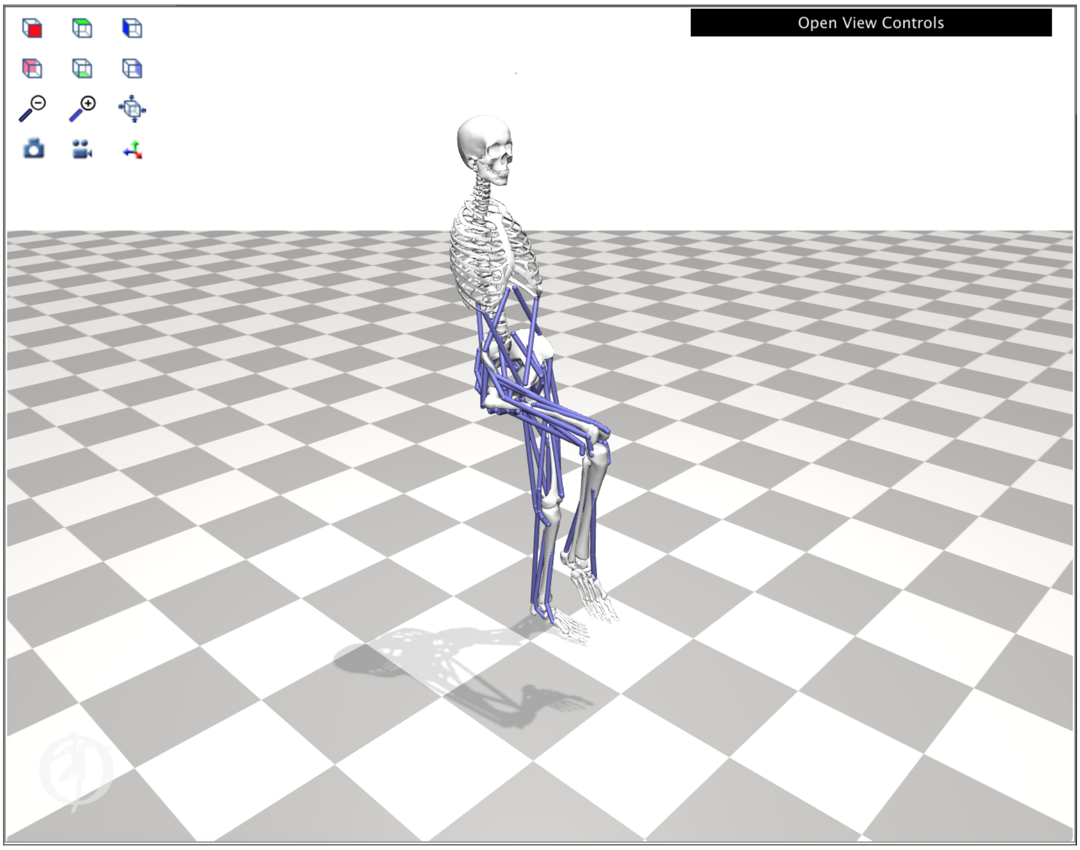


FIGURE A.4: Front Kick Dynamic sequence 4

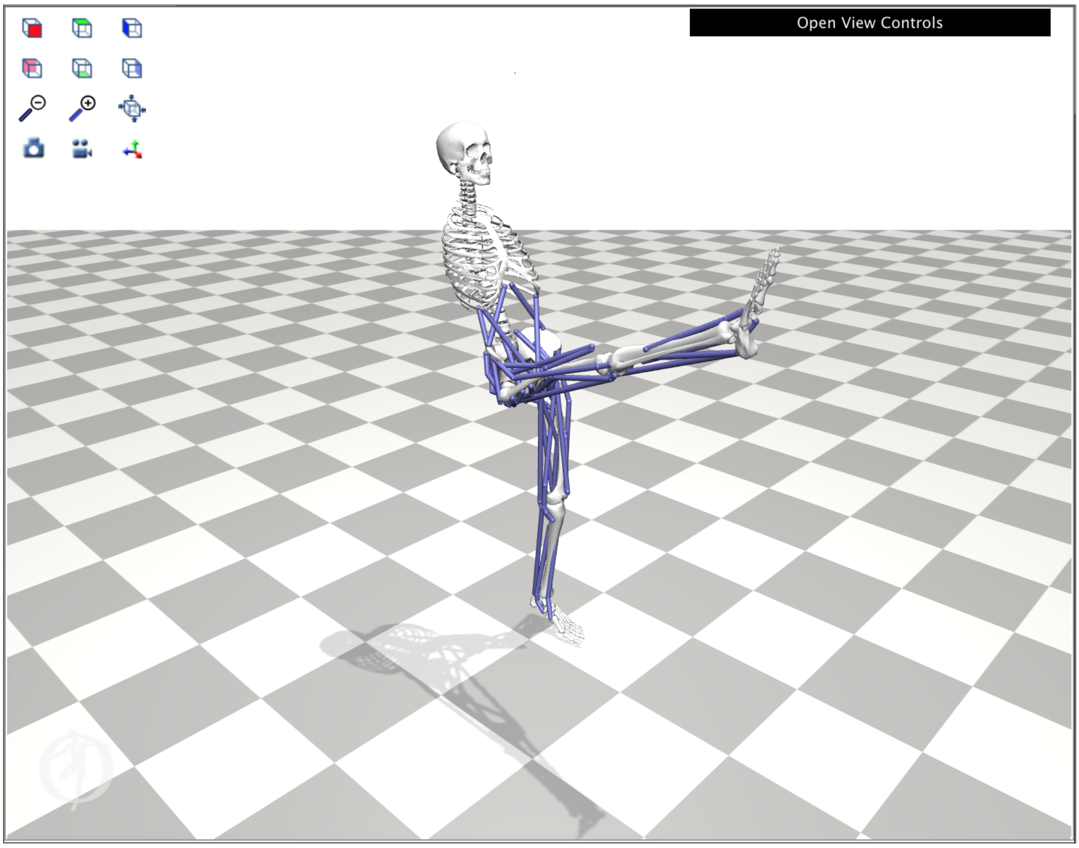


FIGURE A.5: Front Kick Dynamic sequence 5

