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Development of a Prototype of a Biomechanical Device for Assessment of the “Sit-to-Stand” Movement

Project Report to fulfill the Master’s degree in Mechanical Engineering

Specialization in Construction and Maintenance of Mechanical Equipments

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RESUMO

A análise ao movimento “Sit-to-Stand” é importante na avaliação e definição de procedimentos de reabilitação de indivíduos que sofreram um Acidente Vascular Cerebral (AVC), apresentam Doença de Parkinson, possuem alguma imparidade nos membros inferiores, ou em pessoas idosas. Este trabalho teve como objetivo o desenvolvimento do protótipo de um dispositivo biomecânico, para ser usado na avaliação do movimento “Sit-to-Stand”.

O dispositivo incorpora um conjunto de componentes mecânicos com integração de células de cargas que permitem a quantificação da força aplicada pelos membros superiores na execução do movimento, assim como da força de preensão feita pelas mãos do utilizador. Complementarmente dispõe de uma plataforma para aquisição das forças exercidas pelos membros inferiores no decurso do movimento. Assim, o sistema permite a aquisição de um conjunto de variáveis associadas ao movimento, nomeadamente a força exercida pelo pé, força vertical exercida pelo membro superior e a força de preensão manual, tanto para o lado direito como para o esquerdo.

O dispositivo conta com um mecanismo de fixação especialmente desenvolvido para que o mesmo seja adaptável a qualquer andarilho e, com isso, torna-se um sistema portátil e de fácil adaptação em diferentes locais. Incorpora uma unidade de aquisição e controlo baseada no sistema Arduíno e tem uma interface com o utilizador desenvolvida em Excel, que garante a visualização e registo dos dados.

O dispositivo foi testado com um grupo de trinta e três voluntários jovens, saudáveis, tendo evidenciado o comportamento desejado, com a resistência e rigidez mecânica adequadas e permitindo a aquisição sincronizada das forças exercidas em função do tempo associado à execução do movimento.

Palavras-Chave: Levantar; Sentar; Biomecânica; Reabilitação; Biofeedback.

ABSTRACT

The analysis of the “Sit-to-Stand” movement is important in the assessment and definition of rehabilitation procedures for individuals who have suffered a stroke, have Parkinson’s Disease, have some impairment in the lower limbs, or elderly people. This project aimed the development a prototype of a biomechanical device, to be used in the “Sit-to-Stand” movement evaluation.

The device incorporates a set of mechanical components with the integration of load cells that allow quantifying the force applied by the upper limbs on the movement execution, such as the gripping force exerted by the subject’s hand. Complementarily disposes of two platforms to acquire the force applied by the lower limbs in the course of the movement. So, the system allows the acquisition of a set of parameters associated with the motion, namely the force exerted by the foot, the vertical force applied by the upper limbs, and the gripping force, both for the right and the left sides.

The device counts with a fastening mechanism specially developed allowing it to be attached to any walker and, with that, become a portable system with easy adaptation to different places. An acquisition and control unit based on the Arduino system is incorporated into the device and has a user interface developed in Excel, which ensures data visualization and recording.

A group of thirty-three young and healthy volunteers tested the device, evincing the desired behaviour, with the proper mechanical rigidity and resistance, allowing the synchronized acquisition of the forces exerted as a function of the time associated with the movement execution.

Keywords: Sit-to-Stand; Stand-to-Sit; Biomechanics; Rehabilitation; Biofeedback.

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List of Abbreviations

5TSTS	5 Times Sit-to-Stand
30sSTS	30 seconds Sit-to-Stand
ASHT	American Society of Hand Therapists
CAD	Computer-Aided Design
COM	Centre of Mass
DVR	Dominant Vertical Rising
ETF	Exaggerated Trunk Flexion
FEA	Finite Elements Analysis
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
MT	Momentum Transfer
STS	Sit-to-Stand
STSTS	Sit-to-Stand-to-Sit

1. Introduction

Nowadays, with the advance in technology and medicine, the average life expectancy around the world has increased and, consequently, difficulties brought by the advancing age entail changes to performing daily life activities of a person. For example, the manoeuvre Sit-to-Stand (STS) is a constant activity during the day. For healthy adults, this movement can be completed around 60 times in 24 hours (Frykberg & Häger, 2015). And the older the individual becomes, the more difficulty he will have to complete the STS movement, which can be considered a prerequisite for the maintenance of an independent life. The motion of rising from a chair and/or a bed can be an exercise demanding a great physical effort for the elderly and, even more, for people who suffer from an impairment, that can have a relation with the advanced age as, for example, stroke, Parkinson’s Disease, hip fracture, arthritis, sarcopenia, among other conditions (Bohannon, 2012).

As evidence, the study performed by (Nyberg & Gustafson, 1995) with patients in post-stroke rehabilitation analyzed the reasons for fallings, and the actions where the individual is transferring the body position are the reason in around 37% of the times that an individual falls, and the STS motion is one of these. Rising from a chair is one of the daily life activities which demands the most mechanical activity and requires coordination, balance, adequate mobility, and strength, therefore, there is a huge number of elderly who present trouble completing the STS manoeuvre (Aissaoui & Dansereau, 1999).

On behalf of this plight presented by the elderly, commercially, there are many devices aimed exactly to assist these individuals to complete the STS movement in the most independent way possible. It is possible to find walkers, devices to be attached to a chair or bed, and active equipment, that carry out a share of the patient’s movement, which can be tilting the seat and/or executing an auxiliary effort to the person’s body who needs help to complete the move.

As a supplementation for the STS test, which is important to indicate the lower limbs’ muscle activity, grip strength is a parameter used to evaluate the upper limbs’ muscle activity. The grip strength, many times, has a direct relation to the overall muscle activity of a person (Rodacki et al., 2020). Thus, the grip strength assessment is a parameter largely used for the rehabilitation process and in clinical situations (Mahadi et al., 2021).

Besides the use of the gripping force for rehabilitation and clinical settings, the evaluation of the grip strength is also quite useful for sportive analysis, allowing to identify the physical profile in several athletic activities, such as table tennis, volleyball, judo, heavy lifting, among other sports (Fernandes & Marins, 2011).

The grip strength measurement is directly related to the age of the person, studies showed that the average gripping force starts to decrease when the patient is around 32 years old, and this data can provide interesting information about muscle activity reduction for the elderly (Ramos, 2009).

1.1 Motivation

During rehabilitation of people who suffer from impairment in the lower limbs or patients with sarcopenia, Parkinson's Disease, hip fracture, stroke, or, even though, elderly in general, the STS test is widely used to assess the muscular or motor capacity of the individual. According to its value, several studies and equipment are directed to analyse this manoeuvre. In the majority, the STS movement screening is carried out with the individual not allowed to use the arm to boost the motion. Also, the most applied tests are the ones in which time is the main parameter to assess. It presents a good analysis of the lower limbs' muscle activity and is more affordable, whereas having a chair and a stopwatch is already enough to realize the STS test.

So, this project has as motivation, the development of a prototype which can become a powerful tool for rehabilitation processes, acquiring the data of the force applied through different parts of the patient's body. Create a device which can be applied to a walker, which is a common instrument for patients with lower limbs impairments is another aim of the project. Furthermore, provide a biofeedback for the patient is one more focus of this device, in a way that the results of a rehabilitation procedure can be improved.

This project has a few research lines, pursuing to provide a detailed assessment of the Sit-to-Stand movement. The analysis realized by this prototype which was developed can be segmented into three headings: upper limbs' assistance, gripping force, and lower limbs' forces. Moreover, an important aspect is that the assessment is made separately for the left and right sides of the person's body for all the abovementioned three segments.

The first point of the prototype is the affordance of collecting data on the vertical force exerted by the upper limbs during the STS test. With this mensuration during the manoeuvre, it is attainable to evaluate the assistance needed by the individual to complete the task. Therefore, a certain awareness of the degree of difficulty of the person can be noted.

A ground-breaking point of this project according to the Sit-to-Stand test is the gripping force of data acquisition. So, it is expected that with this measurement during the motion it will be achievable to get a picture of the insecurity level of the person during the STS movement.

At last, the lower limbs’ force can be important to provide a full overview of the STS test. With this data, it is possible to know the end of the motion and also the amount of body weight being carried through each leg over the manoeuvre.

Thereupon, with these three ways of STS assessment, it is permitted to raise questions that can be observed and discussed with the tests undertaken with the developed prototype:

- Is there a pattern in the ratio of the upper limbs assistance during the STS movement compared to the overall body weight of the person?
- How are the development of the vertical upper limbs force and the gripping force? Do they grow proportionally? In other words, does the gripping force raise at the same rate as the vertical upper limbs force?

After the validation and some studies done with different groups of patients, other questions related to the instability and how an impairment can affect the manner that the individual applies the force on the prototype during the Sit-to-Stand movement. Some possible topics to analyse are:

- Is it possible to link specific asymmetric forces to specific impairments?
- Is it possible to connect early tendencies of asymmetry to upcoming impairments?
- Do people with the STS movement more unstable exert a higher gripping force during the motion? If so, which reasons can be deducted: Compensatory force? Psychological assistance? Longer movements require higher gripping force?

1.2 Report Structure

The current report contains seven main chapters. In chapter 1, a short introduction, with a contextualization and the motivation for this project, was made. Subsequently, in chapter 2, the literature review about the STS movement and the gripping is presented. Also, some currently available apparatuses were listed. Hereupon, the prototype development steps with its validation protocols were presented, in chapter 3. The data of the volunteers is displayed in the next chapter and, afterwards, in chapter 6, there is an analysis of the results, with comparisons and evaluation of the results obtained. In the end, the author presents the conclusions and recommendations for future studies, in chapter 7.

2. Sit-to-Stand / Stand-to-Sit – Literature Review

Before trying to answer questions related to this hugely performed movement during the day in adult life, an understanding of what is involved in the manoeuvre and its assessment is needed. So, this chapter provides information about the biomechanics of the movement, the STS tests existents and the parameters involved in these tests, and also the factors which influence an individual to conclude the motion successfully.

2.1 Biomechanics of STS Movement

To describe the STS motion, studies define phases to analyze the position changes. Although, different definitions are found in the literature. In (Alexander et al., 1991) the simplest way to characterize the motion is described. It divides the movement into two phases, phase 1 is described from the initial position of the body until the maximal head forward displacement, and this moment is practically coincidence with the seat-off instant, and phase 2 is started from the end of phase 1 to the moment when the individual completes the movement. Figure 2.1 illustrates both phases.

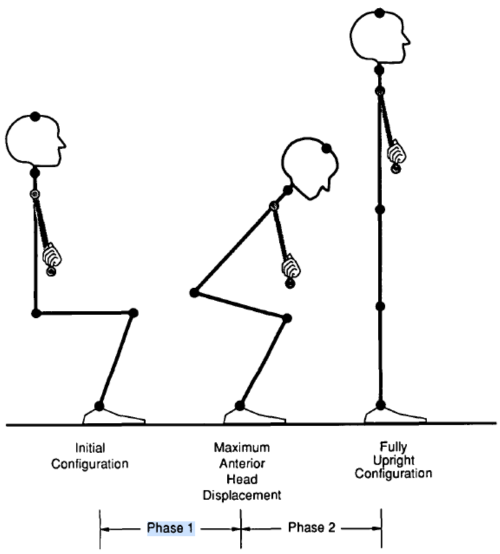


Figure 2.1: STS movement divided into two phases. (Alexander et al., 1991).

Differently from the paper previously described, another investigation done by (Galli et al., 2008) divided the STS motion into three phases: preparation phase (1), ascension phase (2), and stabilization phase (3). During phase 1, the individual is preparing oneself to rise from the chair and this phase's time is from the instant in which the patient starts the movement, tilting the trunk forward and the contact between the feet and the floor is reduced, until the seat-off moment, occurring a position change. In phase 2, starting after the seat-off, the vertical acceleration is converted to deceleration and this phase ends when the person stands up completely. Phase 3 corresponds to the time that the individual needs to stabilize in the standing position and this phase is over when the person is stabilized. Figure 2.2 represents these phases.

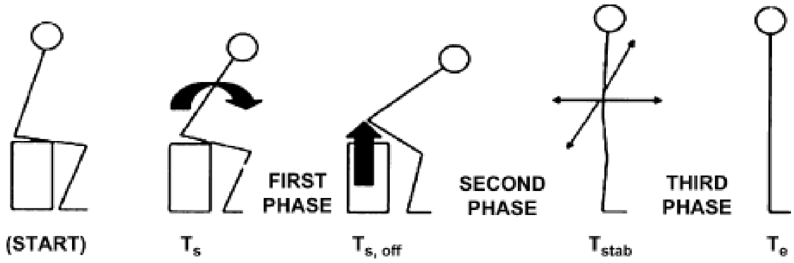


Figure 2.2: STS movement divided into three phases. (Galli et al., 2008).

Lastly, another way to classify the STS movement divide the motion into four phases and this is the most used classification according to the literature. These phases were defined by (Schaknzan et al., 1990) on the following approach: Flexion momentum (phase 1), momentum transfer (phase 2), extension (phase 3), and stabilization (phase 4). Phase 1 initiates with the first movements from the patient and terminates soon after the seat-off instant. Subsequently, phase 2 starts and it is over when the ankle dorsiflexion is maximal. Phase 3 is described from the end of phase 2 up to the hip reaching the maximal extension during the position transfer. To finalize, phase 4 takes part from the end of phase 3 until the individual concludes the stabilization process. These 4 phases are schematically characterized by Figure 2.3.

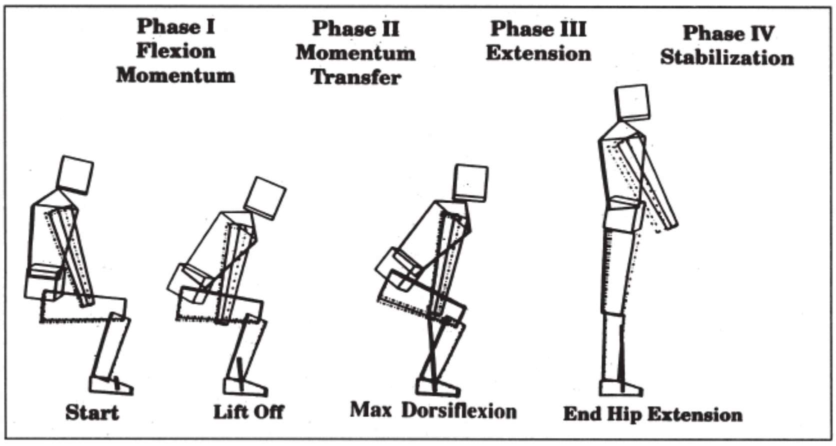


Figure 2.3: STS movement divided into four phases. (Schaknzan et al., 1990).

Another way to depict STS movement is in terms of the strategy assumed by the individual to complete the motion. According to (Scarborough et al., 2007), three different strategies adopted by the patient are described, Momentum Transfer (MT), Exaggerated Trunk Flexion (ETF), and Dominant Vertical Rising (DVR). MT strategy relies on the back and the hip extension simultaneously after the seat-off moment. The ETF strategy is described as excessive trunk extension during most of the position transfer. And, in the DVR strategy, the patients present smaller trunk extensions, and the rising movement is performed mostly in the vertical direction. An illustration of each of the strategies is presented in Figure 2.4.

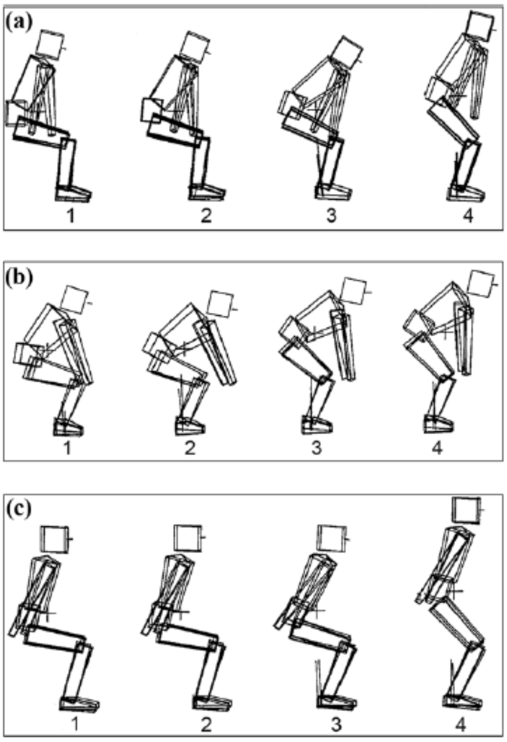


Figure 2.4: Illustration of the three possible strategies adopted to complete the STS movement. a) MT strategy; b) ETF strategy; c) DVR strategy. (Scarborough et al., 2007).

2.2 STS Tests

As it was mentioned before, the STS movement is repeated many times during the day and can be considered a prerequisite for an independent daily life. For this reason, STS tests are widely employed to assess the patient’s lower limb muscle activity. This analysis has great importance during the rehabilitation process, once pre-sarcopenia or muscular frailty is identified, physical exercises facing this impairment can be developed and, therefore, the pre-established clinical picture can be discontinued or, even though, reverted (Shukla et al., 2020).

Among documented STS tests, it is possible to highlight two different directions: the tests which have time as the main parameter and the tests in which the forces and angles measurement is the main parameter.

2.2.1 Temporal Tests

The most extensively used STS test is known as “5 Times Sit-to-Stand” (5TSTS), which consists of the patient being asked to stand up from a chair and sit down 5 times as fast as possible and with the arms crossed around the chest, avoiding, in this way, the upper limbs’ assistance to complete the motion. So, the time that the individual needs to complete these 5 cycles are recorded as the test result, in other words, the stopwatch starts when the test instructor gives the command to initiate the test and it stops when the individual touches the chair in the fifth cycle. With the data from this test, longer times to complete the test are associated with a bigger deficit of muscle activity and a handicap of balance (Whitney et al., 2005).

Another well-known test is the “30 seconds Sit-to-Stand'' (30sSTS), in which the patient is asked by the test instructor, like in the 5TSTS, to stand up from the chair and sit down as fast as possible with the arms crossed around the chest. Also, the person is asked to stand up and sit down completely in each of the repetitions. So, differently from the previous test, the individual has 30 seconds to complete as many as possible cycles and, during this period, the instructor counts, noiselessly, how many cycles of the movement were completed. Therefore, the 30sSTS test result is the number of repetitions completed by the patient for 30 seconds (Jones et al., 1999).

The necessary equipment to do these tests above is a great advantage once the rehabilitation professional needs just one chair and a stopwatch to do the test. And, even without sophisticated equipment, the professional gets a useful parameter for the rehabilitation process and, in case the test is done regularly, feedback for the rehabilitation process is easily obtained.

2.2.2 Timeless

Other ways to do STS tests are those which measure different parameters, and time is not the only element considered to analyze the STS movement. And, among this test range, there is a variety of instructions to do the movement, being possible, inclusive, to use the upper limbs to assist the position transfer, with the free arm movement or using the arms to carry out a percentage of the body weight, reducing the effort required on the person’s lower limbs.

The most used method to analyze the STS movement, not considering the time as the main parameter, is the usage of force platforms, which is equipment commercially available and provides thorough data about the feet’ action over the platform. The force platforms can present the result in a graphic with the vertical force applied through the feet on the platform in the function of the motion time, the peak force, and the centre of pressure of the patient. For that reason, there is a considerable number of papers related to the STS movement using this device to make the assessment.

According to the level of demand stipulated through the experiment being developed, the number of force plates can vary. Studies conducted using two force platforms (Cheng et al., 2001); (Cheng et al., 1998)(Lindemann et al., 2003) (Talis et al., 2008) present the data related to each of the lower limbs separately, enabling the movement asymmetry's assessment during the motion, throughout the exerted force by each of the feet and the centre of pressure sway. (Malouin et al., 2009) carried out a study with three force plates, one under each foot and one under the chair, in addition to the same data as the previous studies, also presents huge accuracy related to the motion time. Once the movement period starts when the vertical force on the platform under the chair varies and it ends when the centre of mass from the individual turns up stable again.

In the investigation completed by (Kneiss et al., 2012), the STS movement data is presented in an even more detailed manner, using four force platforms. One under each foot, one under the chair, and another one under the individual buttocks. In this way, with the force difference between the force platform under the chair and the one under the buttocks, it is possible to measure the arm's action during the STS motion, and how much it assisted the patient to complete the manoeuvre successfully.

Another way to quantify the force exerted by the feet on the ground during the STS movement is replacing the commercial force platform with a force platform built with a load cell, in which the measurement device is fixed in the centre of the plate that the patient places the feet, in a way that the distance between the load cell and each one of the feet is approximately the same (Fleming et al., 1991). One alternative found was the use of a 'Nintendo® Wii Balance Board', which is nothing more than a rigid platform with four strain gauges to assess the vertical force applied on the platform. Consequently, in this study realized by (Yamako et al., 2017), the 'Nintendo® Wii Balance Board' was used to measure the lower limb force that the individual exerts during the STS motion and the centre of pressure.

When the aim is to measure the force applied by the upper limbs, the most widely used instrument is the strain gauge, which is fixed and attached to the bar that is used as support for the patient to stand up from the chair. The strain gauge measures the bar deformation when a force is applied to the bar through the filament resistance variation. After the calibration to convert the results from Volts to Newtons, it is possible to determine the force which is being applied over the instrumented bars.

For example, the aim of the study carried out by (Taghvaei et al., 2017) was to build a device that assisted the patient to stand up, and strain gauges were used to assess the upper limbs force exerted during the STS movement.

Combining the strain gauges with the force platforms, some studies present results analyzing not only the lower limbs' strength but also the strength of the upper limbs. And, thus, these studies present results comparing the force applied by the legs and by the arms in different situations, which can be with the armrest and/or the chair highs varying (Turner et al., 2004) or with the order by the instructor to apply a bigger force through the upper limbs (Bahrami et al., 2000).

A distinct manner to evaluate the STS movement consists of the use of sensors that provide information about the speed, acceleration, joint angles, and displacements. There is even the possibility of combining the parameters, for example, using an accelerometer during the "5TSTS" and "30sSTS" tests (Tulipani et al., 2020). Collecting the data from different sensors, like triaxial accelerometer and electric goniometer, which provide data related to the acceleration in 3 dimensions and the angular displacement of a joint, is one more possibility for an STS test (Kerr et al., 1997).

Pursuing a more complete assessment, a device called 'Inertial Measurement Unit' (IMU) is composed of an accelerometer, gyroscope, and, sometimes, magnetometer, and it is also used to analyze the STS movement (Martinez-Hernandez et al., 2019). IMUs can provide data such as angular velocity and motion time, they are portable and can be attached to the patient's body. Figure 2.5 shows how an IMU can be attached to the person during the STS manoeuvre.

