UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE TELECOMUNICACIÓN

MASTER OF SCIENCE IN NEUROTECHNOLOGY

MASTER´S THESIS

Design and Development of a System to Simulate Underwater Movement in an Exoskeleton to Support Cerebral Palsy Therapies

Juan Miguel Valverde García

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Master of Science in Neurotechnology

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Title: Design and Development of a System to Simulate Underwater Movement in an Exoskeleton to Support Cerebral Palsy Therapies

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Resumen

La parálisis cerebral es la discapacidad física más común en niños, afecta al movimiento, al tono muscular y a la postura. Aunque no existe una cura, para algunos fenotipos es posible mejorar el equilibrio y la marcha a través de terapias a edades tempranas. Entre la diversidad de terpias usadas, los ejercicios bajo el agua, en especial la marcha, se ha demostrado beneficiosa para la rehabilitación, mejorando sus beneficios y aumentando la recuperación de la estabilidad y del desempeño general de la marcha. Sin embargo, estas terapias acuáticas no siempre están disponibles. Por esta razón, en esta tesis se ha desarrollado un sistema de control basado en impedancia que simula la sensación de andar bajo el agua, provocando un comportamiento muscular similar sin necesidad de estar bajo el agua. Usando la plataforma robótica Discover2Walk, el usuario puede experimentar la resistencia al movimiento y las fuerzas de flotabilidad de un líquido dependiendo de la viscosidad deseada, reproduciendo algunos de los beneficios de la marcha bajo el agua sin necesidad de condiciones específicas, haciendo los beneficios más accesibles. Una validación técnica ha sido llevada a cabo para probar la viabilidad del sistema a través del análisis de la actividad muscular del Tibial Anterior (TA) y Gastrocnemius Medial (GM) recogida usando un dispositivo de EMG y dos IMUs durante los experimentos. Los resultado muestran una activación muscular acorde al comportamiento esperado tanto en el GM ($p < 0.052$) como en el TA ($p < 0.0001$), sin embargo, más pruebas son necesarias para validar correctamente el sistema.

Palabras clave

Parálisis cerebral, Discover2Walk, acuático, marcha, flotabilidad

Summary

Cerebral palsy is the most common physical disability in childhood. It affects movement, muscle tone and posture. Even though there is no cure, for some phenotypes it is possible to improve the balance and gait through early therapies. Among the therapies used, underwater exercises, specifically underwater walking, are proven to be beneficial, enhancing its benefits and increasing the improvement in postural stability and walking performance. However, these aquatic therapies may not be always available. For this reason, in this MSc thesis an impedance based control system has been developed that simulates the sensation of walking underwater, making the muscles behave in a similar way without needing water. Using the Discover2Walk robotic platform, the user can experience the resistance to movement and the buoyancy forces of a liquid depending on the desired viscosity, reproducing some benefits from underwater walking and effectively making these benefits more accessible. To test the system, a technical validation was conducted proving the feasibility of the system developed after the analysis of the muscular activity of the Tibialis Anterior (TA) and the Medial Gastrocnemius (GM) collected using an EMG device and two IMUs during the experiments. Results show a muscle activation according to the behaviour expected in both GM ($p < 0.052$) and TA ($p < 0.0001$), but further testing is required to properly validate the system.

Keywords

Cerebral palsy, Discover2Walk, underwater, walking, buoyancy

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Glossary

CP - Cerebral Palsy

GMFCS - Gross Motor Function Classification System

CNS - Central Nervous System

CAR - Center for Automation and Robotics

CSIC - Spanish National Research Council

UPM - Polytechnic University of Madrid

ROS - Robot Operating System

EMG - Electromyography

IMU - Inertial Measurement Unit

PC - Personal Computer

GUI - Graphic User Interface

VR - Virtual Reality

SBC - Single Board Computer

DDS - Data Distribution Service

PBWSTT - Partial Body-Weight Support Treadmill Training

BMI - Body Mass Index

FFT - Fast Fourier Transform

TA - Tibialis Anterior

GM - Medial Gastrocnemius

VL - Viscosity Level

Introduction and objectives

1.1 Introduction

Being able to walk is something most people have for granted without realising how important it is. Ironically, the ones who often appreciate it the most are those who know how it is living without that liberty. With that motivation in mind, this MSc thesis aims to help people gain or recover this ability. Specifically for people with Cerebral palsy who, through early rehabilitation therapies, could be able to ambulate.

With the development of new robotic devices to assist the therapies, the rehabilitation process and effectiveness is expected to improve, increasing the benefits and reducing the duration of the rehabilitation. Specially in cerebral palsy, early interventions and therapies are crucial to develop the motor system and increase the mobility of the patient in the adulthood. With this objective, many devices such as robotic exoskeletons and end-effector robots are designed to assist children specifically, using different control strategies.

Throughout this MSc thesis, a control strategy will be developed to reproduce some of the proven benefits of underwater walking using an end-effector robotic platform for children to assist the rehabilitation therapies.

1.1.1 Cerebral Palsy

Cerebral Palsy (CP) is a group of permanent neuromotor disorders characterized by disparities on the movement and abnormal muscle tone and posture. They are classified, in order of frequency, between spastic, dyskinetic, hypotonic and ataxic, with the most common phenotype being spastic diplegia [1]. Even though the pathophysiology is not fully understood, the cause is known to be a brain injury or malformation during prenatal to neonatal period [1, 2]. Figure 1.1 shows the affected regions depending on the type of cerebral palsy. Spastic CP relates to the motor cortex and pyramidal tracts, dyskinetic CP is caused by damages in the basal ganglia or cerebellum and hypotonic and ataxic CP are caused by damages in the cerebellum [3].

Around 2.0 to 2.5 per 1000 live births are affected with CP, which makes it the most common physical disability in childhood [4].

Although the initial neuropathological lesion is not progressive, as it is produced in the development stages, it may lead to a wide variety of secondary conditions such as motor, communication and learning impairment. Thus, this disorder can be classified based on four functional

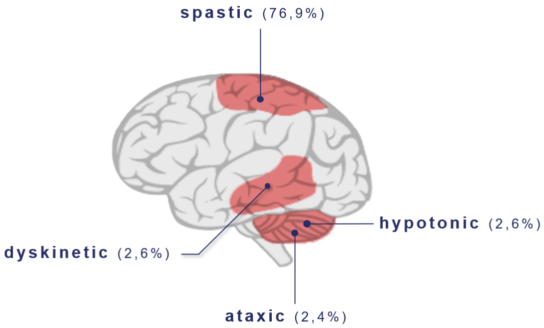


Figure 1.1: Affected brain regions in each CP types and its prevalence. Modified from [3].

classification systems as well as geographical and physiological classifications from which the Gross Motor Function Classification System (GMFCS) [1] has been selected. This system defines five (I-V) levels of CP based on the limitations for walking [1, 2].

1.1.2 Treatments and Walking

At the present time, there is no cure for CP. Nevertheless, through early diagnosis, specific early interventions can be made to optimize the impact on the developing brain's neuroplasticity to reduce the neuromotor function impairment. The treatments vary depending on the symptoms and the motor functions. However, most treatments are focused on reducing the impact of the variety of secondary conditions, using procedures that include treatment of spasticity, orthopedic surgical procedures, physiotherapy, treadmill training and occupational therapy, all of which aim to reduce the movement impairment [1, 2].

Spastic diplegic CP has a good prognosis for independent ambulation [1], provided that appropriate therapies are conducted. In this respect the treadmill training is an important therapy for which several devices have been developed to assist and facilitate the movement of the patient. These devices allows the patients to experiment the sensation of walking, which may induce the neuroplasticity to improve their motor control and overall improve their ability to walk [5], especially in toddlers, whose gait is rapidly maturing within the first months of the start of independent walking [6].

In the special case of toddlers, to experiment the independent walking is crucial to the development of the gait pattern and the reduction of kinematic variability which leads to a better and more stable gait [7]. Over the next six months, following the onset of independent walking, the immature gait, which is thought to be voluntary unlike the adult gait, cause changes in the Central Nervous System (CNS) that increase postural stability and maturates the gait parameters. Due to the poor equilibrium and gait instability, these walking attempts require numerous brain structures which may induce the brain to reorganize in order to optimize the task [6].

1.1.3 Aquatic Exercise

To support the walking therapies and in addition to the common treadmill training, which consist in assisted walking for a specified period of time, many studies defend the benefits of the aquatic exercise [8, 9]. In this case, the patient is meant to walk in a treadmill under water, with the water being commonly at chest level. This approach improves the postural stability [10] by reducing the effect of the gravitational force as well as reduce the risks of joints loading and fear of falling and improve the overall walking performance because of the higher resistance to movement through a viscous fluid [11].

For patients with spastic diplegic CP, who have a relatively high level of GMFCS, underwater treadmill training is feasible and beneficial to improve gait. Specially for children, as mentioned before, the walking exercises are crucial for the development of the CNS and to improve postural stability, thus, assisting the therapies with underwater treadmill training would enhance the improvement in postural stability and gait, making the therapies more efficient.

1.1.4 Virtual Reality

Typically, treadmill training therapies supposes spending extended periods of time just walking. Considering the attention span of children, keeping the attention and focus of the toddlers for the duration of the therapy usually turns out to be a difficult task. With that objective, multiple studies have demonstrated that the use of serious games helps in holding the children's interest [12]. Serious games are video-games designed to convey learning and promote specific skills, that can be used in a wide variety of environment such as teaching, training or rehabilitation. Using these games is useful for maintaining the patient's attention as well as motivate them and enhance their engagement in the therapy [12].

A step further in the use of serious games in rehabilitation is Virtual Reality (VR). Because of the increased immersive sensation, VR games are not only stimulating and intriguing for children [13], which makes the experience more enjoyable, but also give specific tasks that require troubleshooting, which enhance the brain's plasticity and behavioural changes [14, 15, 16], aside from helping to increase muscular strength, walking endurance, and balance abilities [17].

VR games are increasingly being used in rehabilitation therapies, specially for children. Using the immersive experience, the exercises needed for the rehabilitation can be integrated with the game to increase entertainment while giving feedback of the performance to the patient. The Discover2Walk uses VR games to give feedback of the speed at which the children should walk using a pack of wolves that need to be followed. Figure 1.2 shows the headset used with the Discover2Walk to assist therapies using the game shown in Figure 2.6

Figure 1.2: Virtual Reality headset used in therapies using the Discover2Walk.

Using the same concept, some situations can be integrated in the games to make therapies enjoyable while being beneficial for the rehabilitation. Knowing the benefits of aquatic exercises, the sensation of walking underwater can be integrated in a VR game using control strategies that simulates the resistance and buoyancy forces applied to produce the benefits of underwater walking while making the experience more immersive and enjoyable.

1.2 Objectives

1.2.1 Problem Description

As mentioned in Section 1.1.3, although the benefits of the aquatic treadmill training are numerous, conducting these therapies requires resources that may not always be available. The need for a specialised treadmill, hydrotherapy equipment and the movement support devices, makes these therapies less accessible or expensive.

Consequently, the motivation for this MSc thesis is to simulate said underwater conditions using control strategies in a robotic platform for the purpose of producing the same benefits of these therapies without having to use water. Furthermore, the simulation of these conditions should be scalable and simple allow the system to be applied in virtual reality to generate a more immersive experience that would increase the perception of being underwater and help in maintaining the children's attention, hoping for the therapies to be more efficient, more enjoyable and less stressful for the children.

To achieve the reproduction of the desired benefits, the muscular behaviour needed has been studied through literature that analyses the differences in muscular activation in water and in land [18]. The results obtained were a higher activation on the Tibialis Anterior (TA) and a lower activation on the Medial Gastrocnemius (GM) when walking in water respect to land

[18]. The location of both muscles are shown in Figure 1.3.