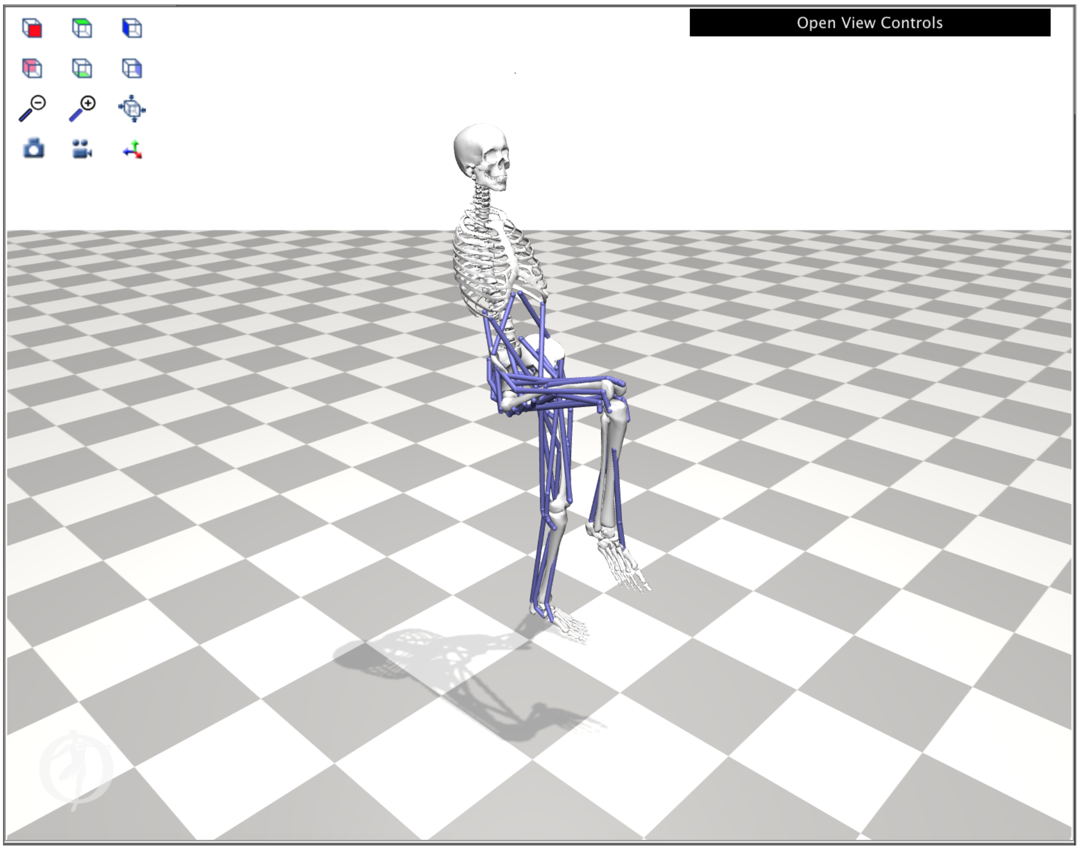


FIGURE A.6: Front Kick Dynamic sequence 6

Appendix B

Front Kick Dynamic results

B.1 Static Optimization

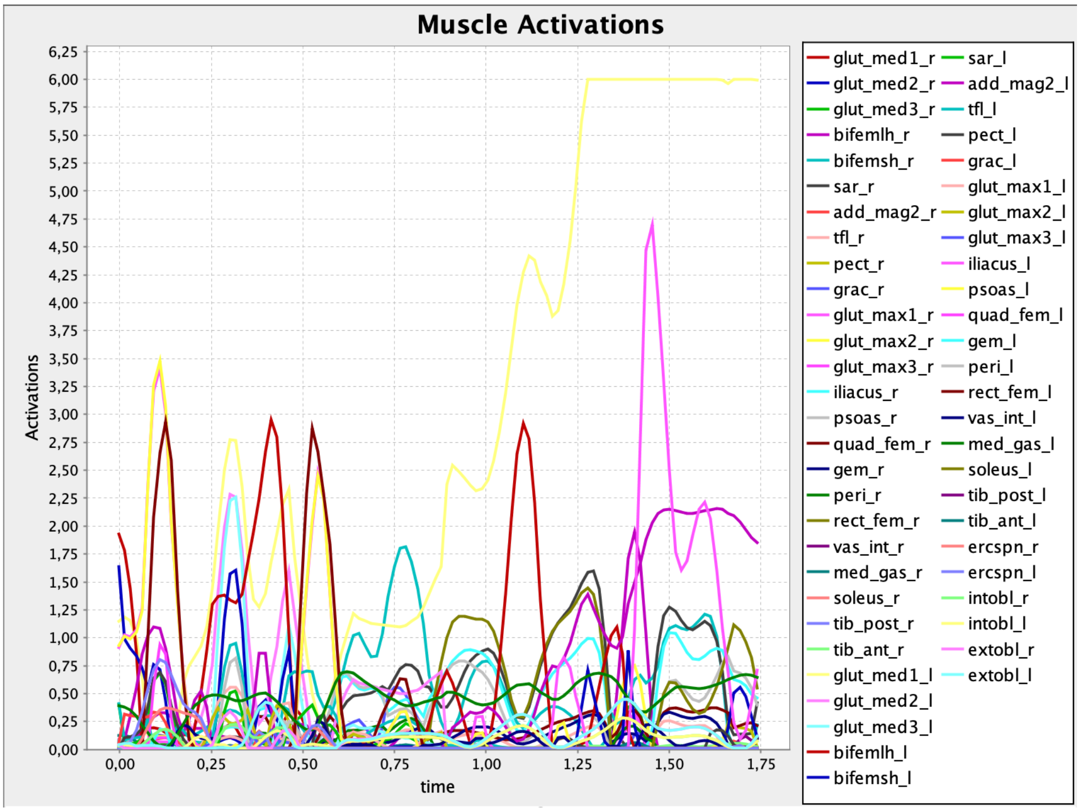