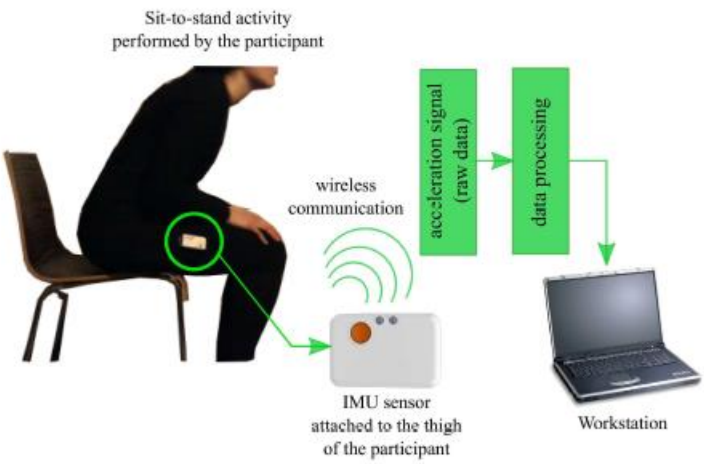
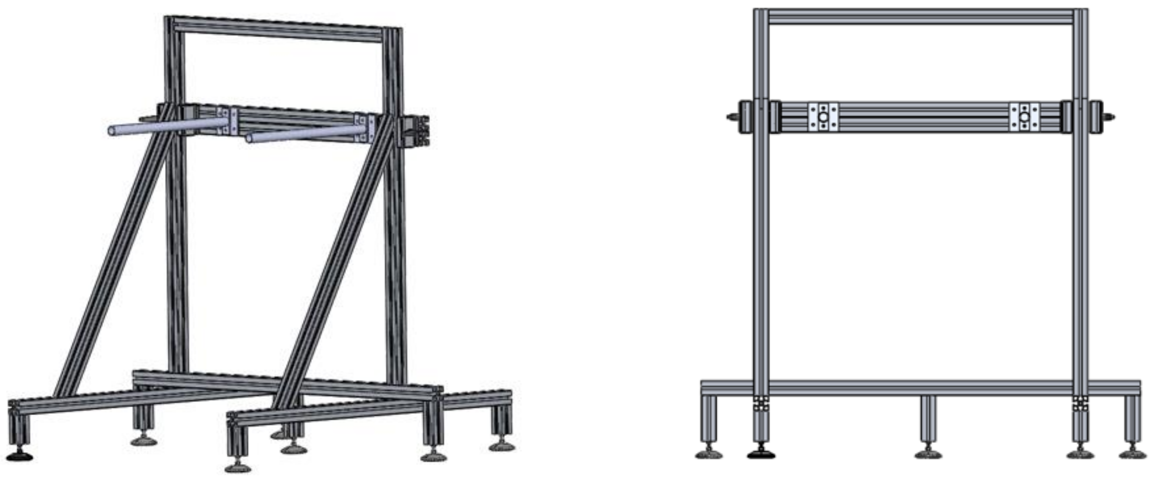


Figure 2.5: IMU sensor attached to the individual's body. (Martinez-Hernandez et al., 2019).

Another approach takes into consideration the evaluation with video systems, being possible to combine with other assessment methods. Usually, in video analysis, colourful markers are attached to evaluation points on the patient's body, to facilitate the movement analysis posteriorly. Studies are combining visual analysis and temporal movement, using a recording system and a stopwatch (Omura et al., 2001). One more possible combination for a video system is with force platforms and, in this way, beyond obtaining the data related to the effort deployed through the limbs, it is achievable to analyze the strategy adopted to perform the movement (Galli et al., 2008).

One more option is a system to monitor, through electromyography, the individual's muscle activity during the STS motion. In studies that embrace this evaluation method, normally, lower limbs’ muscle activity data is collected. The study realized by (Schin et al., 2012) assesses the muscular activity of a few muscles during the STS movement with the chair in different inclinations, relating the muscle activity to the motion time. And (Ferrante et el., 2005) assess the muscular activity of different lower limbs’ muscles and relate it to the use or not of the arms during the position transfer.

At last, one more study by (Oliveira, 2021), which was also developed at Coimbra Engineering University (ISEC) built up a structure to be positioned in front or at the back of a chair. This structure has two beams used as a support for the subject to do the Sit-to-Stand movement. This beam received four strain gauges, in a way that measures the vertical force applied by the individuals when the test is done. With this device, the upper limbs’ assistance can be assessed separately for the right and the left side. Figure 2.6 shows the design developed on this study.



a) b)

Figure 2.6: Device developed for the assessment of the upper limbs’ assistance. a) Isometric view. b) Front view. (Oliveira, 2021).

2.3 Determinants of STS test

To organize an STS test, there are many aspects to take into consideration that can influence the measurement at the end of the experiment. Although, there is not a widely used standardization, with studies assuming different parameters. Besides the point of a pre-established standardization, the test can vary itself, allowing or not the upper limbs assistance, differing the seat and/or armrest highs, the initial position of the patient, the motion speed, inter alia other options of adaptability and availability.

2.3.1 Speed

To describe the effect of the speed during the STS movement, (Carr et al., 2002) determined that the individual completes the position transfer at three different speeds: as fast as possible, as slow as possible, and the natural speed. The initial positions of the patients were standardized. This study obtained results that show that the manoeuvre speed can interfere with the performance and the movement analysis, generating basic changes in the pattern of the motion. When the movement is done as fast as possible, the hip flexion amplitude is smaller, and the hip and knee start the motion practically simultaneously. The same did not occur with the movement completed with the natural speed, in which the hip extension happened before the knee extension. And, in addition, when the manoeuvre is made as slowly as possible, the period that the individual generated a high level of support force was considerably longer, as an effect of the trunk speed reduction, increasing the upper limb force exerted.

2.3.2 Body Position

One element that can result in different results during the STS movement assessment and/or make the individual opt for a distinct strategy is the body position. And, on behalf of this, few studies analyze this regard, demonstrating the differentiation existent from case to case.

In the study developed by (Duclos et al., 2008), the participants were oriented to do the STS movement with two different positions for the feet. One position is spontaneous and the other one is called asymmetric, in which the non-affected foot side, for the people who are in the post-stroke rehabilitation process, is placed slightly ahead of the other foot, and the same happens for the control group when the non-dominant foot side is also placed slightly ahead than the other foot. For the individuals in the post-stroke rehabilitation process, when the non-affected foot is ahead, there was a predisposition toward the use of the affected side of the body, providing, in this way, greater symmetry during STS movement.

Another analysis made by (Fleckenstein et al., 1988) is according to the individual's initial position exposed in another study, in which the patients complete the STS movement with the knees initially flexed at 75° and then at 105°, and these different placements, automatically, generate changes in the person's foot position. As an assessment of this incorporated pattern, the hip extension momentum, and the impulses necessary were considerably greater when the knee flexion was smaller (75°). One more point to be analyzed in this study is the adopted strategy during the STS motion, which had the trunk and arms inclination more significant when the manoeuvre was done with the knee less flexed. In Figure 2.7, a comparison of the used strategy in each of the chosen positions can be evidenced.

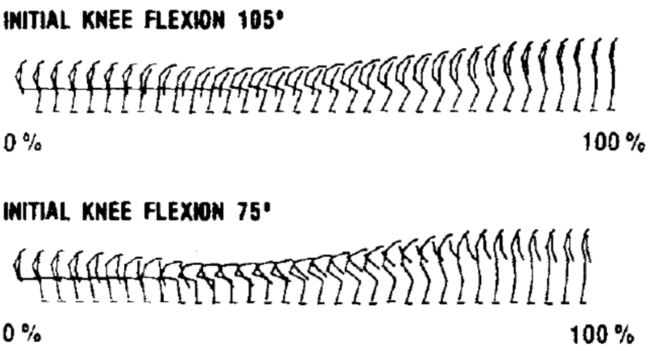


Figure 2.7: Strategies adopted with both initial knee flexion. (Fleckenstein et al., 1988).

2.3.3 Chair Parameters

Chair inclination and high, armrest and backrest presence or not, chair model and armrest high are chair parameters, which are the main apparatus for STS tests, and can vary among the studies undertaken. And, with the parameters variation, the obtained results also can be different, being some parameters more important than others.

As it was discussed by (Schin et al., 2012), an experiment for the STS test using a chair with three different inclinations, 15° and 0° at the front part and 15° at the back part. With these slopes’ possibilities, using electromyography, the individual’s muscle activity and motion time were measured for each of the situations achievable. The longest motion time happened when the chair was inclined at the back and the fastest transition was when the front side was inclined. The same pattern can be observed for the muscular activation time for the test variations, where a muscular activation during a higher period of the movement can be observed when the chair was inclined at the back and the inverse happened for the chair with a front inclination.

An important parameter for the STS movement is the chair height, which generates significant changes in the achieved results. One study analyzing the movement with the chair at six different heights (10, 20, 30, 40, 50, and 60 cm) assesses the movement with a 3D video system and the use of force platforms. According to the motion time, there is a meaningful reduction under the raise of the chair high. In this experiment, with the chair 10 cm high (lowest point) the motion time was around 2.2 s and the time was approximately 1.5 s for the uppermost position (60 cm). And, in terms of the mechanical effort during the position transfer, which is obtained by adding the hip and knee movement, there is no considerable change between 10 and 30 cm, although, there is a great effort reduction when the manoeuvre is performed with the chair between 40 and 60 cm, with the minimum effort required when the chair was in the maximum height (Yoshioka et al., 2014).

2.3.4 Arm use

Among the influencing factors for the STS movement, the use of the armrests is the most beneficial for the individual's performance and, consequently, there are more studies about the use or not of the arms than any other parameter involved in the STS manoeuvre. There are studies relating just the fact that the arms have movement constrained, but not assisting the patient to stand up from the chair, however, the most frequent studies presented are according to the assessment of the upper limbs' effort done as assistance for the STS movement.

In studies analyzing the arm assistance, two of them measured the percentage of the body weight carried by the upper limbs during the STS motion. In one of the studies, the experiment counted three groups. The groups consisted of Young, Old Able, and Old Unable, formed by the elderly who presented difficulty standing up from the chair. And, as a result of this study, the percentage of body weight carried by the hand and the motion time for the Old Unable Group was considerably bigger than the other groups (Alexander et al., 1991), as is seen in Figure 2.8. And this result shows the importance of arm use for those who have some difficulty standing up or impairment in the lower limbs.

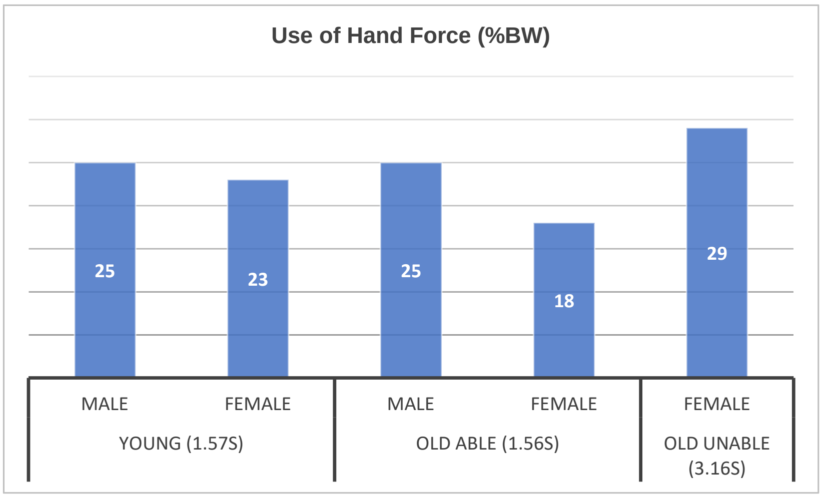


Figure 2.8: Upper limbs' assistance during the STS movement. Adapted from (Alexander et al., 1991).

An investigation was developed by (Turner et al., 2004) analyzing upper limbs' assistance, in addition to comparing the use of the arms with different armrest heights, which showed that each upper limb, on average, carried between 20 and 30% of the individual's body weight. And even the armrest is high ranging from 140 mm to 300 mm, the upper limbs assistance is kept inside the percentage range mentioned above. In Figure 2.9, it is possible to observe the body weight distribution of the patient during the STS movement.

A distinct approach for the arms use, with the individual completing the STS manoeuvre with the arm used in three different ways: with the arms crossed around the chest (in other words, without upper limbs assistance), with normal upper limbs assistance, and with a strong arm-support. For the experiment carried out by (Bahrami et al., 2000), a force platform was used to measure the ground reaction forces and calculate the centre of pressure, and bars instrumented with strain gauges were used to assess the upper limbs' assistance. One important finding in this study was that the time needed to complete the STS movement was slightly longer when the patients used the normal arm support and considerably longer when the strong-arm support was used. But, on the other hand, the peak of the vertical ground reaction for the movement without arm support was 113% of the body weight, with normal arm support this value was 104%, and with strong-arm support, the measured percentage was 68%. This assessment according to the peak vertical ground reaction forces shows that the arm, automatically, shares the dynamics of the movement with the lower limbs, demanding less power for the patient's legs.

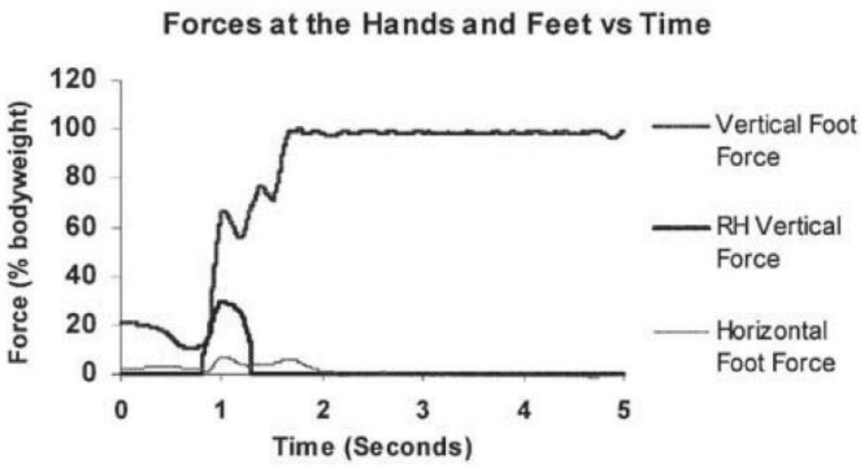


Figure 2.9: Body weight distribution during the STS movement. (Turner et l., 2004).

2.4 Influencing Factors for STS Movement

Apart from the factors cited above, related to chair parameters and strategy adopted by the patient to complete the movement, there are elements associated with the individual's capability to complete daily life activities.

A study by (Itoh et al., 2012) compared the control group, with healthy subjects, to a group composed of patients with hemiplegia. Also, the hemiplegic individuals were separated between right and left hemiplegia. Two of the few assessments realized in this study were the duration and the symmetry of the movement. Their results showed that left hemiplegic subjects need a longer time to complete the manoeuvre (2.42 $\pm$ 0.91 s for patients with right hemiplegia and 2.66 $\pm$ 0.31 s for patients with left hemiplegia) than the right hemiplegic individuals and the control group (1.83 $\pm$ 0.38 s).

As was demonstrated by (Whitney et al., 2005), in a study developed with the 5TSTS test and comparing the results obtained with healthy subjects (control group) and subjects with balance or vestibular disorders. The results achieved showed that older individuals required a longer time for the test than younger ones. And, when collating both groups in the study, people with vestibular or balance disorders completely the task with a noticeably longer lifespan than the control group. Also, it is possible to mention that healthy old individuals needed a similar period as young people with vestibular or balance disorders.

It was shown by (Frykberg et al., 2015) that patients who had a stroke, presented a reduced weight-bearing during the STS manoeuvre, obtaining around 37.5% of weight-bearing on the affected side. In addition, a decrease in force production can be noticed due to the extended period to complete the motion and, in contrast, the non-paretic leg exerts an excessive effort.

The study by (Frykberg et al., 2015) also analysed how the STS transfer happens for individuals with Parkinson's Disease. This group usually adopted a strategy with more displacement in the Centre of Mass (COM), which can be understood by the necessity of improved postural stability during the lift-off moment. The time that people with Parkinson's Disease need to complete the STS movement is sizably longer than healthy subjects need to do the same task.

The study done by (Kneiss et al., 2012) compared two groups of elderly, the control one and the group with people who had recovered from a hip fracture. It was outlined that the post-hip fracture group presented smaller symmetry and the affected lower limb side plied between 25% and 30% less strength than the non-affected one, as it is possible to notice in Figure 2.10. This research also showed that, for these individuals who had suffered a hip fracture, the upper extremity aid did not improve considerably the movement symmetry.

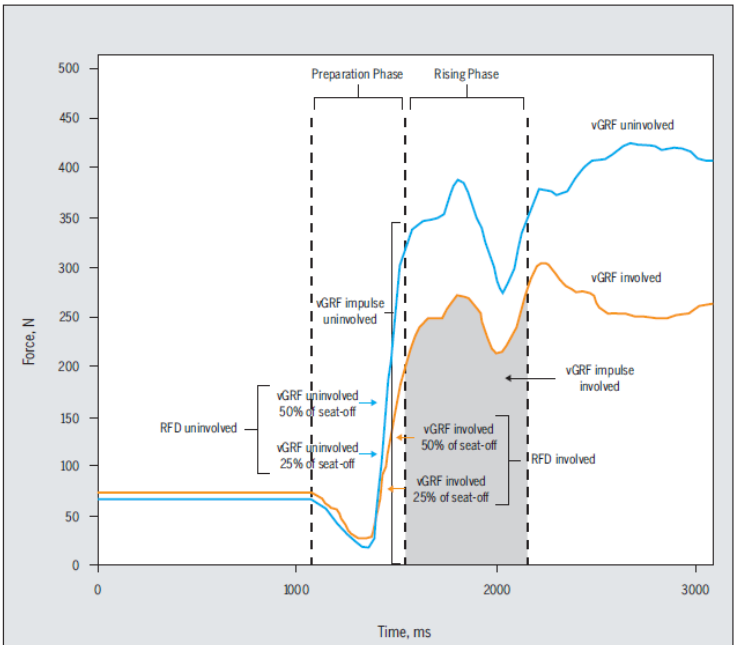


Figure 2.10: Asymmetry on the lower limbs force between the affected and non-affected side. (Kneiss et al., 2012).

The relation to the capability to complete the STS movement with the age was explored by (Yamako et al., 2017). In this study, a scoring system for speed and balance for the STS motion was developed and the individuals were divided by age. Analysing the speed score from the participants, it is possible to detect a significant depletion in the groups for the people from 60 years old and the score is lower as the groups become older. And, for the balance score, it is possible to notice the reduction in the groups from 40 years old and the scores keep reducing also with the age of the participants.

So, it is notorious that physical abilities can be directly related to how the individuals concluded the STS manoeuvre. In line with the drop in motor and/or physical abilities, the results obtained during the STS tests will also indicate an amendment. Thereupon, the employment of these tests as biofeedback for assessing physical loss due to advancing age or monitoring the development of the patient in a rehabilitation process can be an interesting tool.

2.5 Grip Strength

Another widely used way to evaluate muscle activity is the assessment of the gripping force. As in the Sit-to-Stand movement, the hand force from one person can bring multiple insights concerned with their motor function. And also, the functions of the hand are extremely significant for daily life, once severe – or even mild- hand injuries affect the routine of a person (Ryu et al., 2010).

According to (Hamilton et al., 1992), gripping strength is a precise and credible assessment for the use of therapists to analyse the development of rehabilitation processes following injuries or surgeries on the hand and the upper extremity. Moreover, (Newman et al., 1984) write that gripping strength is the most trustful evaluation of human strength, being a statement of the physical aptitude of a human and it even can have a straight relation to the total body strength.

With the advancing age, a way to diagnose Sarcopenia is with the acknowledgement of muscle loss, which can be assessed through the gripping strength measurement or tests with body movement (STS, for example). So, the hand force examination is largely used and recommended, once it has an easy implementation and provides a good prognosis of muscle depreciation (Luo et al., 2019).

2.6 Grip Strength Test

According to the American Society of Hand Therapists (ASHT), the standard position for the grip strength test consists of the individual needs to be comfortably seated, put the shoulder lightly forward, the elbow in a 90° position, the forearm in a neutral position, and the wrist can vary between 0° and 30° in extension (Fess et al., 1981). And the use of the handle in the second position is recommended. In Figure 2.11, a schematic explanation can be observed.

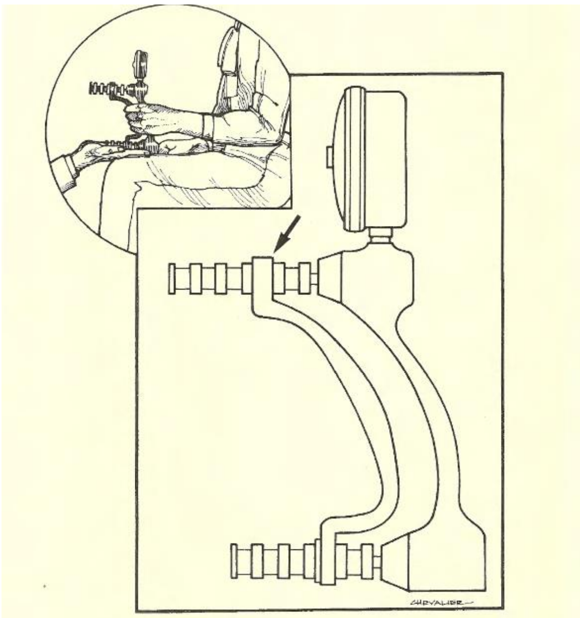


Figure 2.11: Individual's position for the grip strength test recommended by the ASHT. (Fess et al., 1981).

A study by (Fernandes et al., 2011) expounds that for the measurement for the grip force test is asked to the patient contract the hand as much as possible and the assessment is made taking the value of 3 seconds of maximal contraction. This period is advised because a longer time could generate an increasement in the blood pressure and the heart rate of the person, hence the possibility to bring some risk to a portion of society.

The device which enables the assessment of hand force is called dynamometer. And, the most broadly employed device is the Jamar® dynamometer due to its useability and reliability. Therefore, the big majority of the tests use the Jamar® dynamometer as it is seen in the study elaborated by (El-Sais et al., 2014)

An alternative for the Jamar® dynamometer is the implementation of a load cell to the handle. The “S” shape load cell can be observed in two different ways in the literature. The first of them was developed by (Kudrna et al., 2017) and it is the load cell being the gripping apparatus, with an anatomical coating attached to both sides of the measurement device, as it is shown in Figure 2.12. However, this device seems to be not so comfortable for the person exerting the strength to measure the gripping force, once it presents a rigid structure and its size seems bigger than the anatomical diameter for the gripping strength test.

Figure 2.12: Gripping force device with an "S" shape load cell. (Kudrna et al., 2017).

Meanwhile, (Barbosa et al., 2015) used a different “S” type load cell to build up a new device to measure hand force. For this mechanism, a special handle was produced to attach the load cell and allow the assessment of the gripping force. Nonetheless, the way that the handle was attached to the load cell does not allow the force transducer to measure the load correctly, once, for the “S” shape load cell, the load needs to be applied on its extremities, compressing or pulling. Figure 2.13 shows this new device manufactured.

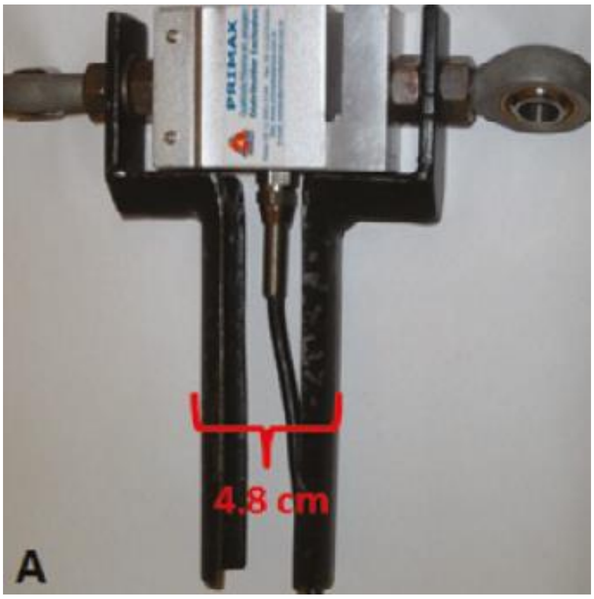


Figure 2.13: Developed device with an "S" shape load cell. (Barbosa et al., 2015).

With a similar way of data acquisition, there are a few devices developed with the use of strain gauges, which is also the transducer located in the load cells. This way of hand dynamometer development, the most simple one relies on a “U” shape structure with two strain gauges attached to one of the sides of the structure and it was designed by (Newman et al., 1984). Like that, the deformation generated by the hand of the person deforms the “U” structure and, consequently, the strain gauges’ filament varies, allowing the measurement to be done.