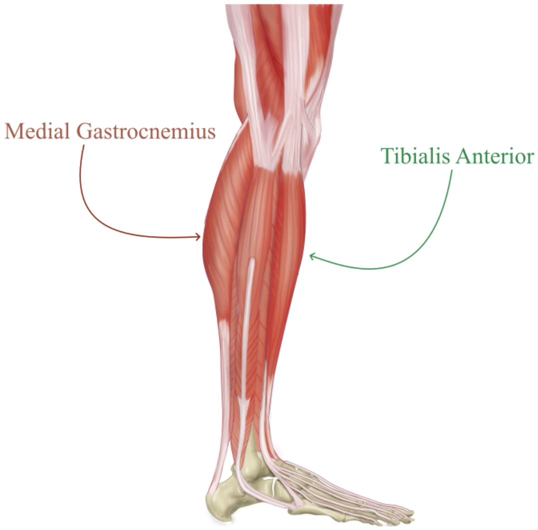


Figure 1.3: Location of Tibialis Anterior and Medial Gastrocnemius

To produce the same benefits of underwater walking using the designed control system the forces applied need to produce the same muscular response that has been stated in the literature studied [18]. Additionally, to prevent harm to the user or to the devices used, the control system should be tested in a simulated environment to ensure its correct performance prior to be implemented in the Discover2Walk.

To test the feasibility of the system, a technical validation needs to be conducted, measuring and studying the muscular activity using an EMG device and Inertial Measurement Units (IMUs) to collect the movement data. To collect the data needed for analysing the results and validate the system, experiments will need to be designed that test the functionalities of the system, after which the collected data will need to be processed and analysed.

1.2.2 Methodology

The Discover2Walk robotic platform, shown in Figure 1.4, is being developed by the group of BioRobotics at the Center for Automation and Robotics (CAR) of CSIC-UPM [19]. Using this robotic platform, this MSc thesis aims to develop a control system to simulate both the buoyancy forces and the resistance to movement through viscous fluids as well as to study the similarity between the real and the simulated aquatic exercises comparing the muscle activity in both conditions, using literature to contrast the results with the differences in muscle activation between land-based and aquatic walking [20, 18, 21].

Figure 1.4: Discover2Walk robotic platform.

For this purpose, the work packages followed in this MSc thesis, in order of development, are mentioned hereafter and explained on Chapter 3.

The control strategy will be designed, programmed and tested using a simulation, prior to the integration in the robotic platform, to ensure its correct performance. Said control will be required to apply an adjustable resistance to movement to simulate different liquids if needed, without completely impeding movement. As the Discover2Walk offers gait assistance, the impedance control must comply with it and be able to act at the same time.

In addition to the impedance control, being in a liquid generates buoyancy forces, described by the Archimedes' Principle, that needs to be simulated to produce some of the benefits of the aquatic exercise. The patient data needed for the calculation of the buoyancy forces will be minimal and easily modified to have a generalized model for any patient.

The communication with the robotic platform, will be programmed using ROS2 [22], which will be explained in Chapter 3, to ensure the compatibility and to be able to monitor the data in real time. Benefiting from some of the ROS2 characteristics, the parameter tuning needed for each user will be done in real time.

As for the validation process, some experiments have been conducted in the Hospital Infantil Universitario Niño Jesús to test the buoyancy and the resistance to movement in which the muscle activity will be read using an EMG and an Inertial Measurement Unit (IMU) to contrast the results with the literature.

The experiments consist on walking for a determined period of time, with and without the assistance of the robotic platform, while changing the resistance to movement and buoyancy forces to measure the difference in the forces applied, the muscle activation, the gait pattern and the personal perception of walking through water.

The resulting IMU signals will be used to determine the phase of the gait, and the EMG signals to measure the muscle activation during each phase and contrast the difference between walking with and without the simulated water forces.

1.2.3 Structure

In Chapter 2, this MSc thesis will study the state of the art, regarding some types of therapies for CP, among which the aquatic therapies will be explained and the existing devices used in children with CP for gait therapies will be mentioned.

Chapter 3 will cover the explanation of the systems used, such as the Discover2Walk and ROS2. The development of the control strategies, such as the viscous liquid resistance to movement and the buoyancy forces applied will be also explained in this chapter. Lastly, the simulation used for testing prior to the implementation in the Discover2Walk, with the needed kinematic modelling and dynamic study of the leg will be explained and the communication with the platform will be covered.

The conducted experiments, signal processing and the results obtained will be analysed in Chapter 4. After the results, the discussion of the results and the conclusion will be included in Chapter 5 as well as the future works and improvements that could be made.

Thereafter, in Chapter 6, the impacts related to the project will be disaggregated and analysed. The last chapter, Chapter 7, will contain a table with the financial budget for the project as is established in the regulations of the Master's Thesis.

State of the Art

One of the fields that has benefited the most from the technological advances of recent years is healthcare. Particularly in rehabilitation, the patients can undergo more comfortable, more efficient and, in general, better therapies using different devices. Which translates in less recovery time, increased functionality recovery and less painful rehabilitation sessions.

2.1 Non device-assisted therapies

Some therapies do not require special conditions or devices. Approaches such as the typical rehabilitation exercises, Hippotherapies and the Bobath Method are proven to be beneficial [7] and aims to promote motor learning and improve motor control without the need of additional devices.

2.1.1 Hippotherapy

Hippotherapies are based on the movement of horses, as it is shown in Figure 2.1. These therapies are demonstrated to influence the electrical activity of the trunk and lower limb muscles, as the pelvis movement produced during horseback riding is similar to the movement produced walking, it can induce a motor learning into the user [23]. However, the need for having access to a horse may hinter the use of this therapy.

Figure 2.1: Hippotherapy. Image retrieved from [24].

Figure 2.2: Bobath Therapy. Image retrieved from [27].

2.1.2 Bobath Approach

The Bobath method consist of the application of personalized physical exercises, like the exercise depicted in Figure 2.2 that uses a large hollow plastic ball to train the balance. These exercises are designed to enhance motor function and autonomy. The improvement of muscle tone and coordination is demonstrated by some studies, whether if its alone [25] or combined with other techniques such as Halliwick hydrotherapy [26].

2.2 Aquatic therapies

Hydrotherapies cover a wide variety of exercises that promote an improvement on muscle tone, coordination and postural stability. Some approaches consist of teaching swimming and address balance and movements encountered in an aquatic environment through exercises, such as the Halliwick concept [26], while others are based on walking with water at certain levels, often at chest level, to enhance the benefits of gait training.

Underwater walking therapies are supported by numerous papers due to the weight reduction produced by the buoyancy forces, the resistance to movement that increases postural stability, the increased movement control by decreasing velocity, and the reduction of fear of falling that may encourage the patient to engage more intensive exercise. [8, 9, 10, 11, 28].

Some works study the differences in muscle activation between the Tibialis Anterior and the Medial Gastrocnemius, stating that the former has higher muscle activation in water while the latter has lower muscle activation [20]. A different approach is studying the effects of underwater walking in the metabolic cost of walking, which is supposedly lower after some underwater treadmill training [9]. The muscle activation comparison will be used in Chapter 4 to contrast the results obtained in the experiments and state the effectiveness of the system in reproducing the benefits of underwater walking.

At the present time, the underwater treadmill training uses specialised treadmills with water tanks, or that can be placed in the bottom of a pool, as shown in Figure 2.3, to produce the desired environment which implies not only the presence of steady water at specific levels but also can produce currents to hinder the movement if needed.

(a) Treadmill placed underwater. **(b)** Treadmill with a water tank.

Figure 2.3: Types of treadmills for underwater exercise.

2.3 Robot-assisted therapies

The ongoing advances to the robotics field are present in healthcare in many forms such as mechanical orthosis, prosthesis, exoskeletons and end-effector robots.

Devices like prosthesis are meant to substitute missing body parts in order to retrieve or gain lost capabilities, while orthosis are usually used to assist rehabilitation therapies and exercises in many forms. Depending on the functionality, orthosis can be mechanical when there is no computation needed, or robotics. Among the robotic orthosis, some can be wearable, commonly called exoskeletons, or end-effector robots, which is the case of the Discover2Walk, that applies forces at the end of the limb, producing the desired movement.

Numerous orthosis and robotic devices are used in a wide variety of therapies. Said devices usually assist the movement and are capable of sustaining a portion of the weight of the patient for therapies such as the Partial Body-Weight Support Treadmill Training (PBWSTT) [29]. Related to this MSc thesis, two of the main robotic devices with similar functionality are the robotic exoskeleton Lokomat, developed by Hocoma [30] and the aforementioned end-effector robot Discover2Walk [19, 31], both used in therapies for children with Cerebral Palsy that can be supported with serious games.

2.3.1 Lokomat

Lokomat is a robotic orthosis with four degrees of freedom designed to automate treadmill training rehabilitation for spinal cord injured and stroke patients [30]. It consists of a treadmill, a suspension system able to support the body-weight and two PCs, which executes the safety and control tasks and serves as Graphical User Interface (GUI) for the physiotherapist while providing biofeedback about the quality of the training [30]. An image of its appearance is shown in Figure 2.4.

Figure 2.4: Lokomat orthosis, image retrived from Hocoma web page [32].

Additionally to the common treadmill training, the Lokomat can provide serious games [15] such as the one shown in Figure 2.5 that is called *Messy Dock*. This game is designed, mostly for children who need more stimuli, to help maintaining the user's motivation and to generate obstacles that need to be avoided, with the objective of making therapies more dynamic and enjoyable. [12]

Figure 2.5: Messy dock game for the Lokomat retrived from [12].

Even though, the Lokomat can be adapted to any age, some robotic devices, like the Discover2Walk, are designed specifically to help children and toddlers experimenting walking at early ages.

2.3.2 Discover2Walk

Similar to the Lokomat, the Discover2Walk is an end-effector robotic platform designed to assist treadmill training therapies. As mentioned in Section 1.2.2, the Discover2Walk will be the hardware used in this MSc thesis to test the developed system. Using nylon strings and 12 motors, this device can move the two ankles and the pelvis independently, allowing children with CP to experiment gait [19].

The Discover2Walk consist of a metallic structure with 12 motors, 4 for each ankle and 4 for the pelvis, all of which can move independently, allowing for full control over the gait pattern using the ankles modules and full weight support and pendulum mechanism movement in the pelvis module. This metallic structure is fixed on a treadmill with incline to allow the movement of the children in the spot. [19]

Recently, a serious VR game for the Discover2Walk has been designed where the user have to follow a pack of wolves through a forest, as shown in Figure 2.6. The speed of the pack of wolves sets the speed at which the patient have to walk in order to provide feedback of the walking speed to the user.

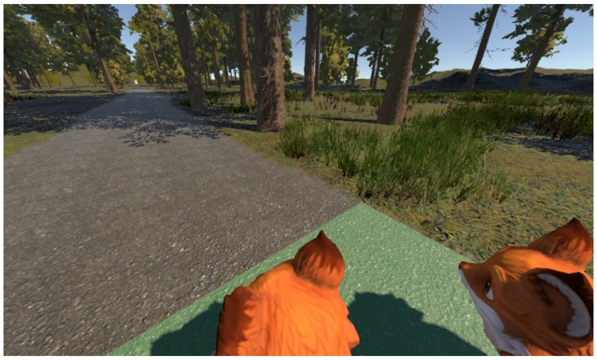


Figure 2.6: Point of view of the VR game for the Discover2Walk.