FIGURE B.1: Front Kick Dynamic without perturbations, SO analysis, Activations

B.2 Computed Muscle Control

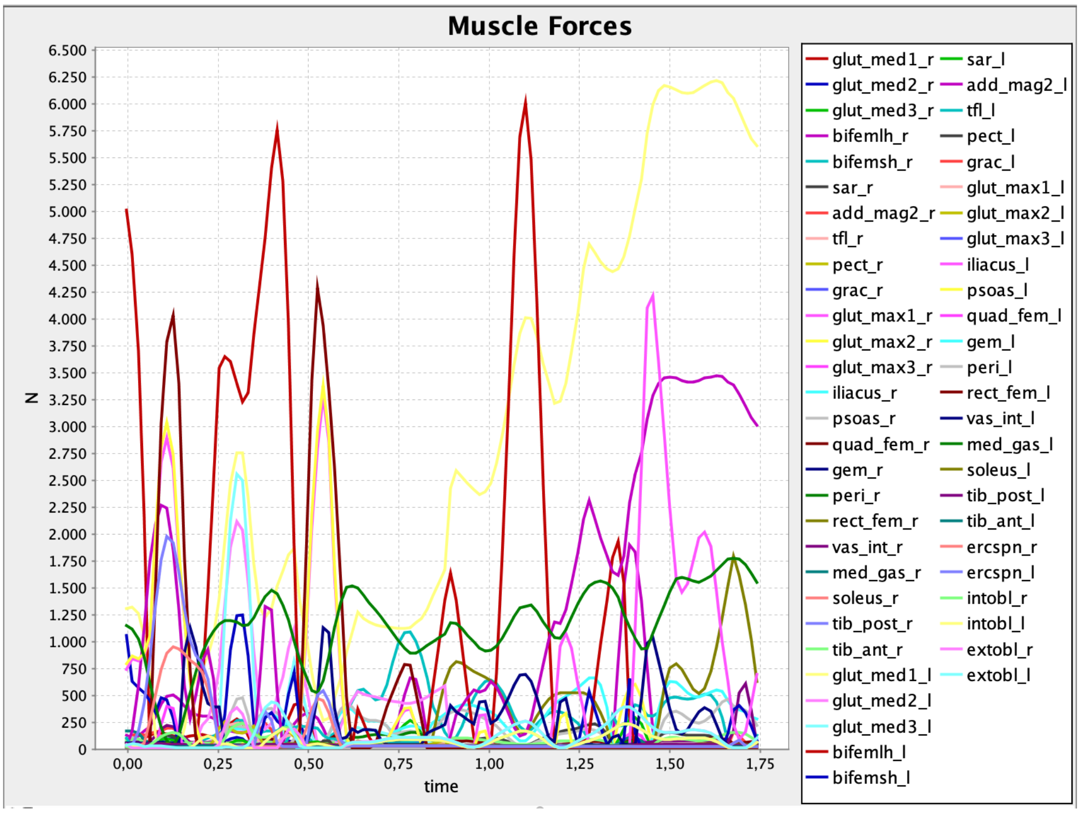


FIGURE B.2: Front Kick Dynamic without perturbations, SO analysis, Forces

