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FINAL DEGREE PROYECT

Degree in Biomedical Engineering

TUNING AND EVALUATION OF A CONTROL STRATEGY OF AN EXOSKELETON FOR SIT-TO-STAND MOTION

Report

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Abstract

The mobility of the lower extremities may be affected by neurological conditions such as stroke or spinal cord injury. When, motor function, gait coordination and muscle strength are impaired. Rehabilitation can improve the autonomy of legs movement in order to carry out everyday tasks such as walking or stand up, also known as a Sit-To-stand. Sit-To-Stand is a task that requires considerable effort for those who have suffered a stroke or other type of injury. To perform the Sit-To-stand movement there are variables such as force, velocities, position angles, among others that can be modeled with the use of robotic exoskeletons.

This project develops a Sit-To-Stand control strategy implemented in a robotic exoskeleton. This is based on previous work on the development of control strategies for the rehabilitation of the Sit-To-Stand. Where Sit-To-Stand transition phases combined with position and admittance control strategies are used. The objectives of this project are to find optimal values of the angles of the joints involved in the transition of the phases and to propose an improvement in the control strategy to assist people with lower extremities movements.

Resumen

La movilidad de las extremidades inferiores puede ser afectada por condiciones neurológicas como un accidente cerebrovascular o una lesión medular. Donde se ve disminuida la función motora, la coordinación de la marcha y la fuerza muscular. La pertinente rehabilitación permite mejorar notoriamente la autonomía del movimiento de las piernas para lograr realizar tareas de la vida diaria como caminar o levantarse de una silla. Este último, también conocido como Sit-To-stand es una tarea que requiere bastante esfuerzo para quienes han sufrido un ACV u otro tipo de lesión. Para realizar el movimiento de Sit-To-stand existen variables como la fuerza, las velocidades, los ángulos de posición, entre otros que pueden ser modelados con el uso de exoesqueletos robóticos.

En este proyecto se desarrolla una estrategia de control de Sit-To-Stand implementada en un exoesqueleto robótico. Esto se realiza a partir de trabajos realizados previamente sobre el desarrollo de estrategias de control para la rehabilitación del Sit-To-stand. Donde se utilizan unas fases de transición de Sit-To-stand combinadas con estrategias de control de posición y admitancia. El objetivo de este proyecto es encontrar valores óptimos de los ángulos de las articulaciones involucradas en la transición de las fases y proponer una mejora en la estrategia de control para asistir a personas con bajo movimiento de las extremidades inferiores.

Acknowledgement

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1. Introduction

One of the leading causes of disability worldwide is a cerebrovascular accident (CVA), commonly referred to as a stroke. This is provoked by an interruption of the blood supply to the brain or a rupture of a blood vessel in the brain [1]. Due to multiple factors or risks that can has a person; these include elderly age, gender, family history of prior stroke or heart attack, hypertension, physical inactivity, diabetes mellitus, cigarette smoking and alcohol abuse. As a result, several impairments and functional limitations may occur after a stroke. Hemiparesis involving the upper or lower extremity, or both, and, patients may also experience sensory loss. Other common impairments include decreased motor control, functional mobility and activities of daily living, for example dressing, walking or bathing [2]. The overriding objective after having had this disease is improving physical function. Therefore, many experienced therapists apply a specific treatment for post-stroke rehabilitation. The most commonly used are the neurodevelopmental treatment (the Bobath approach) and the functional electrical stimulation (FES). These methods focus on encouraging or facilitating normal movements and increased functional mobility, such as walking ability [3].

On the other hand, in the developing countries there are two significant problems for patients with a stroke trauma. One of them is the lack of trained health-care personnel, especially physical therapist in rehabilitation settings. For example, Mexico has 1500 physical therapist for a population of 125.000.000 this means that the ratio of health workers is about 2.85 personnel per 1000 patients in Mexico. The other issue is the economic burden of stroke due to the expensive medication and therapy, considering the average family income is also significantly lower [4]. As a result, many of the above therapies cannot apply in all countries because the high cost of treatment.

Consequently, the Robot-Assisted Rehabilitation has been incorporated with the contribution of engineering to medicine for helping people who has suffered a stroke or sort of disease with motion impairments [5]. The leading objective is to provide mechanical assistance/support while subjects perform various tasks during therapy with the intention of improving functional outcomes, increase access and time of therapy [6]. The tasks are focused on the upper or the lower extremities with the purpose of being more precise with the treatment. Moreover, the robots can be designed for training simple movements that use the shoulder, elbow, wrist, hand, knee or ankle. These devices are denominated Operational machines and their main characteristic is that they have a physical contact just with the treatment part and distal part of the subject´s body. For instance, the subject´s hand and the forearm. This means that subject is free to utilize their own joint movements to execute the tasks that are programmed in the operational space of the robot. However, the only requirement for these kind of devices is that the patient should have enough Degree of Freedom for training different types of movements [7]. In the other hand, it has been designed a device more involved with the subject to realize functions and movement more complex. The Exoskeleton machine are planned to be worn by the patient. Having a similar kinematic structure to the human limbs and these are attached to the subject at different points [8]. In this way, the exoskeleton has the responsibility of controlling the subject´s movements with the aim of providing a rehabilitation of patient´s natural movement the most closely way suffering a stroke.

The Robotic exoskeleton is a device that actuate one or more leg joints of the user. The design is a structure that supports and protects the body, attached to subject´s limbs, to replace or enhance their movements [9]. Currently, the primary use of fully wearable exoskeleton is Locomotor training support [10], mainly meant for a person who has the disability to walk. Work with Rehabilitation exoskeleton has been a strategy with many advantages. With this new resource for treatment the stroke survivors, spinal cord injury patients and similar diseases have a repetitive task-oriented therapy with the benefit that can be automated to relieve some burden off the therapist and expanding their ability to provide more efficient service. In other hand, these devices can serve as a tool for studying the real-time assessment of motor function performance and learning process of extremities [11]. In addition, a final great advantage of the exoskeleton is that there are significant number of papers published concerning robots in therapy, and effectiveness of them for functional recovery after stroke [12].

Several companies, institutes of research and universities have designed exoskeletons for study of gait, balance in standing and sit to stand motion. Examples of these systems include the Lokomat (Hocoma, Inc.) for lower limb gait therapy [13]. The WPAL (Wearable Power-Assist Locomotor) that is comprised of a robotic part and an orthotic part and used while still in the wheelchair, and then stand and begin walking [14]. eLEGS is a rehabilitation exoskeleton that can execute sit-to-stand and stand-to-sit operations and support walking in a straight line [15]. Argo Medical Technologies Inc. has a wearable motorized medical suit known as ReWalk, this is specialized to start different tasks, such as sit-to-stand, walking or climbing stairs [16]. Although, they have different specifications and characteristics such as the cost, design, software, control strategies, in other aspects. All these exoskeletons have the same purpose, improving life quality.

Exoskeleton have a very important role in the daily to day life of physically impaired persons Movements such as back to sit (BTS) and the sit-to-stand (STS) are a part of daily activity [17]. To achieve the sit to stand motion depends on several parameters. The position to start the motion, the angles of joints (hip, knees and ankles), the legs length, among others. Many researchers are interested in evaluating the healthy person´s parameters of STS for the development of systems that can guide the patient movements, since, clinical statistics show that STS is a task demanding high control ability of human motion [18].

This project has been developed from a robotic exoskeleton designed to assist overground gait training to patients with deficits in gait coordination. First, this device has had a solid background to proceed with this study. Bortole 2013 [19] found through experimental results that the exoskeleton can adapt a pre-recorded gait pattern to the gait pattern of a specific user. Also, Vijaykumar et al. worked with the exoskeleton in several projects for the assistance in gait and Sit-to-stand [20]. Then, Pieras Morell 2018 developed an application to assist the movement of standing up from a chair and proposing a new control system based on the definition of different phases during the movement transition, depending on the biomechanical characteristics of each moment [21]. In this point, begins development of the project. Following a timeline of research about the use of exoskeleton robotic with the sit-to stand motion.

The base of project is the use of the exoskeleton with the strategy that involves phases to do the sit-to-stand motion and find in an experimental way a precise parameter of position, admittance and velocity to control the exoskeleton for a person who has a low movement in the lower extremities. In addition, search another strategy that can combine another characteristic with the aim of doing the action of sit-to-stand easier. In this way, give a progress in robotic rehabilitation with the purpose of helping persons who need to recover the legs movement after a stroke or other kind of disease.

The document is organized in five sections. First, the Chapter one contains an introduction to the study, the state of the art in exoskeleton used for the rehabilitation of sit-to-stand and a brief explanation of the biomechanical study of sit to stand motion, finally the objectives to achieve. The chapter two: Materials and methods, describes the exoskeleton used in the investigation, the development of the proposed strategy of sit to-stand and how was realize. The chapter three describes the results and the analysis of them. The environmental impact analysis and economic budget are presented in chapter four. Finally, chapter five enclose the conclusions and future work.

1.1. State of the Art

It is necessary to expose two lead topics for break down the project. The following items include relevant information about lower limb robotics exoskeletons for rehabilitation therapy and aspects about the Biomechanical of sit to stand motion. The exoskeletons that are described are just a bit of this field. These have been chosen due to evidence of restoring mobility in patients. To contribute to the target application area, several skills and strategies in the STS task, has been highlighted by each exoskeleton. Moreover, the advances of robotics devices have been possible thanks to biomechanical study about the joint, neurons, muscles and bones behavior, in a healthy subject and how can be modeled in a mathematical way to control systems for real limbs through exoskeletons.

1.1.1. Robotic Exoskeletons used for the rehabilitation of sit to stand

The first exoskeleton that is described, is comprised of a robotic part and an orthotic part. The WPAL (wearable Power-Assist Locomotor). The orthotic part is composed of shoes, calf cuffs, and thigh cuffs, which are customized to fit the lower extremities of individual patients. In addition, the robotic part consists of hip, knee, and ankle joints, which independently perform flexion-extension movements. The maximal range of motion of each joint is hip, 40 degrees; knee, 120 degrees; and ankle, 50 degrees.

The external design is mostly made of carbon fibers and polypropylene, figure 1.1 shows the WPAL, its weigh is about 1.5 kg. Also, the weight of the robotic part depending on the length of the upright strut according to the height of the user. Nevertheless, is about 12 kg. The main controller, remote controller, and battery are built into the custom-made reciprocal waling frame.

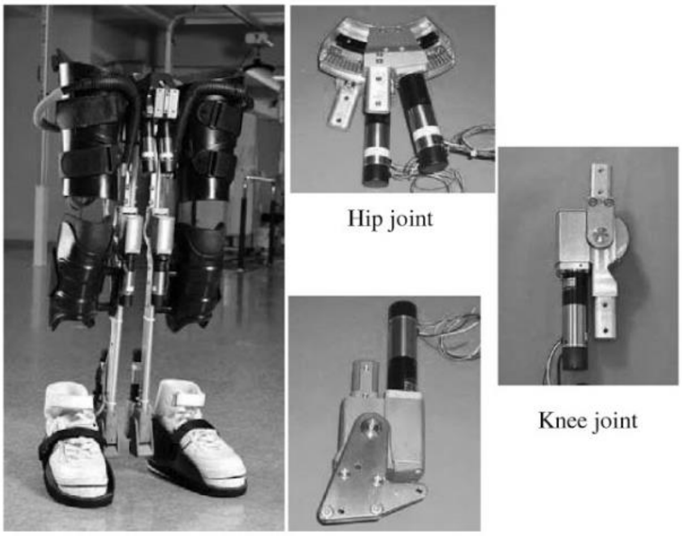


Figure 1.1 (WPAL) Wearable Power-Assist Locomotor, designed of a robotic part and orthotic part to allow the user to stand up and sit down as well to walk with the walking frame.

The control design is made from movement patterns of the robotic joint angles in walking. This are constructed based on the results of walking of healthy subjects with orthosis by the three-dimensional analyzer. A template of combination of joint angles was made from orthotic walking of healthy volunteers. Users can completely combine the robotic and orthotic parts while still in the wheelchair, and then stand and begin walking. This is possible thanks to WPAL was designed to allow the user to stand up and sit down as well to walk with the walking frame [22].

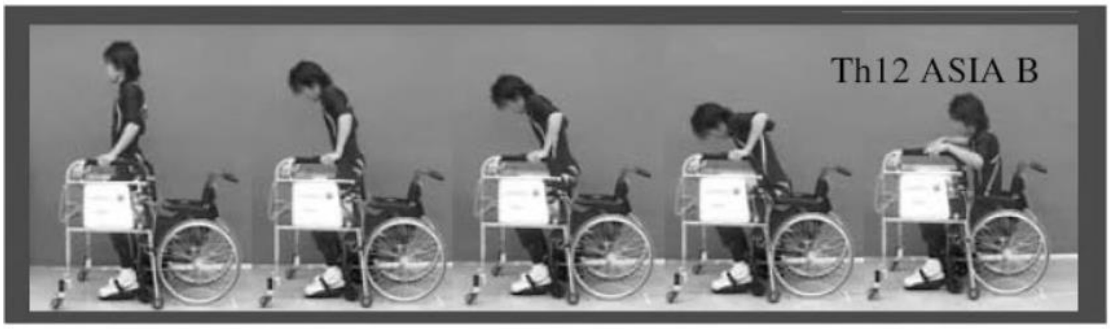


Figure 1.2 Subject with the WPAL executing the Sit-to-Stand motion [22]

Tasks such walk, turn, sit down, and stand up; are arduous to persons with mobility disorders. Berkeley Bionics with this premise designed eLEGS. Katie Strausser has developed the human machine interface composes of a hardware and software package which use natural human motion to safely translate the user´s intention into the required exoskeleton action. Tim Swift developed the control algorithm for eLEGS and implemented it on the exoskeleton micro-computer. His research focuses on using sensory information from eLEGS to determinate how to execute a specified action such as sitting, walking or turning. As a result, this exoskeleton has several demands in the rehabilitation field. It began to be used in therapy centers and clinical trials. With the collaboration between UC Berkeley and Berkeley Bionics is a successful model of industry-university work to bring critical technologies to end users [23].