2.4 Future expectations

As it has been shown, many rehabilitation therapies aims to produce similar benefits with different approaches. Some therapies, despise the enhanced benefits, require specific conditions to be conducted that may not be always available. The motivation for designing and developing new devices and systems is to reproduce the benefits of these therapies to make them more accessible. Both the Lokomat and the Discover2Walk are robotic devices designed to assist in treadmill training rehabilitation therapies providing customizable assistance to produce the benefits of increased controlled effort during walking. However, there is no device capable of producing the same benefits of underwater walking by simulating the conditions.

Referring to hydrotherapies, even though the underwater walking is supposed to have better benefits than land-based walking, the feasibility of this rehabilitation technique may be low for some patients. Consequently, technology is progressing to overcome these problems. This MSc thesis aims to reproduce the effects of underwater walking by simulating the conditions. Creating the possibility of experiencing the resistance and the buoyancy forces of liquids without the need to have a source of water nor additional devices. Producing the same benefits with the objective of enhancing the treadmill training therapies. Following the example, more devices will be created to solve complications of rehabilitation techniques in pursuit of making therapies as effective, secure and enjoyable as possible.

Development

This chapter covers the main development done in this MSc Thesis. This counts for the hardware and software used, the control strategies for the resistance to movement and buoyancy, the kinematic modelling and dynamic study of the leg, the simulation used for testing and the communication to the robotic platform.

In order to develop a system capable of simulating underwater movement, is important to notice the benefits of aquatic exercises that can be replicated. The first main benefit is the reduction of spastic movements, which consist in involuntary contractions that can potentially be harmful for the patient. The reduction of spastic movements is produced thanks to the resistance to movement of water, which reduce the velocity of movement and can slow or potentially fully mitigate quick movements as the spasms. In addition, higher resistance means a higher effort needed for the patient to walk, which is useful for some exercises during therapies. The second principal benefit is the weight support provided by the buoyancy forces, this lowers the workload on the joints and prevents lesions and fear of falling.

With the two main benefits of the underwater walking stated, the control systems needed for implementing the benefits in the end-effector robot will be studied. For the resistance to movement of water, an impedance-based control will be applied to reduce the velocity of the movement, which based on its characteristics explained later, can reduce the velocity of the control without affecting the position. For safety reasons, prior to implementing the control to the Discover2Walk, it has to be tested to check its viability using a simulation with a human leg model.

To reduce complexity of the code and make the system as modular as possible, the buoyancy forces will be applied using a control mode already implemented in the robotic platform. The force sent to the platform is obtained using the BMI, the fat percentage and the Brozek formula to calculate the body volume, which will be used to calculate the force using the Archimedes' principle.

Before explaining the implementation of the control strategies, the hardware and software systems used needs to be explained to fully understand the development and functioning of the system.

3.1 Used Systems

As mentioned in Section 1.2.2, two systems will be used in this MSc Thesis, the first and main one, the Discover2Walk end-effector robotic platform, with its main characteristics being mentioned in Chapter 2, the control system used to control the Discover2Walk will be explained hereafter. The second system to be explained is ROS2, which will be used for communication between computers and the Discover2Walk and to collect data for posterior analysis.

3.1.1 Discover2Walk

The control of the Discover2Walk robotic platform is divided into the ankle and the pelvic modules, each of which are independent. While the ankle module controls the movement in the sagittal plane of each foot, the pelvic module is in charge of moving the pelvis of the patient to allow the pendulum mechanics, which are needed for postural stability and are produced during walk [19].

In the ankle module, additionally to other approaches, the main control strategies are based on impedance [19]. Impedance control makes use of the error in position, speed and acceleration; which are obtained as the difference between the real and the desired states. These components are multiplied each by its respective gains, being stiffness K_s, damping D and inertia I respectively as depicted in Equation 3.1 [33].

$$F_{impedance} = K_s \xi_\theta + D \xi_{\dot{\theta}} + I \xi_{\ddot{\theta}} \tag{3.1}$$

where ξ_θ, $\xi_{\dot{\theta}}$ and $\xi_{\ddot{\theta}}$ are the error in the position, velocity and acceleration respectively, with $F_{impedance}$ being the resulting force.

Using a previously generated gait pattern [31], the desired states of position and velocity (as the inertia is yet to be implemented) can be obtained, while the real states can be measured. This strategy increases the forces of the control according to the error, that is the distance between the desired state of position, velocity and acceleration to the actual position, velocity and acceleration. This creates a pliant interaction that drags the foot into the desired pattern without being too harsh with an increase of the forces only when needed, preventing the user from lesions or harm.

Additionally, the pelvis module can be controlled, depending on the required task, using the tension of the cables, the desired weight to be supported or the desired forces to be generated. For the buoyancy force, as it will be calculated using the user age, sex, height and weight, the best approach to produce the desired effect is to send the resulting force to the Discover2Walk and use the forces control. Additionally, using this control allows the system to be prepared to implement transversal forces to simulate currents if some motors are added to the robot.

Apart from the platform, the speed of the treadmill can also be remotely controlled to synchronize the control and set the gait parameters.

With regard to the data analysis and communication, all the collected data, such as the position of the ankles, the gait pattern, the real gait parameters and the states in each moment can be seen in real time and stored to be analysed using ROS2, which is also used for the communication between the GUI, the pelvic and the ankle module and the treadmill.

Figure 3.1 shows a scheme of the Discover2Walk system. It is divided in three levels, containing the clinical interface in the highest level, the gait pattern generator in the middle level and the modules in the lower level. The communication between each level is made through ROS2.

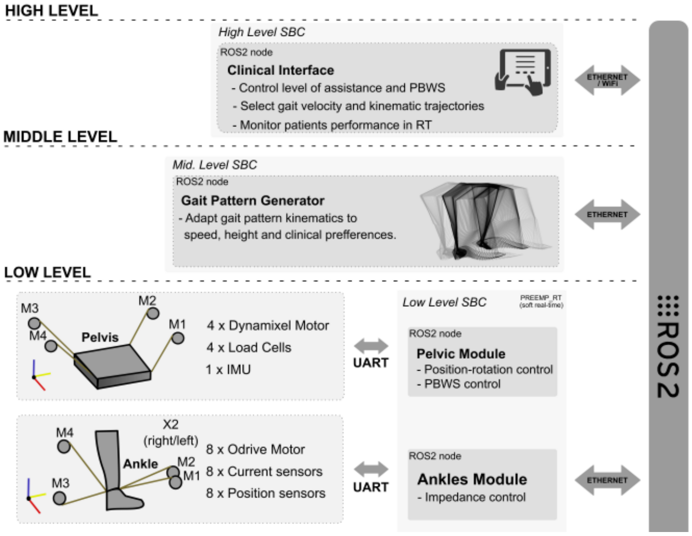


Figure 3.1: Discover2Walk general architecture. Is divided in three hierarchical levels with the higher level being the clinical interface, the middle level is the gait pattern generator which synchronizes the low level modules that sense and control the system. Each level has a single board computer (SBC) which communicates via Ethernet or WiFi. All programs are built as ROS2 nodes. Image retrieved from [19].

As it is shown, the Discover2Walk implementation rely in ROS2 for numerous functions such as communication, parameter tuning using GUI, data storage and data visualization in real time. Consequently, the developed system has to be implemented using ROS2 to maintain the modularity of the Discover2Walk and ensure a proper communication between the systems.

3.1.2 ROS2

ROS2 is a middleware made to ease programming robotic systems. Using a publisher-subscriber communication method based on *nodes* and *topics*, several devices can communicate with each other in real time.

Nodes are programs that can publish or subscribe to *topics* to send messages. One *topic* can have multiple publishers and multiple subscribers but only one type of message. However, messages can be defined to contain numerous types of data, making communication easier.

The basic communication in ROS2 consist of a *node* being a publisher in a certain *topic* that has a different *node* subscribed. When the publisher sends a message, it is received by the subscriber. Every publisher in a *topic* can send messages that will be received by every subscriber.

Unlike its predecessor, ROS2 is based on DDS (Data Distribution Service) as communication standard, which allows the communication to be secure and more reliable [22].

Another ROS2 characteristic are the *parameters*, which are exclusive for each *node* and can be modified by code, by a special file to run nodes, named *launcher*; by terminal or by a different *node*. This parameters can be used to change variables in the code in real time allowing for more control during the workflow [34].

All the data sent through *topics* can be recorded using *Rosbags*. This contains all the messages sent through the specified *topics*, which typically have a timestamp. Therefore, the data can be replayed or turned into graphics for better visualization.

Applying some of the ROS2 characteristics, the parameters needed for the implementation of the developed system can be tuned in real time during the therapies to modify the exercises based on the feedback of the patient or the requirements of the clinician. Additionally, the communication and implementation of the system can be easily done benefiting from the already used *topics* from the Discover2Walk implementation ensuring compatibility in the communication and modularity.

3.2 Simulation of liquid resistance

With the used systems explained, the control system for water simulation development can be covered, starting from the generation of the resistance forces and the subsequent simulation model to test its feasibility.

The first thing noticed while walking underwater is that there is a resistance to the movement that depends on the viscosity of the liquid, the more viscous it is, the higher the resistance. In terms of the impedance control of the Discover2Walk, this resistance would mean less velocity during the gait, as the positions is not modified and the inertia is not implemented. As the module in charge of moving the legs of the user is the ankle module, only the impedance control has to be modified to produce the desired effect. Adding resistance forces to the ankle module control based on the velocity and the viscosity of the liquid, the user can experience a decrease on the assistance of the module which will effectively produce the feeling of higher resistance when walking. As the extent of the force is related to the viscosity, the user can experience resistance forces lower or higher than water resistance.

To generate said resistance forces using the impedance equations mentioned in Equation 3.1, only the damping constant D and the error in the velocity ($\xi_{\dot{\theta}}$) component will be needed. Because the viscosity makes the velocity tend to 0, it will be the used for reference. As a result, Equation 3.2 describes the difference in velocity that will be used in the expression of the resistance to movement in Equation 3.3.

$$\xi_{\dot{\theta}} = 0 - \dot{\theta}_{measured} = -\dot{\theta}_{measured} \tag{3.2}$$

$$F_{resistance} = D(-\dot{\theta}_{measured}) \tag{3.3}$$

where D represents the viscosity of the liquid. The calculated force $F_{resistance}$ will be the resisting force needed to simulate the resistance to movement of a liquid depending on the viscosity.

3.2.1 Simulation

Prior to the implementation in the robotic platform, the control strategy has to be tested to ensure it will not cause damages to the user nor the device, as well as to analyse the effects of the impedance control to check its feasibility.

For the simulation, a model of the actuated limb is needed. Considering that, during gait, the movement of both legs are the same at contrary phases, can be concluded that the model of one leg is enough to test the control. To create the model of a human leg, the kinematics of the model have to be calculated to reproduce the movements correctly. Apart from doing the kinematic study, a dynamic study is needed to understand how forces interact with the model, whether the forces are gravity or input forces to control the movement.

3.2.1.1 Kinematic Study of the leg

As the actuation will be applied in the ankle, there is no need to include the foot. However, both the hip and the knees have to be included to be able to reproduce a step. Using this configuration of hip, femur, knee, tibia and the ankle as the tip, the result is a two-links planar robotic arm as it is shown in Figure 3.2 with the chosen reference system.

To carry out the kinematic study it is needed to calculate the direct and inverse kinematics, where the direct kinematics calculate the position of the tip based on the configuration, in this case, the angle of the joints (q_1 for the hip, and q_2 for the knee); and the inverse kinematics calculate the possible configurations based on the position of the tip.

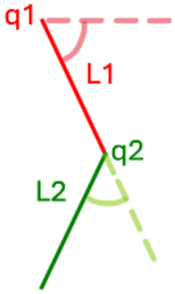


Figure 3.2: Simulated Leg

To calculate the position of the tip based on the angles of the joints, only the length of the segments are needed. For simplification, the length of the femur (L_1) and the tibia (L_2) are 1.