Another device using strain gauges was designed by (Chadwick et al., 2001) and it has a great advantage to its purpose, once it can assess the force in different directions on the handle. This apparatus consists of six active beams, assembled as cantilevers on a hexagonal core. So, the greatest point of this hand dynamometer is the fact that it is possible to analyse the distribution of grip around the person’s hand. Figure 2.14 presents this mechanism.

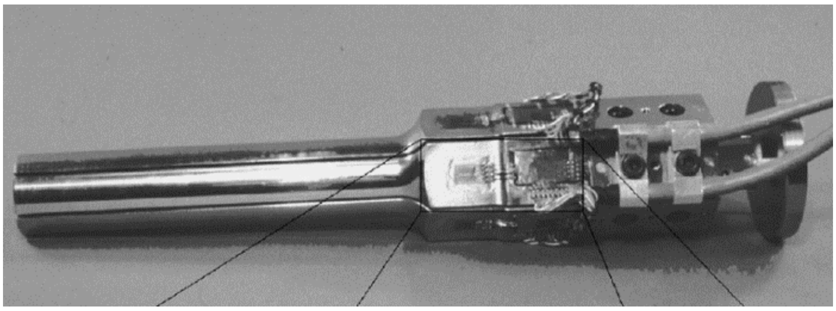


Figure 2.14: Dynamometer with six active beams. (Chadwick et al., 2001).

Another workaround to measure the gripping force was created by (Makino et al., 2018) with a dynamometer that assesses the grip force of each finger. To build this device, the grip part of a hand dynamometer was replaced by four pressure sensors, one for each finger which grabs the handle. However, the rest of the structure was maintained, and, in this way, it is possible to measure the force of each finger and also the grip force as the original gadget can do. Figure 2.15 shows how this new component works.

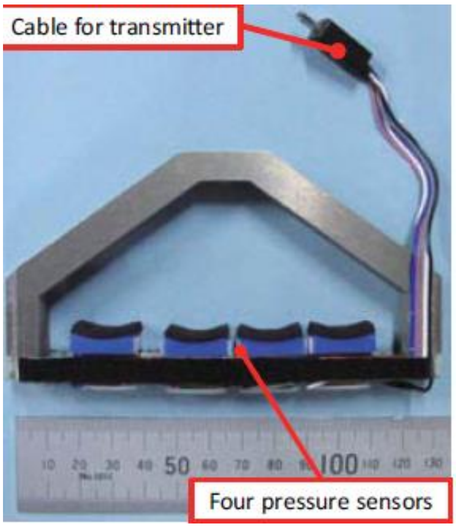


Figure 2.15: Hand dynamometer with a pressure sensor for each finger. (Makino et al., 2018).

Among the existent commercial hand dynamometers, such as the Jamar® that was mentioned above, there is the Electronic Hand Dynamometer, which is shown in Figure 2.16. This device was used to measure the volunteer's maximal gripping strength before the STS test was done. In this way, it was collected one more data about the health of the volunteer and, if necessary, compare to the results obtained on the test.

Figure 2.16: Electronic Hand Dynamometer.

2.7 Influencing Factors for Grip Strength

One neat factor that considerably influences the data acquisition on a gripping strength test is the position whereby the patient stands. Therefore, to analyse how much this element affects the gripping strength test, (El-Sais et al., 2014) elaborated on a study where the hand strength of the volunteers was measured in different positions with a Jamar® dynamometer. For this study, the individual should apply the maximal gripping strength in five different positions: sitting, supine, prone, side-laying, and standing.

The measurements show that the person's highest hand force is while standing (approximately 45.5 N), with a not great difference from the sitting position (approximately 43.5 N). However, when the force applied on the standing position is compared to the prone position (approximately 40.5 N), it is possible to observe a considerable divergence.

Age is an aspect with a strong influence on the person's gripping strength. And, it is exhibited by (Massy-Westropp et al., 2011) that in the age group between 60 and 69 years old, the hand force application capability decreases notably, exposing that the muscular loss due to ageing has an impact on this test. One more point analysed in this study is the grip strength difference on account of gender, whereon men have substantially more gripping strength than women. And, it does not matter the gender, the effect of ageing is noticeable in the data from both groups, as it is possible to verify in Figure 2.17.

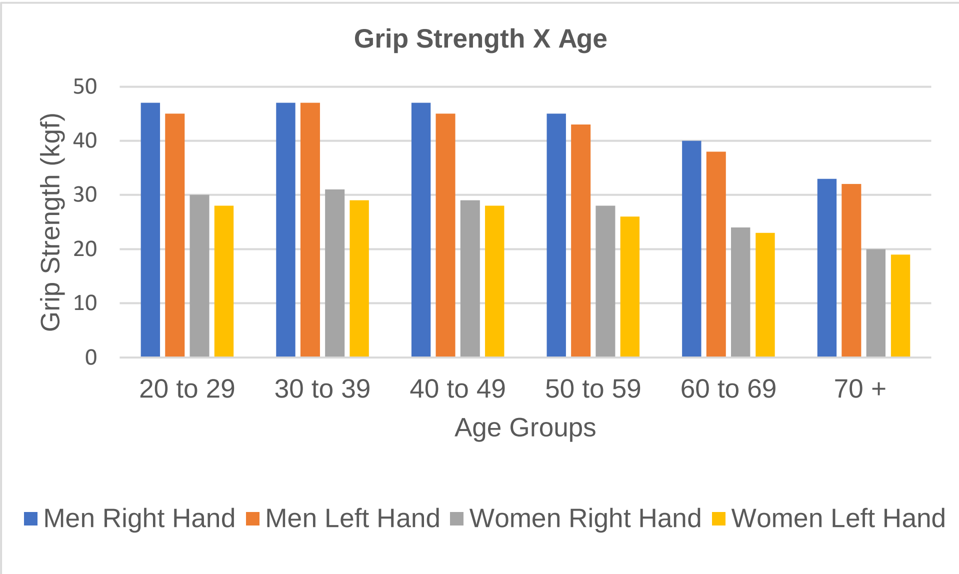


Figure 2.17: 'Grip Strength x Age' for the gripping strength test. Adapted from (Massy-Westropp et al., 2011).

A study performed by (Stock et al., 2019) compared the grip strength on the affected side to the non-affected side during the first year of stroke rehabilitation. In the first weeks, the hand force of the affected side is extremely lower than the non-affected one. However, the recovery of the affected side is acute in the first six months (week 2 to week 28), once the discrepancy between the affected and non-affected sides reduced, on average, from 197 N to 112 N. And in the second half of the analysis (week 28 to week 54), the progress made was slower, and the difference from the sides reduced, on average, from 112 N to 72 N. Through the data acquired in this study, it is possible to observe that the gripping force is extremely influenced on the affected side after a stroke and it presents progress with the rehabilitation program, but even after one year, it shows an important difference when it is compared to the non-affected side.

3. Prototype Development

In this chapter, the whole concept of the project will be described and analysed. The first point will be the design concept, with the alterations that occurred during the project. Then, the entire conception will be detailed, and it is separated through the three fields of measurement which belong to this prototype: lower and upper limbs' vertical force and gripping force. And lastly, an explanation of the calibration method adopted for the load cells is provided, followed by the load cells connection guide and the software instruction guide.

Figure 3.1 presents a flow chart of the phases of the prototype's development.

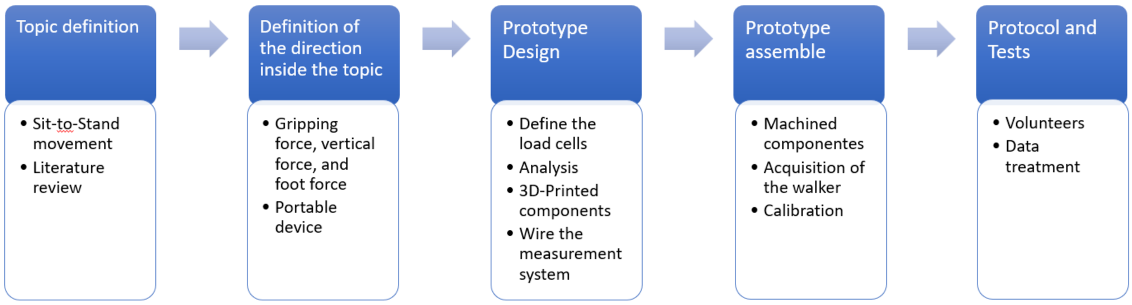


Figure 3.1: Flow chart with the phases of the prototype development.

3.1 Conceptual Design

The idea of the project was, from the beginning, to elaborate a new device, with innovative aspects for the STS test. The baseline consisted of the assessment of the lower and upper limbs' effort during the manoeuvre differentiating the left and right sides in both cases.

So, from this first insight, the research was done to advance to a direction not usually explored for this type of test. Therefore, the measurement of the gripping force while the person performs the STS movement was established as the project's main point. However, other ideas were likewise a challenge during the prototype development.

The device exposed in Figure 2.6 can be considered a starting point for this prototype development. (Oliveira, 2021) developed a device to measure the vertical force of the upper limbs, but it was interesting to increase the number of parameters assessed. So, it was defined that the gripping force is a key point for this project as also the implementation of two foot platforms, with more complete data of the STS tests, with the upper and lower limbs efforts analysed.

Hence, the principle of developing the device in a way that is as portable as possible was a key aspect. And this idea matured during the research time for the project. And, as it is shown in Figure 3.2, the first concepts for the portable prototype needs a strong support mechanical structure. This and all the others concepts for the prototype were developed with the CAD software SolidWorks® 2021. However, over the brainstorming, the direction of the project became the development of a framework which could be easily transported to different venues turned up as an interesting and useful solution.

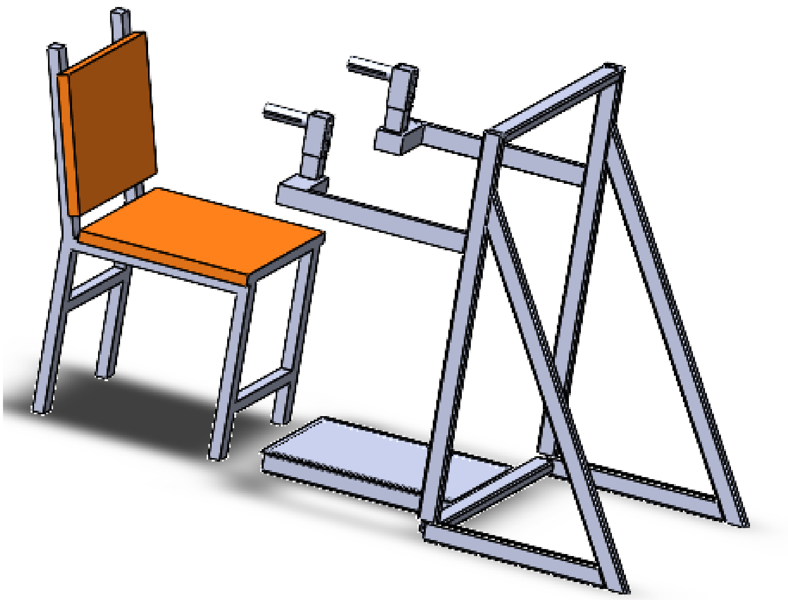


Figure 3.2: The first idea for the prototype.

As mentioned above and noticeable in Figure 3.2, the first prototype designed would demand a lot of space and work to transport the mechanical structure to another place where the test would be done. So, the final design is considerably different than the first idea, but the measurements done remained the same, the upper gripping force and the vertical force of the lower and the upper limbs.

The follow-up sub-chapters of this section describe the new design and the working conditions of the selected prototype for this project. The succeeding topics rely on the description of the design, the walker used on the project, the developed clamping device, and how the whole measurement system was produced.

3.2 Design

As was exposed in previous chapters, the prototype’s design consists of a portable device, which is hitched to a walker and allows the assessment of the upper limbs’ vertical force, the gripping force, and the lower limbs’ vertical force. Also, the measurement is done on the left and the right sides separately.

Even if the idea is to build up a mechanism adaptable to any walker, it was necessary to select and consider a sample to attach the developed device and to carry out the test during the project. So, the walker Brio 6291E-A from the company Invacare was chosen as the model for the mechanism to be attached to the prototype. Figure 3.3 shows the walker and its dimensions. In addition to the advantage of the easy and quick use of the device which is largely used by people who suffer from an impairment in the lower limbs, the walker has a system to adjust its height, important to reach all types of persons.

Figure 3.3: Walker Invacare Brio 6291E-A. (https://www.invacare.pt/pt/produtos-de-apoio/andadeiras/invacare-brio).

To hitch the measurement system to the walker, a clamping device needed to be developed. The first idea was a clamping device divided into two parts, which would be attached next to both extremities of the handle where the people grab the walker. However, this arrangement would not fit every walker, once there are some types (such as the considered one) that, just after the handhold, the structure bends. Therefore, the first clamping device designed, which can be observed in Figure 3.4, would not fit every case.

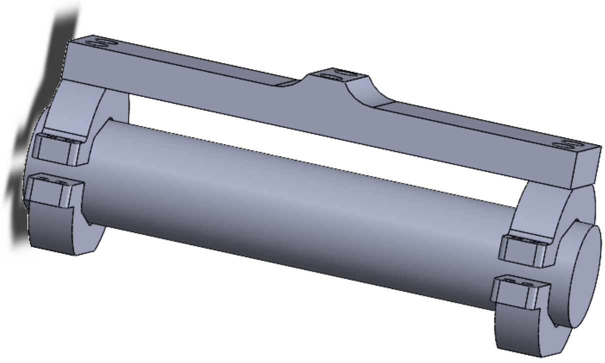


Figure 3.4: Previous design for the clamping device.

As a solution to this problem related to the walker structure, a new clamping device was developed and, the way to attach it has a big difference when it is compared to the previous idea. The new tube clamp is attached directly to the part where the person grabs the walker. In this way, it does not matter the tube's shape around the handhold, as the pressure exerted by the tube clamp provides the necessary stability to the system.

A great advantage of this new tube clamp is the number of components which needs to be machined. Figure 3.5 shows the new design of the clamping device. Another positive point is the fact that this new design offers more stability to the whole mechanism than the preceding one. Also, this clamping device allows the prototype to be attached to variable diameters due to its geometry specifications. As it is exposed in Figure 3.5 (b), with the example of the clamping device attached to a tube with a diameter of 36 mm, there is still some space to attach to different diameters, once the upper and lower parts can get closer or further to each other and work perfectly to another dimension, just varying the space (in this example it is 11 mm) between the components of this mechanism.

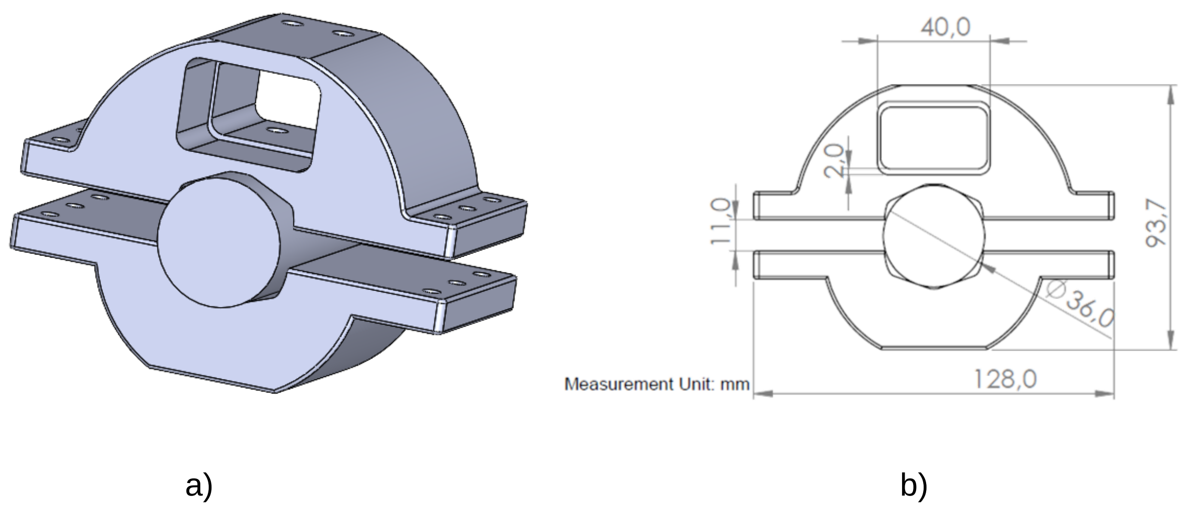
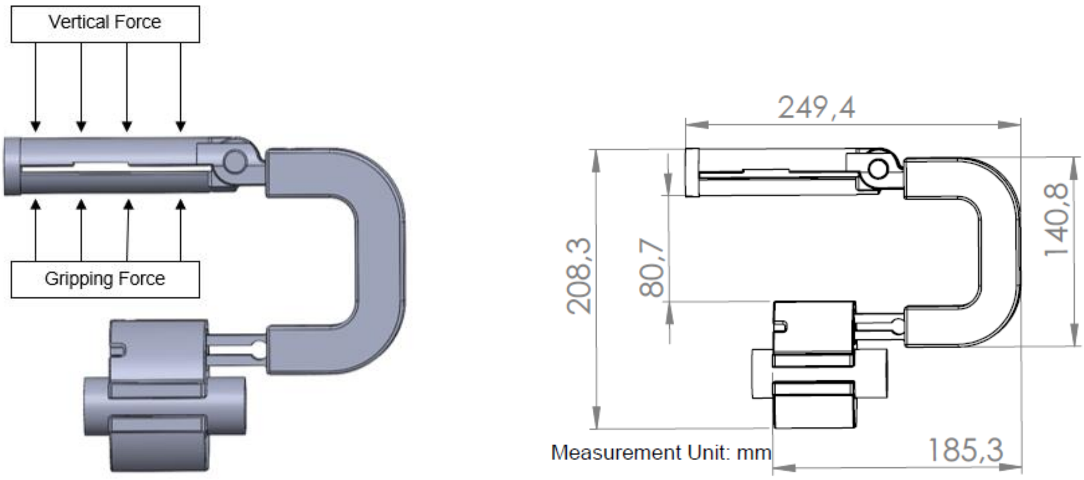


Figure 3.5: a) Design of the clamping device. b) 2D draw of the clamping device with some quotes.

This hole opened in the tube clamping was created to attach the load cell which measures the vertical force from the upper limbs. And, as is seen in Figure 3.5, there is an unevenness of 2 mm between the front and the back section in the inner part of the hole. This exists to allow the dwarfish deformation of the load cell, allowing it to quantify the force which is being applied to the opposite extremity of the load cell.

At this stage, the walker and the tube clamping were presented, in Figure 3.6 it is possible to see the design of the part corresponding to the prototype’s upper limbs assessment. In this figure, it is observed a draw simulating the beam load cell, the tube clamping, the handle which measures the gripping force, and the components to adjust the measurement system to its necessities. The small space between the upper and lower parts of the clamping device is there to lodge the load cell which measures the gripping force.

Also, in Figure 3.6 (a), it is shown the 3D drawing of the prototype with the illustration of the forces that are applied to it. It is possible to notice that the vertical and the gripping forces are measured distinctly, with the first one exerted on the top and getting its measurement through the single-point load cell attached to the tube clamp device that was designed. And the gripping force is applied exclusively on the handle’s lower part and, as the only contact point is the load cell positioned between the lower and the upper components, the measurement of the vertical force does not influence the gripping force measurement. And Figure 3.6 (b) shows a 2D drawing of the prototype with its global dimensions.



a) b)

Figure 3.6: a) 3D drawing with the illustration of the forces applied. b) 2D drawing with the prototype dimensions.

Figure 3.7 shows an exploded view of the prototype, to have a better view of each one of the constituent components. The components in the picture received number, on which: (1) tube simulating the walker's tube; (2) Clamping device's lower part; (3) Clamping device's upper part; (4) Single-point load cell for the vertical force's measurement; (5) Connector component for the single-point load cell to the upper part of the handle; (6) Pin connecting the handle's components; (7) Handle's lower part; (8) Handle's upper part; (9) Component to control the handle's aperture.

With this concept exposed above, the handle is overhead the tube clamping, which offers two main advantages to the system. The first one is the fact that the mechanism became more compact, needing less space on the top of the walker. And the main advantage of this device is that the force appliance axis on the handle is nearly over the centre widget which attaches the prototype to the walker. This second cited gain on the design reduces the bending moment at the point where the vertical force's load cell is screwed to the clamping device.

Load cells are the instruments used to measure the forces understudy on the project. This apparatus works based on the functionality of strain gauges, an electrical sensor which provides a different electrical output according to the force that the load cell is under request. This variable output is induced according to minimal deformations that the surface where the strain gauge is glued suffers. This occurs because this electrical sensor is composed of a conductive and resistive filament, that varies the size according to the deformation that takes place in the measurement region of the load cell. If the surface where the strain gauges are glued is under traction, the readable voltage output will raise, and if it is under compression, the voltage output will decrease.

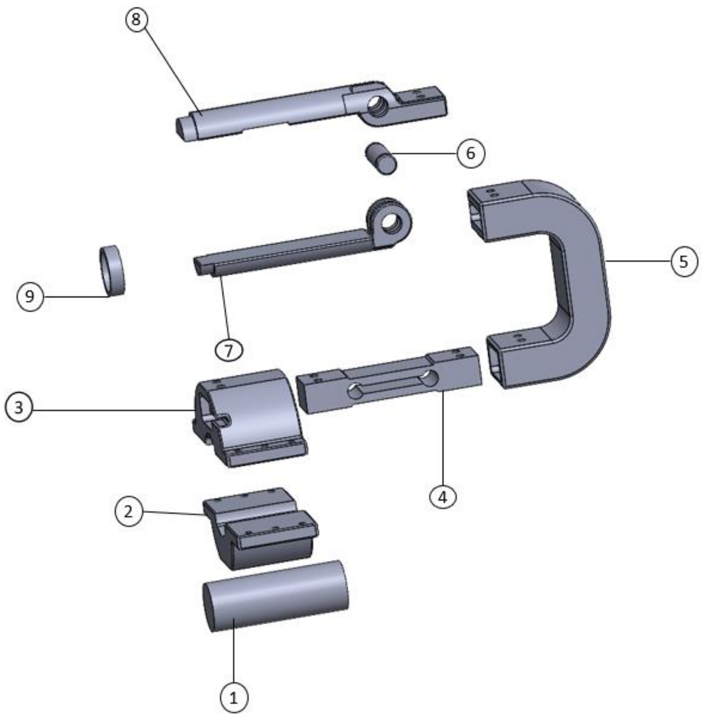
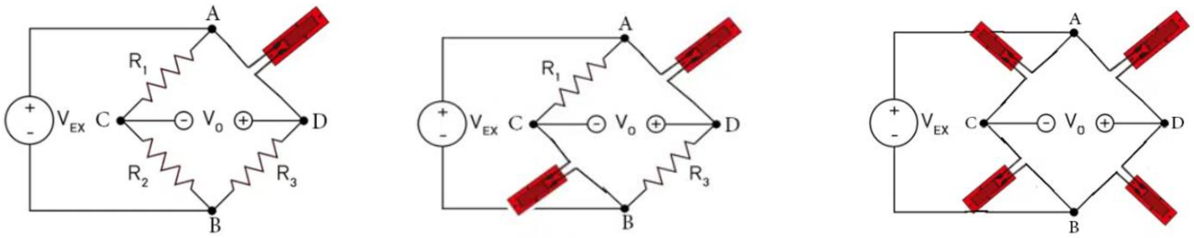


Figure 3.7: Prototype’s exploded view. (1) Tube; (2) Clamping device’s lower part; (3) Clamping device’s upper part; (4) Single-point load cell; (5) Connector component; (6) Pin; (7) Handle’s lower part; (8) Handle’s upper part; (9) Controlling component.