Figure 1.3 Subject with the eLEGS during an evaluation [24]

An equipment more industrialized is ReWalk. Which, is a wearable robotic exoskeleton that provides powered hip and knee motion to enable individual with spinal cord injury to stand upright, walk, turn and, climb and descend stairs. The system allows independent, controlled walking while mimicking the natural gait pattern of the legs. There are two types of ReWalk. One of them is a personal device. Is designed for all day use at home and in the community. It is the most customizable exoskeleton and is configured for each person. This precise fit optimizes safety, function and joint alignment. Its main characteristics are: wearable exoskeleton with motor at the hip and knee joints, the control movement using subtle changes in his/her center of gravity. A forward tilt of the upper body is sensed by the system, which initiates the first step. Repeated body shifting generates a sequence of steps which mimics a functional natural gait of the legs. On the other hand, exist ReWalk rehabilitation edition, this one is designed in like manner. Nevertheless, this edition provides a preparation for using their own ReWalk personal system and this one has a graphical user interface that allows therapists to enter a broad range of parameters for an individual and change them as they progress in their training [25].

Figure 1.4 Patient rises with the ReWalk Rehabilitation Version [26]

In Europe, The Swiss Federal Institute of Technology Zurich, developed a robotic device, named MAXX (Mobility Assisting textile exoskeleton). The robot primarily consists of functional textiles and lacks rigid structures as they are used in conventional, lower-limb exoskeletons. It is soft, flexible and lightweight, and thus, does not restrict or interfere with the wearer. Their goal is to increase the independence and autonomy of physically impaired patients that will facilitate the full reintegration into their communities as well as their work life. The lead approach solely relies on force transmission through functional textiles. Tendon actuators are used to induce tensile forces into the exoskeleton. By anchoring the exosuit at specific body landmarks, the forces in combination with the human bone structure translates into considerable torques at the joints aiding during physically challenging activities such as transfers from sitting to standing, stair ascent or walking.

The exoskeleton is enabling to simultaneously support multiple joints with only one actuator per leg. By actively supporting extensor moments at the hip, knee and ankle, the multi-articulated suit architectures can support the gluteus maximus, Quadriceps and Triceps Surae as the main anti-gravity muscles [27].

Figure 1.5 Sit-to-stand transfer with MAXX [27]

1.1.2. Biomechanical study of sit to stand motion.

Robotic exoskeletons haves the capability to help persons to improve the performance in gait, sitting, turn, and climbing stairs, among others. All of this, thanks to mechanic and electronical design; and its intern controllers. The software is behind these devices is designed from the physical and biological study of human body motion. The list of professionals interested in applied aspects of human movement is quite long: orthopedic surgeons, athletic coaches, rehabilitation engineers, therapist, kinesiologists, prosthetists, psychiatrists, sports equipment designers, and so on. In view of this, an emerging discipline blending aspects of psychology, motor learning and exercise psychology, known as, Biomechanics. Is built on the basic body of knowledge of physics, chemistry, mathematics, physiology, and anatomy. Can be defined as the interdiscipline, that describes, analyses, and assesses human movement. As a result, it is necessary to have a basic background about how the low extremities work to understand the biomechanics of sit to stand motion and explore how to translate that movement in a mathematic language to combine with a robotic exoskeleton.

Standing up requires the ability to translate the body mass forward from a relatively stable sitting position (thighs and feet) to a small base of support, the feet. This involves an anterior and then vertical movement of the body´s center of mass. This movement is executed primarily by a flexion of the hips and anterior movement of the head-arms-trunk segment, followed by an extension of the hips, knees, and ankles [28].

Generating angular and linear momentum sufficient to perform this smooth translating movement is potentially destabilizing. Therefore, the ability to balance the body mas by segmental movement and lower limb muscle activity while propelling it away from the seat is an important feature of standing up [29]. To simplify in how to approach the movement behavior, previous investigators have described STS in 2 or more phases. Hirschfeld et al described the STS movements as comprising the preparation phase (initial onset of movement to seat-off) and the rising or extension phase (seat off to erect stance). Schenkman et al defined 4 phases of STS: the flexion momentum phase (initial onset of movement to seat-off), the momentum-transfer phase (maximum dorsiflexion to full hip extension), and the stabilization phase (full hip extension to quite stance) [30].

In this project, it is taken the movement like four different stages to develop, as shown in fig. 1.6, to perform a simulation as real as possible, a division of the STS on stages were analyzed, mainly the division is:

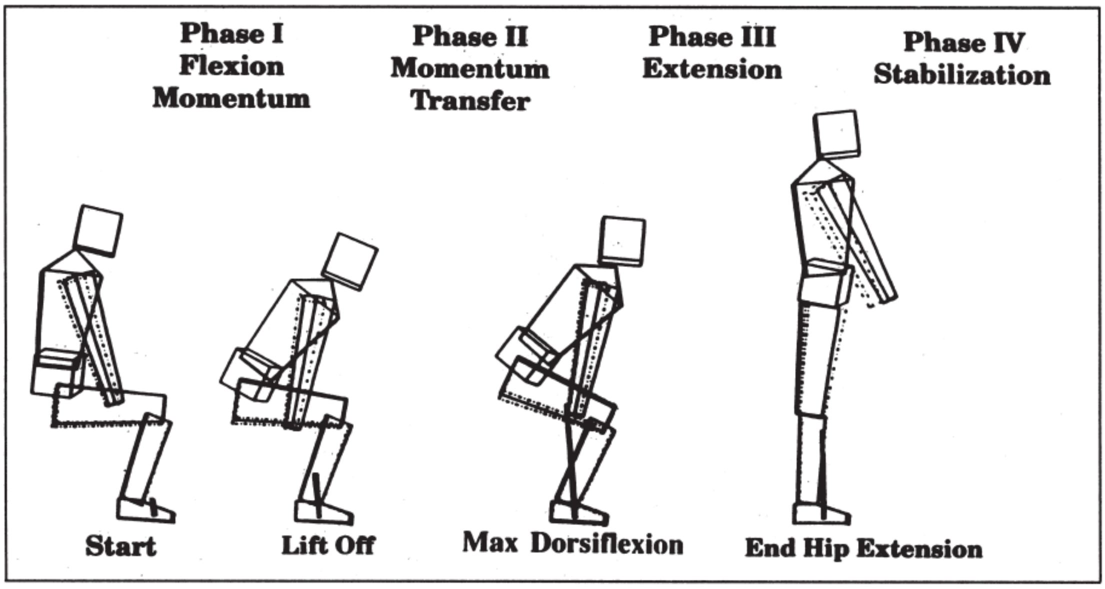


Figure 1.6: Phases division in the Sit-to Stand model [31]

Phase 1: Movement begins

Trunk flexes forward. Thigh, shank and feet remains stationary on both legs. Body movement on this phase is essentially forward. This stage finishes a moment before gluteus lift off the seat.

Phase 2: Transfer phase

Starts when gluteus lift off the seat. This phase finishes when maximum ankle dorsiflexion is achieved. During this stage, the center of mass of the body travels forward and upward. The maximum position of the center mass on forward direction is reached before the maximum dorsiflexion.

Phase 3: Extension phase

This stage starts after maximum dorsiflexion on the ankle and it is completed when the hip extends until its anatomical position. On this stage, full extension of the knee is reached.

Phase 4: Stabilization phase

Starts just after hip joint reaches zero angular velocity and continues until every movement associated with stabilization on standing up is completed [32].

The biomechanical study of sit to stand can be universal, across the time has supported the diverse phases, proposals and their necessary parameters like the appropriate angle, torque and correct performance in each phase. In other hand, may exist several strategies that now are not implemented and evaluated. Due this, it is necessary to continue with the research of sit to stand motion. In this study is evaluated the results of use these phases with the aim of tuning the values and limits of each phase parameters.

1.2. Objectives

The importance of this project emerges from the development of a Robotic Exoskeleton for the assistance and rehabilitation of gait and sit to stand motion. Vijaykumar worked with the exoskeleton proposing a control model with a combination of stiffness-damping control for a sit to stand task in rehabilitation. In addition, Pieras Morell, developed a combination of several control strategies with an algorithm that manages transition between the phases in real-time. Consequently, this study continues with the research about improve the work made by Pieras Morell, with this, it was raised the follows objectives.

1.2.1. General Objective

Development a control strategy of sit to stand motion with the use of position, admittance and torque, controllers for impaired persons in lower extremities and contribute with improvement to future investigations.

1.2.2. Specific Objectives

- Collect data of sit to stand trajectory in healthy subjects with the aim of tuning the parameters (angles and torques of hip, knees and ankles) limits in each phase. In addition, establish the duration time of each sit to stand phase.
- Implement the proposed strategy in the robotic exoskeleton to evaluate the behavior of the strategy in a group of persons
- Analyze the obtained results and compare them with those of previous researches.

2. Materials and Methods

For the development of this study, it was indispensable to design a plan to respond to the stablished objectives. To achieve this, first, it was necessary to know with what tool was counted to work in the research. The exoskeleton H1 was used for the project. Device developed in HYPER PROJECT used for the lower limbs rehabilitation. Secondly, it was made, a work line with the aim to improve the previous strategy of sit to stand and/or propose a new one, for then obtain results to compare with other researches. The project started with a review of sit to stand motion literature and the idea of strategy control proposed by Rajaskaran et al [33] and with the study of the strategy made by Pieras Morell [34].

The Sit-To-Stand control strategy developed by Pieras Morell proposes from the sit-to-stand phases implementing some conditions that determine phase change using an admittance control, speed and position control with the aim of following and help the user´s movement; unlike, in this project using the admittance and position control it is proposed to control the change of phases by means of equations that model the movement of the sit to stand. Also, calibrate the phase change conditions. With the aim of developing a strategy that uses greater torque to lift the user in rehabilitation.

First, it recorded several healthy people performing the sit to stand to collect parameters significative of investigation. As a result, it was designed a trajectory control to observe the behavior of the exoskeleton H1 executing the sit to stand with the average values collected. After this, it was designed a control strategy that modelling the sit to stand motion through mathematical expressions with the aim of reading the subject´s intention of standing up and give an enormous support to performance the movement. Finally, was implemented the strategy in four subjects, two men and two women. The results were compared with the previous strategy and were obtained conclusions about the study. Fig. 2.1 shows the process to develop this research and it explains in the follows items.

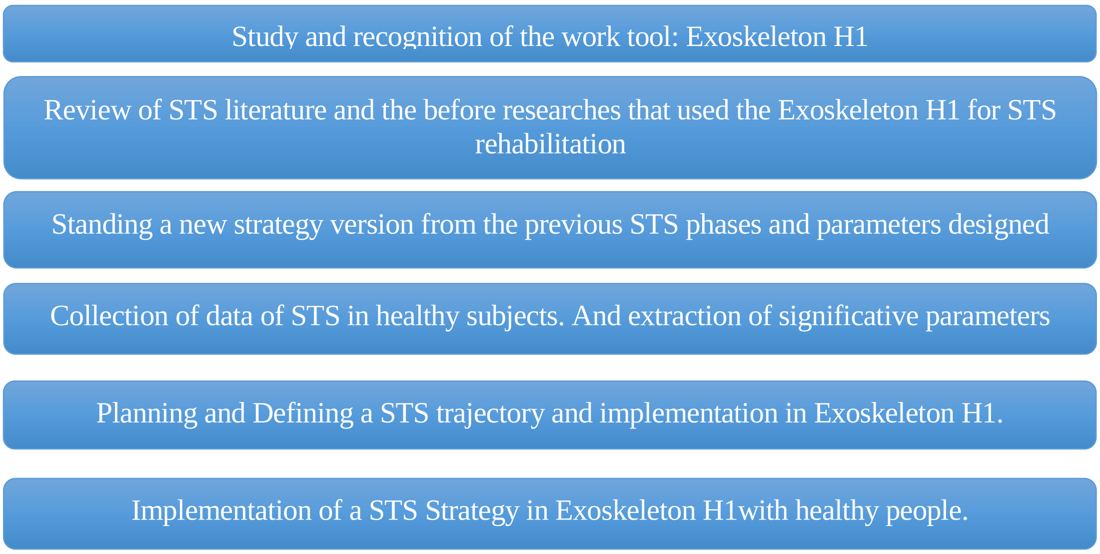


Figure 2.1 Diagram of the investigation of STS study using Exoskeleton H1

2.1. Work Tool: Exoskeleton H1

The exoskeleton H1 is a wearable lower limb orthosis with an anthropomorphic configuration to assist individuals with incomplete Spinal cord injury or Stroke [35]. This is a prototype of robotic exoskeleton developed in the framework of the HYPER project (Hybrid Neuroprosthetic and Neurorobotic Devices for Functional Compensation and Rehabilitation of Motor Disorders) for the rehabilitation of persons with partial or total legs paralysis. This ambulatory robotic exoskeleton could improve sit-to-stand movement and make possible some balance training exercises in addition to gait rehabilitation. Fig 2.2 shows the exoskeleton H1 structure that has three joints for each leg: hip, knee and ankle. Each joint is powered by a DC motor coupled with a harmonic drive gear. The exoskeleton is equipped with potentiometers and strain gauges to measure the joint angles and human-orthosis interaction torques on the links respectively. A detailed description about the exoskeleton structure and communication parameters is elaborated in the following items.