Using trigonometry and knowing q_1 and q_2, the position in x and y coordinates of the end effector can be calculated as follows:

$$x = L_1 \cos(q_1) + L_2 \cos(q_1 + q_2) \tag{3.4a}$$

$$y = L_1 \sin(q_1) + L_2 \sin(q_1 + q_2) \tag{3.4b}$$

For the inverse kinematics, as q_1 will depend on q_2 due to the possibility of different configurations, it is possible to calculate q_2 first using the law of cosines which relates the length of the sides of the triangle and the angles within as follows:

$$r^2 = L_1^2 + L_2^2 - 2L_1L_2\cos(\alpha) \tag{3.5}$$

where r is the distance from the origin to the tip given by $\sqrt{x^2+y^2}$ and $\alpha = \pi - q_2$. Working the equation, $\cos(\alpha)$ can be obtained as:

$$\cos(\pi - q_2) = -\frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2} \tag{3.6}$$

To take into account the different quadrants, using trigonometric correlations, $q2$ can be obtained as:

$$q_2 = arctan(\frac{-\sqrt{1-d^2}}{d}) \tag{3.7}$$

where $d = \dfrac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}$. Having q_2, q_1 can be calculated as the difference of the angle of the hypotenuse and the corresponding angle of the triangle as follows:

$$q_1 = arctan(\frac{y}{x}) - arctan(\frac{L_2\sin(q_2)}{L_1 + L_2\cos(q_2)}) \tag{3.8}$$

Thus, the inverse kinematics study conclude having that q_1 and q_2 can be calculated based on the position of the end effector in x, y coordinates. However, this does not describe the movement of the leg nor the effect of external forces.

3.2.1.2 Dynamic Study of the leg

To model the movement of the leg, a dynamic study has to be made to understand how external forces affects the model. To do so, the state equations are needed, as well as its derivate to calculate the evolution of the movement. Using the Lagrangian mechanics, the system can be described using the Lagrangian function:

$$L = T - V \tag{3.9}$$

where T is the kinematic energy of the system and V is the potential energy. Applying the Euler-Lagrange equation, the motion of the system can be described as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = u \tag{3.10}$$

where $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the Coriolis matrix, $G(q)$ is the gravity matrix, u are the forces acting on the system, in this case, the control input; and q is a matrix containing q_1 and q_2, with $\dot{q}$ being its derivate and $\ddot{q}$ being its second derivate.

These matrices for the studied system are defined as [35]:

$$M(q) = \begin{bmatrix} c1 + 2M_2L_2D_2\cos(q_2) & I_2 + M_2L_2D_2\cos(q_2) \\ I_2 + M_2L_2D_2\cos(q_2) & I_2 \end{bmatrix} \tag{3.11}$$

$$C(q,\dot{q}) = c2\begin{bmatrix} \dot{q}_2 & \dot{q}_1 + \dot{q}_2 \\ \dot{q}_1 & 0 \end{bmatrix} \tag{3.12}$$

$$G(q) = \begin{bmatrix} (M_1D_1 + M_2L_1)g\cos(q_1) + gM_2D_2\cos(q_1+q_2) \\ gM_2D_2\cos(q_1+q_2) \end{bmatrix} \tag{3.13}$$

defining $c1$ and $c2$ as:

$$c1 = I_1 + I_2 + M_2L_2^2 \tag{3.14a}$$

$$c2 = -M_2D_2L_2\sin(q2) \tag{3.14b}$$

where I_i is the moment of inertia, M_i is the mass, L_i is the length and D_i is the distance to the centre of mass of the specified link (i).

Working with Equation 3.10, the second derivate of q can be isolated as follows:

$$\ddot{q} = M(q)(u - C(q, \dot{q})\dot{q} - G(q)) \tag{3.15}$$

Knowing q, $\dot{q}$ and $\ddot{q}$, the evolution of the movement can be described as:

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \dot{q} \\ M(q)(u - C(q, \dot{q})\dot{q} - G(q)) \end{bmatrix} \tag{3.16}$$

This expression is able to predict how the movement of the system will evolve in the next instant taking into account the external forces u applied to the system, which allows the model of the leg to have a realistic movement and to control the leg using the external forces.

3.2.1.3 Controlling the leg

To be able to control the leg into making a step, the first thing needed is a trajectory to be followed. As the pattern of a step is difficult to code, the simple trajectory most similar to a step is a horizontal ellipse, defined by Equation 3.17:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} C_x \\ C_y \end{bmatrix} + \begin{bmatrix} w \\ h \end{bmatrix} \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} \tag{3.17}$$

where C_x and C_y are the coordinates of the centre of the ellipse, w and h are the width and the height of the ellipse respectively, and α is an angle that will be incremented in each step to describe the ellipse shown in Figure 3.3. The derivative and second derivative of the expression depicted in Equation 3.17 can be calculated to obtain the velocity and acceleration respectively in each point.

Figure 3.3: Ellipse pattern

Having the desired point and velocity in the trajectory, the leg can be controlled. To simulate both the movement produced by the user and the human-robot interaction forces, the control of the leg will consist in two separate controllers. The first being based on impedance, as depicted in Equation 3.1, to simulate the forces produced by the user, while the forces of the second controller will be applied in the tip, which represents the ankle. These two controllers will be called **Impedance** and **FeedForward** control, respectively.

For the **Impedance** control, the error in position and velocity are needed. However it has to be referring to the joints. The current position and velocities of the joints are known by the state variables q and $\dot{q}$. As for the goal position and velocities, which are known in coordinates from the trajectory, can be translated to the joints using inverse kinematics for the position, and the inverse of the Jacobian matrix for the velocity.

The Jacobian matrix is obtained by finding the partial derivatives respect to q_1 and q_2 of the direct kinematics equations as:

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial_{q1}} & \frac{\partial f_2}{\partial_{q2}} \\ \frac{\partial f_1}{\partial_{q2}} & \frac{\partial f_2}{\partial_{q2}} \end{bmatrix} \tag{3.18}$$

knowing from Equation 3.4 that f_1 refers to the equation for x and f_2 refers to the equation for y, the partial derivatives are obtained by finding the derivative of each one respect to q_1 and q_2 as follows:

$$\frac{\partial f_1}{\partial_{q1}} = -L2\sin(q_1 + q_2) - L1\sin(q_1) \tag{3.19a}$$

$$\frac{\partial f_2}{\partial_{q2}} = -L2\sin(q1 + q2) \tag{3.19b}$$

$$\frac{\partial f_1}{\partial_{q2}} = L2\cos(q1 + q2) + L1\cos(q1) \tag{3.19c}$$

$$\frac{\partial f_2}{\partial_{q2}} = L2\cos(q1 + q2) \tag{3.19d}$$

thus, obtaining the Jacobian matrix as:

$$J = \begin{bmatrix} -L2\sin(q_1 + q_2) - L1\sin(q_1) & -L2\sin(q1 + q2) \\ L2\cos(q1 + q2) + L1\cos(q1) & L2\cos(q1 + q2) \end{bmatrix} \tag{3.20}$$

with the inverse of the Jacobian being the following matrix:

$$J^{-1} = \begin{bmatrix} \dfrac{\cos(q_1+q_2)}{L1\sin(q_2)} & \dfrac{\sin(q_1+q_2)}{L1\sin(q_2)} \\ -\dfrac{L2\cos(q_1+q_2)+L1\cos(q_1)}{L1L2\sin(q_2)} & -\dfrac{L2\sin(q_1+q_2)+L1\sin(q_1)}{L1L2\sin(q_2)} \end{bmatrix} \tag{3.21}$$

Using the inverse of the Jacobian matrix, the velocity of the joints can be related to the velocity in the tip as follows:

$$v_{joints} = J^{-1} v_{tip} \tag{3.22}$$

Knowing the real and goal positions and velocities on the joints, the error can be obtained so Equation 3.1 can be applied. Using values for K_s and D found experimentally, the equation for the impedance control of the simulated leg is the following:

$$F_{impedance} = K_s(q_{goal} - q) + D(v_{joints} - \dot{q}) \tag{3.23}$$

To simulate the forces in the ankle, the **FeedForward** control is similar to how the velocity in the tip can be translated to $\dot{q}$. Using the inverse of the Jacobian matrix and its derivative, the acceleration on the tip can also be translated to $\ddot{q}$ using the expression depicted in Equation 3.24. With force being $F = ma$, knowing the mass and obtaining the acceleration by finding the second derivative of the goal position in the trajectory, the force applied to the ankle can be known and translated to the joints.

$$\ddot{q} = J^{-1} a_{tip} \dot{J^{-1}} v_{tip} \tag{3.24}$$

where the derivative of the inverse Jacobian matrix is the following one:

$$\dot{J}^{-1} = \begin{bmatrix} -\dfrac{\sin(q_1+q_2)}{L1\sin(q_2)} & \dfrac{\cos(q_1+q_2)}{L1\sin(q_2)} \\ \dfrac{L2\sin(q_1+q_2)+L1\sin(q_1)}{L1L2\sin(q_2)} & -\dfrac{L2\cos(q_1+q_2)+L1\cos(q_1)}{L1L2\sin(q_2)} \end{bmatrix} \tag{3.25}$$

Using the derivative and second derivative of the ellipse expression depicted in Equation 3.17 to obtain the velocity and acceleration in the tip, $\ddot{q}$ can be obtained using Equation 3.24 and used in Equation 3.16 to calculate the effect of the forces applied to the tip on the model.

Using the **Impedance** and the **FeedForward** controllers along with the dynamic model of the leg, the states can be updated to show the model at each instant and effectively simulating the leg with the human and the interaction forces.

For the simulation to work, all the variables regarding the characteristics of the leg such as moment of inertia, mass, length and distance to the centre of mass have to be 1. This occurs because of the lack of a rotational resistance force or friction. As the system is similar to a double pendulum, which is chaotic, meaning that it can not reach an equilibrium point without being controlled [36]. For that reason, the system cannot be tested with realistic proportions using the simulation, even though it should not be necessary.

With the leg being controlled by the **Impedance** and the **FeedForward** control, the **Viscosity** can be applied. As explained before, only the velocity will be used as the viscosity does not change the position but the speed of the object in the liquid. The expression for the control is the one depicted in Equation 3.3.

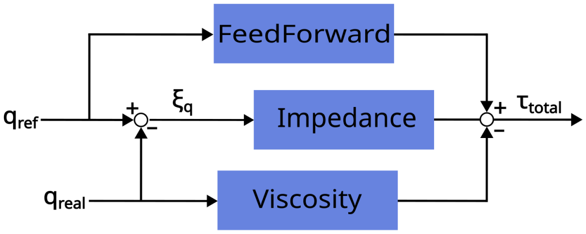


Figure 3.4: Control Diagram of the simulated leg

Adding this control to the fully controlled leg, is expected to produce the same results as when added to the Discover2Walk control system, thus, the behaviour observed in the simulation can be useful to test the feasibility and effectiveness of the developed system prior to the implementation in the real robot.

3.2.1.4 Analysis of the control system

To analyse the behaviour of the resistance, the velocity and position of both the hip and knee joints were stored at every instant during three loops of the trajectory. This was repeated for levels of viscosity from 0 to 9, as higher levels were observed to destabilize the system.

Figure 3.5 shows a progression from black being level of viscosity 0 to blue being level 9. Through the progression, the velocity (continuos lines) and position (dotted lines) can be observed to be more retarded at higher levels. With level more than 0, the velocity is observed to have less spikes, which translates into a smoother movement. Consequently, the resistance to movement can be observed to act as a filter for velocity, which in practical environments might be useful for reducing the effects of spasticity.