The operating principle of the strain gauges is the Wheatstone Bridge circuit. To build the circuit, it is possible to use one strain gauge (quarter bridge), two strain gauges (half bridge), and four strain gauges (full bridge). In a Wheatstone Bridge circuit, an excitation voltage is applied to one pair of diagonal corners of the circuit and the measurement is made on the other one. In a Quarter Wheatstone Bridge, it is necessary three resistors to complete the circuit and, this type of connection, presents much more unstable measurements, due to the wire’s resistance and the fact that there is only one strain gauge responding to the voltage application.

A way to improve the measurement is by adding one strain gauge to the circuit, building, with two strain gauges and two resistors, a Half Wheatstone Bridge. Like this, the measurement is more stable than the previous one, once the circuit has two active strain gauges responding to the voltage excitation. And, to have a much more stable and precise measurement, it is necessary to build a Full Wheatstone Bridge, with four strain gauges and no resistor. In this way, the four corners of the circuit are actively responding to the voltage excitation. Figure 3.8 shows each one of the circuit settings cited above.



a) b) c)

Figure 3.8: a) Quarter Wheatstone Bridge; b) Half Wheatstone Bridge; c) Full Wheatstone Bridge. (https://www.bestech.com.au/blogs/understanding-a-wheatstone-bridge-strain-gauge-circuit/)

To implement the assessment system in the prototype, with the load cells, the microcontroller Arduino was the chosen device. Arduino consists of a physical circuit board and the Integrated Development Environment (IDE), software on which the code is written and then uploaded to the physical board. This is an open-source platform used for electronic projects.

Lastly, to connect the load cell to the Arduino, the HX711 amplifier was a great option for the project. This small circuit board allows the reading of the load cell's resistance variation when a force is applied against it. The operation mode of this device is converting the resistance variation from the load cell to an electrical signal.

3.2.1 Gripping Force Assessment

Now, considering the handle, the developed arrangement consists of five parts, the lower, the upper, the pin, the load cell, and the ring to control the handle's slit. In the middle of the handhold, there is a space between the top and the bottom pieces. This distance exists to allow the insertion of the load cell and to compel the unique contact point between both parts in the area of force application is the load cell's protuberance which measures the force exerted. Figure 3.9 shows how the load cell is placed on the device.

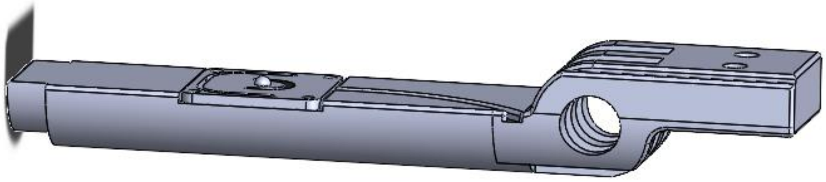


Figure 3.9: Load cell placed into the cavity.

The cavity was created on the upper part of the handle to enable the load cell's operation. It was necessary because the strain gauges are disposed on the central region of the instrument, and this section requires a minimal space to deform and measure the force applied against it. Therefore, this recess has the function to attach the load cell to the correct position, allowing its minor deformation. The load cell has holes on the four corners for the usage of screws, also the strain gauges are glued to the bottom part of it, and they have a protection to minimize the interference of external factors such as temperature.

So, the handle needs to count with the cavity to accommodate the load cell, a way to attach it, and a duct to its wires through the handhold. In Figure 3.10 these three features of the handle and the load cell used are exhibited.

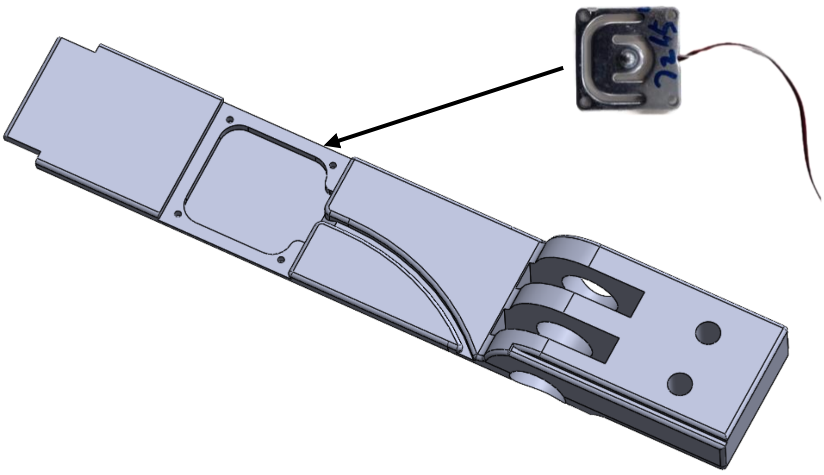


Figure 3.10: Cavity for the load cell and Load cell Kern CK 50-Y4 50kg.

The connection between the major two parts is made in a way like a hinge, using the pin to hook it up. The idea to develop these components in this shape is to reduce the possible torsion which can be caused when the person applies the force onto the handhold. In Figure 3.11 it is possible to observe how it was designed.

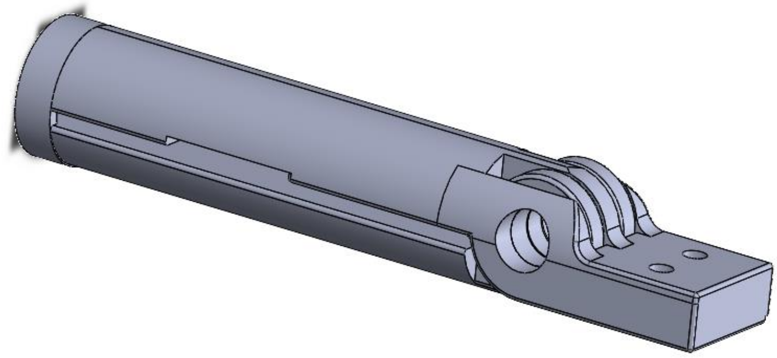
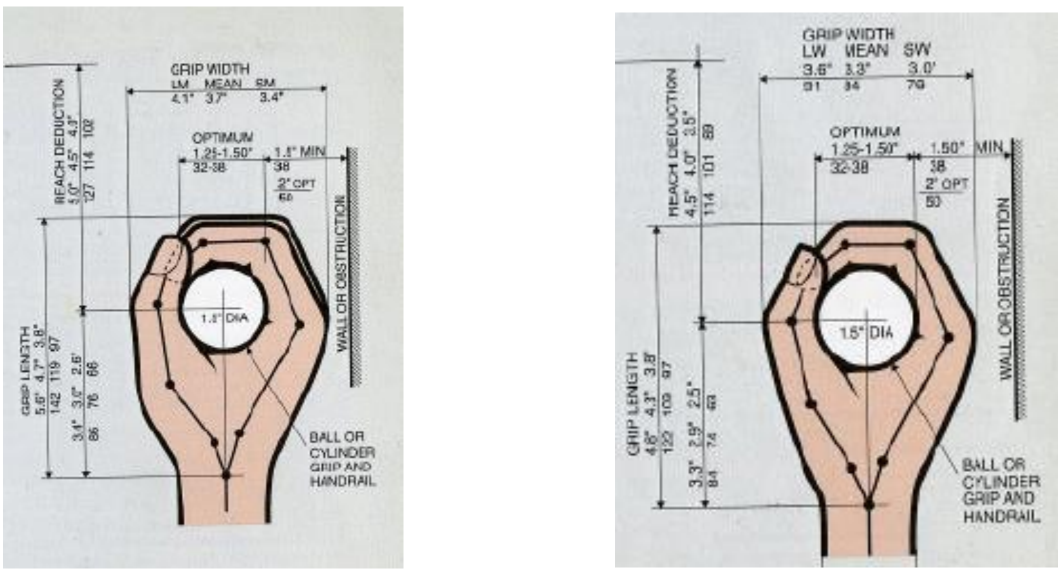


Figure 3.11: Connection in "hinge way".

According to (Tilley, 1993), the optimal diameter for a handhold should be in the range of 32 mm to 38 mm, as it is shown in Figure 3.12. So, the developed handle has 35 mm in diameter for the machined mechanism. And, with the coating protection developed for the device, the diameter raises to 36.7 mm diameter.



a) b)

Figure 3.12: Ideal diameter for a handle. (a) Men and (b) Women. (Tilley, 1993).

During a gripping force test, the maximal strength applied by the individual is around 461.1 N for men and around 304.1 N for women, as was demonstrated by (Massy-Westropp et al., 2011). Even if the gripping force during the Sit-to-Stand movement is much smaller than in the ordinary test, the chosen load cell for the project supports

490.5 N, which is enough to assess this parameter under any condition during the STS test.

The load cell for this case needed to be small enough to fit inside the handle. So, the load cell in Figure 3.10 was shortlisted, once it has approximately 6 mm high, 34.5 mm in width, and 34.5 mm in length, dovetailing perfectly to the 35 mm diameter handhold. Nonetheless, this load cell is constituted by a Half Wheatstone Bridge, making it necessary to build the other half of the Wheatstone Bridge with two 1k Ω resistors, compounding, in this way, the circuit to enable the measurement of the force to be done. Figure 3.13 shows the connection between the load cell, the resistors, and the HX711 amplifier.

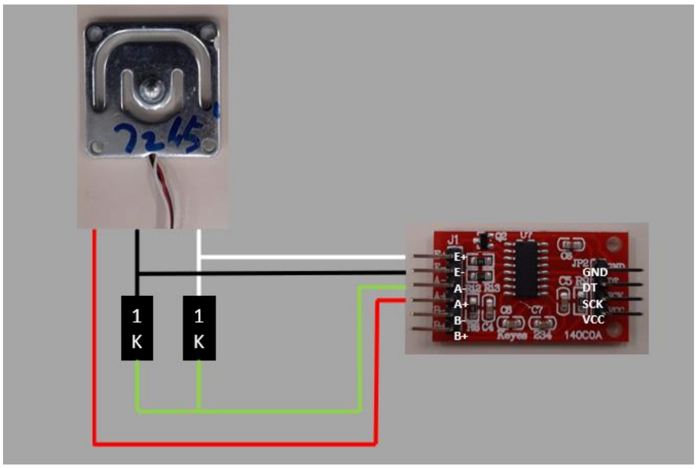
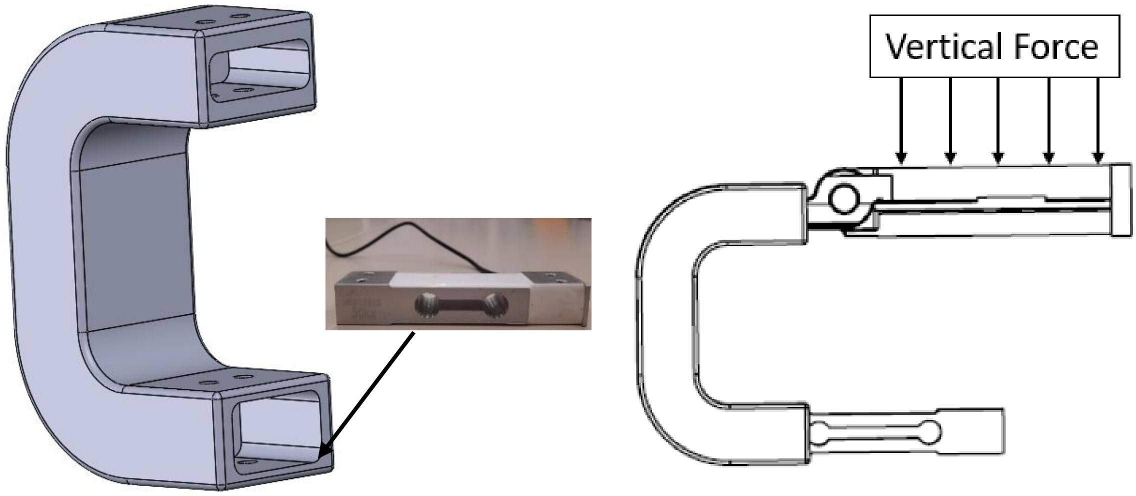


Figure 3.13: Wire configuration with one load cell, two 1k Ω resistors, and HX711.

3.2.2 Upper Limbs Assessment

The vertical force from the upper limbs is assessed with another type of load cell, the single point one. With this transducer, one extremity is attached to the clamping device and the other one to the component which connects the load cell to the handle. On both sides, it was designed a slot to attach the load cell and the handle’s upper part on which the components are tight fit placed. Thereby, with the screws and these notches, the components are well fastened providing a better property to the prototype. Figure 3.14 shows the connecting piece developed with the cavity to connect the load cell and also the load cell used for this measurement. The other extremity of the load cell is connected to the clamping device, which has been previously exposed in Figure 3.5.



a) b)

Figure 3.14: a) Component to connect the handle to the load cell and the load cell Tinker Forge 6128 50 kg CZL601. b) 2D drawing of the component with an illustration of the vertical force.

As it is possible to see in Figure 3.14, the component designed, in addition to the function to connect both parts of the prototype, transmits the load applied vertically to the handhold to the load cell used to assess the upper limbs' vertical force. And, as one extremity of the load cell is attached to the component that connects it to the handle and the other extremity is fixed on the tube clamping device, the vertical force will cause a deflection on the load cell corresponding to the force applied. So, in this way, the vertical force is measured separately from the gripping force.

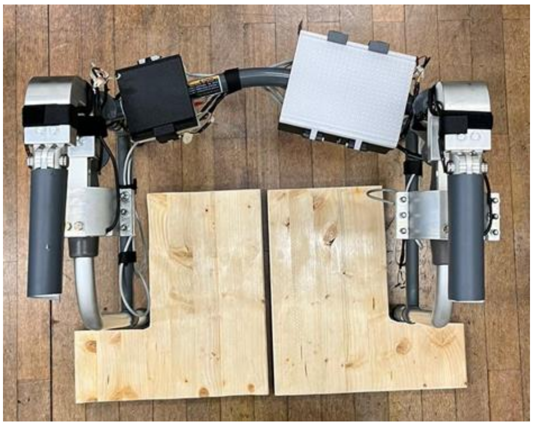
Unlike the load cell used for the gripping force measurement, the one employed for the vertical force has a Full Wheatstone Bridge, hence there is no need to use any resistor on the system for this situation. So, the load cell wires are directly connected to the HX711 amplifier.

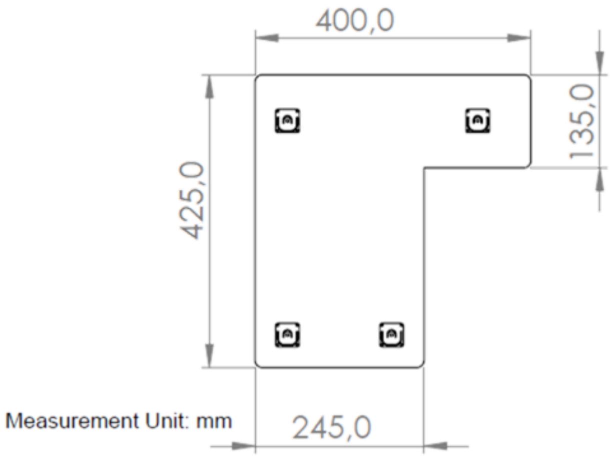
According to (Turner et al., 2004), the maximal vertical force applied by the upper limbs during the STS movement is between 20 and 30 % of the individual's body weight on each side. So, the vertical force applied on each handle of the prototype would be around 30 kg for a person who weighs 100 kg. On behalf of this data, the selected load cell supports 50 kg.

3.2.3 Lower Limbs Assessment

To measure the force applied through the feet on the floor, two foot platforms were developed, one for each side. And, for this part of the prototype, wood was the material chosen to attach the load cells and be the place where the volunteers will lay their feet.

For each of the platforms, four load cells, like the one presented in Figure 3.10, and one HX711 amplifier were used. The wooden platforms present a shape which allows it to be closer or further to the walker, by necessity. Figure 3.15 shows this format adopted for this part of the prototype and Figure 3.15 (b) shows, in a 2D drawing, the approximate load cells' position on the wooden platform.





a) b)

Figure 3.15: a) Top view of the wooden platforms. b) 2D view of the foot platform and the load cells' positions.

As it was made with the upper part of the handle, the load cell support needs to allow its minimal deformation to get the measurement of the force exerted on it. So, a mechanism to attach the load cell and allow this minimal displacement was developed for the foot platforms. In this way, for each side, the four load cells are allocated in a way that it is permitted its necessary displacement and, also, the four load cells are the only contact point between the wooden platform and the floor.

Even using the same type of load cell as the one for the measurement of the gripping force, the electronic system has a difference when it is compared to the previous one. To develop the scale, it is better if the platform has, at least, three contact points to provide stability during the person's movement. So, it was defined the use of four force transducers and each one supports 50 kg, therefore, in total, the platform measures up to 200 kg, but the real force applied on it is much smaller, once there will be one platform for each foot, sharing the individual's body weight.

As each of these load cells has a Half Wheatstone Bridge, when all of them are connected, the system counts with a Full Wheatstone Bridge. This way, differently than the gripping force assessment, there is no need to use resistors in the circuit. So, the four load cells are connected between themselves and, afterwards, connected directly to the amplifier HX711 and the Arduino board. It is important to reinforce that each measurement circuit needs its amplifier before connecting to the microcontroller. So, it is necessary one for the left and one for the right foot. Figure 3.16 shows a schematic drawing of the circuit with the four load cells and the HX711 amplifier.

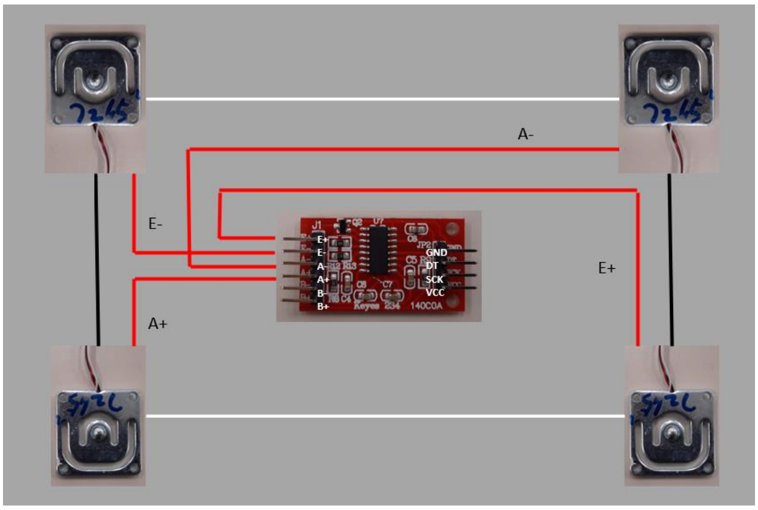


Figure 3.16: Wires configuration with 4 load cells and HX711.

3.3 Structural Analysis

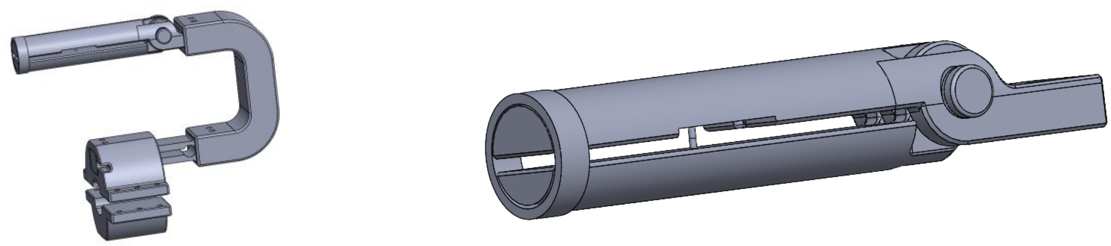
As the effort on the handle generates some bending moment and the load exerted by the person is up to 350 N on each side, the chosen material is the Aluminium Alloy 7075 thermally treatable, which is also largely used in the aeronautical industry. The main reason for this choice derived from its high mechanical effort resistance. Beyond the great relation between weight and resistance, this alloy has good ductility and fatigue resistance.

The Aluminium Alloy 7075 has zinc as the major alloy element and, for this project, the material used was submitted to a thermal treatment followed by artificial ageing. On behalf of this treatment, the alloy has the designation T6. Table 3.1 shows the alloy’s properties (Simão, 2019).

Table 3.1: Aluminium Alloy 7075 T6 properties.

Alloy	**Chemical Composition (%)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Elastic Modulus (MPa)**
7075	5.6% ZN 2.5% Mg 1.6% Cu 0.23% Cr	505	570	72000

Before going ahead with this choice, the Finite Elements Analysis (FEA) of the whole structure was made with SolidWorks Simulation considering different materials. As expected, the Aluminium alloy 7075 presented a great result in the tests made. To complete the test, it was considered the whole developed system for the upper limbs, and for the single point load cell, which measures the vertical force, the same material as the rest of the prototype was considered. To simulate the contact point of the load cell which measures the gripping force, an extrude was made on each side of the handle, replacing, like this, the contact point in reality. Figure 3.17 shows these extrudes.



a) b)

Figure 3.17: a) The CAD used for the FEA. b) Extrude simulating the load cell measuring the gripping force.

The study carried out on the prototype’s structure was a linear static analysis using tetrahedral solid elements, with the forces applied vertically to the handle. The finite element model considers the assembly with all the components and due to their geometry, the option was to use volume elements (SOLID element from the Solidworks database), with 3 degrees of freedom, the translations in the 3 orthogonal directions.

To obtain the model for the FE simulation, the walker was disregarded, once the aim was to analyse the forces on the project's prototype. So, the fixing point was in the inner part of the designed tube clamping, inhibiting the movement, at the fixing zone, in any direction. Then, all the degrees of freedom were constrained on these surfaces. Also, the screws were replaced for virtual ones, once it saves a considerable amount of time in the simulation. In the end, two different forces were applied to the handle, one upward and another downward. Both loads were applied vertically in a *'split line'* created on the external side of the half-cylinders. The force downward was considered 355 N, once (Turner et al., 2004) presented the results that the upper limbs' assistance is between 20 and 30 % of the individual's body weight, so, in this case, the simulation was enough for a person who weights around 120 kg. And, upward, the deemed force was 200 N, because the gripping force applied is considerably smaller than the maximal gripping force presented on tests, so it was considered approximately half of the gripping force presented in the results presented by (Massy-Westropp et al., 2011). Figure 3.18 presents all the boundary conditions and loads applied to the model.

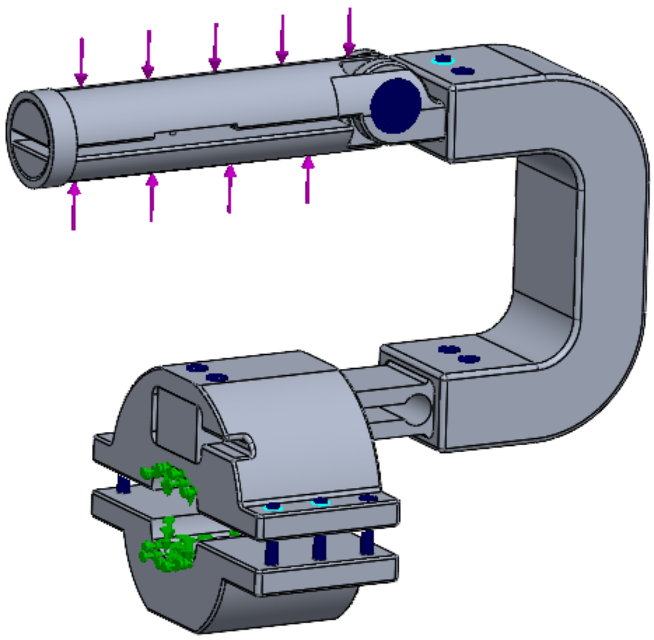


Figure 3.18: Fixing point, virtual bolts, and forces applied for the FEA.