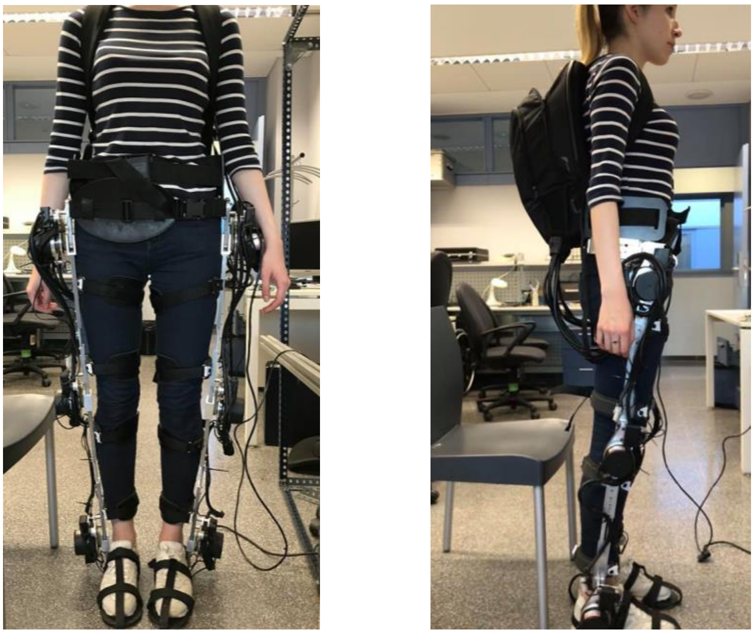


Figure 2.2 Robotic Exoskeleton H1 used in development of this project

2.1.1. Structure of Exoskeleton

The exoskeleton is designed for rehabilitation of adult people in the range of 1.50 and 1.90 meters height, with a maximum body weight of 100 kg, with gait disabilities. The mechanical structure weighs about 9 kg, its material is mainly of aluminum and stainless steel to obtain a superb resistance and reduce weight. The exoskeleton frame has bilateral uprights for the thigh and the shank, hinged hip, knee and ankles and articulated footplates and waist area. The knee hinge function was performed by a four-bar mechanism, like the anatomy of knee joint. Moreover, to move the exoskeleton joints it was necessary the use of actuators. The Brushless DC motors were selected as they offer several advantages for wearable devices, including higher efficiency, more torque density, increased reliability, reduces noise, longer lifetime and reduction of electromagnetic interference. In addition, the exoskeleton joints need more torque and less speed than DC motors, with these requirements it is implemented a “harmonic drives” that is a strain wave gears, a special type of mechanical gear system. In each pack of joint there are two types of sensors: Kinematic and kinetic. Kinematic sensors are used for measuring angular position, velocity and acceleration; kinetic sensors measure the force of interaction between user´s limb and exoskeleton. Each joint has a precision industrial potentiometer used as an angular position sensor and Strain gauges are used as force sensors to measure the torque produced. The fig. 2.3 shows the exoskeleton parts previously described.

Figure 2.3 Structure design of exoskeleton H1

In another hand, to control the exoskeleton it is necessary to have an electronic architecture that manages the information acquired by the sensors, processing data to decide what supposed to do the actuators and these parameters chosen can be sent to activate the exoskeleton. First, there is the core, is based on a PC104 computer. PC104 in an embedded computer standard controlled by PC/104 consortium that defines a form factor and a computer bus. This is the central board of communication between the exoskeleton joints and the software control in a computer. The communication with the joints is through a CAN board and two I/O boards with digital and analog capabilities. These boards communicate with the PC104 via PCI bus. The CAN board is connected to receives the information of all exoskeleton´s sensors. The I/O boards manage the transduction between the main board and the motor analogic drivers. They function like a converter A/D digitalizing the torque output signal provided by the drives. Apart from that, the communication with the computer is through an Ethernet bus that connect the PC104 with the software environment MATLAB and Simulink where it is developed the control system. The fig 2.4 explains the connection scheme of electronic architecture.

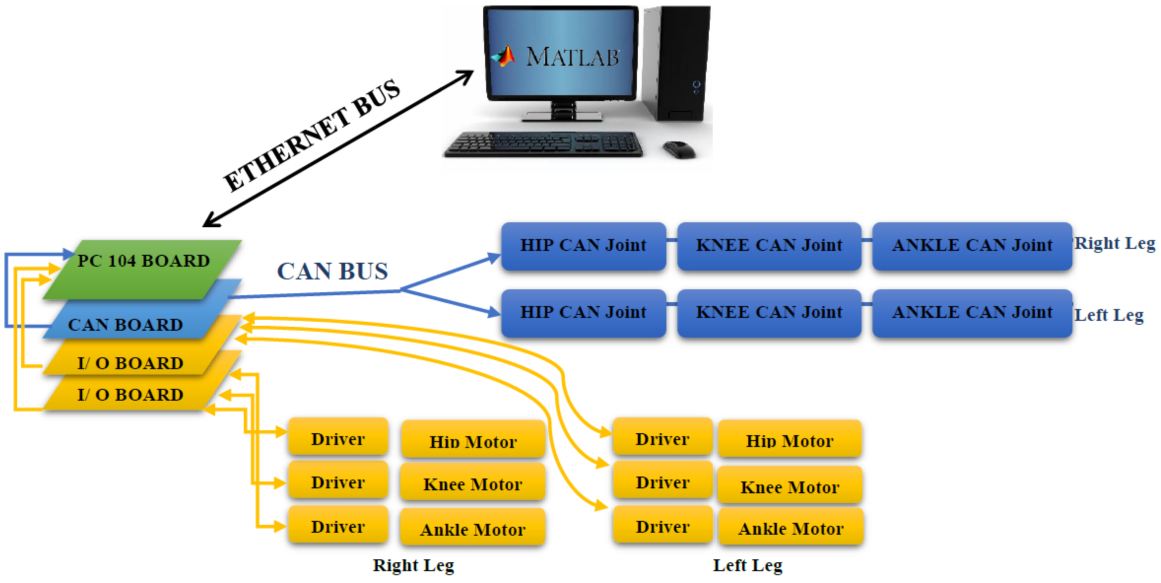


Figure 2.4 Connection scheme of electronic architecture

2.1.2. Software of Exoskeleton

First of all, the previous studies by Vijaykumar and Pieras Morell developed an exoskeleton control. Which is an architecture made using Simulink which is a block diagram environment for Model-Based design belongs to MathWorks and works with MATLAB. It was chosen this visual programming environment due to certain advantages. Simulink has the possibility to work in real time with PC104. Moreover, has an option for generating code that can be executed in external devices. The architecture control has two fundamental parts. The low-level control, this software layer can control the exoskeleton actuators in position, admittance or torque. In another hand, the High-level control that is responsible for implementing different strategies to control the exoskeleton. In this section it is explicated the low-level control for understand how is connected the strategy made in the High-level control.

The low-level control is a program that is uploaded in the PC104. As showed in fig. 2.5 the design has five main blocks. The two orange blocks are responsible for receive the data bus from the High-Level control and send a data bus to exoskeleton actuators. The protocol that is used for sent and receive the message is UDP (User datagram Protocol). The green block "Command Decoder" has the task of decoding the received message in a data bus and send the information to the red and blue blocks. These represent the right and left leg.

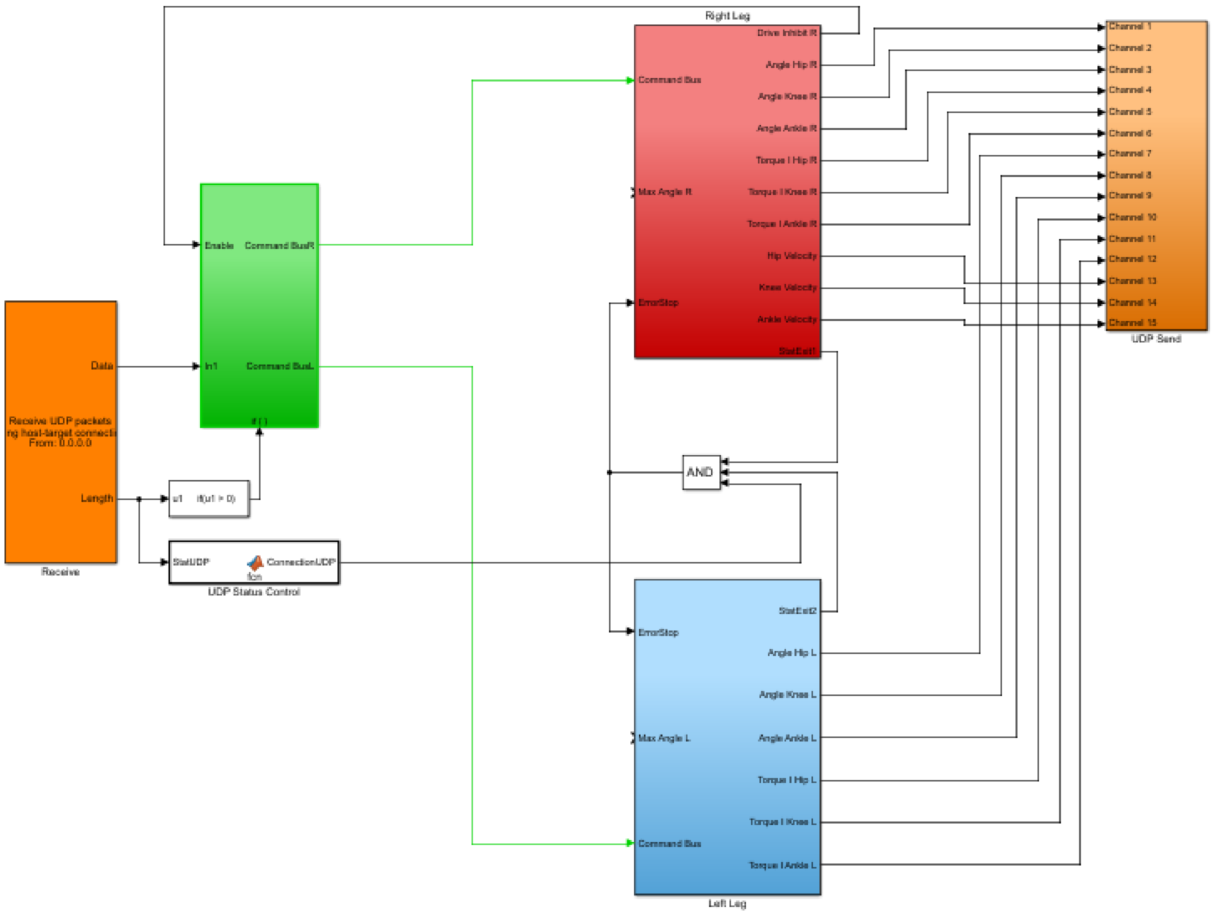


Figure 2.5 Schematic design of Low-Level control made in Simulink

The right and left leg blocks are independent. Nevertheless, they contain the same sub-blocks. In the Fig. 2.6 it is showed the subunits that they have. First, there are two blue blocks that are responsible of signal reception and processing coming from the sensors. Then, the signal goes into the gray block where it realized the signal calibration to convert it in an appropriate scale. The green block contains the control strategies for admittance, position and velocity. The last blocks are designed to send the digital signal to D/A module of each motor. The gold block has the special function to assure that it blocks the output signal if the sensors connection are lost or if anything with the High-Level control is wrong.

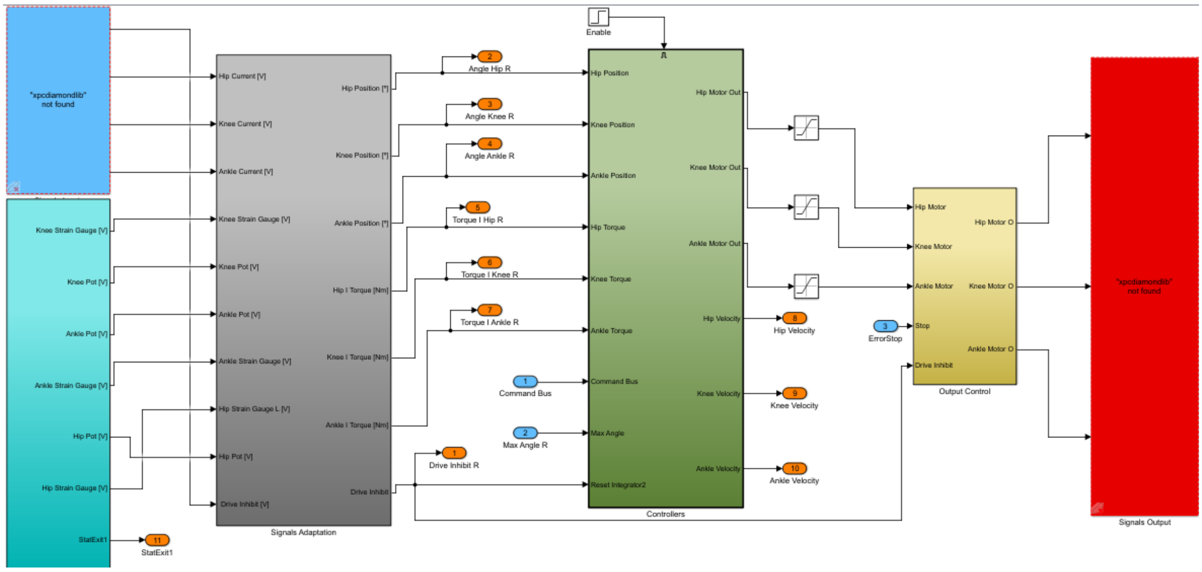


Figure 2.6 Schematic design of subunit blocks in one leg.

Inside of the controllers' block there are blocks that are important to highlight. The admittance and position control are the mainly strategies used in this study. First, the admittance control reacts to interaction forces generating a movement in the desired direction. Applying a force to exoskeleton this will act like a low impedance system, making it manageable for a subject without strength. The fig. 2.7 has the model of admittance control. The main signal input is "Hip Torque" that is the torque detected in the joint. Then passes through gain block to give a proportional output. In addition, there is a gravity filter for compensate the torque caused by the exoskeleton weight above each joint.

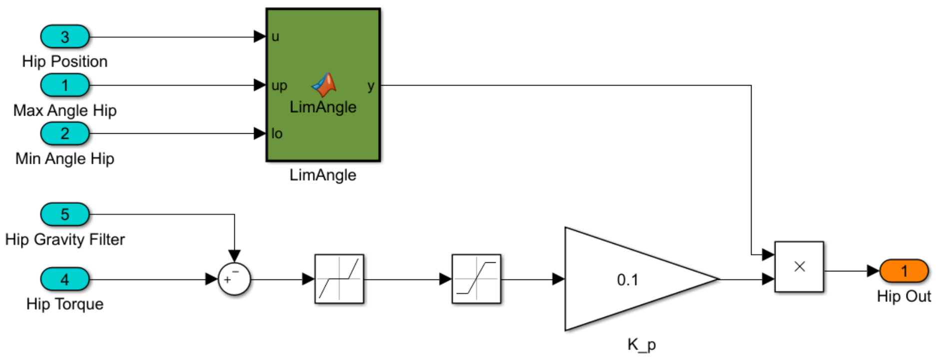


Figure 2.7 Schematic design of admittance control.