In general, the viscosity control produces a smoother response with a small delay, which indicates the desired effects of resistance and can potentially produce the wanted benefits.

As the control is shown to produce some desired effects in a simulated environment, it can

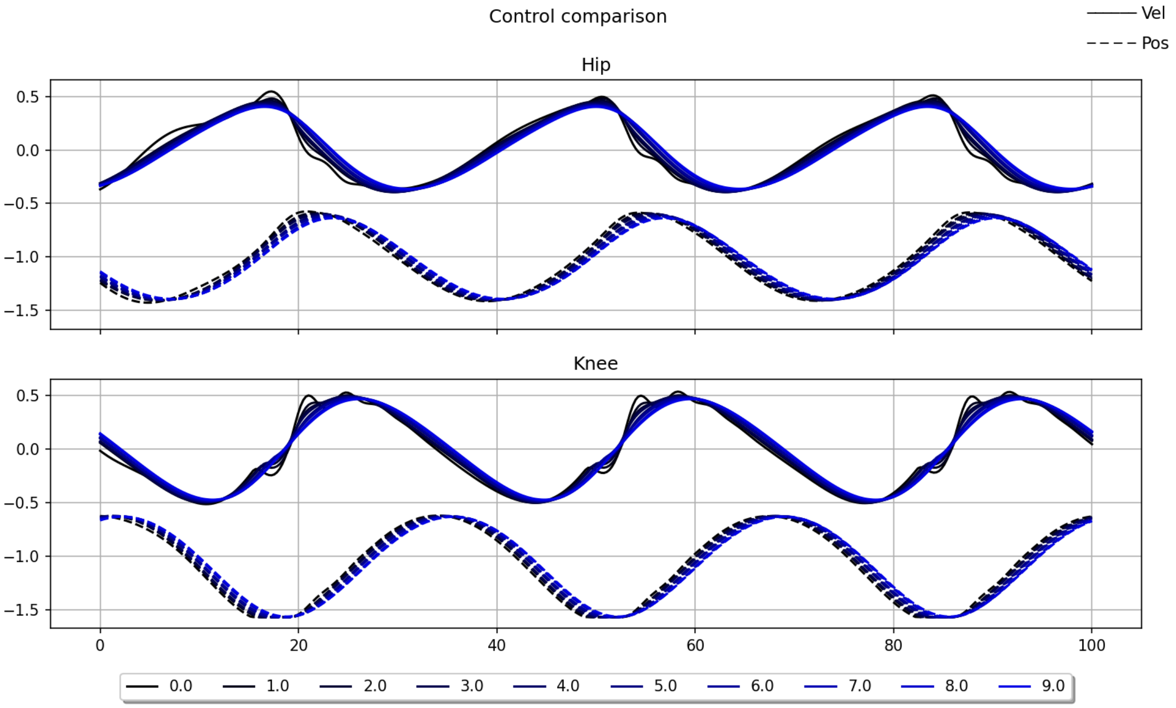


Figure 3.5: Effects of different levels of viscosity on the velocity and position of the limbs. The continuos line is the velocity while the dotted line is the position. The movement describes three loops of the pattern. The legend in the bottom part is referring to the viscosity levels.

be implemented into the robotic platform for further testing under more real conditions. In order to implement the code into the Discover2Walk, the control has to be programmed into a ROS2 *node* to be able to communicate with the platform, to acquire the information needed and to store the data for the final validation.

3.2.2 Implementation in the Discover2Walk

As mentioned earlier, all the communication between the platform and external devices are through ROS2, using *nodes* for every module and numerous *topics*. In addition, the level of viscosity will be defined using *parameters* to ensure that can be modified in real time and from any device.

The resistance is implemented inside a *node* called *viscosity node* which publishes the resistance forces and is subscribed to a *topic* named **get system state** to get the actual position and velocity of the ankles, used for the calculation of the resistance forces. As the viscosity is not directly related to the viscosity of the desired liquid to simulate and is a gain that modifies the extent of the resistance forces, it is referred as viscosity level. The higher the level, the strongest the resistance forces. Additionally, the viscosity level can be modified remotely in real time, when it is modified, the *viscosity node* publishes the new value of the level to have a record.

As the control of the platform is defined in the Cartesian Space, the expression defined in Equation 3.3 will be used to obtain the force of each axis as depicted in Equation 3.26.

$$F_x = D(0 - \dot{\theta}_x) \tag{3.26a}$$

$$F_y = D(0 - \dot{\theta}_y) \tag{3.26b}$$

$$F_z = D(0 - \dot{\theta}_z) \tag{3.26c}$$

where $\dot{\theta}_x$, $\dot{\theta}_y$ and $\dot{\theta}_z$ will be obtained from the *topic* in which the *ankle node* publishes the real states of the system at each moment using custom messages.

When a message is published in the *get system state topic*, the *viscosity node* calculates the resistance force and publishes them into the correspondent *topic* named **get viscosity** for the *ankle node* to add the resistance forces to the assistive control.

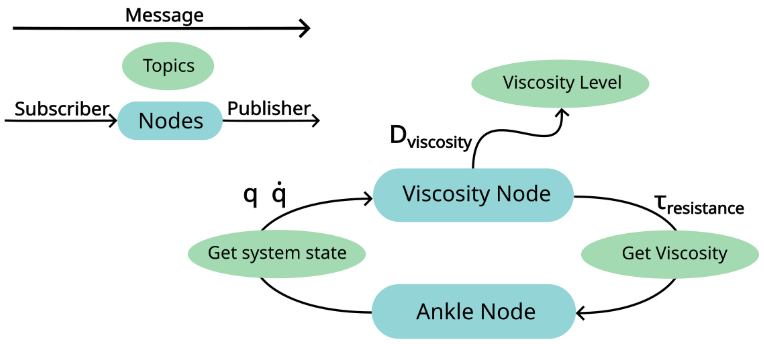


Figure 3.6: Communication diagram for the ankle movement

Messages from get system state and get viscosity *topics* are custom. For the *get viscosity topic*, the custom message called *viscosity forces*, contain the forces in the x, y and z axis for each ankle as depicted in Equation 3.26. Whereas for the *get system state topic*, the custom message named *Ankles system state* contains the position and velocity of each ankle in the Cartesian space, similar to the *viscosity forces* message.

This communication scheme completes the implementation of the simulation of liquid resistance. Using a *node* that calculates the desired resistance force and sends the result to the ankle module, the Discover2Walk can apply the specified force in each axis, producing the effect of walking underwater and its benefits.

3.3 Buoyancy

Another important benefit of the water exercise is the low workload in the joints that prevents the patient from getting injured. This effect is produced by the buoyancy force that lift a portion of the weight of the patient. The pelvic module can support up to 20kg of weight, however, the upward force applied needs to be calculated based on the viscosity of the simulated liquid, as different liquids have different densities, the buoyancy forces vary from one to another.

3.3.1 Buoyancy force calculation

For the simulation of the buoyancy, the upward force needed to apply can be calculated using the Archimedes' principle, which relates the buoyancy force with the volume of the body as follows:

$$F = -dgV \tag{3.27}$$

where d is the density of the liquid, g is the gravitational force and V is the volume of the body [37].

To make the device more efficient and flexible for any child, the time taken into measuring the body volume has to be minimized. As the precision needed is not high, the volume can be approximated with the Brozek equation using the body fat percentage [38] which in turn can obtained from the Body Mass Index (BMI) [39]. Through this approximation, the body volume can be estimated knowing the height, weight, age and sex of the child.

The equation for the BMI depends on the height and weight of the person as follows:

$$BMI = \frac{W}{H^2} \tag{3.28}$$

where W is the weight in Kilograms and H is the height in meters. The equation for the prediction of body fat percentage uses the BMI, age and sex of the person, however, it is different for adults and children. As the therapy is oriented to children, the equation that predicts the body fat percentage in children is the following [39]:

$$BF\% = 1.51BMI - 0.7age - 3.6sex + 1.4 \tag{3.29}$$

where *sex* is 0 for female and 1 for male. For the body volume estimation, the Brozek equation used to calculate the body fat percentage using the body density is the following [38]:

$$BF\% = (\frac{4.57}{BD} - 4.142) * 100 \tag{3.30}$$

where BD is the body density in kg/m^3. Knowing the body fat percentage, the body density can be calculated as follows:

$$BD = \frac{4.57}{\frac{BF}{100} + 4.142} \tag{3.31}$$

Lastly, the volume can be obtained with the weight and the density as:

$$V = \frac{W}{BD} \tag{3.32}$$

Having the Volume and knowing the gravitational force, only the density is needed. As the viscosity level can be modified, the higher is the level, the more resistance is applied and hence, the greater the buoyancy force has to be. Conducting some tests using the previously implemented ankle control, the viscosity level observed to produce similar sensation with respect to the resistance of water is 30.0. Knowing that the density of water is close to 1 at room temperature, the relation between the viscosity level and the density used in Equation 3.27 is a thirtieth of the viscosity level:

$$d = \frac{vl}{30.0} \tag{3.33}$$

where vl is the viscosity level.

3.3.2 Implementation in the Discover2Walk

To implement the buoyancy forces, the same *viscosity node* is modified to be subscribed to a *topic* named *get forces* which publishes the current forces applied by the pelvic module. As the *viscosity node* receives the information at an update rate, it is used as a *callback* to calculate and publish the buoyancy force into a *topic* called **set forces** at the same rate the pelvic module is operating. The forces published in said *topic* are applied in the force-based control of the pelvic module. As the forces are represented in the Cartesian space, the user can apply forces in each axis.

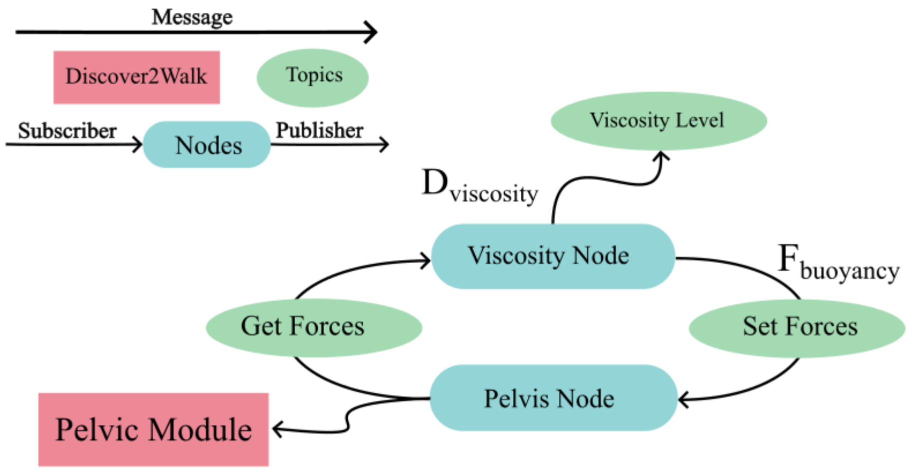


Figure 3.7: Buoyancy Communication Scheme

In the case of the buoyancy force, after being calculated using Equation 3.27, the result, which correspond to the reference forces in the Z axis, is published on the specific *topic* for the pelvic module to apply the upward force.

Additionally, for easier modifications, the information needed for the calculation such as height, weight, age and sex will be obtained using ROS2 *parameters* so that they can be changed in execution time if needed.

Using both the impedance control for the simulation of the resistance to movement of a liquid and the simulation of buoyancy forces, most of the benefits of underwater walking should be able to be reproduced. In the next chapter, a technical validation of the system developed will be conducted to test the effectiveness and feasibility in reproducing the benefits and analyse the similarities with walking under real water.