Beyond the use of 13 virtual pins, replacing the screws, as connectors, the simulation presents a specific contact setup. To define the way that the components interact with each other, it was used local and global interaction types. For local interaction, it was defined as *'bonded'* for the components that are attached to the other one and do not present the possibility to move or deform. As the single point load is attached through the tiny cavity and also the screws in the tube clamping device and the designed connector, this load cell has the interaction *‘bonded’* with these two components. And, as happens with the load cell, the handle’s upper part also is attached through the tiny cavity and screws, so the interaction *‘bonded’* was used between this component and the designed connector. In these cases, the bonding formulation is surface-to-surface. Figure 3.19 shows the surfaces of the components where the interaction ‘bonded’ was used.

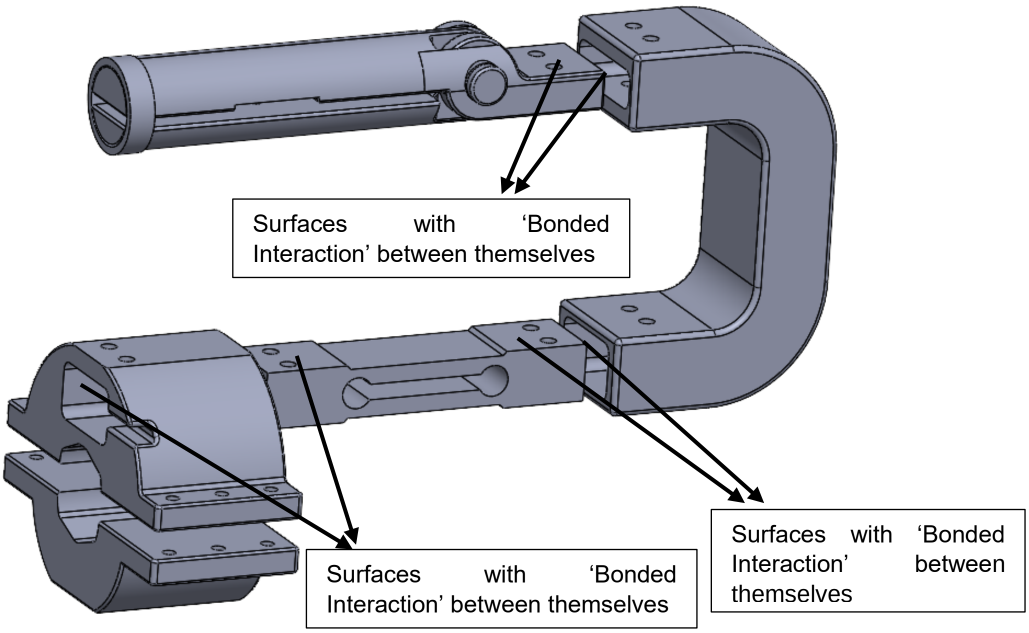


Figure 3.19: Surfaces where the ‘bonded’ interaction was used.

And, for the rest of the contacts between the components, it was defined as global interaction the *‘contact’* interaction, as the components are not attached and, with this interaction, it is not allowed that one component penetrates another one.

To complete the simulation preparation, the mesh conditions were defined, and the model was adjusted to parabolic elements with 10 nodes (high definition in the software). After that, apart from the *‘extrudes’* created to simulate the load cell contact, the zone, among the machined components, that was submitted for the highest effort was the *‘hinge’* connection between the upper and lower parts of the handle. So, to refine the mesh in the whole prototype, it was used the blended curvature-based mesher, which adapts the element size to the local curvature of the geometry automatically. Figure 3.20 shows the mesh after being refined.

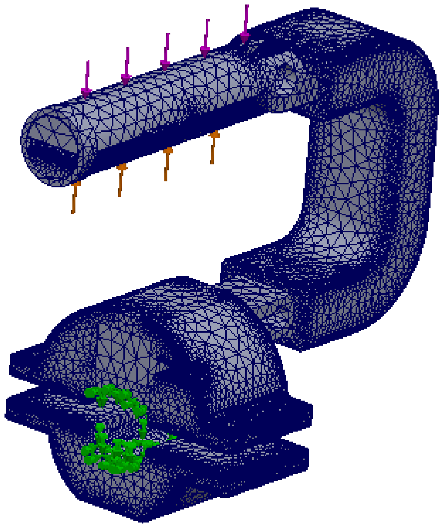


Figure 3.20: 3D visualization of the mesh applied for the linear static study.

As previously exposed, the ‘hinge’ connection between the handle’s parts is the area of the machined components submitted for the highest effort during the simulation. So, to improve, even more, the analysis in this zone, it was used the mesh control parameters. This option allows to select different element sizes in the mesh at specific points. With smaller elements, more accurate results are presented and, on the other hand, require a longer time to have the study done. Figure 3.21 presents, in detail, the mesh at the ‘hinge’ connection area.

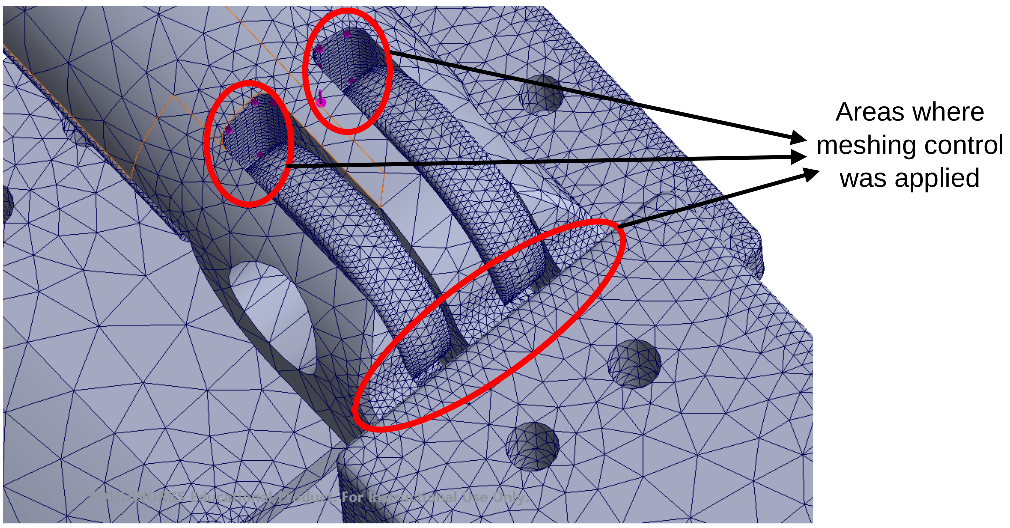


Figure 3.21: Focus on the area with mesh control applied.

Table 3.2: Mesh convergence.

Number of elements	Maximal von Mises stress (MPa)	Maximal displacement (z-axis) (mm)
291140	35.489	0.261
314120	32.883	0.326
393644	32.738	0.330
458522	35.766	0.335
546993	35.292	0.338

After simulating the efforts, it is possible to check the deformation suffered through the components, the stress, and the reaction at specific points. As the forces are applied to the handle and the only contact point with reactions is the extrude replicating the force sensor which measures the gripping force, this area presents high stress, as is expected. Figure 3.22 shows the distribution of the von Mises stress among the components.

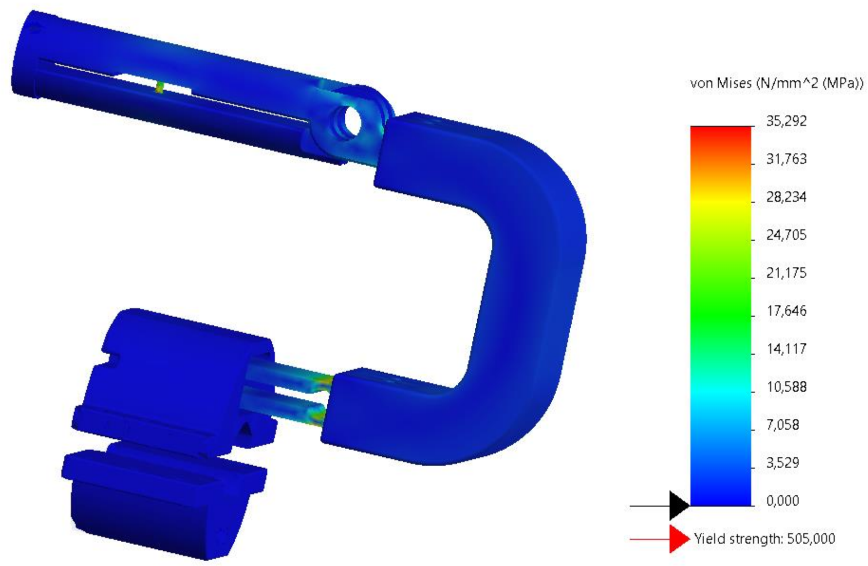


Figure 3.22: Distribution of the von Mises stress.

As it is shown in the legend of the study in Figure 3.22, the maximal von Mises stress is 35.292 MPa. This stress is considerably smaller than the yield strength of the material used in the prototype (505 MPa), so it is clear that this material is resistant enough for all the effort that it is submitted during the tests.

After the study, it is possible to notice some critical zones, with the von Mises stress over 10 MPa. The first remarkable zones are the extremities of the zone designed to suffer the deformation of the single-point load cell. Another zone with higher stress is the extrudes simulating the contact of the load cell that measures the gripping force, as it was expected. Both of these zones are not from the machined components, once the load cell is a transducer made with high resistance to support the load on its extremities and the extrudes were designed just to simulate the contact point. So, among the machined components in the project, the zone with the highest von Mises stress is the ‘hinge’ connection between the upper and lower parts of the prototype’s handle. Figure 3.23 shows the distribution of the von Mises stress over 10 MPa.

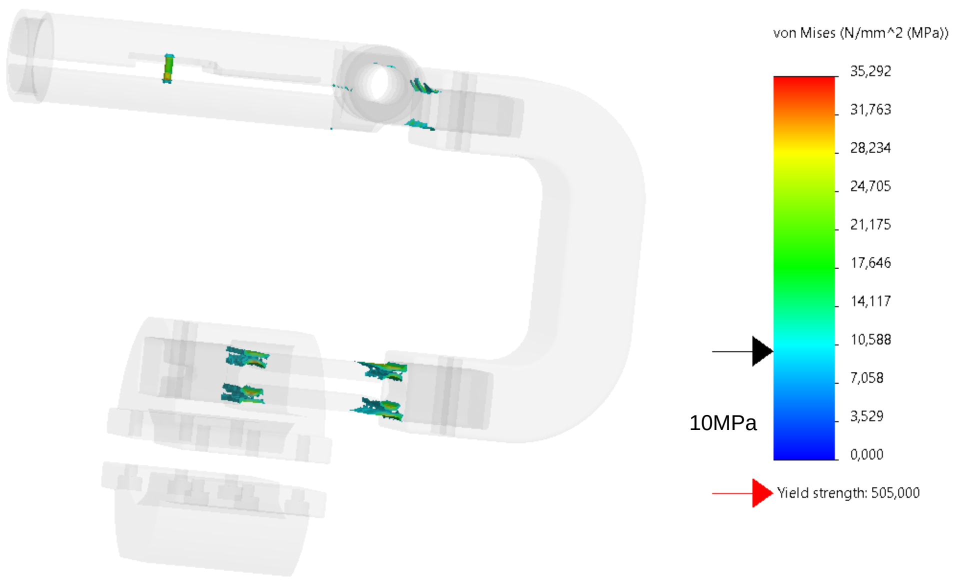


Figure 3.23: Distribution of the von Mises over 10 MPa.

Disregarding the contact point between the ‘extrudes’ created on the lower and the upper parts of the prototype’s handle to simulate the load cell actuation, once this was just created for the FEA, the zone that presents the highest stress point is at the ‘hinge’ connection. Even the highest stress point, at the ‘hinge’ connection, is greatly smaller than the yield strength of the material. Figure 3.24 shows the distribution of the von Mises stress among the upper part of the prototype’s handle, which presents the highest stress zone, and also the point where the maximal stress (30.653 MPa) is exerted.

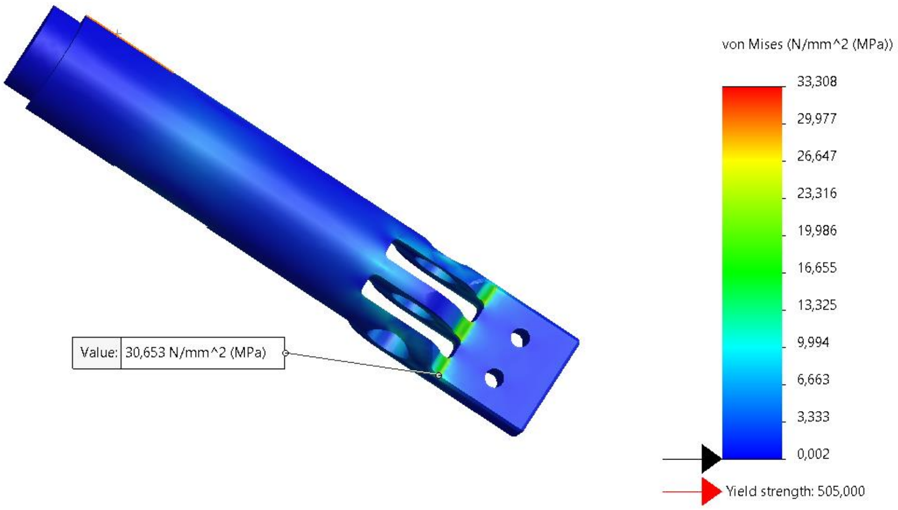
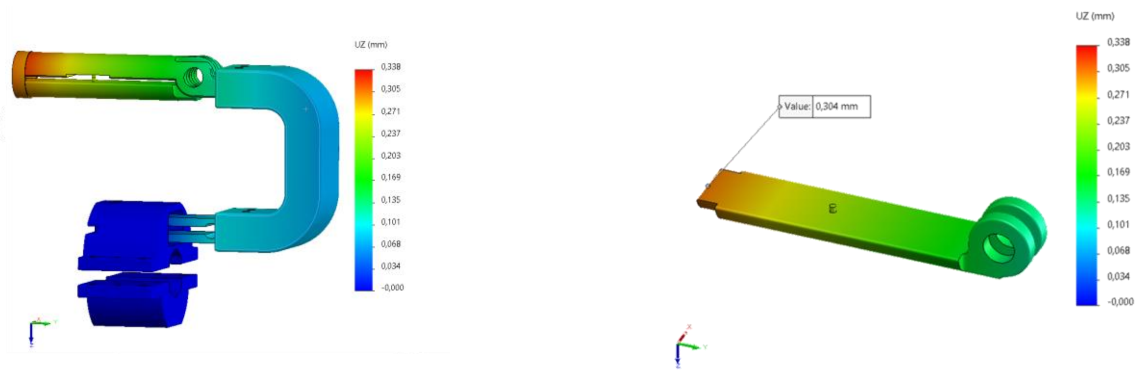


Figure 3.24: Distribution of von Mises stress among the handle's upper part and the maximal stress point.

Beyond the stress on the prototype components, another interesting point to analyse is the displacements. Figure 3.25 shows that the maximal displacement in the z-axis of the mechanism is 0.338 mm and it happens on the extremity of the upper part of the handle, which can be explained by the higher force applied on the top of this component. And, if it is considered the lower part, which is the moveable one when the gripping force is applied on the handle, the displacement is a bit smaller than the one on the upper part of the handle. The analysis of the displacement of this part brings more details about the gripping force. And, Figure 3.25 (b), shows the displacement of the handle’s lower component (0.304 mm), with a focus on the maximal displacement in the z-axis (0.338 mm), which is similar to the one on the upper component. Once the free span between the upper and lower part is 3.87 mm, the rigidity of the chosen material is adequate for the project purpose.



a) b)

Figure 3.25: a) Displacement, in the z-axis, among the prototype. b) Maximal displacement, in the z-axis, on the handle's lower part.

Another point that can be analysed is the screws that fix the handle's upper part to the designed component that connects the single-point load cell to the handle. These screws are located at the top of this connecting component. The distance between the centre of the screws until the central point of the prototype handle (d_1) is 114 mm, as shown in Figure 3.26. For this calculation, the vertical force was considered to be applied on its totality on the center of the handle. The screw received the name S_1 and Equations 1, 2, 3, and 4 were used to discover the minimal diameter to be used on the screws.

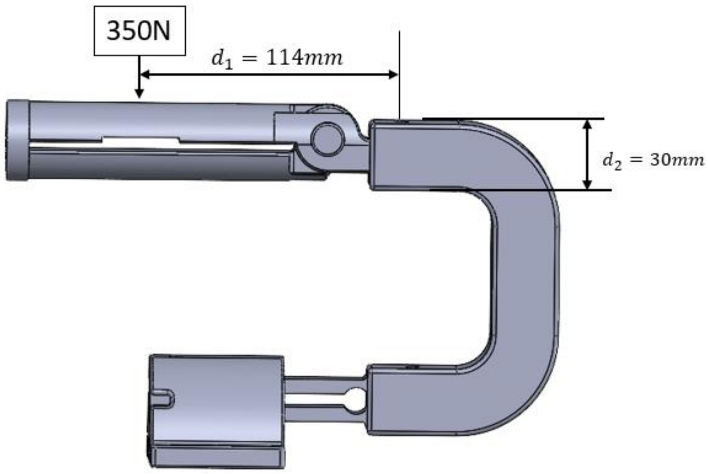


Figure 3.26: Side view with the distances used.

$$S_1 = \frac{F * d_1}{d_2} \tag{1}$$

$$S_1 = \frac{350 * 114}{30} = 1330N$$

$$\sigma_s = \frac{S_1}{A_s} \tag{2}$$

$$A_s = \frac{\pi * d_s^2}{4} \tag{3}$$

$$\sigma_s \leq \sigma_{adm} \tag{4}$$

The screw used has a hexagonal head and belongs to class 8.8, which means that the yield stress is 800 MPa and the allowable stress is 640 MPa. So, by replacing equation 2 with equation 4, it is possible to determine the minimal screw diameter.

$$\frac{S_1}{A_s} \leq \sigma_{adm} \Rightarrow \frac{1330}{A_s} \leq 640 \Rightarrow A_s = 2.08mm^2$$

$$A_s = \frac{\pi * d_s^2}{4} \Rightarrow d_s = 1.63mm$$

Equation 5 is used to calculate the smaller diameter of the screw, where D_s is the thread diameter, d_s is the smaller diameter, and p is the screw pitch.

$$d_s = D_s - (p * 1.23) \tag{5}$$

$$d_s = D_s - 1.85 \Rightarrow D_s = 3.48mm$$

Therefore, after the calculations, the minimal screw that can be used is the M4. As, in the prototype, the screws used are M6, and the resistance is enough for the efforts that the device is under request. To confirm this deduction, it was compared the tension of the M6 screw to its allowable tension, through equation 4.

$$A_s = \frac{\pi * d_s^2}{4} \Rightarrow d_s = 15.2mm$$

$$\sigma_s \leq \sigma_{adm} \Rightarrow 87.5MPa \leq 640MPa$$

As it was shown, the tension on the M6 is much smaller than its allowable tension. So, the one used on the device is resistant enough for the load that is applied to it.

3.4 Prototype Production

As was described in the subchapter above, after a few attempts, the final prototype was decided as a portable one with a tube clamping to attach it to the walker, which measures the gripping, vertical, and foot forces. In Figure 3.27, it is possible to see the whole machined mechanism assembled on the walker. These components were produced through subtractive manufacturing in a machining centre.

a) b)

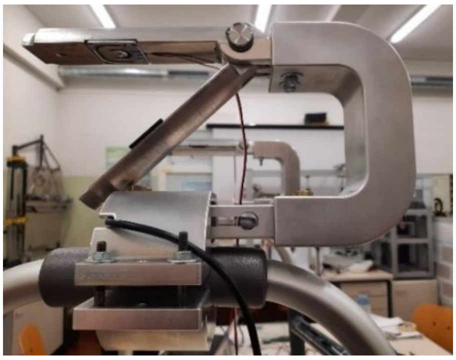
Figure 3.27: a) Top view of the prototype. b) Side view of the prototype.

The way the load cell for the gripping force measurement is assembled on the prototype can be observed in Figure 3.28. On it, is noticeable the cavities made for the wire and the load cell, and also the rubber which is used to be the contact part between the lower part and the measurement point of the load cell.

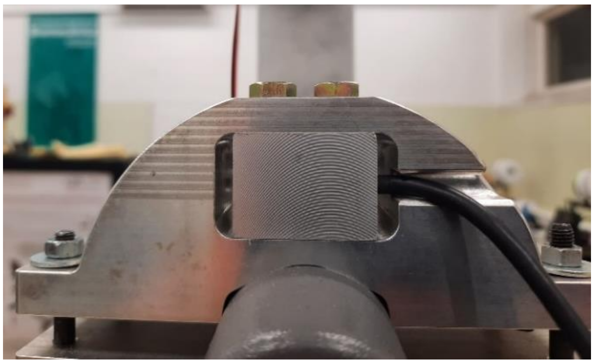
a) b)

Figure 3.28: a) Load cell for the gripping force in detail. b) Load cell in detail.

Figure 3.29 shows the tube clamp manufactured and, in detail, the voids on it to fit the single-point load cell which is used to measure the vertical force and also the wire. In these images, it is displayed how the single-point load cell is positioned on the system.



a)



b)

Figure 3.29: a) Side view of the tube clamp. b) Front view of the tube clamp.

3.5 Load Cells Connection Instructions

To connect all the load cells, the necessary material is the load cells, six HX711 amplifiers (one for each measurement system), the Arduino Uno, a breadboard, the cables, and two 3D-printed boxes to keep the other components attached to the walker. Inside ‘Box 1’ is the Arduino, two HX711 amplifiers, and the breadboard. While inside ‘Box 2’ is the other four HX711 amplifiers. How these boxes, dedicated to keeping the Arduino, the amplifiers, and its respective wires, are disposed of on the walker is shown in Figure 3.30.

A clamping mechanism was developed to attach the two 3D-printed boxes to the walker and each of the boxes has a half-cylinder shape in a way that both can be fastened to the walker’s tube. In Figure 3.31 (a) it is possible to see both boxes with the characteristic above cited and Figure 3.31 (b) shows how the upper and the lower components are adjusted on the tube and how the clamping mechanism works.

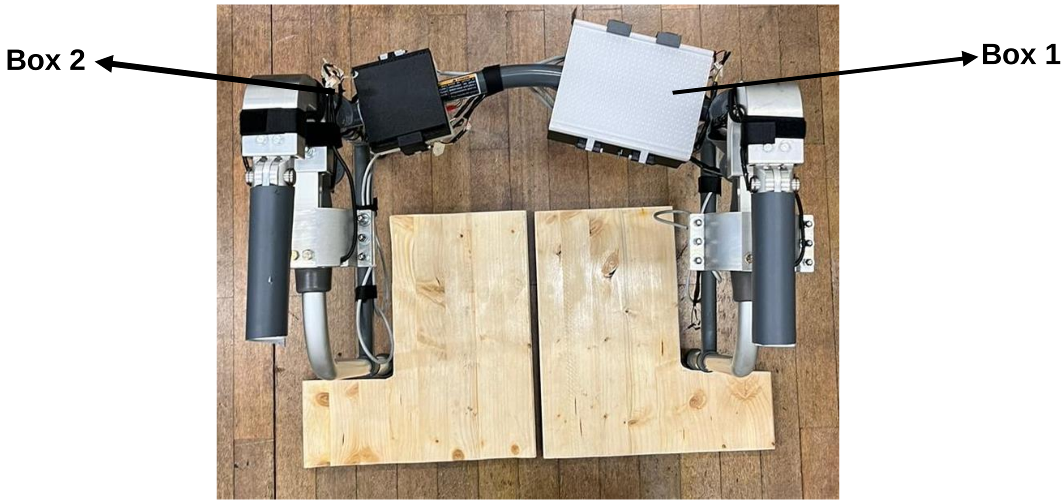


Figure 3.30: Top view of the prototype with boxes identification.