Secondly, the position control is designed to avoid abrupt movements that can cause discomfort to the user in the interaction zones and instability. For this reason, the position controller should avoid oscillations in the trajectory and overshoot response. In control theory, the best way to evade these oscillations is through a PID (Proportional-integral Derivate) controller. First, as show in the fig. 2.8 it calculates the error between the current angle in the exoskeleton and a reference angle. Then, the value resultant in the PID provides an output with a low error. For calculate the parameters Kd, Kp and Ki in the PID controller, it used the Ziegler Nichols tuning method, followed by a manual correction to avoid overshoot and stationary error.

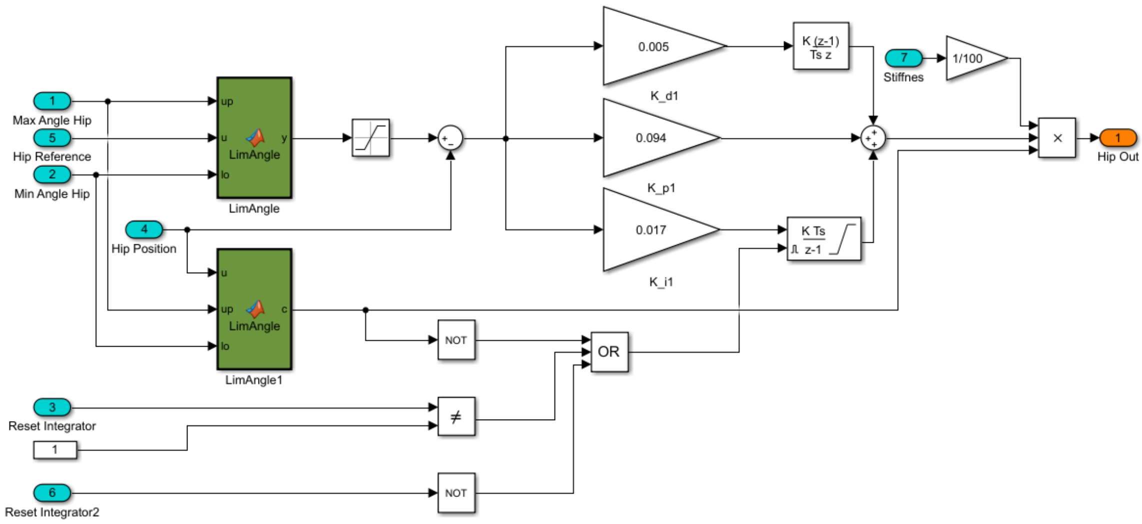


Figure 2.8 Schematic design of position control.

2.2. Proposal of control Strategy for the Sit-To-Stand phases previously described

This study is based on the Sit-to-Stand control strategy made by Pieras Morell. Where it used an admittance control, speed control and position control. These controllers are used in sit-to-stand phases. The first phase implemented the admittance control to gives freedom to user. The phase two is managed by a speed control to keep a constant speed. Finally, in the phase three, the position control ensures the final position. This strategy has important features that have been inherited in this project. First, the Sit-To-Stand phases. The division of each phase is determined by the angles of hip, knees and ankles. Secondly, the admittance control implemented in the phase one is important to allow preparing the body to lift. Another feature extracted is the position control, allows performing the desire position in any instant of time. Consequently, from this previous work, this Project has focused on determining the parameters that allow a smooth transition from on phase to the next, that is the joint angles, and thus reduce the effort required to rise the user body without a greater low limbs effort. In this way, finding the pros and contras of the strategy developed by Pieras Morell and the strategy proposed in this project.

To propose and evaluate a sit to stand control strategy was necessary to perform three steps. First, it was taken several Sit-to-Stand trajectories of healthy subjects to make an average of angles to compare with the previously angles used in the STS control strategy developed by Pieras Morell. In second place, it was designed the STS control strategy with the general base of uses the Sit-To-Stand phases. Thus, the strategy consisted, the first phase, is a preparation and starting phase where establish the lower limbs position, designed in admittance control to allows the body motion. The second phase, is the transition from leaves the chair to be almost standing. It was used the position control and was proposed the use of a linear function to perform the movement of STS. In the third phase also used the position control. The user is ensuring the body to be standing. It was proposed an exponential function to perform the last STS motion. Finally, the third part of the project is implemented the STS control strategy in the Exoskeleton H1 to take data in healthy subjects and compare the results with the behavior of the STS control strategy developed by Pieras Morell.

It was developed the Sit-to-Stand control strategy in the Software MATLAB with the environment for model-Based Design: Simulink. It was created a Simulink model to record the Sit-to-Stand motion to several healthy people. With this, it was implemented a Sit-To-Stand trajectory for demonstrate a correct performance. Finally, it was defined the control strategy to incorporate in the exoskeleton H1 to be evaluated in a group of people.

2.3. Experimental Development: High Level design of the exoskeleton control

This section describes the development plan for the design of the control strategy. For this, it is necessary understand the hardware, software, network and communication components used to implement them in the acquisition of sit to stand movement parameters. First, the hardware directly involved with the high-level design is the exoskeleton Core, the PC104 Board. For this, it was explored the PC104 board and all its components for understand the electronic protocols that follow it the board. Inside the card is the low-level control, in charge of receiving the information from the computer, decoding it and sending it to the exoskeleton actuators. On another hand, the Software design the High-level control was developed in MATLAB/Simulink 2011 Version. It was established the communication between the exoskeleton and the computer Software. It was possible using the User Datagram Protocol (UDP) through an Ethernet network. After this, the data acquisition of sit to stand movement parameters could be performed. The following paragraphs describe the development process described above.

The first step was establishing a communication between the exoskeleton and the computer Software (MATLAB/Simulink). Simulink has the advantage to have UDP network protocol blocks. These helped to receive information from a PC104 port to Simulink port. Fig. 2.8 shows a UDP diagram block that receives the information from the PC104 board. In the same way, send a data bus to PC104 board with orders to the actuators its possible using the UDP protocol.

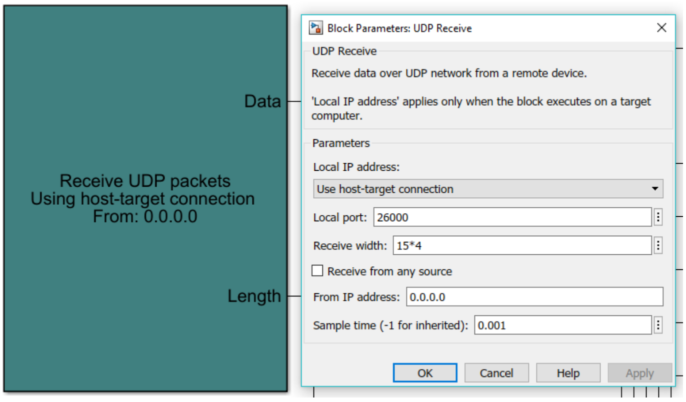


Figure 2.9 UDP block used to establish the communication between the PC104 board and Simulink.

In another hand, to upload the Low-level-Control to The PC104 board it was used the Simulink Real-Time Explorer. Which is an application to manages targets. Creating a communication with UDP protocol. In addition, this application has the property of create a boot, responsible to load an operating system into the computer´s main memory. Fig 2.10 shows the main window of the Simulink Real-time Explorer. With the target network settings, it was created the communication. Moreover, it was designed the boot with stand Alone feature. Thus, the exoskeleton always had the program ready to work inside the TC104 Board.

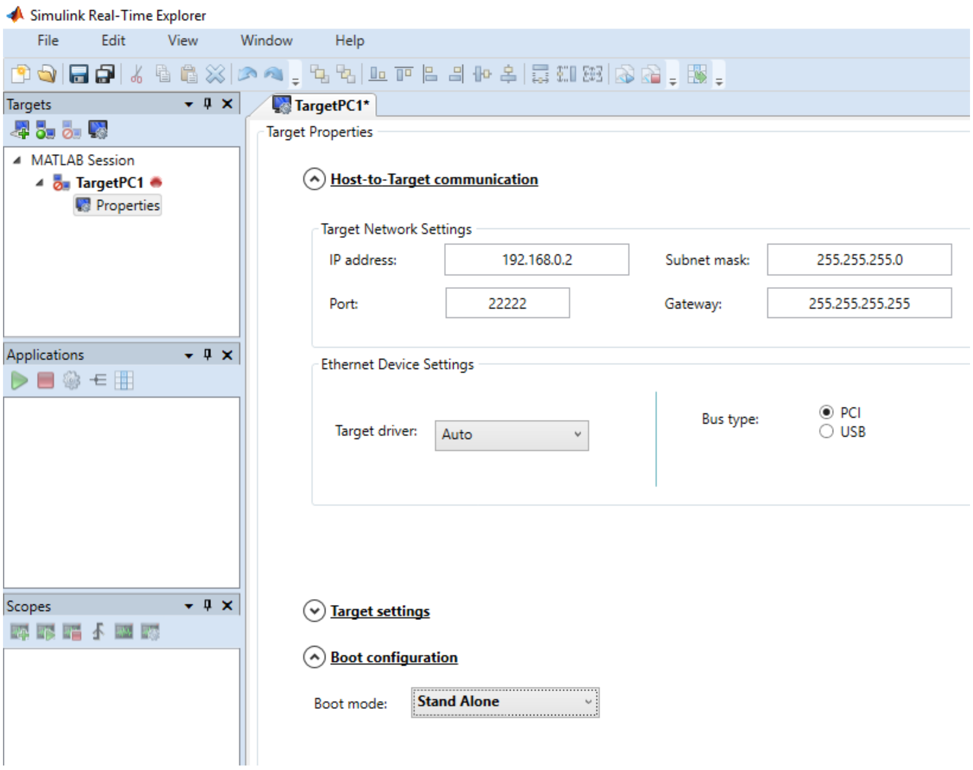


Figure 2.10 Simulink Real Time explorer used for creating a system boot of Low-Level control

Several tests were made it to secure that the communication between the Exoskeleton and Simulink was stable. Nevertheless, there were communication issues and problems with traffic were solved and confirmed the traffic data through a Wireshark analyzer, used for network troubleshooting, software and communications protocol development.

Afterward, it was created a Simulink model to send simple tasks for each joint. It is essential understand in what form is constitute the bus data. The Low-level control was designed to receive a command bus that is basically an array of six bits. This is addressed for each one of the six joints. Where the joints can be independently controlled by three types of control: Position, admittance and torque. Moreover, depending on the type of control, it can choose the joint target, and the stiffness that it required. It is worth mentioning that the values of joints to be controlled: 1 = Right Hip, 2 = Right Knee, 3 = Right Ankle; 4 = Left Hip, 5 = Left Knee; 6 = Left ankle. The table 2.1 summarizes the command data.

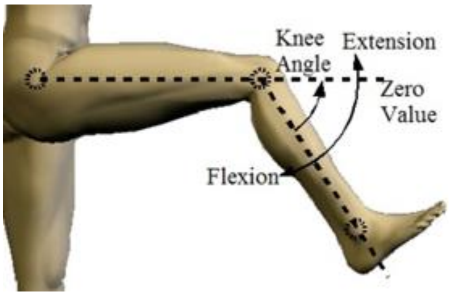
Table 2.1 Command data sent from High level control to Low-level control inside Exoskeleton´s PC104 board

	Type of Information
Bit 1	Joint Target
Bit 2	Type of Control
Bit 3	Value
Bit 4	Stiffness
Bit 5	Aux
Bit 6	Enable

When the exoskeleton is working, Simulink acquires in real time the value of angles, torque and velocity of each joint. This is possible through a data bus that Simulink receives from the exoskeleton. This is an array of six bytes with information related to the type of control and the value of the magnitude each joint in an instant of time. In another hand, position and torque have a range limit of movements to secure the subject safety and describes the range values that the human joints have. In table 2.2 was explained. where the negative limits mean a joint flexion and positive value a joint extension. To conclude this experimental section and continue with the development of control strategy. It was implemented a DEMO gait trajectory made by Rajasekaran et al 2015 with the aim to confirm the correct performance of the algorithm.

Table 2.2 Position and Torque values range for each joint.

JOINT	POSITION	TORQUE
Hip	-20° to +100°	-40 to 40 Nm
Knee	-5° to 100°	-20 to 20 Nm
Ankle	-20° to 15°	-20 to 20 Nm



2.3.1. High level control used for data acquisition in healthy people

The base of High level control was made with toolboxes of real-time and MATLAB. First, it was created two UDP communication blocks, one for receive the data from exoskleton and another to send the control information necessary to do this experimental part. Attached to the UDP receive block, it was designed a UDP decoder block. This has the cabability of decoding the bus data and extract in individual way the values of angles, torque an velocity of each leg. Then, for convenience to read and manipulate the data, it was agrouped the variables per type of magnitude and separated by leg. In second place, for record the trajectory, it was selected the type of control in mode addmitance, due to this mode the exoskeleton acommpany the subject's movement. This mode was used in the hip and knees. In the ankles was used a position control because the behavior of ankles in addmitance control was incoungruous in several times. Fig 2.11 it can apreciate the previosly mentioned.