Results

In this chapter, some experiments are being conducted to obtain data regarding the similarities on the perception and the muscular activation between walking in water and using the developed system. As stated in some studies, there are differences in the activation of some muscles depending on the conditions during gait. While some muscles, like the Tibialis Anterior (TA) have higher activation when walking in an underwater treadmill respect to a conventional treadmill, others, like the Medial Gastrocnemius (GM) have lower activation [18]. The analysis of the perception of walking in water using the system, are made with the objective of stating how convincing the feeling is to check the feasibility of implementing the control in a VR game to make the experience more immersive while having the benefits of underwater walking.

The data is analysed to verify the performance of the system and the expected behaviour of the muscle using the Discover2Walk.

4.1 Experiments

Using the Discover2Walk and the control strategies developed in Chapter 3, the resistance to movement and the partial support of the weight is expected to produce some benefits similar to the underwater treadmill trainings.

To test the effectiveness of the control, a experiment is conducted where both the resistance to movement and the buoyancy forces are applied while the muscle activity is measured with a Quattrocento EMG device with sampling frequency of 2048Hz, developed by OT Bioelettronica. Additionally, the movement of the feet are obtained using two IMUs with sampling frequency of 40Hz, developed by XSense, to analyse rotation, velocity and acceleration.

Although the ideal user would be a child, due to accessibility and time limitations the first technical experiments are conducted by a healthy adult (1.75m/65Kg) with no gait impairments. Because of the increased strength and weight of adults respect to children and the technical limitations of the Discover2Walk, the effects of the upward forces and the resistance to movement can be decreased.

4.1.1 Protocol

For the technical validation of the system, two experiments were conducted, each with different protocols designed to test the functionalities and subjective sensations as well as to collect the data needed for the posterior analysis.

With the objective of testing the sensation of walking in water to check the feasibility of the integration of the system with VR games, the first experiment consists in walking with the Discover2Walk while changing the Viscosity Level (VL), which value is ranged between 0 and 40. This value refers to the damping constant D depicted in Equation 3.1. The chosen range is selected to test and characterize the limits of the maximum resistance that the robotic platform could provide, even though such high levels will not be used in real scenarios. During this experiment no EMG nor IMU data was recorded, as the only goal was to test the functionality of the system and the sensations while using it.

Starting with level 0, it is incremented by 10 after the stability and the change in sensation is checked. When the level reaches 40 it starts decreasing with the same conditions until reaching 0. The level is then raised and decreased again in increments of 20, and finally one increment of 40 followed by returning back to 0. Through this experiment the maximum VL designated to simulate water is 30, based on the limitations of the robotic platform and the similarities with the sensation of walking in water.

During the second experiment, the EMG device and the two IMUs, were used to collect the data needed for the technical validation. The protocol to collect the data consists of four trials, with the first trial being a quiet standing for calibration. The second trial is the recording of baselines of the muscular activation without the liquid simulation. Three baselines were recorded while walking under different conditions: without the ankle modules of the Discover2Walk, with the Discover2Walk in passive mode and with the Discover2Walk with minimal resistance. The third trial of the second experiment was testing the liquid simulation walking with the viscosity being increased by 10 every 20 seconds from 0 to 30 and repeating the process back to 0, it was named *scaled*. The last and fourth trial, named *contrast* or *jump*, consists in walking with 0 viscosity for 25 seconds, then increase the viscosity to 30 for around 40 seconds and then back to 0.

4.1.2 Signal processing

In order to be analysed, the data collected has to be processed to eliminate the noise and be prepared to be interpreted. The signal processing techniques done are demeaning, filtering, rectification and envelope for better visualization of the EMG [40].

To enhance the visualization of the difference between muscles activation, the signal has been segmented into steps, using the IMUs information, and the mean activation in the steps has been obtained.

4.1.2.1 EMG

Prior to the filtering, the data has to be padded to avoid edge effects. Then the derivative of the n-point discrete Fourier transform is calculated and used in the Fast Fourier Transform (FFT) algorithm to calculate the Discrete Fourier Transform in order to analyse the signal in the frequency domain. Then a Notch filter in 50Hz is applied to remove power-line noise followed by a band-pass filter in 20-500Hz. The Inverse Fourier Transform is performed to get the filtered data in time domain and the padding is removed.

For the rectification step, the absolute values of the filtered signal are taken. To improve the visualization of the signal, the envelope is obtained applying a second order Butterworth low-pass filter at 4Hz including padding to avoid ringing. This last filter is used to allow only frequencies lower than 4Hz to pass, which after removing the padding, the envelope of the signal is obtained. All the steps mentioned are depicted in Figure 4.1 for better visualization.

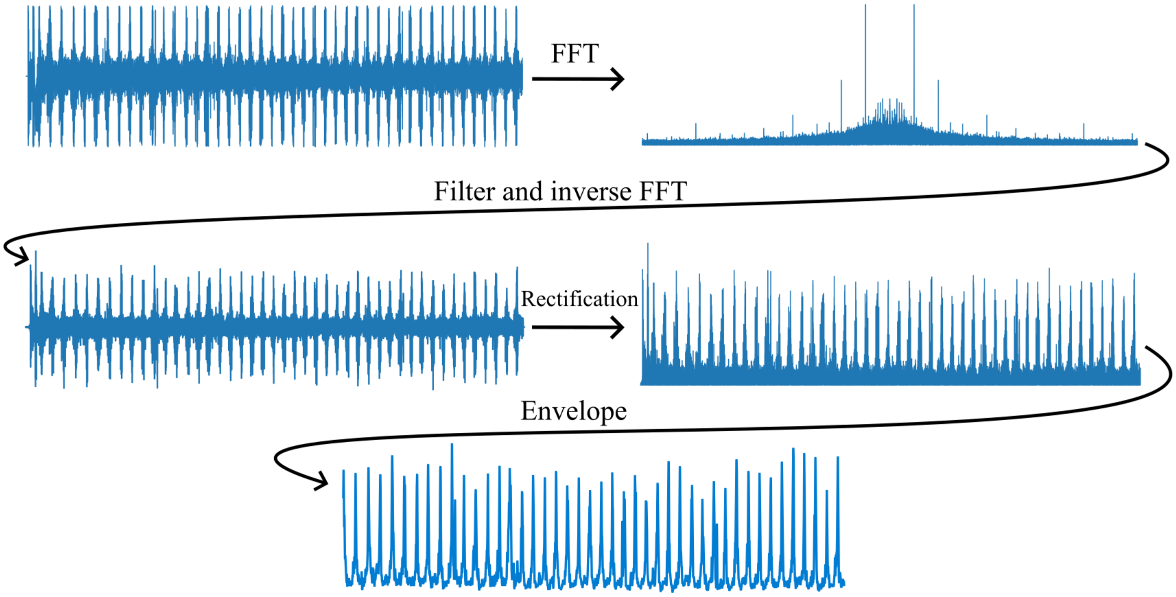


Figure 4.1: Steps of the Signal Processing

Despise the signal processing done to the EMG data, due to the length of the signal, the desired differences are difficult to notice. For that reason, the signal will be segmented into each step to obtain the average muscular activity during a single step, based in the percentage of the step pattern. This will enhance the differences between the muscular activity of both muscles and make the signal more interpretable.

4.1.2.2 IMUs

The IMUs are used to obtain the velocity, acceleration and rotation in the X,Y and Z axis. As the IMUs are placed on the bridge of the foot and knowing the reference system depicted in Figure 4.2, the selected axis to analyse is the Z axis, which corresponds to the vertical. As mentioned in Chapter 3, the Discover2Walk operates only in the sagittal plane, thus, the movement in the Y axis is barely noticeable. Although both X and Z axis could be chosen to segment the signal, as the treadmill is always moving, it is easier to detect the different step phases using the Z axis.

Figure 4.2: XSens IMUs reference system. Retrieved from [41]

To segment the steps using the velocity in Z, the IMU signal corresponding to the *contrast* trial for better visualization, depicted in Figure 4.3, was analysed and valleys were observed that correspond to the heel strike [42]. Extracting the position of the valleys and with the EMG and IMU data being synchronized, each step can be segmented from one heel strike to another.

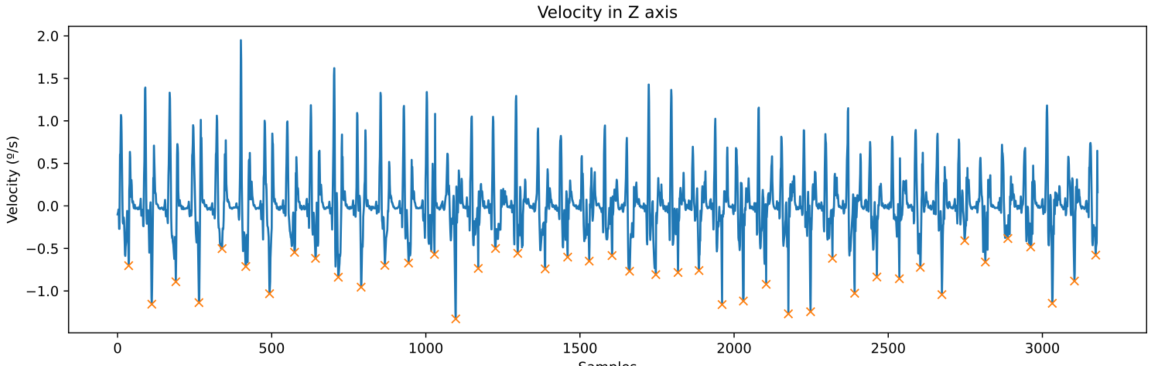


Figure 4.3: Velocity in the Z axis during contrast trial.

As the EMG and the IMUs have different sampling frequencies, the number of samples of each signal was used to find the proportion and be able to extrapolate the sample index of the IMU signal to the corresponding in the EMG signal. Additionally, the number of samples in each steps may differ from one to another. For that reason, it is necessary to interpolate the data to add more samples among the measures until every step has the same number of samples. With the data interpolated, it is possible to obtain the mean of each position of every step and obtain the mean activity of the steps based on the percentage of the pattern.

To compare the steps with and without simulated water, the segmented steps were separately extracted from both conditions using the signal corresponding to the analysed trial. The *land* steps were obtained from the signal where the level of viscosity is 0, and the *water* steps were obtained form the signal where the level of viscosity is 30.

4.2 Results

The signals obtained to compare the results with the studies found represent two leg muscles: the Tibialis Anterior and the Medial Gastrocnemius. For technical problems, the signals analysed are only from the left leg due to problems with the right ankle module during the collection. However, as the gait is symmetric, it should be enough to analyse the behaviour of muscles, which should be similar in both legs considering healthy users.

For better visualization, the muscle activation signals recorded during the trials of the second experiment are shown in graphs that contain the processed signal with the peaks highlighted and the background coloured in green when the VL is 0 or blue when the VL is 30.