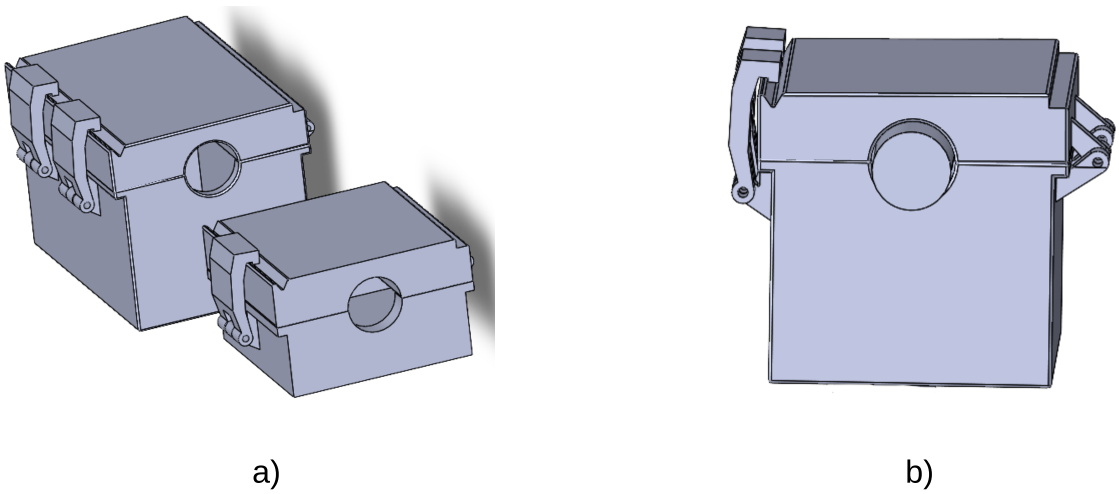


Figure 3.31: a) The design of both boxes. b) Design of how the boxes are fastened on the walker's tube.

To the amplifiers from ‘Box 1’, the load cells from the vertical and gripping force from the right side are connected. For the gripping force load cell, the red wire is connected to the ‘A+’ slot of the amplifier, the wire which comes from the soldering point of both 1k resistors is connected to the ‘A-‘, the black wire is connected to the ‘E-‘, and the red one is connected to the ‘E+’, as it is seen in Figure 3.13. Hereupon, the ‘GND’ and ‘VCC’ slots are connected to the ‘GND’ and ‘5 V’ designated slots on the breadboard. The ‘DT’ slot is connected to the Arduino’s ‘3’ slot and the ‘SCK’ to the ‘2’.

For the vertical force, the green wire is connected to the ‘A+’ slot, the white one to the ‘A-‘, the black one to the ‘E-‘, and the red one to the ‘E+’, like displayed in Figure 3.16. And, as it is for the gripping force load cell, the ‘GND’ and ‘VCC’ slots are connected to their space on the breadboard. The ‘DT’ slot of this amplifier is connected to the Arduino’s slot ‘5’ and the SCK, to the ’4’. These connections between the single-point load cell and the HX711 are shown in Figure 3.32.

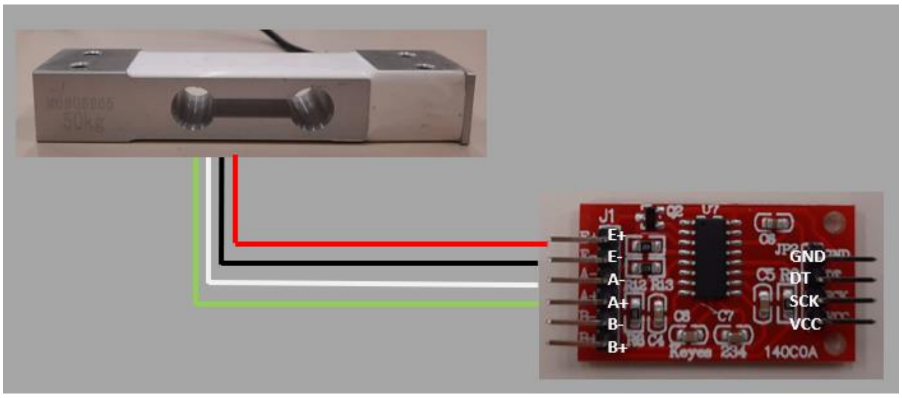


Figure 3.32: Wires configuration for the single point load cell and HX711.

For ‘Box 2’, all the amplifiers have their connections to ‘Box 1’ building the link to the Arduino and the breadboard. As it happens in ‘Box 1’, the ‘GND’ and ‘VCC’ slots of each one of the HX711 amplifiers are plugged into the designated space for it on the breadboard. The connections for the ‘A+’, ‘A-‘, ‘E-‘, and ‘E+’ slots for the gripping and vertical force measurement systems are the same as in the previous paragraph. However, the ‘DT’ slot for the gripping force on the left side is connected to the Arduino’s slot ‘7’ and the ‘SCK’ to slot ‘6’. For the vertical force, the ‘DT’ slot is connected to the Arduino’s slot ‘9’ and the ‘SCK’ to the slot ‘8’.

For the foot effort measurement, the load cells’ wires are connected to the HX711 amplifier in an ‘X’ way with the opposites corners being connected to the ‘A+’ and ‘A-‘, and the other corners to the ‘E-‘ and ‘E+’, as it is shown in Figure 28. After that, the connections for both measurement systems to the amplifier are just following the adhesive labels attached to each wire.

For the left foot measurement, the slot ‘DT’ from the amplifier is connected to the Arduino’s slot ‘11’ and the ‘SCK’ slot to the slot ‘10’. And, for the right foot measurement, the slot ‘DT’ is connected to the Arduino’s slot ‘13’ and the ‘SCK’ to the slot ‘12’.

3.6 Forces Measurement

The HX711 amplifier has a library inside the Arduino IDE, called *"HX711.h"*, and it assists to write the codes to read the measurements done through the load cells. So, using this available library, the code to read the measurements made by the load cell was written on the Arduino software on which the programming language is based on C++. The code created to read all the forces measurements independently is exposed in 'Appendix A'.

It is possible to have instantaneous access to the forces applied by the person during the STS movement with the tools Serial Monitor, with the data in numeral, and Serial Plotter, with the data in a graphic, directly from the Arduino's IDE. However, this way of data acquisition would require a few more lines on the code to have the measurements in a way that it is possible to work out and make a deeper study on how the individual is completing the manoeuvre under request.

On behalf of this demand to analyse, compare, and entrench the understanding of the data of each patient or volunteer, an extension existing in the software Excel arose as a great alternativity for this situation. It is called 'Data Streamer' and presents satisfactory functions for this project. To use it, the code from Arduino's IDE needs to be uploaded into the microcontroller board and, after that, every command is done straight from Excel.

With this extension, the operator can start, pause, and stop the data acquisition. It is also possible to tare the load cells' measurement in case it is necessary. Another great advantage is the option to record all the measured strengths immediately in Excel format and hammer out the data acquired. But, maybe, the greatest advantage is the functionality is the live broadcast of the forces in graphics *force x time*, with an individual graphic for each force or gathering all the measurements in the same graphic.

The chance to develop an interface to the patient with the live data of their force distribution among the STS test can improve considerably the results obtained in a rehabilitation process. This has good potential once the individual can observe, each time that the manoeuvre is done, if the upper limbs' assistance is excessive and/or one side of the body is carrying much more of the total effort during the motion. So, with this live biofeedback, the person can auto-amend the movement and, as is shown in the study developed with people in the stroke rehabilitation process (Nelson, 2007), this can bring faster and better results during the recovery procedure.

3.7 Calibration

Before starting the force measurements, it is necessary to calibrate the force transducers and to do it an extension was written to the main code, which can be read in Appendix B. With these extra lines on the original code, it is possible to adjust the calibration factor simultaneously to the measurement of the load cells.

To calibrate, it was necessary known weights and the load on each sensor was raised gradually. After that, a table with the data was created to register the calibration factor, the measurements for each load, and the error. With the error under 2 %, the calibration factor was extracted and included in the main code, which can be read in Appendix A. Apart from the system placing the load on the load cell, the process to get the calibration factor of the others force transducers is the same.

To get the calibrations factors of the single-point force transducers, which are applied for the vertical force measurements, a mounting clamp was used to set the weight on the prototype’s handle, as can be seen in Figure 3.33. And, applying the known loads, with the code and the Serial Monitor from Arduino, the operator changes the calibration factor until it is adjustable to the weight on the extremity of the force transducer.

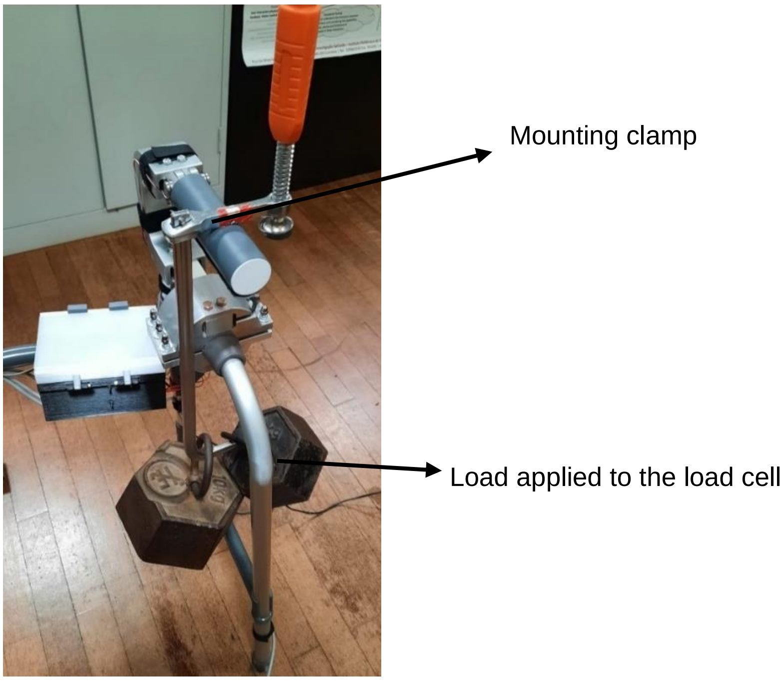


Figure 3.33: Mounting clamp being used to place the load on the handle.

Once this is done, the calibration factor is adjusted. And then, it is possible to start to get measurements from the force transducer at issue. For the left side, the calibration factor adjusted was 86250 and for the right side was 87610. Table 3.3 shows the calibration table, with the known load, the measurement, and the error, from the left-side vertical force, and Table 3.4, presents the data according to the right-side vertical force.

For the forces from the feet, the way to place the weights was leaner than the previous one. As the measurement systems are platforms, the load was just placed on top of it gradually, as it is seen in Figure 3.34. Tables 3.3 and 3.4 show the data for the left-side foot force and the right-side foot force, respectively.

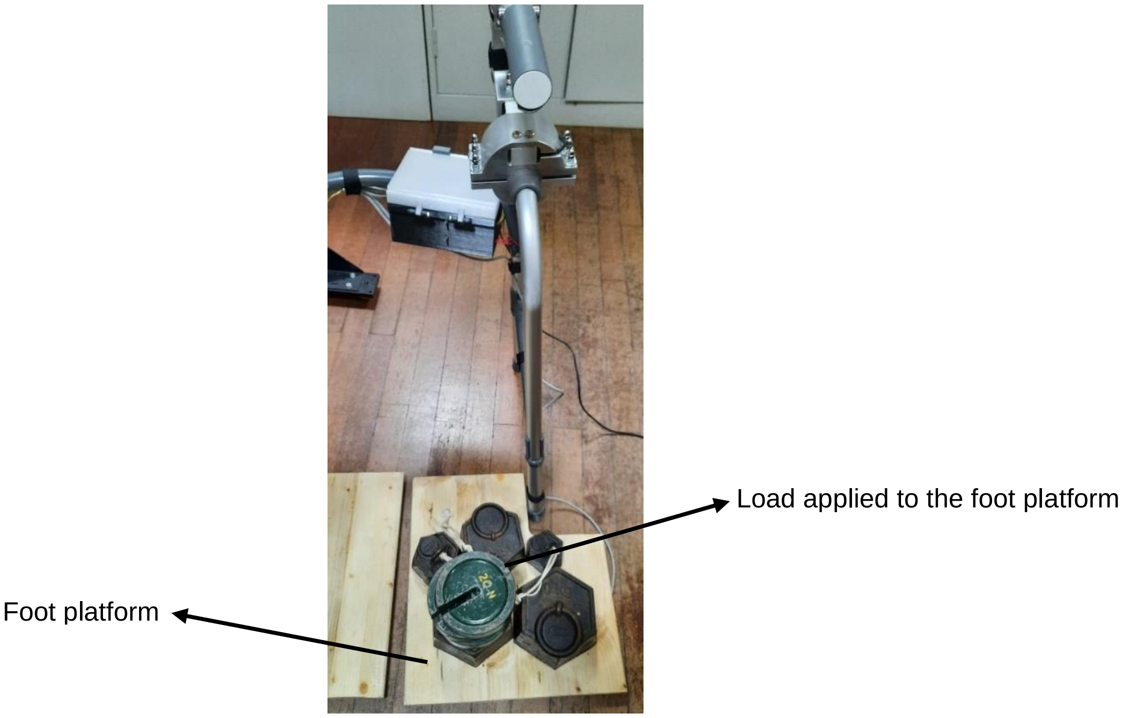


Figure 3.34: Load applied on the foot platform.

At last, to calibrate the gripping force measurement system, it was necessary to develop a mechanism to apply the force from the bottom to the top. For this, a rope and two pulleys were used, with the load tied up to one of the rope's extremities and the other extremity was knit to the prototype's handle. Pulley 1 is vertically in the direction of the load applied and pulley 2 is vertically in the direction of the prototype's handle. This arrangement is shown in Figure 3.35. And Tables 3.3 and 3.4 show the data from the left-side foot force and the right-side foot force, respectively. These tables also show the mean error for each parameter, which was obtained by calculating the average of the errors derived from the measurement of each of the applied loads.

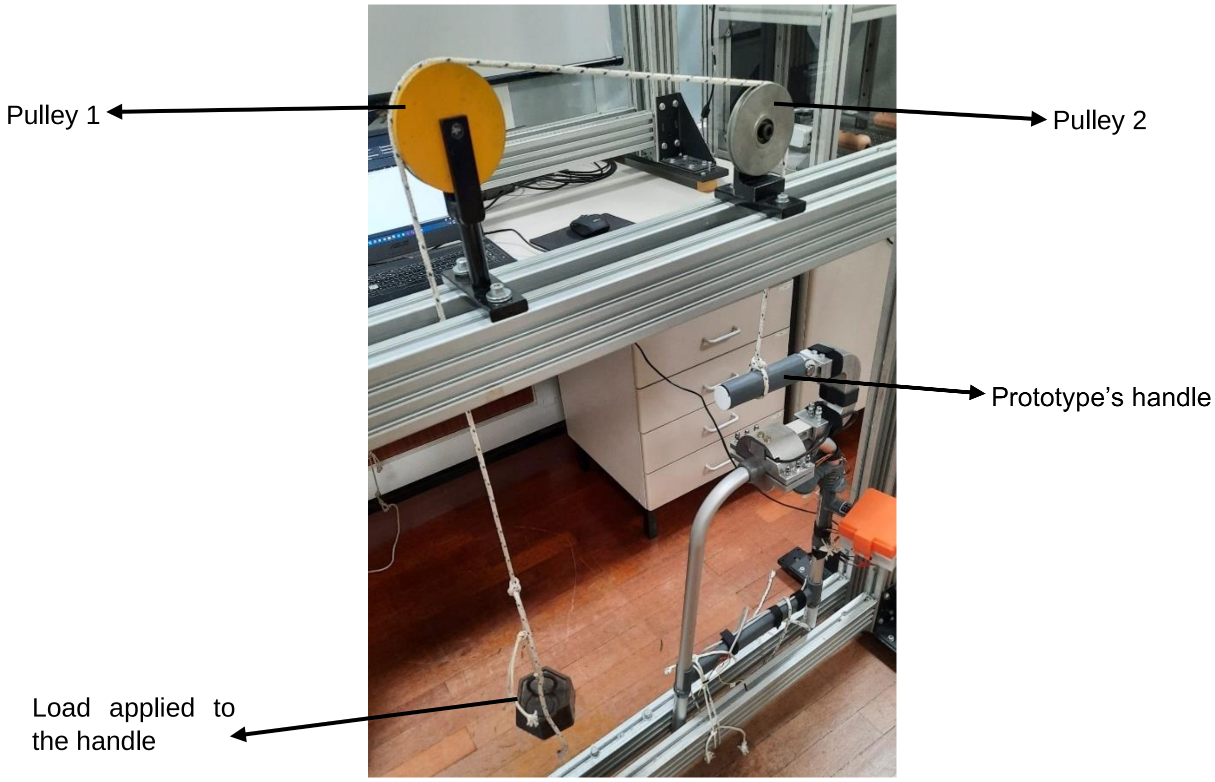


Figure 3.35: Mechanism to apply the load on the prototype's handle.

Table 3.3: Calibration data from the gripping, vertical, and foot forces for the left side.

Applied Load (N)	Force Measurement average (N)		
	Gripping Force	Vertical Force	Foot Force
9.80	9.99	9.60	9.99
19.60	19.26	19.46	19.89
49.00	47.94	49.76	50.19
98.10	98.24	97.78	97.80
147.20	150.97	146.50	147.39
196.20	198.87	196.63	197.20
245.30	246.19	246.50	246.34
274.70	271.81	276.00	275.60
334.70	339.39	335.70	335.27
350.00	350.38	350.10	350.10
470.00	-	-	468.60
Mean Error (%)	1.28	0.66	0.73

Table 3.4: Calibration data from the gripping, vertical, and foot forces for the right side.

Applied Load (N)	Force Measurement average (N)		
	Gripping Force	Vertical Force	Foot Force
9.80	9.90	9.71	9.63
19.60	19.57	19.00	19.48
49.00	48.56	48.30	48.66
98.10	98.41	97.57	96.66
147.20	147.55	147.23	145.69
196.20	198.23	197.23	196.28
245.30	247.11	246.91	245.65
274.70	275.22	276.57	275.57
334.70	340.57	337.27	334.91
350.00	352.36	352.86	349.71
470.00	-	-	469.90
Mean Error (%)	0.7	0.95	0.56

After the process to adjust the calibration factor for each one of the force assessments that is done, the value obtained with the extension on the code, from Appendix B, is updated on the original code, written to read the force transducers measurement. So, there is a calibration factor for the gripping force, one for the upper limbs' vertical force, and another one for the lower limbs' vertical force. A single code is used for all the mensuration on the prototype, and it can be seen in Appendix A.

3.8 Software Instruction Guide

After making all the connections between Arduino, amplifiers, and load cells, it is necessary to upload the code onto the microcontroller. So, the code presented in Appendix A needs to be uploaded through Arduino IDE to the board. With this code, all the six measures made with the prototype are made at a frequency of 10 Hz and the measurement unit is Newton.

After uploading the code, it is possible to follow the data acquirement on the tool 'Serial Monitor'. However, as it was exposed previously, an extension of Excel called 'Data Streamer', which allows the data analysis and treatment straight on Excel, is used on this project. So, the first step is select the tab 'Data Streamer' and the option 'Connect a Device' to connect to the Arduino, which is demonstrated in Figure 3.36.

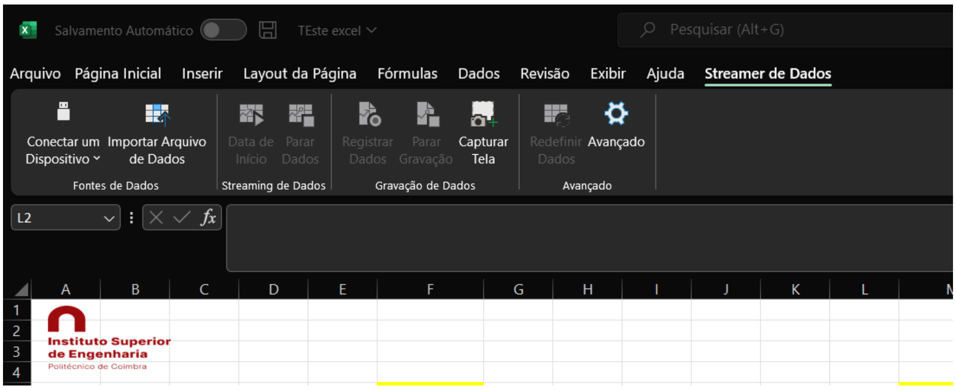


Figure 3.36: Data Streamer's interface.

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Then, the instructor must start the data acquisition on ‘Start Data’ and the measurement will be automatically acquired in Excel. To tare the load cells before the test, it is needed to send the command ‘T’ or ‘t’ on the ‘Data Outgoing’ tab, as this was the command created on the Arduino’s code. Figure 3.37 shows this step.

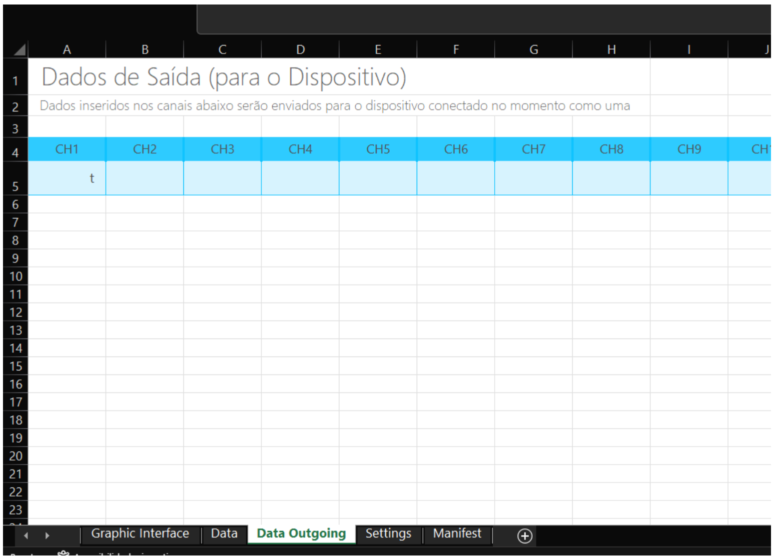
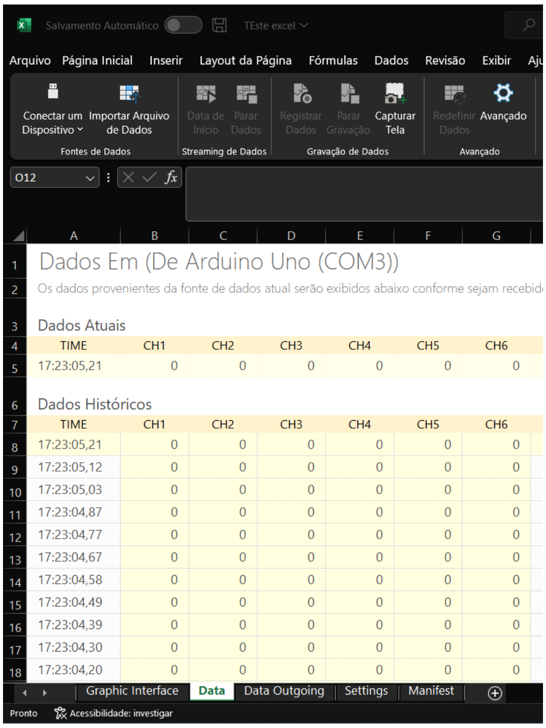


Figure 3.37: Interface to send commands to Arduino.