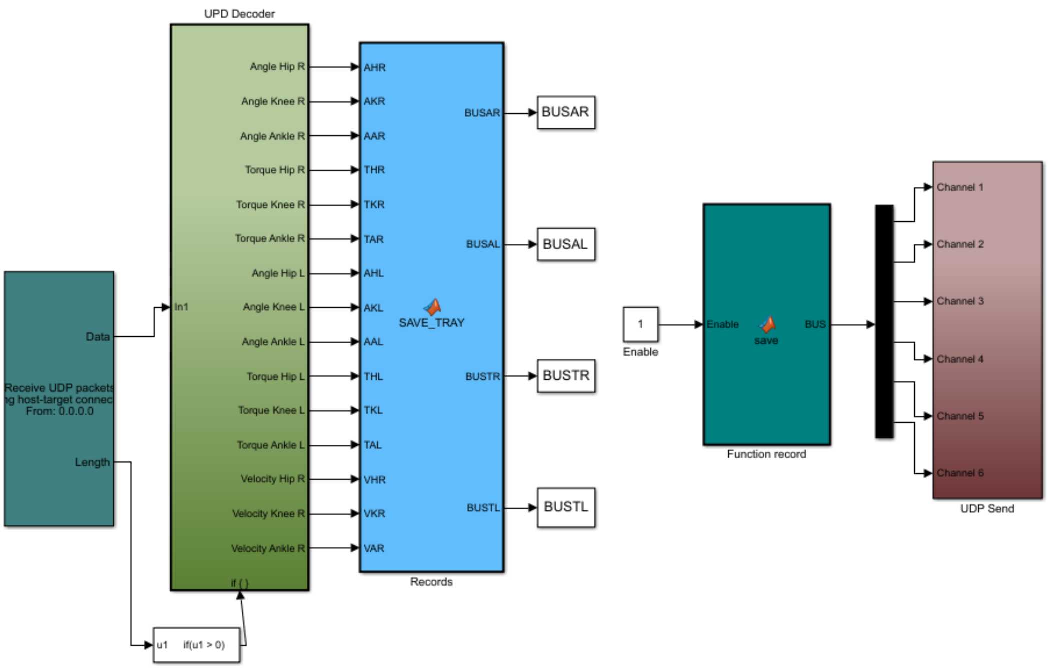


Figure 2.11 Schematic Design of High level control to record the Sit to Stand motion

It was recorded 4 people´s performance in a Sit-to-stand movement, two men and two women between 21 and 24 years old with a weight between 54 and 68 kg and height of 1.68 and 1.75 meters. The volunteers of study signed a consent document for participate in the research. It was explained the activity and in what consists the project. Each volunteer performed 3 times the Sit to stand motion to ensure the correct motion. After the collected data. It was made a table with information the values of angles, torque and duration time of each phase. Then it was calculated an average of the registered values for angles and duration time per phase. The next tables 2.3 and 2.4 contain the parameters of angles and torques taken from the Sit-To-Stand trajectory performed by four healthy subjects. The data reflect the start values of each phase. The values were chosen in an experimental way. Supported with an investigation about the duration of time between phases of Sit-To-Stand by Lara Barrios et al [36].

Table 2.3 Significant values of the left leg extracted from the STS trajectories for four volunteers

LEFT LEG					
STAGE		**ANGLES°**		**TORQUE (Nm)**	
	TIME(s)	**HIP**	**KNEE**	**HIP**	**KNEE**
Phase 1 to 2	0	92.6	95	-5	12
	0	98	91	-3	4
	0	93	94.5	-6	10
	0	91	93	-4	5
2	0.7	45.5	37.5	-25	-5
	0.6	52	39	-20	-3
	1	44	49	-10	-5
	1.1	49	49	-15	-7
3	1.85	12.6	4.5	-6	-2.5
	1.5	23	0	-14	-2
	1.5	20	3	-15	0
	1.95	11	9	-12	-3
4	3.05	10	2	-14	-5
	2.7	15	1	-10	-3
	2.35	13	0	-7	-6
	2.35	10	0	-8	-7

Table 2.4 Significant values of the right leg extracted from the STS trajectories for four volunteers

RIGHT LEG					
STAGE		**ANGLES°**		**TORQUE (Nm)**	
	TIME(s)	**HIP**	**KNEE**	**HIP**	**KNEE**
Phase 1 to 2	0	80	99	7	19
	0	93	98	5	9
	0	84	99	3	-15
	0	84	97	4	7
2	0.8	43	38	-13	-5

	1.25	50	43	-10	0
	1	60	54	-10	0
	1.3	50	53	-10	-3
3	1.92	15	10.5	-9	3
	1.95	20	5	-7	-2
	1.7	22	7	-7	-4
	2.4	13	5	-7	-5
4	3.01	10	5	-9	-3
	3.35	12	3	-6	-2
	2.7	8	8	-4	0
	3.1	12	0	-2	-4

Table 2.5 Averages of start angles of each phase for hip and knees

Average angles to begin each phase	HIP	KNEE
Phase 1 to 2	89.45	92.8125
2	49.1875	45.3125
3	17.075	5.5
4	11.25	2.375

Table 2.6 Averages duration of each Sit-to-Stand phase

Average Phase times (s)	1 to 2	0.96875
	2 to 3	0.8775
	3 to 4	0.98
Total duration of STS (seconds)		2.82625

To incorporate a trajectory of Sit-To-Stand, it was taken one of the trajectories previously recorded. This was implemented inside of schematic designed made previously (see Fig. 2.10). The script was written in a “Function MATLAB block”. The algorithm contains an array with the angles of hip, knees and ankles that model the Sit-to-Stand trajectory. To send the values to each joint, it was implemented a loop that allows to assign the angle to its corresponding joint.

2.3.2. Control Strategy proposed for Sit-To-Stand assistance

A crucial issue happened before beginning with the development of the control strategy. As described above in table 2.2, the exoskeleton has limits of movement that were fixed in the Low level. These limits are defined with the aim that the engines do not overstep these thresholds and do not get in a conflict with the harmonic drives. Generally, the exoskeleton works without mechanical mishap. Nevertheless, several times the knee left joint was locked because the engine overstepped the limits. As a result, it had to disassemble the harmonic drive and the engine for find the correct position between both.

It was analyzed the results of angles and the averages duration times of each phase (see table 2.5- 2.6) with the aim of tuning the angles limits of Sit-to-Stand phases and use the duration time like a new parameter of strategy. To the phase 1, the preparation phase, the subject should have a required position where the angles of knees are larger than 92°, the hip are larger than 89° and the ankles have a notorious flexion position for leverage. In this way, it was obtained a better position of center of mass (see Fig 2.12). The type of control in this phase is admittance control, thus, the subject had freedom to move the hip and could try to stand up.

Figure 2.12 Initial position required to activate the movement of exoskeleton

In the phase 2, the sit-to-stand movement starts, with hip angle minor than 89° and knee angle minor than 92° (see Table 2.5) these angles was obtained from calculating an average of the angles that the subjects presents at the instant they leave the thighs of the chair. The most important part of this phase is ensuring that exoskeleton rises the body without a greater low limbs effort, thus, it is necessary to generate a high torque to compensate the lack of legs strength. For achieve this, based on the data collected from the angles and duration of each phase for healthy subjects, it was shown for the phase two of the graphics obtained from de Sit-to-Stand, the behavior of the change of position of the hip and knees is almost linear. It was decided to model this behavior like a linear equation. Bearing in mind that, the equation of a line is:

$$y = mx + b \qquad \textbf{(Eq. 2.1)}$$

Where, m is the slope and b the intercept point on the ordinate axis (y). This can be write in terms of the variables that are used in this project.

Where, (x) is the independent variable, the time (t); $(y)$is the position variable, the angles (θ) of each joint; m is the change of position (angle) respect to time.

Rewriting the linear equation:

$$\theta = mt + b \tag{Eq. 2.2}$$

The angles parameters calculated (see table 2.5 and 2.6) for the phase 2 are: For the Hip the initial angle is 89° and the final angles is 17°. For the Knee the initial angle is 92° and the final angle is 5°. The duration time of this phase is divided in two parts due to in the most Sit-to-Stand recorded there was a change in the behavior of the graph. The first one has a duration of 0.9687s and the second of 0.8775s. Nevertheless, it was chosen to unify both parts because, it was evaluated the behavior using the Exoskeleton and the movement was not good, because the exoskeleton stopped between both parts. Thus, the time was unified. For a duration time of 1.8462. With this data, it was possible to calculate the linear equation that models this trajectory.

To calculate the slope (m):

$$m = \frac{\theta_{final} - \theta_{initial}}{t_{final} - t_{initial}} \tag{Eq. 2.3}$$

And b the intercept point on the ordinate axis (θ) in the instant $t = 0$.

The linear equation for phase 2 of Hip and knees are:

$$\theta = -38.99t + 89 \ (Hip\ linear\ equation) \tag{Eq. 2.4}$$

$$\theta = -47.1238t + 92 \ (Knee\ linear\ equation) \tag{Eq. 2.5}$$

The third phase the body is almost standing, thus, the exoskeleton does not need greater effort to finish the movement, the position change is minor. In addition, it was shown for this phase, the graphics obtained from de Sit-to-Stand, the behavior of the change of position of the hip and knees acts like an exponential decrease equation. It was assumed to approximate this equation. From there, the exponential equation is:

$$y = ae^{bx} \qquad \textbf{(Eq. 2.6)}$$

Where, (x) is the independent variable, the time (t); $(y)$is the position variable, the angles (θ) of each joint; $a\ and\ b$ are the constants that allow to obtain the desired behavior of the equation.

Rewriting the equation:

$$\theta = ae^{bt} \qquad \textbf{(Eq. 2.7)}$$

The angles parameters calculated (see table 2.5 and 2.6) for the phase 3 are: For the Hip the initial angle is 17° and the final angles is 11°. For the Knee the initial angle is 5° and the final angle is 2°. The duration time of this phase is 0.98s.

To calculate the constants a and b:

$$a = \frac{\theta_{initial}}{e^{b(t_{initial})}}\ and\ b = \frac{ln\frac{\theta_{final}}{\theta_{initial}}}{\theta_{final} - \theta_{initial}} \qquad \textbf{(Eq. 2.8)}$$

Calculating the equation for the hip and knees:

$$\theta_{HIP} = 17e^{-3.5545t} \qquad \textbf{(Eq. 2.9)}$$

$$\theta_{KNEE} = 5.0002e^{-5.2130t} \qquad \textbf{(Eq. 2.10)}$$

The fourth phase ensure that the subject is completely standing. When the high-level control detects an angle lesser than 11° the exoskeleton finishes the sit to stand motion. Fig 2.13 summaries the algorithm for transition sit-to-stand phases.

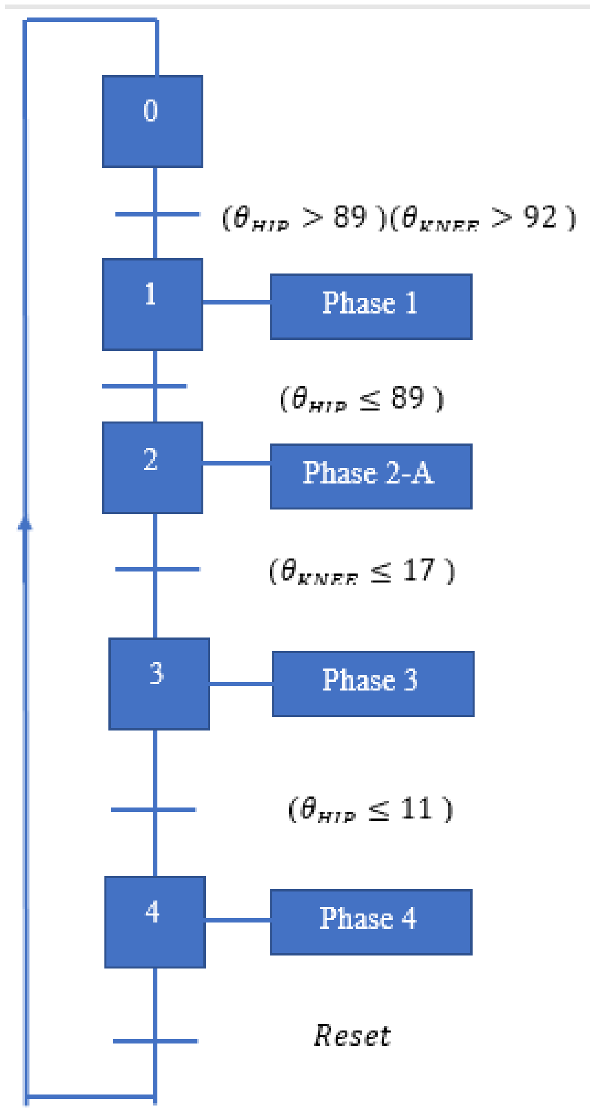


Figure 2.13 Control algorithm for transition phases in the Sit-to-Stand motion

It was implemented the strategy in 3 volunteers. Two women and one man. These people had the physical aspects like the previous test subjects. The volunteers of this study signed a consent document for participating in the research. In addition, was recommended moving the legs the less possible. Each volunteer performed 3 times the Sit to stand motion to ensure the correct motion.

3. Results and Discussion

This chapter presents the experimental results obtained in order to achieve the stated objectives at the beginning of this work. These results compare the behavior of Sit-to-Stand strategy developed by Pieras Morell with the Sit-to-Stand strategy propose in this project. The results submit, the Sit-to-Stand trajectory perform by a healthy subject to analyses the initial position before gets up and the body behavior during the movement. In addition, it was presented the model of STS trajectory with the characteristics of each phase. Then, it was exposed the angles and torque of hip, knees and ankles registered with the application of STS trajectory develop in this work and the Pieras Morell Strategy. Finally, it was extracted aspects of each strategy that represent advantages in the robotic assistance to people with impairments in the lower extremities.

The next experimental results are of a healthy person (23 years old, female). The subject was informed about the project and its importance.it was performed several records for both STS strategies with the aim of the subject training how to manage the exoskeleton. In this way, it was obtained results more naturals for its analysis and interpretation.

Fig. 3.1 shows the Sit-to-Stand trajectory step by step performed to obtain an ideal angles and times of each STS phase. It was observed in the initial moment the subject prepares the low limbs to support the weight body. The hip moves towards the edge of the chair, achieving to carry the center of mass from the trunk to the legs, thanks to this, the body keeps the balance and allows to do the Sit-to-Stand movement. As the body moves upwards the center of mass is displaced in a vertical line generating speed until the middle of legs extension. Then, the speed of center of mass decreases progressively until the lower extremities finish the extension. Finally, the trunk carries up positioning the center of mass above the feet. On the other hand, it was observed at the beginning the maximal ankle dorsiflexion just before starts the movement. In addition, it was found that the hip half trajectory is in flexion and another one is in extension. Because the hip tries to keep the center of mass in balance until finishing the sit to-stand. While the knees always are in extension movement.

Figure 3.1 Healthy person performing the sit-to-Stand motion with the Exoskeleton H1.

After taken several records of STS motion in four healthy subjects, it was made an average of the main aspects, like the angles in the hip, knee and ankles. Fig. 3.2 shows the position transition in the joints involved a Sit-to-Stand trajectory; this record is chosen because its data adjust to the average STS variables perform by Healthy subjects. It is important to mention; the movement was done with admittance control because in this control, the exoskeleton moves the joints with the user´s intention and performs the same movement. The exoskeleton accompanied the trajectory of each joint. Nevertheless, in this experimental part, the ankle joint has not a very well lecture because the exoskeleton has a high sensitive in these ankle joints. So, the movement was unstable. For this reason, the ankle lecture in the Fig. 3.2 is not precise. The angles of hip and knees are consistent with flexion and extension described previously. The trajectory phases (see Fig 3.1).