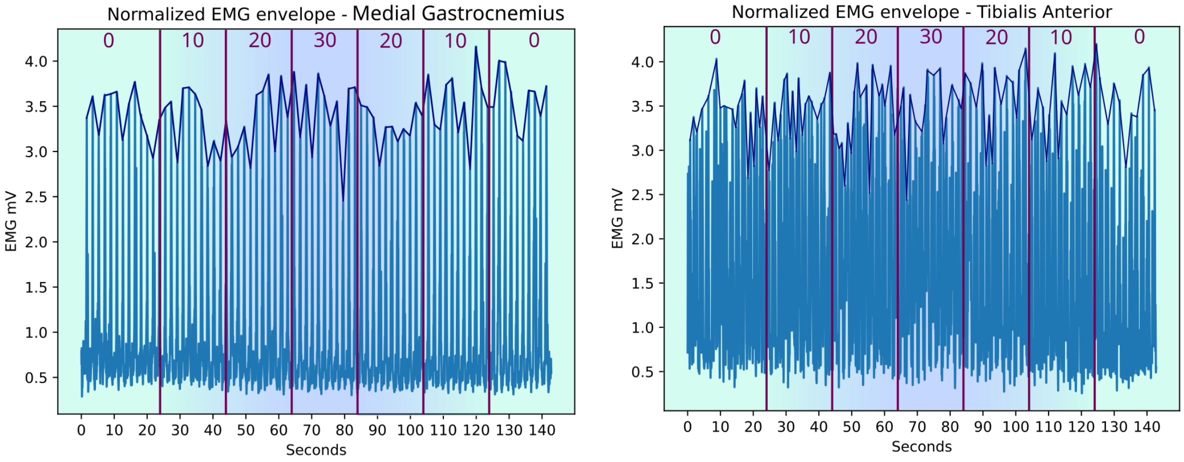
In Figure 4.4a and Figure 4.4b, the signal depicted corresponds to the recorded during the *scaled* trial. The former being the signal of the Medial Gastrocnemius and the latter being the signal of the Tibialis Anterior.

Comparing both graphs, it can be observed greater activation in the TA than in GM, represented by slightly smaller spikes in Figure 4.4a at maximum VL, while the greater spikes are shown with lower VL. On the contrary, in Figure 4.4b, greater spikes can be observed with higher VL.

The signals of the *contrast* trial are depicted in Figure 4.5a and Figure 4.5b. In this trial, the differences in muscular activation are more easily appreciated than in the *scaled* trial due to the shorter duration and the consequent shorter length of the signal.

In Figure 4.5a a decrease in muscular activity is easily perceived in the blue zone, which represents the VL being at 30, depicting lower activity on the GM. On the contrary, in Figure 4.5b an increase can be appreciated in the blue zone respect to the green zones, which shows higher muscular activation in the TA when the water is being simulated.

Due to the long duration of the trials and the length of the signals, the changes in muscular activation might not be as easily appreciated. For that reason, a study of the average muscular



(a) Medial Gastrocnemius.

(b) Tibialis Anterior.

Figure 4.4: Muscle Activation during the *scaled* trial. Each delimited zone is containing the signals recorded with the specified level of viscosity above, with green background when level is 0 and blue background when level is 30.

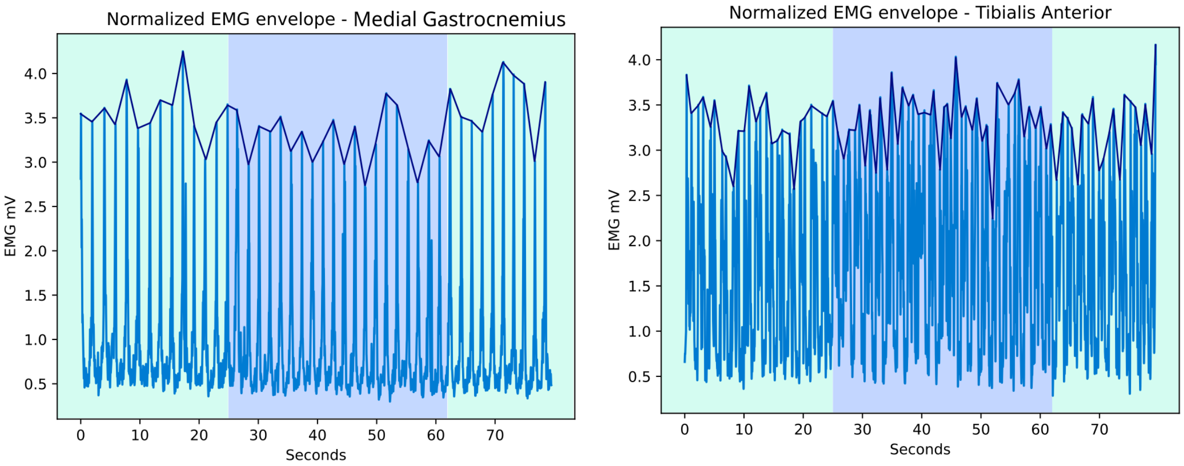
activation of a step and a quantitative analysis, including a t-test to check if the differences are significant, of the average muscular activation have been made with and without simulating water.

To better analyse the difference in walking with and without the simulated water, an analysis of the mean step in each condition has been made. As explained in Section 4.1.2.2, the signal was segmented into steps, from one heel strike to the next.

Figure 4.6 represents the average muscular activation and the standard deviation during a step in the *contrast* trial based on the percentage of the step. Land and water is referring to the VL being 0 and 30 respectively and the background coloured in brown represents the swing phase of the step, while the rest is the stance phase. The mean muscular activation of a step during the *contrast* trial (continuos line) is compared to the mean of every step under the same conditions across trials (dotted line).

In Figure 4.6a can be observed a similar early activation of the GM and the TA in simulated water respect to land. Apart from the early activation, the GM has higher activation during the stance phase in water than in land, but lower from around the 50% until the end of the step, while the TA has overall higher activation in water except for a zone at the end of the swing phase.

Similarly, the mean step in the *scaled* trial is shown in Figure 4.7, which represents the average muscular activation and the standard deviation during a step in the *scaled* trial based on



(a) Medial Gastrocnemius. **(b)** Tibialis Anterior.

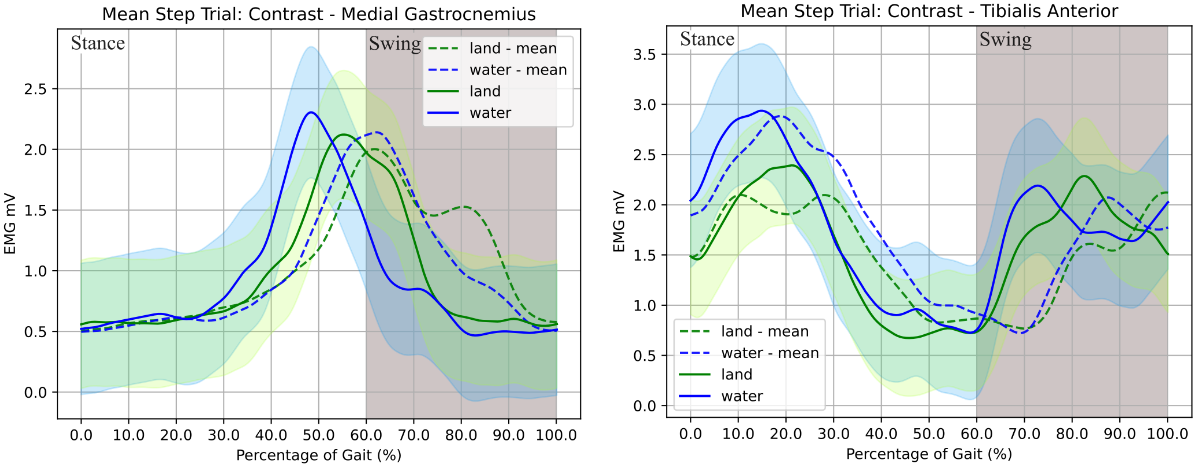
Figure 4.5: Muscle Activation during the *contrast* trial. Green background represents the level of viscosity being 0 and blue background, the level of viscosity being 30.

the percentage of the step. The mean muscular activation of a step during the *scaled* trial (continuos line) is compared to the mean of every step under the same conditions across trials (dotted line).

Contrary to the *contrast* trial, in Figure 4.7 the activation of the GM is slightly slower in water than in land, being generally higher in land except from a spike at the end of the stance phase, around 50% to 68% of the step; while the activation of TA is also slower in water and generally higher except from the zones closed to heel strike, around 0 to 10 % and 80 to 90 %.

Both trials can be observed to have slightly different muscular behaviour, the GM has an earlier activation in water than in land during the *contrast* trial but a later activation in water respect to land during the *scaled* trial. This can be argued by the differences in the changes in the walking conditions. While in the *contrast* trial the change in viscosity is sudden, in the *scaled* trial this change is progressive. Considering that every step analysed for the water and land condition have been obtained when the VL is 30 and 0 respectively, the progression of the *scaled* trial could allow a familiarization process with the increasing resistance and buoyancy forces until the steps are measured, on the contrary, during the *contrast* trial, this familiarization process is not present, which would lead to changes in muscular behaviour to compensate the sudden change.

In both Figure 4.6 and Figure 4.7, the mean of every step under the conditions studied across trials is represented with a dotted line, blue for the mean under water conditions (VL = 30) and green for the mean under land conditions (VL = 0). Using this mean, both trials can be compared and the general behaviour of the muscles can be stated. The behaviour observed



(a) Medial Gastrocnemius.

(b) Tibialis Anterior.

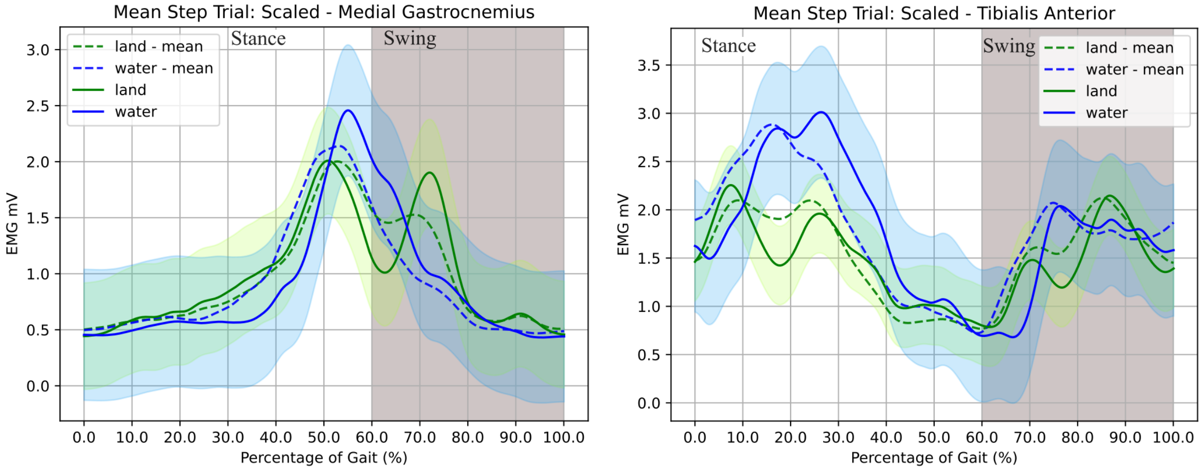
Figure 4.6: Average Muscle Activation and standard deviation based on the percentage of the step during the *contrast* trial (continuos line) is compared to the mean muscle activation of a step across trials (dotted line). The coloured background represents the duration of the swing phase of the step

in the general mean is an alignment in the activation of both GM and TA in water and land conditions, which could support the explanation of the different muscle behaviour depending on the time between condition changes and its magnitude.

The overall behaviour of the GM is a lower activation in water respect to land except at the 40 to 60% of the step, which corresponds to the toe off. However, the analysis of the significance of the difference conducted using a t-test, showed that the differences in the GM activation across steps are roughly significant ($p = 0.051$).

In the case of the TA, the overall behaviour is generally higher activation in water than land except for an increase in the activation in land at the end of the swing phase, around 80 to 90 % of the step. The differences in the TA activation across steps are significant, with the t-test analysis result being ($p < 0.0001$). This behaviour is expected to be produced by the co-activation of the TA during the swing phase of the contrary leg needed to maintain balance during the increased effort to make a step with resistance.