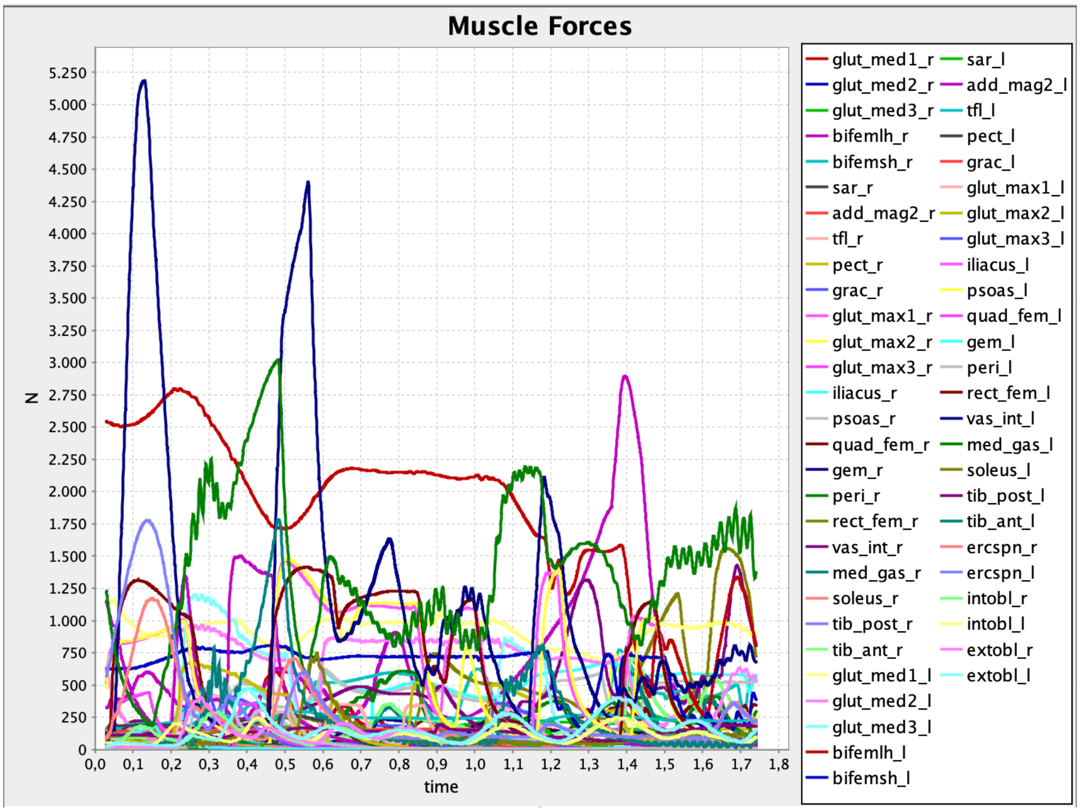


FIGURE B.3: Front Kick Dynamic without perturbations, CMC analysis, Forces

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