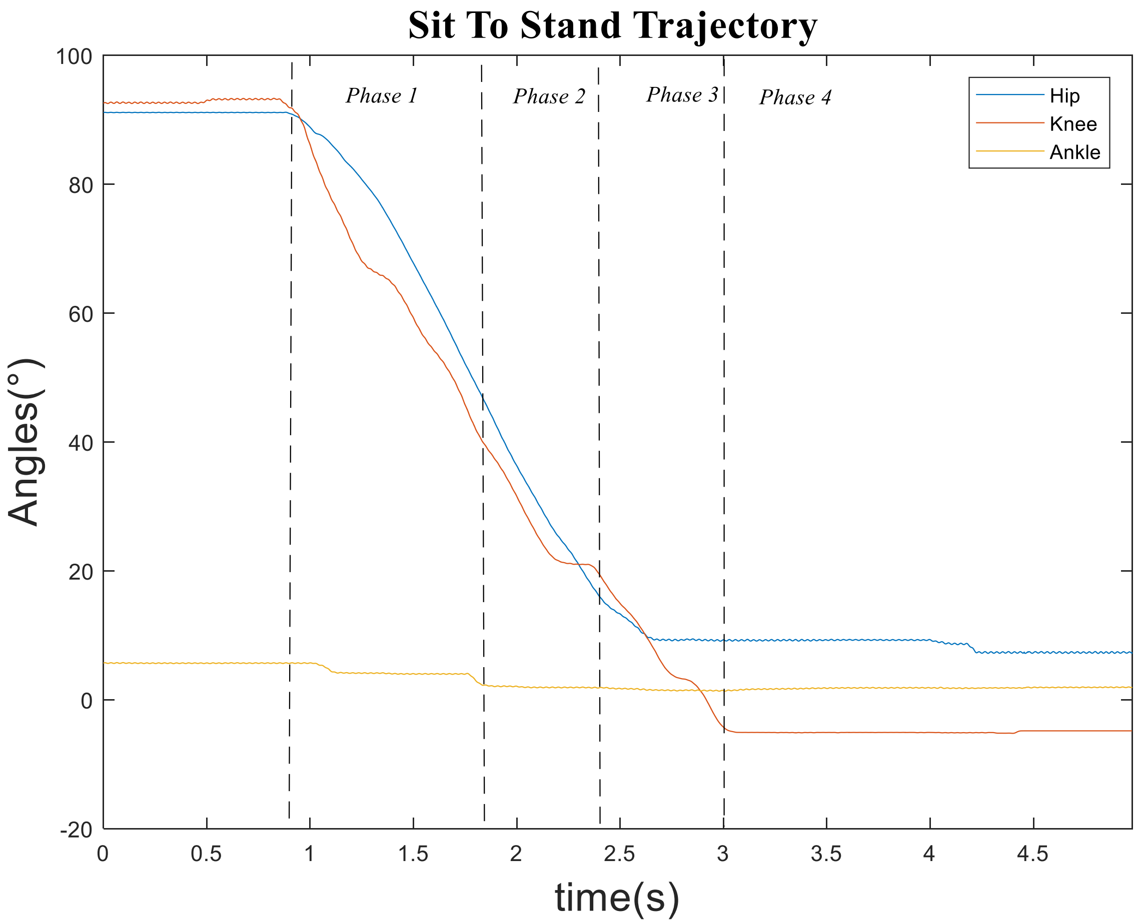


Figure 3.2 Division of Sit to Stand Phases by angles and duration time parameters.

Understand the changes in angles and torque of STS trajectory in healthy subjects allowed extracting characteristics for establish a movement that the exoskeleton reproduces like human body. The following graphs comparing the behavior of the STS developed by Pieras Morell (Strategy A) with the STS strategy developed in this study (Strategy B). As shows Fig. 3.3 the variation of hip angles in both strategies are faster than healthy subject movement. At the beginning of the movement the Strategy B start with a higher hip flexion encourages the position of center of mass closer the legs. but the strategy A produces a faster movement. Nevertheless, the hip angle not finish in a totally extension. This could cause a bit lost balance.

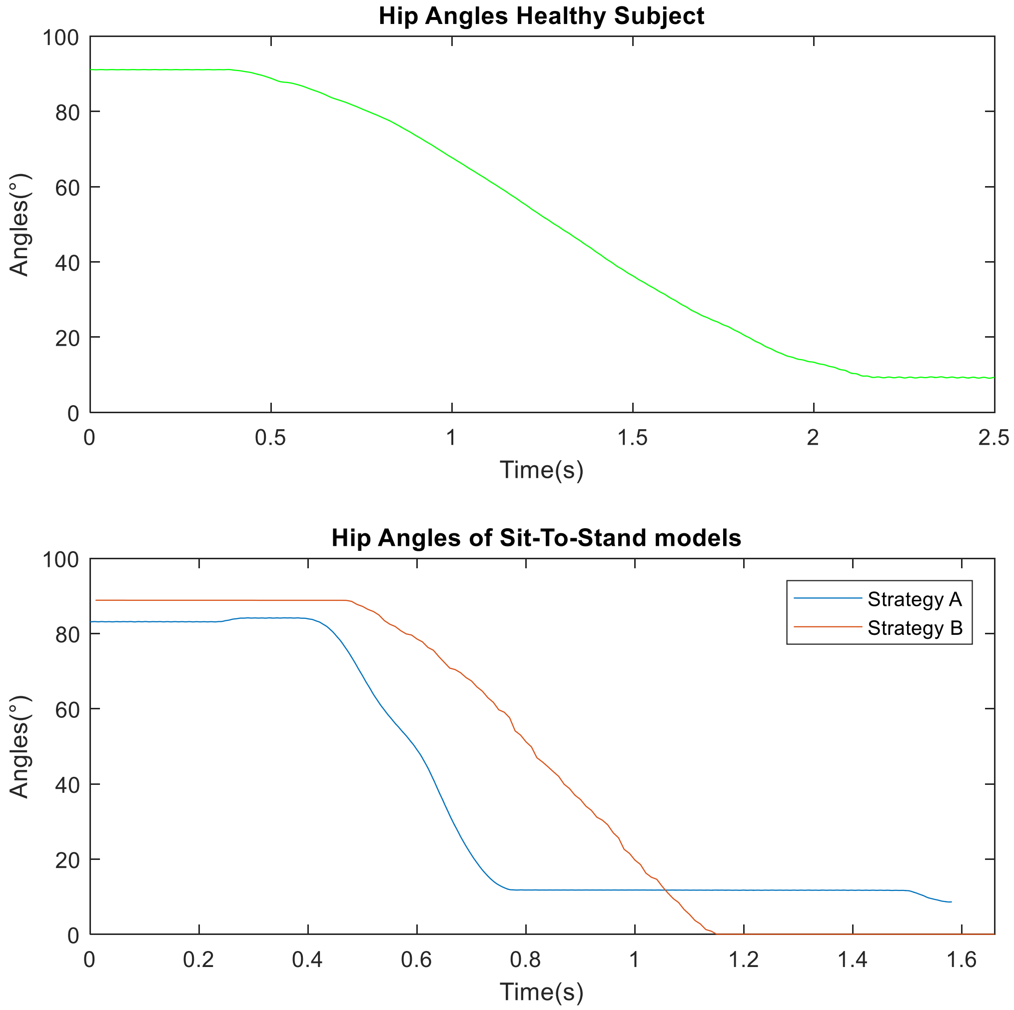


Figure 3.3 Comparison of Hip angles in three STS models: Healthy Subject, Strategy development by Pieras Morell (Strategy A), Strategy development in this project (Strategy B).

The follow graph is important due to knees provide the support for rise the body. In the Fig. 3.4 was observed a few differences in the angles behavior of each strategy. The phase 1 also called phase preparation presents knee higher angles in both strategies than healthy subject. This gives greater support to transmit major force in the exoskeleton joints. In addition, to end the movement, both strategies finish in the phase 4 with the full knees extension. However, the strategy A has a smoother movement during all trajectory.

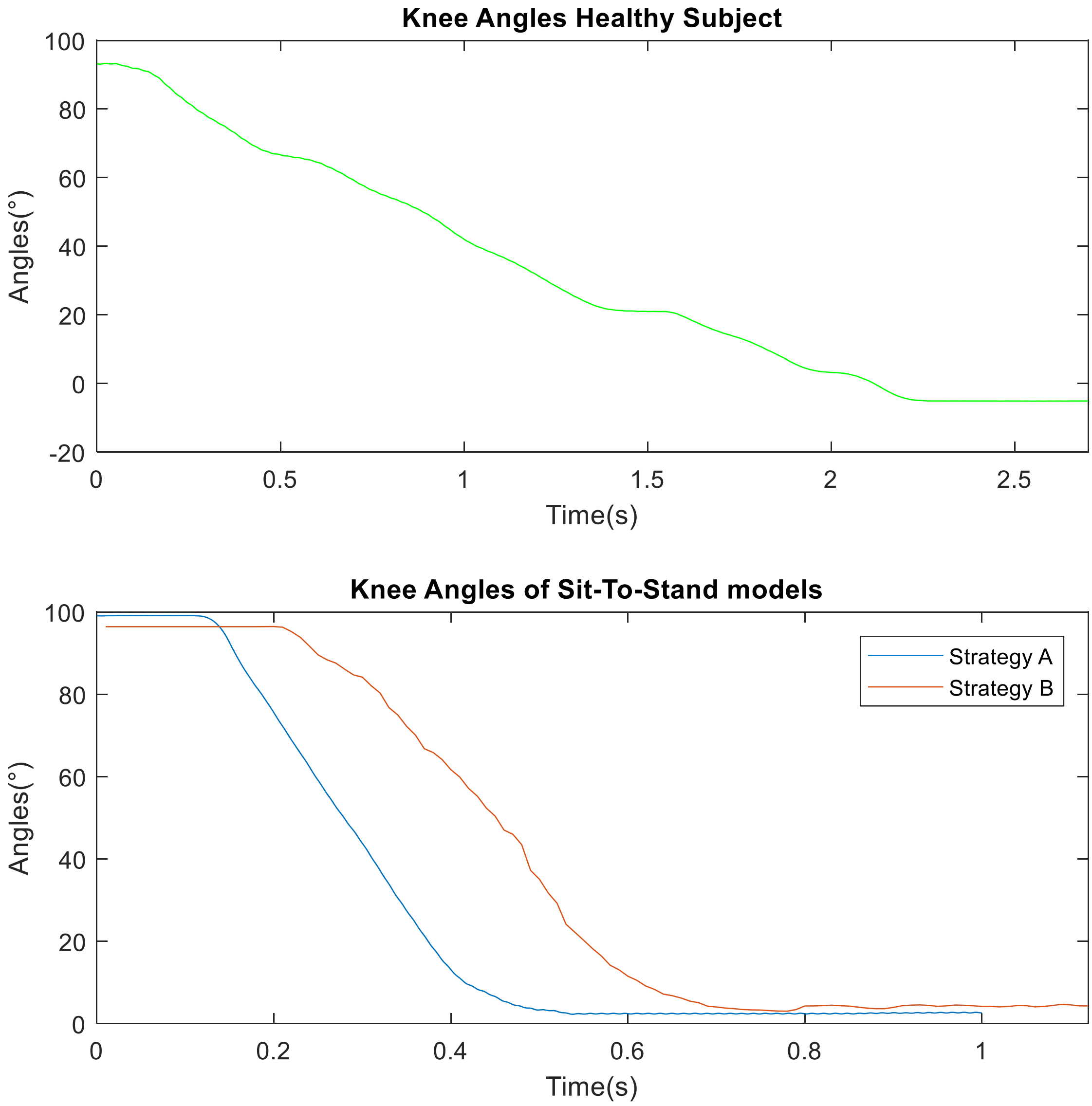


Figure 3.4 Comparison of knee angles in three STS models: Healthy Subject, Strategy development by Pieras Morell (Strategy A), Strategy development in this project (Strategy B).

Fig. 3.5 presents the angles behavior in the ankles. The main characteristic found in the three trajectories (Healthy subject, Strategy A and Strategy B) is the time in ankles activity is lower than the hip and knees. In the second place, the strategy B begins with a higher dorsiflexion. Thanks to this, the legs have a better lever to get up. The control strategy B ensure the ankle trajectory to decrease smoothly. In contrast, the strategy A finishes in angle zero, but its behavior is not clear, this can cause low body stability.

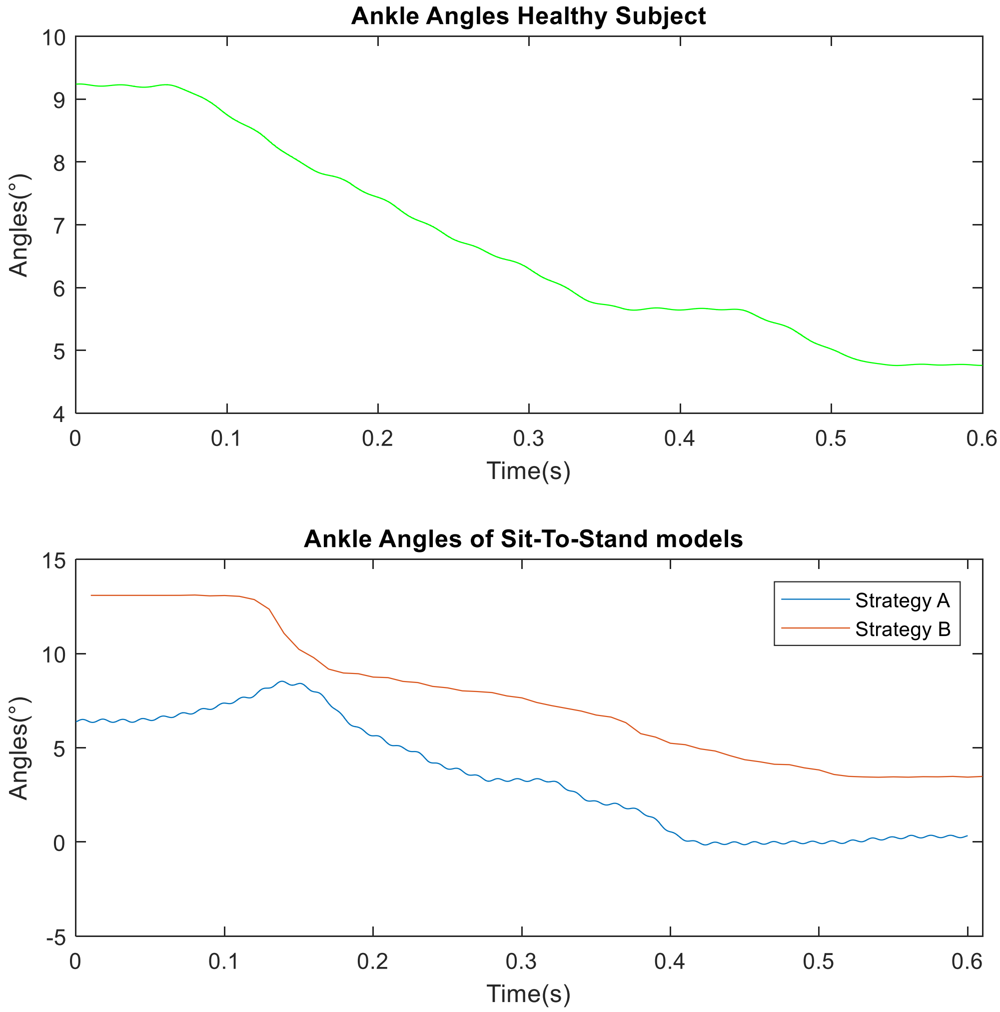


Figure 3.5 Comparison of ankles angles in three STS models: Healthy Subject, Strategy development by Pieras Morell (Strategy A), Strategy development in this project (Strategy B).