With all the force transducers adjusted, the data can be observed on the tab ‘Data’, which shows the time on which the measurement line was made and all six measurements from the prototype, like it is shown in Figure 3.38.


Dados Em (De Arduino Uno (COM3))

Os dados provenientes da fonte de dados atual serão exibidos abaixo conforme sejam recebid

Dados Atuais

TIME	CH1	CH2	CH3	CH4	CH5	CH6
17:23:05,21	0	0	0	0	0	0

Dados Históricos

TIME	CH1	CH2	CH3	CH4	CH5	CH6
17:23:05,21	0	0	0	0	0	0
17:23:05,12	0	0	0	0	0	0
17:23:05,03	0	0	0	0	0	0
17:23:04,87	0	0	0	0	0	0
17:23:04,77	0	0	0	0	0	0
17:23:04,67	0	0	0	0	0	0
17:23:04,58	0	0	0	0	0	0
17:23:04,49	0	0	0	0	0	0
17:23:04,39	0	0	0	0	0	0
17:23:04,30	0	0	0	0	0	0
17:23:04,20	0	0	0	0	0	0

Figure 3.38: Tab with the measurements' data.

Although to follow the test, another tab, called ‘Graphic Interface’ was created, which counts with the graphic of each one of the forces, shows the instant forces, the maximal forces during the movement, and if the movement is being made symmetrically or not. So, this tab is used as the biofeedback for the volunteer as well, once it is possible to follow the live data of the movement. Figure 3.39 demonstrates the interface of the software.

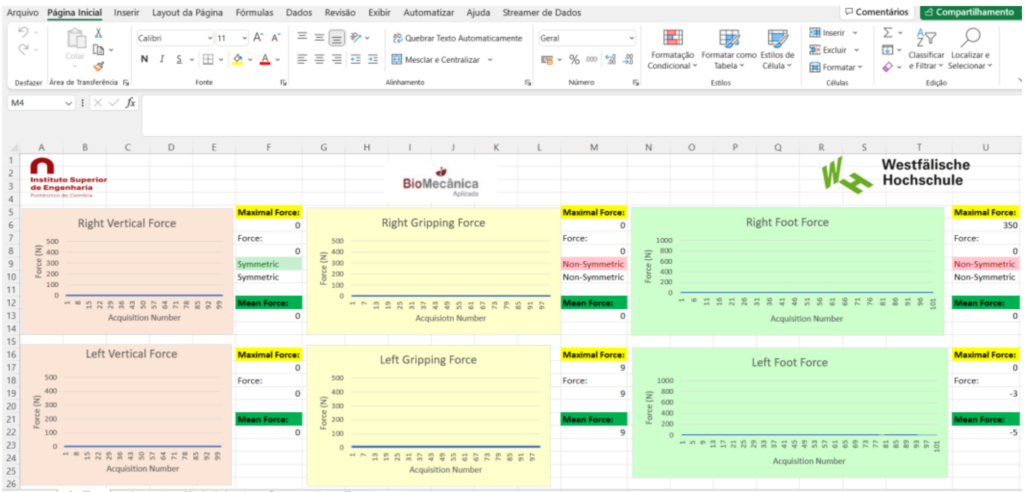


Figure 3.39: Interface for the volunteer.

For a later and better data treatment, this extension on Excel allows exporting the data in a .csv file. So, the instructor may select ‘Record Data’ when the test is started and, when the test is over, select ‘Stop Recording’. In this way, the .csv file will be automatically generated, and the instructor only needs to select the folder in which it will be saved.

So, the steps for the test can be summarized in the following sequence:

1 – Connect all the system and the Arduino to the USB port on the computer;

2 – Upload the code on Arduino IDE;

3 – Open the tab ‘Data Streamer’ and connect a device (Arduino);

4 – Tare the load cell on the tab ‘Data Outgoing’;

5 – Check the measurements on the tab ‘Data’;

6 – Follow the measurements on the tab ‘Graphic Interface’;

7 – Record the data only for the test moment, using the options ‘Record Data’ and ‘Stop Recording’;

8 – Treat the data on the .csv file for a better analysis.

4. Prototype Validation

To validate the prototype developed, a test protocol was developed to have the test performed by healthy young volunteers, students from the Coimbra Institute of Engineering. At first, the test is done with healthy young people, checking the functionality of the mechanism, and also defining a pattern for the expected results of the test with the prototype. To validate the mechanism, in addition to the Sit-to-Stand (STS) test, the Sit-to-Stand-to-Sit (STSTS) test was developed, in which the volunteer needs to stand up, stabilize, and sit down, starting and ending the test in the same position.

The necessary authorization to perform the usability tests was obtained from the Ethical Committee of Coimbra Polytechnic, reference Number 136_CEIPC/2022. The study follows all the ethical principles from the Declaration of Helsinki.

4.1. Test Protocol

The first stage is an explanation of how the prototype works and its aim, which is directly related to the question raised in the Introduction chapter, as it is expected to get the answers to these inquiries after having the STS test done using the prototype. Afterwards, the volunteer signs a term according to participate in the experiment and a code of identification is provided to each one of them, avoiding, in this way, to have mentions to personal data during the tests realized, ensuring the volunteer’s confidentiality. Then, the following data from each participant is gleaned: age, gender, height, weight, the maximal gripping force for both sides, body mass index, dominant side, and injury history.

After that, the experimental set-up is positioned according to each person’s characteristics (the position of the chair, the walker, the two foot platforms, and the developed mechanism high). For the habituation effect with the prototype, it is asked the volunteer to complete two times the STSTS movement. Afterwards, it is asked that the volunteers do the movement from the sitting position on a chair to the completely standing position and then from the standing to the sitting position, using the prototype assistance, 5 times with a resting period between the attempts. When the subject is established in the standing position, it is asked to remove both hands from the prototype, so it is possible, when the data treatment is being done, to separate the Sit-to-Stand movement from the Stand-to-Sit. After each test movement, the participant’s data is saved on a .csv file for further data processing.

During the test, the volunteer can monitor the forces' graphics on the test's Excel file, and its interface is demonstrated in Figure 3.39. In this way, the volunteer has biofeedback for the Sit-to-Stand-to-Sit movement.

The test protocol can be summarized in six steps:

1 – Project explanation and its goal;

2 – Data collection;

3 – Experimental set-up adjustments;

4 – Habituation movements;

5 – Measurements acquisition of five movements completed;

6 – Data treatment.

In the end, the .csv file contains the assessment for the left and right sides of the gripping force, the vertical upper limbs force, and the lower limbs' vertical force. After treating the data and comparing the results, it is possible to draw conclusions about the movement's symmetry, the instability of some individuals, how much assistance from the upper limbs is needed, and how is the raising ratio of the gripping and the upper limbs' vertical forces.

4.2 Volunteers Characterization

For the first phase of the project, with healthy young people, the tests were done at the Applied Mechanical Laboratory, at the Coimbra Institute of Engineering (ISEC). The volunteers were 33 students. It followed the previously cited test protocol and the Table 4.1 shows how the participants are divided by age.

As the individuals of this group are young and healthy, perhaps it would be possible to complete the STS movement without any upper limbs' assistance. However, as the idea of this test was to assess the developed prototype and to define a pattern on how the forces are applied, it was requested to the volunteers use the handles during the manoeuvre.

Table 4.1: Volunteers divided by age.

Age	Gender	Height [cm]	Weight [kg]
24.6 ($\pm$6.7)	Men [24] Women [9]	172.6 (± 9.6)	74.3 ($\pm$ 16.0)

With the tests and the data treatment with the students, it is possible to establish a pattern for the STSTS movement. Later, this standard can be applied and used to compare the results obtained with people in recovery from any injuries and/or elderly.

4.3 Experimental Set-up

The experimental set-up contains six components which need to be positioned before starting the tests: a chair, a walker, two foot platforms, and two systems for the upper limbs' assessment (gripping and vertical force). So, to start the measurements, it is necessary to establish how each one of the components is positioned. And, to have a starting point, the chair is always the reference point.

Once the chair is in a place with enough space for all the equipment and the people who will follow up on the test, the walker needs to be positioned in a way that is comfortable for the volunteers to grab it and do the motion. So, to provide a standard, the walker needs to be centralized with the chair and the handle's maybe by as high as the participant's haunch. In this way, the position to grab the prototype is similar to the one adopted by a person who calls for the use of the walking frame to walk. The prototype's height adjustment is made through the mechanism of the walker which is being used, as the tube clamping is attached to the middle of the piece on the walker where the users grab it.

The foot platform needs to be in a position in which each foot is aligned when on top of it. To adapt its placement to each person and keep the same starting point for the movement, the distance of the foot platform from the chair and the chair height are determined by the angle on the knee joint, which should be approximately 90°. Figure 4.1 shows the sequence of movement during the Sit-to-Stand-to-Sit test.

In this way, the variables due to the system positioning are reduced and the measurements may show the difference exclusively in how each volunteer executes the STS movement. This is an important action, once it minimizes the system variables, improving the result comparison and analysis.

Figure 4.1: Sequence of movement during the STSTS test.

5. Data Acquisition

In this chapter, a brief characterization of the volunteers was made and an explanation about the importance of carrying out tests for the validation of the prototype. Also, a short clarification about the way that the test takes place is presented in this chapter.

The tests during the project were made just with healthy subjects so, in this way, the prototype could be validated. The aim is to use this biomechanical device with subjects who suffer from some impairment in the lower limbs, for example, persons with Parkinson’s Disease, sarcopenia, the elderly, or who had suffered a stroke. So, this prototype can become a powerful tool during the rehabilitation process, on what it is possible to observe and analyse the evolution of the person along the whole process.

An important point of the tests being done by healthy subjects is the establishment of a standard of the analysed forces. With this standard, it is possible to have a better analysis of people in rehabilitation process, once the results obtained can be compared between these two different groups.

This standard is created by analysing the forces measured during the STSTS (Sit-to-Stand-to-Sit) test and building a pattern for how the movement is completed. This standard can set some criteria to define a balanced and well-distributed for a normal STS manoeuvre completed by a healthy subject. In this way, it is feasible to build up an aiming range as a parameter for the movement done by people in rehabilitation process.

During the tests, the volunteer was requested to stand up from the sitting position using the prototype as a natural support for the movement and after the person is stabilized in the standing position, the individual needed to sit down again. Each of these movements sequence accounts for one try and each volunteer completed it five times. Between the two actions (sit-to-stand and stand-to-sit), the individual was asked to remove the hands from the prototype during the stabilization time in the standing position, to be noticeable, the moment in which the first action is over and the second begins.

6. Results and Discussion

In this chapter, the data is divided into upper limbs’ assistance, asymmetry, gripping force, and the questions raised in the Introduction chapter. The results are addressed according to age, gender, weight, and height. As the individuals are all healthy students, the injury history of the subjects is not a parameter that presents relevant importance in the analysis of the results.

This device presented an appropriate operation, it had easy handling for both the instructor and the volunteers. The mechanism did not raise a problem during the 165 STSTS repetitions done by all the participants. The subjects also filled up an anonymous questionnaire, which can be read in Appendix C, evaluating the prototype. In this survey, there were some statements that the volunteers could completely agree, agree, do not disagree or agree, disagree, or completely disagree.

For the statement “I felt discomfort to do the Sit-to-Stand movement!”, 81.8% of the volunteers disagree or disagree completely. For the assertion “The device has all the necessary functions for the procedure”, 97.0% agree or agree completely. For the phrase “I consider that the device performs its function in a simple, correct and adequate way”, 100% agree or agree completely. For the statement “I consider the device ergonomics adequate”, 87.9% agree or agree completely. 93.9% agree or agree completely to the assertion “I consider the application of the measurement system to a walker added value for the device”.

For the statement “I consider that the cable/wires do not represent any restriction for the movements and/or device’s manoeuvrability” 93.9% agree or agree completely. For the phrase “The foot platform did not disturb me to use the device” 93.9% agree or agree completely. For the assertion “I consider the interface to visualize the exerted forces is adequate” 90.9% agree or agree completely. 96.8% agree or agree completely that “Clinically, the device can be an added value on the diagnosis of patients with locomotion problems And, at last, 100% agree or agree completely that “Clinically, the device can be an added value for a patient who is on rehabilitation process for the lower limbs”.

6.1 Upper Limb Assistance

The first parameter to be analysed is the upper limbs’ assistance during the movement to stand up and sit down. Although the acquired data collect the volunteer’s effort throughout the movement, the peak force, that is, the maximal force is an interesting point for analysis.

So, to have a more personalised analysis for each volunteer, the maximal force in percentage of the body weight was considered. Figure 6.1 shows the data of the maximal vertical force applied by the volunteers with its extremes and the quartiles for both genders during the Sit-to-Stand movement.

It is possible to observe that 25% of the male individuals had less than 2.85% of the body weight carried by the right side of the upper limbs during the test, 50% of the volunteers carried less than 7.33% of the body weight, and 75% of the individuals carried less than 10.14% of the body weight with the upper limbs. For the left side, the results were similar with 25% of the volunteers carrying less than 2.16% of the body weight on the test, 50% carrying less than 5.44% of the body weight, and 75% carrying less than 10.59% of the body weight.

For the women, Figure 6.1 shows that 25% carried less than 5.14% of the body weight with the right-side upper limb on the test, 50% carried less than 10.09% of the body weight, and 75% carried less than 10.93% of the body weight during the Sit-to-Stand movement. And for the left side, 25% carried less than 4.47% of the body weight, 50% carried less than 10.62% of the body weight, and 75% carried less than 11.24% of the body weight.

Taking this data into consideration, it is possible to affirm that the volunteers, man or woman, carry, on average, between 15% and 20% of the body weight with the upper limbs. Even if the subjects are healthy students and might not need the arm to complete the Sit-to-Stand manoeuvre, a considerable percentage of the body weight is carried by the arms. Another point is that in the percentage of body weight, women carry slightly more than men during the movement of standing up from a chair.

The same analysis was done for the Stand-to-Sit test and Figure 6.2 shows the data of the maximal vertical force in percentage of the volunteer's bodyweight with the extremes and the quartiles for both genders.

For men, Figure 6.2 shows that 25% carried less than 1.97% of the body weight with the right-side upper limb, 50% carried less than 4.35% of the body weight, and 75% carried less than 7.81% of the body weight. And for the left side, 25% carried less than 1.82% of the body weight, 50% carried less than 3.39% of the body weight, and 75% carried less than 9.29% of the body weight.

And for the women, 25% carried less than 2.58% of the body weight with the right-side upper limbs, 50% carried less than 3.08% of the body weight, and 75% carried less than 6.96% of the body weight. And, for the left side, 25% carried less than 2.51% of the body weight, 50% carried less than 4.06% of the body weight, and 75% carried less than 7.13% of the body weight.

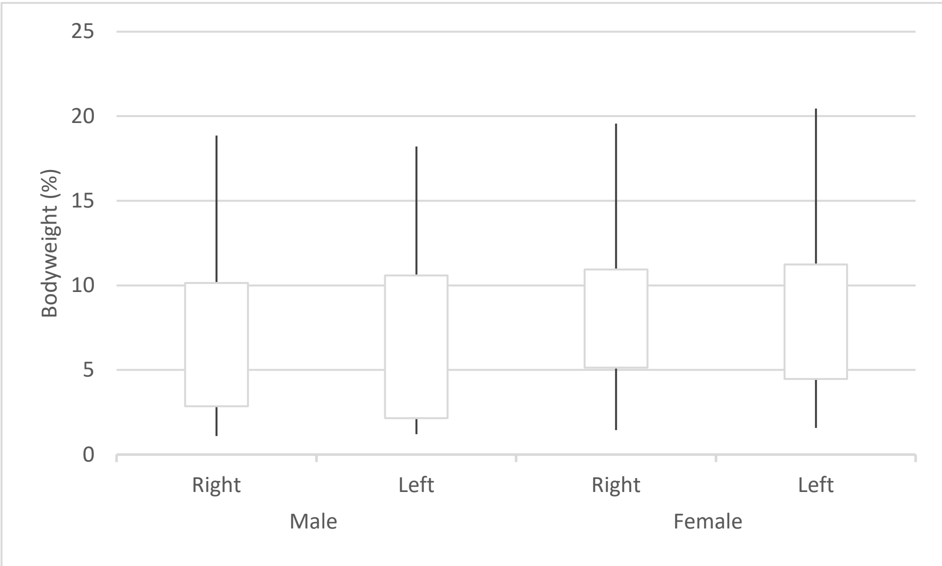


Figure 6.1: Graphic of maximal vertical force in percentage of body weight during the Sit-to-Stand movement.

With this data, it is feasible to assert that men and women carry nearly 10% of their body weight during the movement Stand-to-Sit, even if this group of volunteers would be able to complete the motion only with the lower limbs' activity.

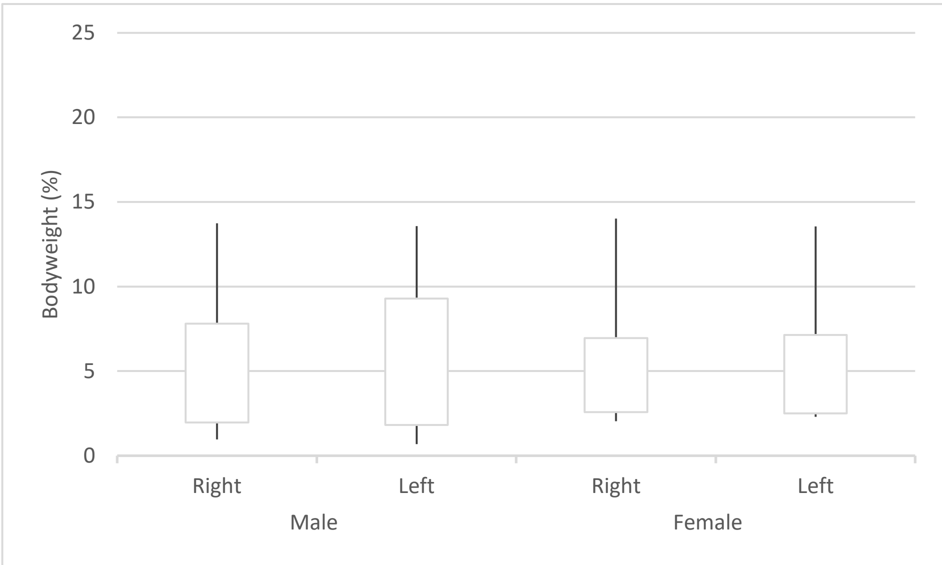


Figure 6.2: Graphic of maximal vertical force in percentage of body weight during the Stand-to-Sit movement.

Another way to analyse the maximal force applied vertically by the upper limbs is by comparing the load exerted to the weight and the height of each volunteer. In this case, gender is not considered and the graphics are generated only focused on the force and the weight or height.

The first of these parameters is the weight. Figure 6.3 presents the maximal vertical force for each volunteer. It is shown the force for the right and the left sides for the Sit-to-Stand and the Stand-to-Sit movements. The volunteers were organized according to their weight, in other words, the first volunteer is the lightest and the volunteer number 33 is the heaviest. Analysing the chart, it is possible to observe that, normally, the force applied is higher when the individual is standing up than sitting down. Also, it is seen that there is symmetry between the right and left sides. However, it is not possible to affirm that the upper limbs' assistance raises by the person's weight and, perhaps, this can be explained by the fact that all the volunteers are healthy students, and, in theory, they would not need to use the prototype support to complete the motions.

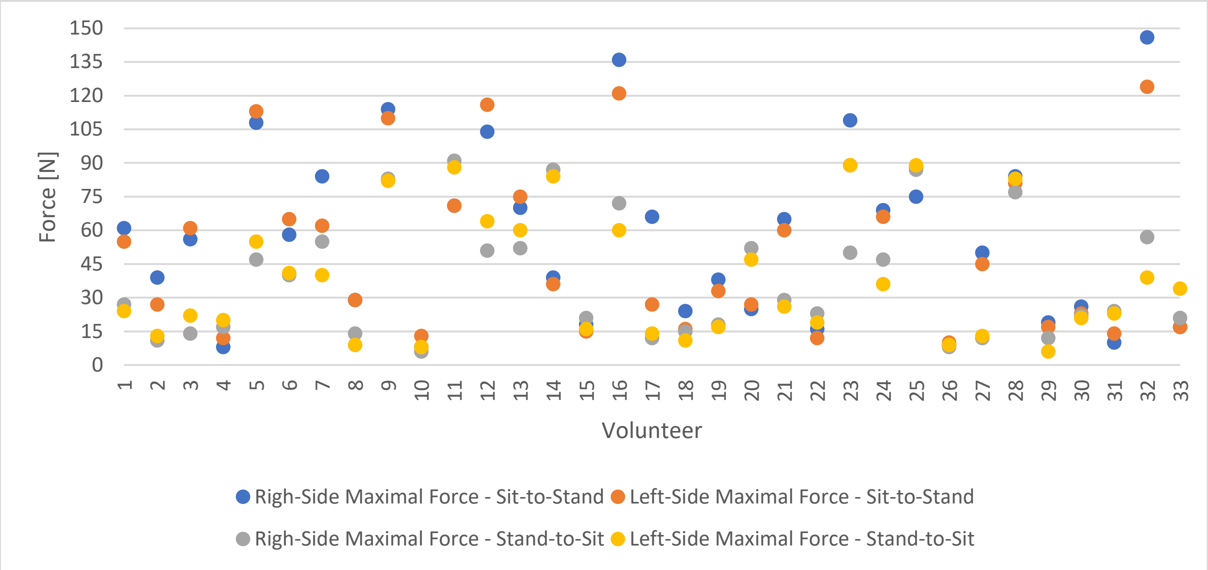


Figure 6.3: Graphic of mean maximal forces during the Sit-to-Stand and Stand-to-Sit movements.

The behaviour of force in relation to height is similar to that shown in Figure 6.3. In other words, the forces are higher when the individual is performing the movement of standing up than to sitting down and symmetry can be noted during the movements, what was the expected result. Figure 6.4 shows the results obtained for the mean maximal vertical force applied by the upper limbs for each volunteer. The individuals were arranged from lowest to highest, that is to say, volunteer 1 is the lowest and the volunteer 33 is the highest.

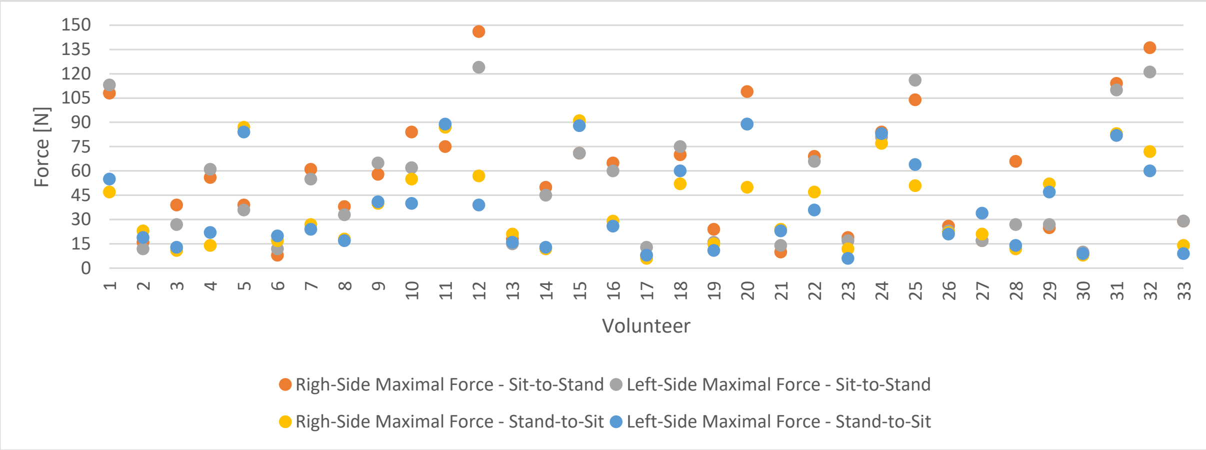


Figure 6.4: Graphic of mean maximal forces during the Sit-to-Stand and Stand-to-Sit movements.