Aside from the step analysis, a quantitative analysis of the mean muscular activation has been made, as depicted in Table 4.1, where the muscular behaviour of the TA and GM are compared using the mean of the total activation during different conditions. The condition of the measures taken into account for the mean on land were when the viscosity level (VL) was 0 in any trial. On the contrary, for the mean on water the measures were taken into account when



(a) Medial Gastrocnemius. **(b)** Tibialis Anterior.

Figure 4.7: Average Muscle Activation and standard deviation based on the percentage of the step during the *scaled* trial (continuos line) is compared to the mean muscle activation of a step across trials (dotted line). The coloured background represents the duration of the swing phase of the step.

the VL was 30 in any trial. The results obtained shows that the Tibialis Anterior has a mean of activation of 0,19 mV higher when walking in simulated water than land, which corresponds to around a 4,75% of the highest muscular activation measured during the experiment. In the case of the Medial Gastrocnemius, the mean of activation is 0,33 mV lower when the Viscosity Level (VL) is 30, corresponding to a 8,25% of the highest activation.

Table 4.1: TA and GM Overall Mean Activation Comparison.

Muscle	Mean on Land (mV) (VL = 0)	Mean on Water (mV) (VL = 30)	Difference (mV)
TA	1.5816	1.7726	0.1909
GM	1.2564	0.9228	-0.3337

Comparing the results of the quantitative analysis and the mean activation of a step with the literature [18], both the TA and the GM behave similar when walking in real water and when walking using the system designed with the VL at 0. The difference is of around a 4,75% in the case of the TA and around a 8,25% in the case of the GM, which are lower than the 15% difference in the study [18], but is on track with the expected behaviour.

Conclusions and future works

The technical limitations, discussion of the results, conclusions and future works will be approached within this chapter. With a comparison of the results with the studied literature and the justification of the behaviour observed, as well as future works that could improve the system.

5.1 Technical Limitations

The principal technical limitations were relative to the experiments conduction. As the Discover2Walk is designed for children but none could be present to conduct the experiments, only an initial technical validation was possible with a healty adult (1.75m/65Kg) with no gait impairment.

The technical limitations of the Discover2Walk justify the reduction observed in the differences of muscular activation. As the end-effector robotic platform is designed for children, the maximum force and the maximum weight that can be supported is limited and less efficient in adults than children. The maximum Viscosity Level supported for the Discover2Walk does not produce enough effort in an adult but is expected to be enough for children. As for the weight support of the simulated buoyancy force, the Discover2Walk can support a peak of 20Kg, which is enough to support all the weight of a children but a fraction of an adult. For this reason, the system is expected to be more effective with children.

For the EMG data acquisition, the availability of the Discover2Walk and the Quattrocento EMG device was limited, which is the reason why only two experiments were conducted although further testing would be beneficial.

5.2 Discussion

Despise the technical limitations, the results shown in Chapter 4 depict a similar behaviour of the TA and GM when walking in real water and when walking with the designed system with level of viscosity 30. As the Discover2Walk is designed for children and the experiments were conducted by an adult because of the limitations, the results shown are less remarkable. However, the behaviour of the muscles can be stated and the differences in muscular activation are expected to increase when measured in children.

The behaviour of the TA and GM in each phase of the step can be justifiable by the conditions of higher resistance in simulated water and the buoyancy forces that produced partial weight support, considering the overall behaviour of the muscles.

The GM showed less overall activation in water than in land except for an increase at 40 to 60 % of the step which represents the end of the stance phase, which could be explained as the GM produces the movement needed for the foot to be at the correct position for toe off. The overall less activation is justified by the partial weight support of the simulated buoyancy force with the consequent reduction on workload of the GM. However, the significance analysis of the differences in steps in both water and land conditions, showed that the behaviour stated is roughly significant with the p value of the t-test conducted being $p = 0.052$.

On the contrary, the differences on the behaviour of the TA across steps in water and land are significant ($p < 0.0001$). The overall behaviour of the TA was a higher activation in water than in land along the step with the exception of the last 80 to 90 % where the activation of the muscle in land suddenly increases. This behaviour is possible to justify considering that the mentioned percentage of the step correspond to the end of the swing phase, where the foot needs to be moved upwards to prepare the heel strike, that movement is produced by the contraction of the TA. In land, as there is no additional resistance, the foot is prepared earlier than in water, when the extra resistance to movement is present, the foot is prepared instants before the heel strike, which can also be observed in the activation of the TA.

With the justification of the muscle behaviour observed, the system is expected to be able to simulate correctly the mentioned benefits of underwater walking depending on the results of further testing with healthy children and children with CP. When used with children, the constant and meaningful weight support as well as the higher resistance felt by the children is expected to increase the effectiveness of the system, producing better results.

As explained in Chapter 1, the use of Virtual Reality can be beneficial for increasing engagement, postural stability and enjoyability. Moreover, if applied with Virtual Reality the subjective sensation of being walking in water may increase, potentially producing additional benefits such as the less fear of falling and the willingness to carry out more intense exercises.

5.3 Conclusions

The developed system integrated with the Discover2Walk has shown results in accordance to the muscular activation when walking in real water. Quantitative results demonstrate a 4,75% higher activation on the TA when walking in water and a 8,25% lower activation on the GM. Despite the relatively small difference, the behaviour of both muscles can be determined to be similar when walking in real water and when walking using the Discover2Walk with the developed system at a Viscosity Level of 30.

Further testing with children may show greater results more in accordance to the electromyographic analysis made in real conditions. However, the results obtained comply with the expected behaviour of the muscles measured [18], thus, the system is expected to be beneficial if used for effective treadmill training therapies simulating the underwater walking benefits.

Nevertheless, the developed system supposes an advance in rehabilitation technologies as a control system able to reproduce some benefits of underwater walking without needing water, potentially increasing the efficiency of the therapies and encouraging researchers to keep improving the rehabilitation therapies using robots.

5.4 Future Works

Although the system is expected to be beneficial for assisting rehabilitation therapies, some improvements can be made to enhance the benefits.

Regarding the control system developed, the maximum level of viscosity has been stated based on the similarity in the subjective sensations, according to the technical limitations of the Discover2Walk. However, conducting an study to relate the Viscosity Level and the density of water could improve the experience and the sensation relative to each patient, producing a more realistic effect and increasing the benefits.

The limited number of experiments conducted generates a necessity for further testing and an extensive validation with healthy children to ensure its effectiveness in simulating the effects and to measure with more accuracy the impact that it should have on therapies. Aside from testing during experimental therapies with children with Cerebral Palsy supported with the system to measure the real long-term benefits and compare the results with the benefits of real underwater walking therapies. This would be beneficial to state if the system could be used to replace support land-based therapies.

Regarding the EMG data collection, only two muscles were measured, however measuring also the Vastus Intermedius or Vastus Lateralis would be useful to further study the higher effort needed to walk underwater and state how this extra effort benefits the maturation of gait in children with CP.

Regarding the benefits produced by VR, as mentioned in Chapter 1, the use of the developed system could be integrated with Virtual Reality games to enhance the perception of being in water, making serious games more immersive and enjoyable while better supporting the therapy. Being also possible to improve the electronics and functionality of the Discover2Walk to be able reproduce more environments, as water currents, which benefits are being studied.

Ethical, economic, societal and environmental aspects

As stated in Chapter 1, Cerebral Palsy is the most common physical disability in childhood. Hence, the objective of this MSc thesis directly concerns not only the patients but also their families in both personal and economical aspects.

6.1 Introduction

This MSc thesis is based on the design and development of a system to simulate underwater walking to support treadmill training therapies for children with Cerebral Palsy. As many studies support the use of aquatic exercises due to its numerous benefits, this system aims to increase the accessibility of this benefits by simulating the conditions.

The possibility to produce the same behaviour in muscles and to reproduce some benefits of aquatic exercises not only is expected to make therapies more effective but also more enjoyable for the children through the use of immersive VR serious games to support the therapies. Moreover, as the system is based on control strategies using the existing device, there is no need for specialized aquatic treadmills or for a tank of water to be filled, which imply potentially less economic cost and a better care for the environment as it does not need water.

This MSc thesis is expected to have an impact in societal, economical and environmental aspects as its objective is to enhance therapies for children with CP, to potentially reduce costs of the therapies respect to the underwater treadmill trainings while maintaining most of the benefits and to avoid the heavy use of water that is needed for some aquatic treadmills.

6.2 Description of Relevant Impacts Related to the Project

Regarding the societal impacts, the system aims to support therapies in order to make them more effective and enjoyable without compromising its safeness. This translates into a faster and potentially better improvement, in this case, of the gait and the gross motor function. Thanks to these therapies, the affected children can be more included in society, have a higher degree of independence and reduce the stigma around them.

The principal economical impacts are the lack of specialised equipment needed, aside from the Discover2Walk, as the underwater treadmill trainings usually need aquatic treadmills and access to a pool or to a tank full of water, these kind of therapies may have a higher cost than land-based therapies. Thanks to this system being based on control strategies, no additional devices are required, hence there is no increase in the therapy cost while producing the benefits of the aquatic therapies. Moreover, for the families of children with CP, having a member with this condition suppose a cost of between 250 € and 890 € each week [43], therefore, these therapies should help also in reducing the cost.

As the principal environmental impact is regarding the development of the Discover2Walk and its mechanical and electronical components, this MSc thesis has not an actual environmental impact aside for the potential saving of water if this simulation is used instead of actual underwater treadmill trainings.

In this MSc thesis no experiments were conducted by patients or children, however, to test the actual performance in a real therapy, these experiments should be done. In that case, the experiments will need to be evaluated and approved by an external ethical committee with the authorization of the parents or guardian of the child. These experiments, if conducted in the Hospital Niño Jesús, must comply with the rules and proceedings of the institution. The designed experiments in this MSc thesis ensure the Human Rights and should be approved by the ethical committee.

6.3 Detailed Analysis of One of the Principal Impacts

The principal impact of this MSc thesis is the societal impact. As mentioned in Chapter 1, 2.0 to 2.5 per 1000 live births are affected with CP [4]. Depending on the phenotype and the degree of disability, some of these children can experience difficulties in daily life tasks, social stigma and have high degrees of dependence throughout their life. Through the therapies, some children could recover gross motor function and increase their motor functionalities to be able to ambulate and perform daily tasks easier. This would lead to a lower degree of dependence, contribute to reduce the social stigma and help the children be raised with less difficulties.

Regarding the affected families, lower degrees of dependence allows the parents and guardians to reduce some economical and physical charges associated to taking care of a dependent child.

6.4 Conclusions

In conclusion, the use of the system in treadmill training therapies is expected to reduce costs for the affected families, to reduce the harm to the environment by not using water; and to help integrating children with CP to the society thanks to the benefits of underwater therapies for recovery of the independent gait and postural stabilization.

Financial Budget

PERSONNEL COSTS (direct costs)	**Hours**	**Hourly cost**	**Total**
	600	15 €	**9.000 €**

MATERIAL RESOURCES COSTS (direct costs, DC)	**Purchase price**	**Months of use**	**Depreciation (in years)**	**Total**
Personal computer (including software)	2.168,00 €	4	5	**144,53 €**
Quattrocento EMG device (including accessories)	52.320,00 €	4	8	**2.180 €**
Xsens IMUs (2 units)	1.798,20 €	4	8	**74,93 €**

	TOTAL COSTS OF MATERIAL RESOURCES	**2399,46 €**

GENERAL COSTS (indirect costs)	15%	on DC	**1.709,92 €**
INDUSTRIAL BENEFIT	6%	on DC+IC	**786,57 €**

SUBTOTAL BUDGET		**13.895,95 €**
VAT	21%	**2.918,15 €**
TOTAL BUDGET		**16.814,10 €**

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