The previous results provide a general view of the visual behavior sit-to-stand, this movements are thanks to different values of torque in the joints to be able to rise the body. A person who has suffered a stroke or sort of disease with motion impairments have not the ability to produce high joint torque neither has a good muscle activity. Consequently, the exoskeleton should produce higher torques to counter the gravity effects and helps the joints to move the lower limbs. The following graphs show the applied torques in each joint during the sit to stand motion.

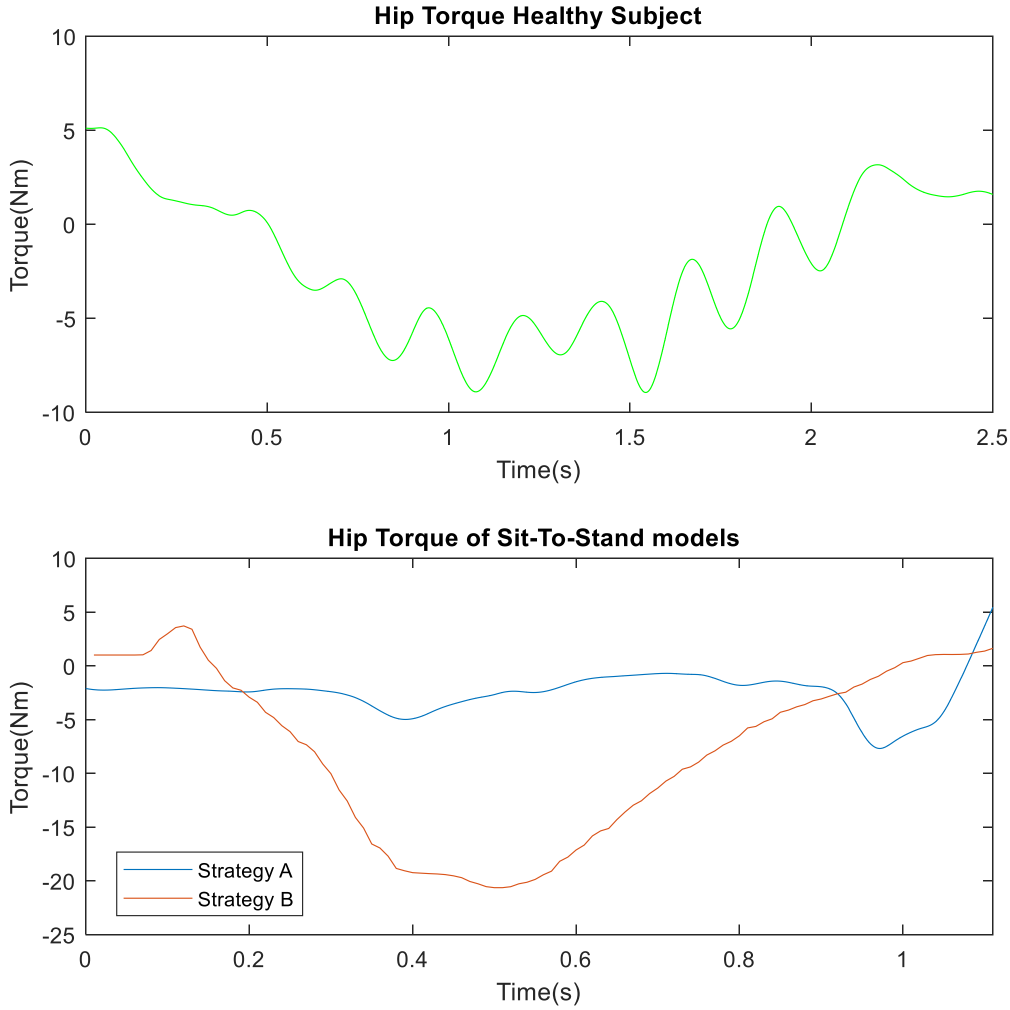


Figure 3.6 Comparison of hip Torque in three STS models: Healthy Subject, Strategy development by Pieras Morell (Strategy A), Strategy development in this project (Strategy B).

Before comparing the strategies performance, it is important to mention, the variation position in the hip angle follows two movement, hip flexion and extension (see Fig. 3.1). As shown Fig. 3.6 the torque in the healthy subject presents down to -10Nm, then, goes up to zero, this represents the flexion as the extension. On another hand, the strategy A produces low force, the torque peaks are 6-7Nm and is a constant value. Thus, there is not a big user support. In contrast, the strategy B presents a higher torque peak, with this the exoskeleton generates a big force to move the user hip.

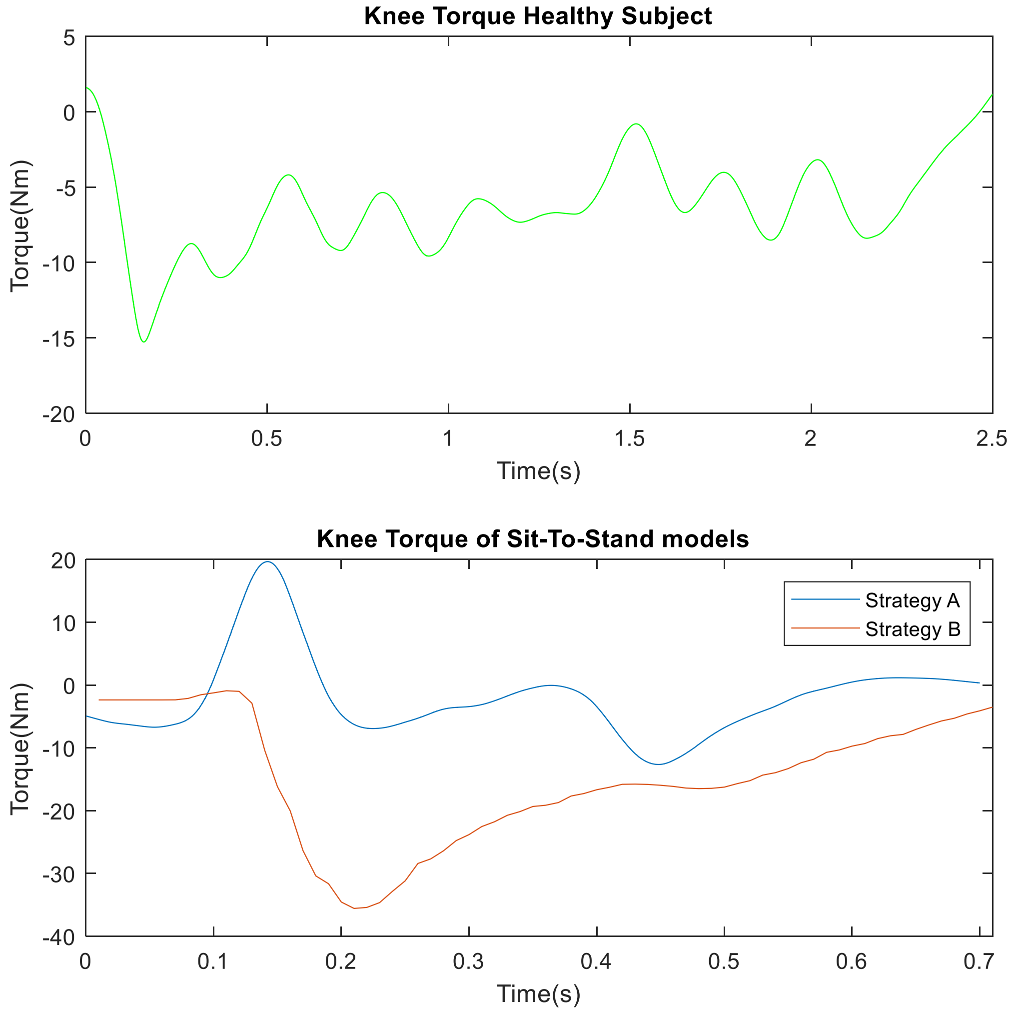


Figure 3.7 Comparison of knee torque in three STS models: a) Healthy Subject b) Strategy development by Pieras Morell c) Strategy development in this project.

One of the main objectives in the strategy development was the knees capacity to rise the subject with the minimal user effort. Fig. 3.7 shows the torque applied in the knees joints. First, the curve in the healthy subject apply a high torque to position the legs and start the movement, then, declines slowly to zero to finish the sit-to-stand trajectory. The Strategy A begins with a legs flexion, so the curve starts in 20Nm, then apply a 25Nm of torque in extension. In contrast, the strategy B generates a 35Nm torque in extension. Then declines to zero keeping high torques while decrease. In view of this, the exoskeleton has more possibilities to assist the movement of sit to stand to person with legs disabilities.

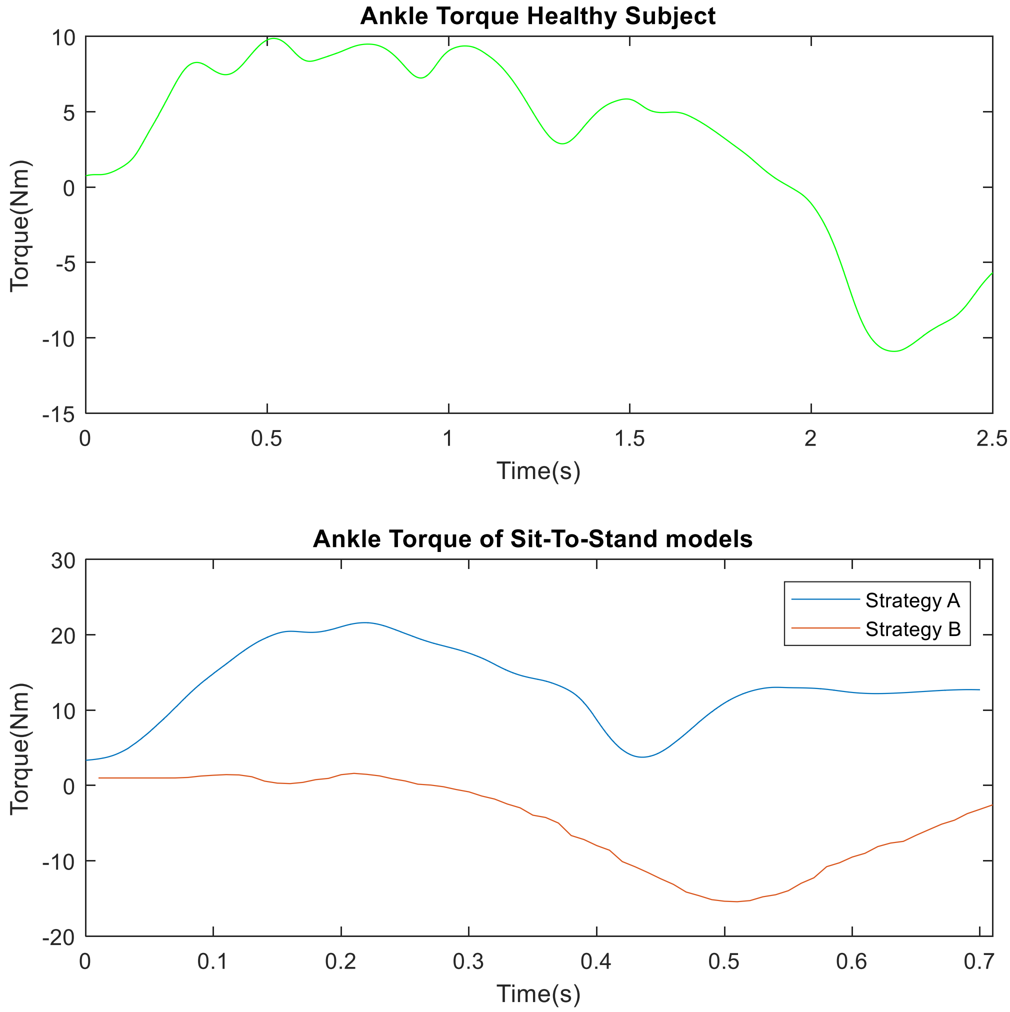


Figure 3.8 Comparison of ankle Torque in three STS models: Healthy Subject, Strategy development by Pieras Morell (Strategy A), Strategy development in this project (Strategy B).

With the aim of comparing which strategy has a movement more like healthy subject and what strategy provides a higher torque. First it is important to mention that a high ankle torque is important to keep the lever with the legs in to realize a correctly sit-to-stand. Fig 3.8 shows in the first place, the ankle torque in a healthy subject. It was that observed the torque preserve the same value until almost the end. Then, there is a fast change necessary to extend the ankle. While, the strategy A has a higher torque from beginning. With this, the ankle presents a major dorsiflexion. In contrast, the Strategy B maintains a low torque until the subject is almost standing where the torque increase notoriously.

Conclusions

It was observed the importance of robotics exoskeletons in the rehabilitation field and the contribution to people who suffer any kind of mobility limitation. In addition, how the robotics exoskeletons can provide an assistance in tasks like Sit-to-Stand. Movement required for performing activities of daily living. Finally, it was found how the rehabilitation of Sit-to-Stand movement using robotics exoskeleton can improve the quality of life.

It was collected the data of hip, knees and ankles angles for tuning the Sit -to-Stand phases and establish an average time of each phase. Thanks to this, the Sit-to-Stand control strategy is developed with experimental parameters thus, the STS control strategy can be used by different types of bodies and responds an optimal way for assistance and rehabilitation of Sit-to-Stand.

The comparison between the Sit-to-Stand control strategy developed by Pieras Morell and the STS control strategy developed in this project, allowed to conclude several features to benefit the rehabilitation and assistance to users with impairments in the lower extremities.

First of all, the results of the control strategy implemented in the exoskeleton H1 demonstrated a Sit-to-Stand behavior like a healthy subject. In addition, the results support the implementation of an equation model to represent the trajectory of each phase, using the phases duration time and the limit angles to phases transition.

It was possible to determine between both strategies a better way to allows the exoskeleton H1 lift a person without major lower limbs' effort. The control strategy developed in this project presented torque values higher than the control strategy by Pieras Morell and healthy subject in the three joints (Hip, knees and ankles) thanks to this, the possibility of user falling backwards is lower.

It was established that the Sit-to-Stand control strategy made by Pieras Morell has a softer respond in the knees, because keeps a velocity control constant. Therefore, the movement is smooth and similar to that of a healthy subject.

It was observed the importance to begins the sit to stand trajectory with an optimal position of lower extremities, the control strategy developed ensure the position of center of mass to support and balance through the hip flexion in the preparation phase.

In conclusion, this project contributed to presents another kind of Sit-To-Stand control strategy to rehabilitation of persons with motor disorders and lower extremities limitations with the main feature of gives major user support in the lower limbs at the moment to perform the Sit-to-Stand movement.

Future work

Future extensions of this work are designed under the premise of obtaining an exoskeleton with advanced software that allows its implementation in people with disabilities to walk, in rehabilitation process or with weakness in the lower limbs. The different types of researches that have been carried out with this project have been aimed at to improve it with the hope of obtaining a device that can be used in hospitals or rehabilitation centers as an aid to the quality of life of the human being. Following is some of the advances that could contribute to an improvement of this great project.

First of all, an ergonomic study of the exoskeleton would be a broad field of research to do more advances of the project. The design of the exoskeleton is not very comfortable for those who use it. Depending on the type of body the person has, the exoskeleton can hurt it, because its design, although it can be adjusted, is not designed for any type of person. It could also be of interest to researchers to look for lightweight materials that can withstand large weights, with the aim of improving the design of the exoskeleton and making it more comfortable for those who use it.

Second of all, modifications could be made to the electronic system of the exoskeleton's backpack in order to remove it or make a smaller one, with smaller electronic elements and plates and if possible, find a way to create a communication via Wi-Fi or Bluetooth between the exoskeleton and the computer. This would create a more comfortable design for the user, because carrying a backpack on the back is not comfortable or advisable for someone who is in rehabilitation therapy.

Finally, to create better rehabilitation strategies, it would interesting combine the both strategies developed, taken the best of each one and getting a strategy with a high reliability, that can lift any kind of person with impairments in lower extremities.

Environmental Impact analysis

The environmental impact refers to any man-made activity that produces a change in the environment. It necessary. It is necessary to carry out an environmental analysis with the aim of taking care of the planet and preserving it. In this work the risk factors that can be a threat to the environment are:

- The computer´s energy consumption
- Metal casting to design the structure and supports of the exoskeleton, because the vapors and substances released in the steel melting process are harmful to the atmosphere.
- The exoskeleton, in a Future it could affect the environment. Because it is composed of materials that contaminate the earth.

In conclusion, there is no significant environmental impact, this could be considered in the future when the exoskeleton goes out of service.

Budget and economic analysis

This chapter presents the budget necessary to carry out the project. In order to perform the economic analysis of this project, it has been decided to divide the costs into two types, direct costs and indirect costs.

Direct costs refer to all types of costs that have a direct relationship with the final product, in this case, the design of a sit to stand control strategy for a robotic exoskeleton. In this group, the manpower factors and raw materials are taken into account.

As the exoskeleton was not created in this project, but was the main tool of the work and the element where the strategies were tested, it was considered as a raw material.

Table 6.1 Direct costs

DIRECT COSTS					
MANPOWER	Concept	Quantity of Engineers	Cost (€/hr)	Hours of work in the project	Total of Costs (€)
	Biomedical Engineer	1	30	600	18.000
RAW MATERIALS	Concept	Quantity	Cost (€/unity)	Total of Costs (€)	
	Exoskeleton	1	50.000	50.000	
	MATLAB license	1	2.000	2.000	
	Computer	1	1.800	1.800	
TOTAL OF DIRECT COSTS				71.800	

Indirect costs are those that maintain a collateral relationship with the final product. These costs do not have a direct influence on the product but are essential for the realization of it. Within these costs can be considered factors such as services, places of work, among others. Table 6.2 describes these costs.

Table 6.2 Indirect costs

INDIRECT COSTS			
Concept	Cost (€/month)	Months of work in the project	Total of Costs (€)
Electricity	70	4	280
Rent of the Laboratory	450	4	1.800
		TOTAL OF INDIRECT COSTS	2.080

The total cost of the project is calculated by adding direct costs plus indirect costs as it showed in Table 6.3

Table 6.2 Indirect costs

Concept	**Value (€)**
Direct Costs	71.800
Indirect Costs	2.080
TOTAL COST OF THE PROJECT	73.880

The total cost of the project is 73.880€

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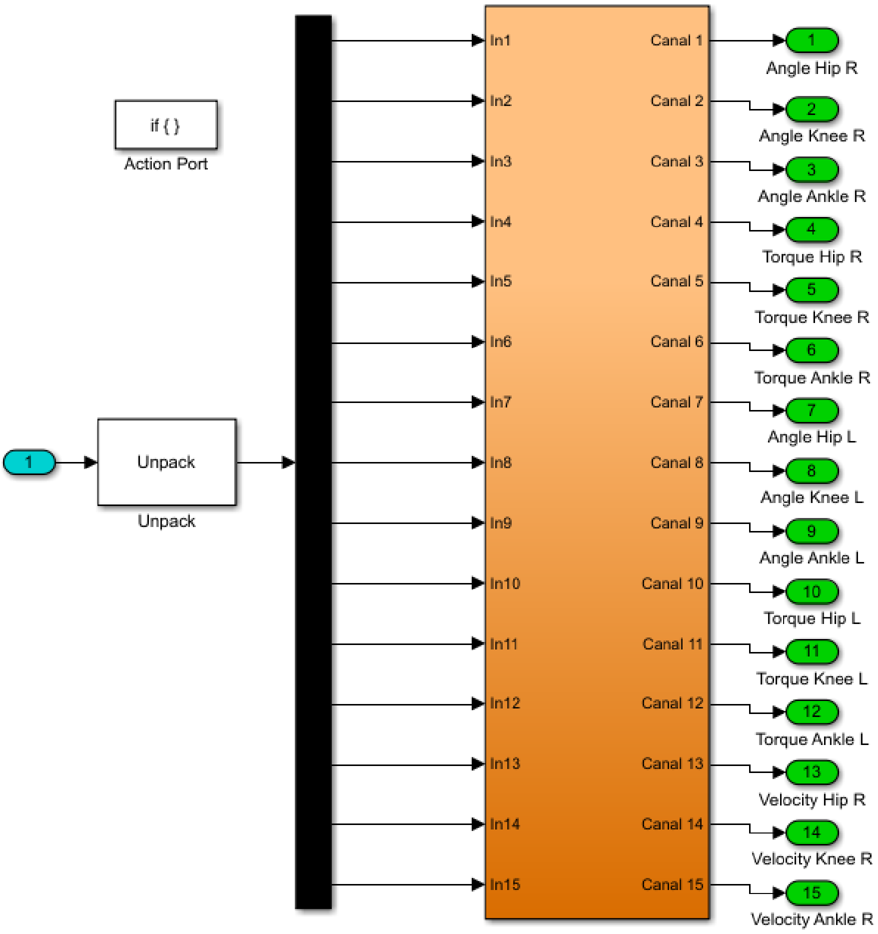
Annexes

This section contains the codes designed in MATLAB in the development of the project. In addition, the High-level control subsets. Also contains the informed consent used for the data collection.

A.1 High level-control designed in Simulink.

A.2 Diagram blocks used for decoding the Data bus form Low-Level control



A.2 Algorithm designed to collect the data of Sit-To-Stand in Healthy subjects.

```
function BUS = save(Enable)
persistent x
persistent a
persistent torque
persistent ToC
persistent cont
persistent i

if (isempty(x))
    x = 0;
end
if (isempty(a))
    a = 0;
end
if (isempty(ToC))
    ToC = 0;
end
if (isempty(torque))
```

```
    torque = 1;
end
if (isempty(cont))
    cont = 0;
end
if (isempty(i))
    i = 1;
end
x = x + 1;
if x > 6
    x = 1;
end
AS = [0 2 3 4 5 6 6 5 5 5 4 4 4 3 3 2 2 0 0 0];
if Enable == 1
    if (x == 3 || x == 6)
        ToC = 1;
        torque = 60;
        cont = cont +1;
        if cont > 20000
            i = i + 1;
            if (i>20)
                i=1;
            end
            cont = 1;
        end
        a = 0;
    end
    if (x == 1 || x == 2 || x == 4 || x == 5)
        ToC = 2;
        torque = 30;
    end
end
switch x
    case 3, a = AS(1,i);
    case 6, a = AS(1,i);
end
BUS = [x ToC a torque 0 Enable];
```

A.3 Algorithm designed to Sit-To-Stand control strategy.

```
%STRATEGIE MODE, STS CONTROL BY ANGLES AND TORQUE(STIFFNES)
function BUS = STRATEGIE_STS_TORQUE_ANGLES(enable, AHR, AKR, AKL, AHL)
persistent m %JOINT
persistent v %VALUE OF PARAMETER
persistent t %TORQUE REPRESENTED IN STIFFNES
persistent ToC %type of control
persistent x %value in time

%'BUS' IS THE MODEL OF TRAJECTORY WHO HAS THE PARAMETERS TO DO A STS
if (isempty(v))
    v = 0;
end
if (isempty(m))
    m = 0;
end
```

```
if (isempty(ToC))
    ToC = 0;
end
if (isempty(t))
    t = 0;
end
if (isempty(x))
    x = 1;
end

%phase 1 (admitance control and starter
if enable == 1
    if ((AHR > 89) && (AKR > 92) && (AKL > 92)) % limits to sure that the
person has the right position
        switch m
            case 1
                ToC = 2;
            case 2
                ToC = 2;
            case 3
                ToC = 1;
                v = 10;
                t = 100;
            case 4
                ToC = 2;
            case 5
                ToC = 2;
            case 6
                ToC = 1;
                v = 10;
                t = 100;
        end
    end
%phase 2
    if ((AHR<=89) || (AHL<=89) ) %limits
        for x = 1: 18462
            ToC = 1;
               switch m
                   case 1
                       v = (-0.0039*x)+89.0039;
                       t = 100;
                   case 2
                       v = (-0.0047*x)+92.0047;
                       t = 100;
                   case 3
                       v = (-2.7084e-04*x)+10.0003;
                       t = 100;
                   case 4
                       v =(-0.0039*x)+89.0039;
                       t = 100;
                   case 5
                       v = (-0.0047*x)+92.0047;
                       t = 100;
                   case 6
                       v = (-2.7084e-04*x)+10.0003;
                       t = 100;
               end
```

```
        end
    end

     if ((AKR<=17) || (AKL<=17))
        for x = 1:9800
            ToC = 1;
            switch m
                case 1
                    v = (17.0006)*(exp((-3.5545e-05)*x));
                    t = 90;
                case 2
                    v = (5.0002)*(exp((-5.2130e-05)*x));
                    t = 90;
                case 3
                    v = 2;
                    t = 100;
                case 4
                    v = (17.0006)*(exp((-3.5545e-05)*x));
                    t = 90;
                case 5
                    v = (5.0002)*(exp((-5.2130e-05)*x));
                    t = 90;
                case 6
                    v = 2;
                    t = 100;
            end
        end
     end
% %phase 4
     if ((AHR <= 11) ||(AHL <= 11))
            switch m
                 case 1
                     ToC = 1;
                     v = 5;
                     t = 100;
                case 2
                    ToC = 1;
                     v = 3;
                     t = 100;
                case 3
                    ToC = 1;
                    v = 0;
                    t = 100;
                case 4
                    ToC = 1;
                     v = 5;
                     t = 100;
                case 5
                    ToC = 1;
                     v = 3;
                     t = 100;
                case 6
                    ToC = 1;
                    v = 0;
                    t = 100;
            end
      end
```

```
end
%Choose which joint to send the order:
%1. HR 2.KR 3.AR 4.HL 5.KL 6.AL
m = m+1;
if m > 6
    m =1;
end
MID = m;
VALUE = v;
STIFF = t;
AUX = 0;
BUS = [MID ToC VALUE STIFF AUX enable];
```

A.4 Informed Consent document

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Barcelona Est

CONSENTIMIENTO INFORMADO

Respetado(a) señor(a) ______________________________________, por medio del presente documento le solicitamos su participación voluntaria en la realización de una prueba con el uso de un exoesqueleto robótico de miembros inferiores como parte de un proyecto investigativo de final de grado de Ingeniería biomédica que tiene como objetivo establecer una estrategia de control de un exoesqueleto para la acción de Sit-To-Stand. La fecha de aplicación de la prueba será el día ____ a las _____ en el laboratorio 204 del edificio K2M de la universidad politécnica de Cataluña (UPC) en compañía de los investigadores.

La información obtenida a partir de sus respuestas en la prueba tendrá un carácter eminentemente confidencial, de tal manera que su nombre no se hará público por ningún medio. De igual manera, podrá retirarse de la prueba en cualquier momento.

En consideración de lo anterior, agradecemos su participación en la realización de la prueba **(Si desea participar por favor marque sus datos personales en la parte inferior y firme en el espacio designado)**

Datos personales:

Edad	
Altura	
Peso	

En constancia firma,

____