6.2 Gripping Force

Another parameter to be analysed on the STSTS tests done with the volunteers is focused on the gripping force. When the data from the subjects was collected, the gripping force test was done with the device shown in Figure 2.16. On this test, the volunteers are asked to apply the maximal gripping force on the standing position. So, with this data collected, the gripping force during the STSTS test was compared with the maximal gripping force previously collected and the figures in this sub-chapters present the gripping force during the test in the percentage of the maximal gripping force collected.

Figure 6.5 shows the data of the gripping force during the Sit-to-Stand movement with the extremities and the quartiles obtained. It is possible to observe that for the right side, 25% of the men applied less than 5.6% of the maximal gripping force, 50% applied less than 8.4% of the maximal gripping force, and 75% applied less than 12.6% of the maximal gripping force. For the left side, 25% of the men applied less than 3.9% of the maximal gripping force during the test, 50% applied less than 7.9% of the maximal gripping force, and 75% applied less than 10.0% of the maximal gripping force.

For the right side of the women, Figure 6.5 shows that 25% applied less than 12.5% of the maximal gripping force, 50% applied less than 14.8% of the maximal gripping force, and 75% applied less than 20.7% of the maximal gripping force. For the left side, 25% of the women applied less than 7.8% of the maximal gripping force, 50% applied less than 13.4% of the maximal gripping force, and 75% applied less than 14.4% of the maximal gripping previously collected.

In the grip strength test performed before the STSTS movements, women exerted approximately 37% less force than men, either for the right and the left sides. This difference explains that women used more grip strength in percentage of the previously collected maximal gripping force than men.

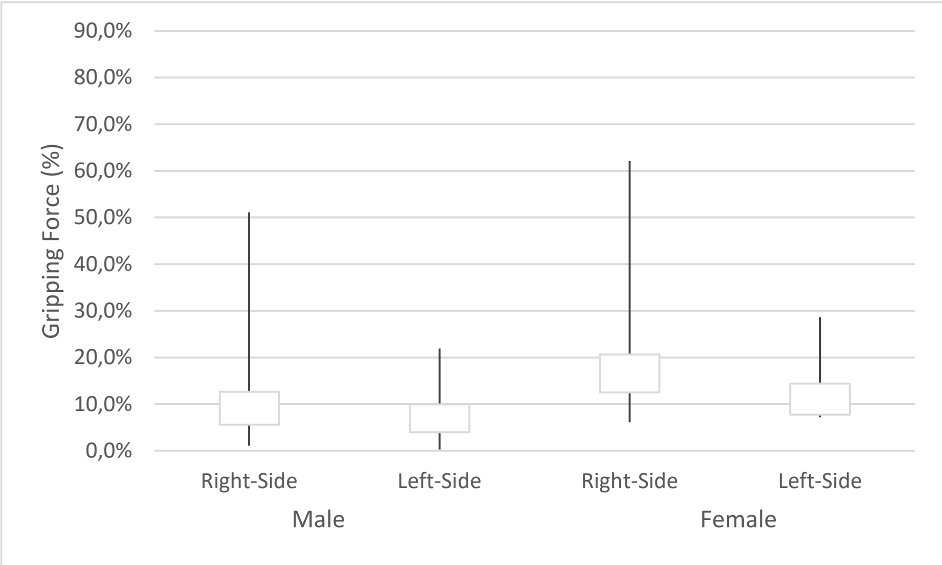


Figure 6.5: Graphic with the maximal gripping force in percentage of the maximal gripping force during the Sit-to-Stand movement.

For the Stand-to-Sit movement, the data with the extremities and the quartiles are shown in Figure 6.6. For the right side, 25% of the men applied, during the test, less than 4.6% of the maximal gripping force, 50% applied less than 6.0% of the maximal gripping force, and 75% applied less than 9.5% of the maximal gripping force. For the left side, 25% of the men applied less than 2.3% of the maximal gripping force, 50% applied less than 4.8% of the maximal gripping force, and 75% applied less than 8.3% of the maximal gripping force.

For the women, on the right side, 25% applied less than 6.7% of the maximal gripping force, 50% applied less than 13.9% of the maximal gripping force, and 75% applied less than 23.8% of the maximal gripping force. And, for the left side, 25% of the women applied less than 6.7% of the maximal gripping force, 50% applied less than 7.8% of the maximal gripping force, and 75% applied less than 14.9% of the maximal gripping force.

As happens with the Sit-to-Stand movement, on the Stand-to-Sit motion, women presented the usage of the gripping force in a higher percentage of the maximal gripping force previously collected than the men.

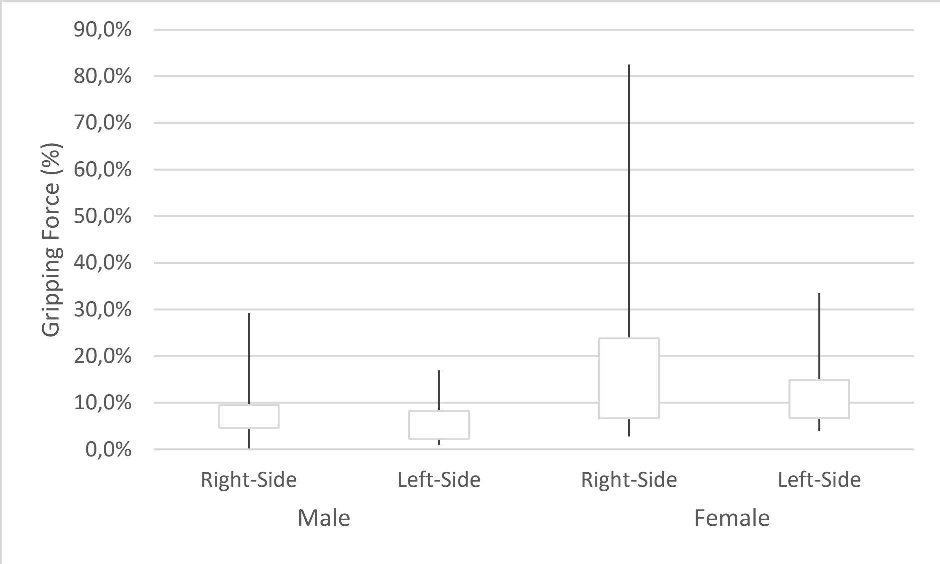


Figure 6.6: Graphic with the maximal gripping force in percentage of the maximal gripping force during the Stand-to-Sit movement.

Analysing the figures, it can be observed that the gripping force during both movements is similar. For men, the percentage of the gripping force is slightly higher in the Sit-to-Stand movement. And, for the women, the top extremity is considerably higher on the Stand-to-Sit movement, nonetheless, the averages of both movements are similar.

6.3 Asymmetry

One great advantage of this prototype is the measurement that is made separately for the right and the left side. So, in this way, it is possible to compare the forces for both sides and analyse the symmetry of the volunteer during the STSTS movement. So, this chapter will analyse the symmetry of the motions for the upper limbs, lower limbs, and gripping force.

6.3.1 Lower Limbs

As all the volunteers are healthy students, the movement to stand up from a chair or to sit down can, normally, be done only using the lower limbs to complete these motions. The measurement of the force applied by each foot varies according to the individual's body weight.

However, to make a general analysis of the volunteers of the prototype, the average of the maximal foot force exerted by each foot from all the volunteers was converted into graphics. For the Sit-to-Stand movement, Figure 6.7 shows that the mean maximal foot forces for men are 363.63 N for the right side and 365.13 N for the left side, and for women the values are 300.00 N and 274.89 N for the right and left sides, respectively. Meanwhile, considering the standard deviation, both gender exerted a symmetric movement during this motion.

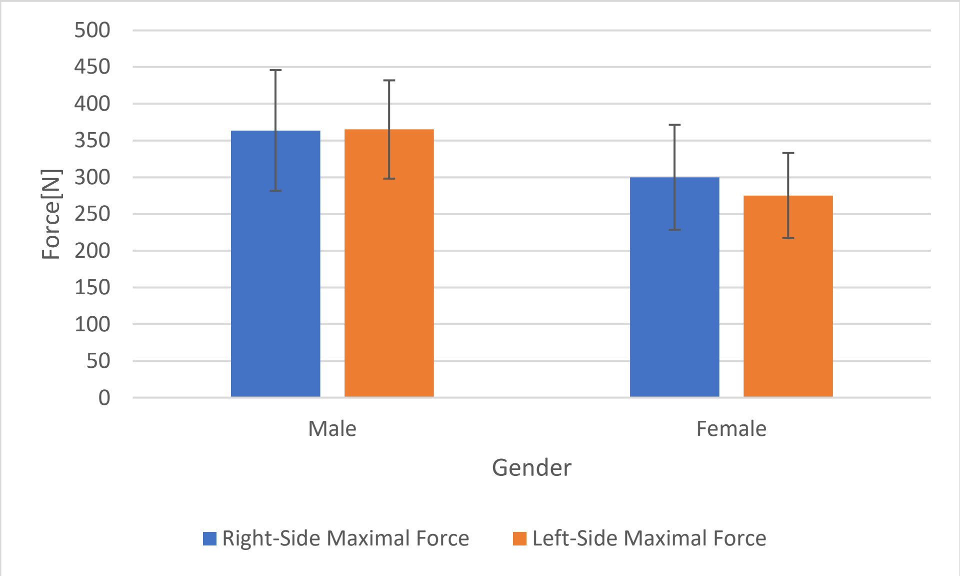


Figure 6.7: Graphic of mean maximal foot force during the Sit-to-Stand movement.

As is shown in Figure 6.8, for the movement Stand-to-Sit, the mean maximal foot efforts measured were similar to the motion previously cited, which demonstrates that the individual, usually, did not exert much different effort for the movements. In this situation, the mean maximal foot forces presented by the men were 369.54 N and 357.13 N for the right and the left sides, respectively. For the women, these efforts are 305.78 N for the right side and 276.44 N for the left one. So, for this motion, taking the standard deviation into consideration, women and men applied symmetric forces.

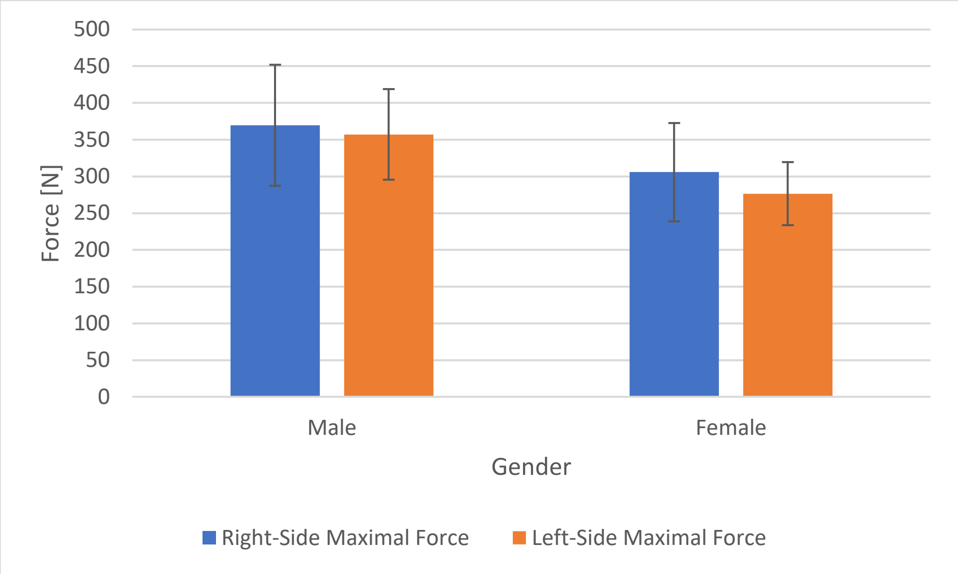


Figure 6.8: Graphic of mean maximal foot force during the Stand-to-Sit movement.

Analysing these two figures above, it is possible to affirm that, in this test, men presented higher symmetry than women either on the Sit-to-Stand or the Stand-to-Sit movements. As expected, the male individuals exerted bigger force than the female ones for the Sit-to-Stand movement, once the men are, normally, heavier than women. However for the first movement, the men exerted a higher force, the same can not be observed for the Stand-to-Sit movement.

6.3.2 Upper Limbs

Another parameter where the symmetry is assessed is the upper limbs’ vertical force. So, in this case, the average maximal vertical force is exposed and compared by side, gender, and movement. In this way, it is possible to analyse if the upper limbs’ assistance is done in a similar way on the right and the left sides.

As it is shown in Figure 6.9, during the Sit-to-Stand movement, men exerted, on average, 58.17 N and 53.38 N for the right and the left side, respectively. And women exerted 50.56 N for the right side and 49.89 N for the left one. However, for this force, the standard deviation is large, which suggests that the force applied vertically by the upper limbs varied considerably among the volunteers and, also, a symmetric movement can be considered symmetrical.

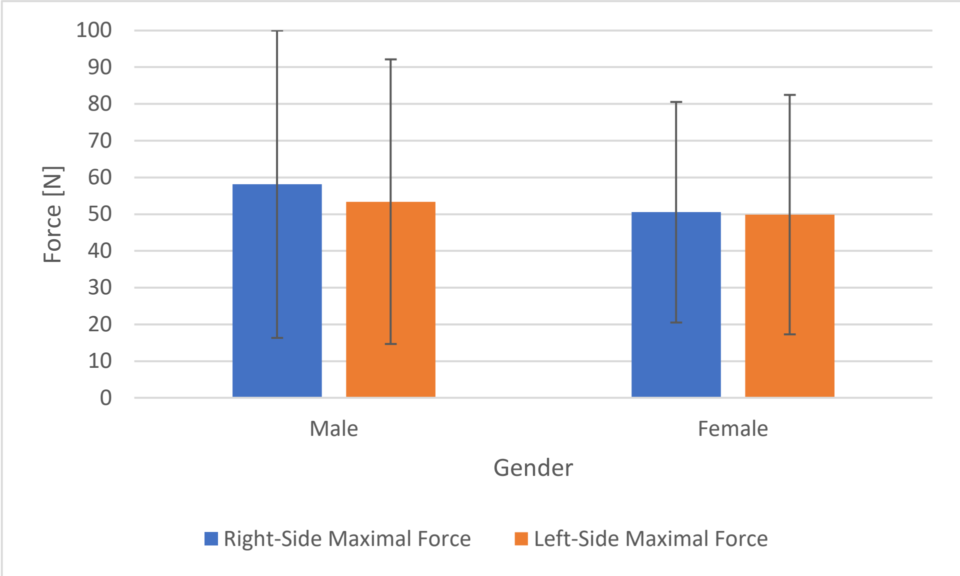


Figure 6.9: Graphic of mean maximal upper limbs' vertical force during the Sit-to-Stand movement.

After the subjects stood up, they were asked to remove their hands from the prototype's handle, so it was possible to separate the movement of standing up from the movement to sitting down. This separation happens when the person is in the standing position and, as the upper limbs measurements (gripping and vertical force) go to 0, it is possible, during the data treatment, to know when one movement ends and the other one starts.

Then, the same analysis that was done for the Sit-to-Stand movement is done for the Stand-to-Sit movement. When it is compared the upper limbs' assistance during both motions, the applied force during the Stand-to-Sit is smaller than the applied force during the Sit-to-Stand movement. This difference exists for both genders, while for men the force goes from 58.17 N and 53.38 N to 40.25 N and 40.13 N for the right and left sides, respectively. For the women, this difference goes from 50.56 N and 49.89 N to 32.00 N and 33.22 N for the right and left sides.

The applied force is smaller, but the behaviour of the standard is as wide as in Figure 6.9, so it can be considered that there was a symmetry for this executed movement. if the symmetry between the sides in both movements is compared, a better result is observed for men. Figure 6.10 shows the mean maximal force for the upper limbs' vertical force during the Stand-to-Sit manoeuvre.

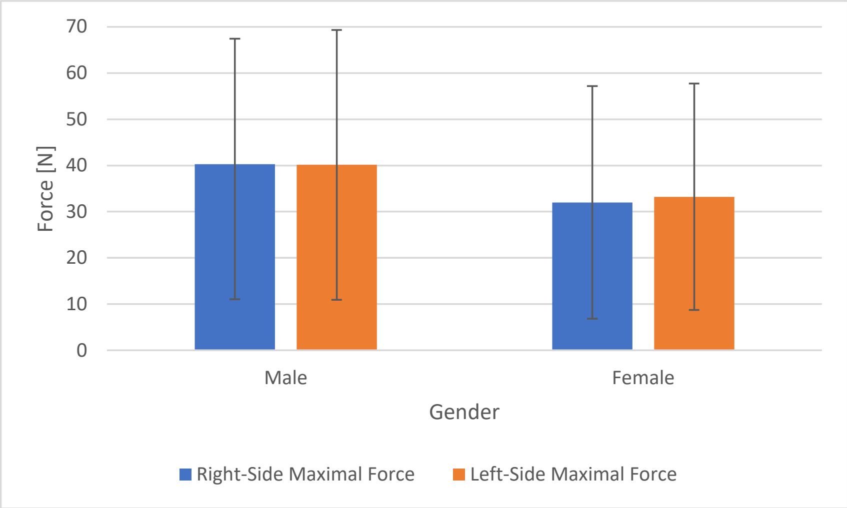


Figure 6.10: Graphic of mean maximal upper limbs’ vertical force during the Stand-to-Sit movement.

6.3.3 Gripping Force

The last parameter that the symmetry is analysed is the gripping force. Figure 6.11 shows the mean maximal gripping force for men and women during the Sit-to-Stand movement. For men, the mean maximal gripping force on the right side is 45.71 N and on the left side is 31.38 N, with the right side exerting more force than the left side. For the women, the mean maximal gripping force was 47.67 N and 31.11 N for the right and the left sides, respectively. So, the women applied more gripping force on the right side than on the left one. Although, with the standard deviation, the force exerted varied between the volunteers, which can lead to the conclusion that the gripping force applied does not present great asymmetry in each of the individuals involved in the validation of the prototype.

Figure 6.12 shows the mean maximal gripping force for each side during the Stand-to-Sit movement. For men, the mean maximal gripping force was 37.58 N and 24.25 N for the right and the left sides, respectively. Meanwhile, the mean maximal gripping force for the women was 43.11 N on the right side and 25.78 N on the left one. Again, the behaviour of the standard deviation is similar to the graphic in Figure 6.11, suggesting that, for the Stand-to-Sit movement, the symmetry in the gripping strength of the volunteers is not very great, even if it is bigger than for the Sit-to-Stand motion.

One aspect to take into consideration is that the dominant side of the vast majority of the volunteers is the right side. So, it is possible to make a direct relation between the fact that the highest gripping force was presented on the right side and the dominant side of the volunteers.

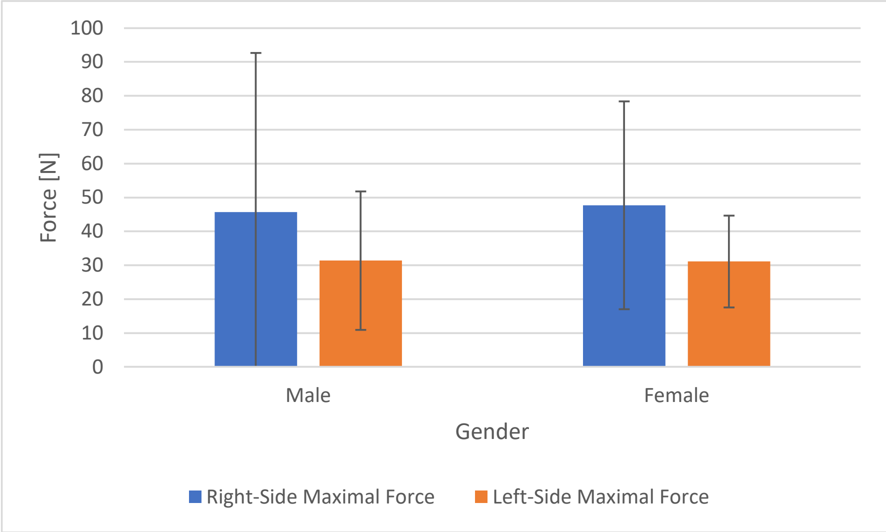


Figure 6.11: Graphic of mean maximal gripping force during the Sit-to-Stand movement.

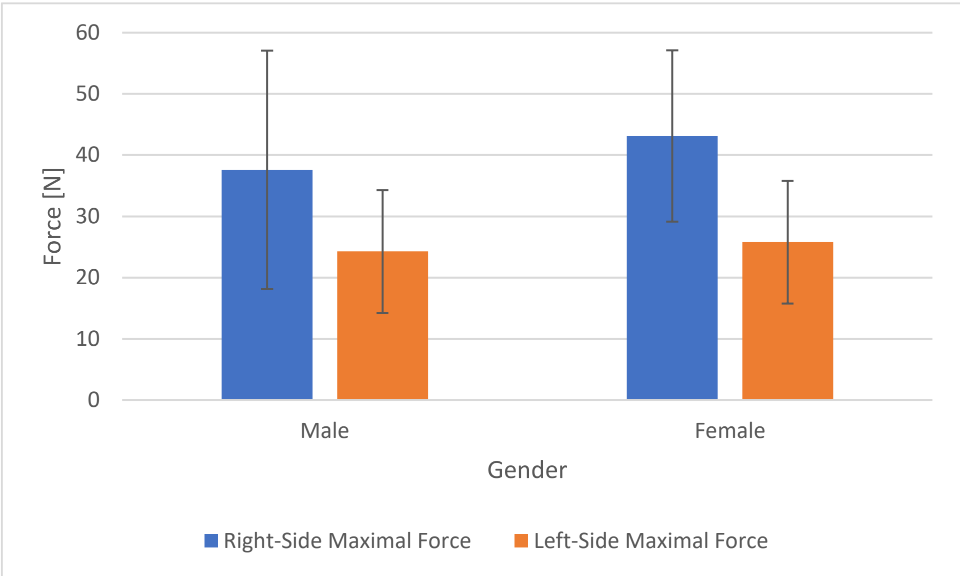


Figure 6.12: Graphic of mean maximal gripping force during the Stand-to-Sit movement.

6.3.4 Overall

After analysing these results focused on the asymmetry of the movement obtained on the STSTS tests, it is not possible to stablish a relation between the person's health level, since all the volunteers were healthy students from the ISEC. It does not matter if the assessment was made with men or women, the result, according to the symmetry of the motion, is similar between the genders.

Taking into consideration the force exerted by the feet of the subjects, the movement is a bit more asymmetric for the women. When this asymmetry is presented, the right side carries more load than the left side, which can be explained by the fact that for the great majority of the volunteers, the dominant side is the right one. There is no perceptive difference between the two manoeuvres under assessment. For the upper limbs’ vertical force applied during the STSTS tests, the movement, either for the men or for the women can be considered symmetric, once it is not observed a big difference in the forces measured for the right and the left sides.

Among the parameters analysed, the gripping force is the one with some noticeable asymmetry during the movements. Both genders exerted more force on the right side than on the left side and this difference is noticeable, once it is between 45% and 67% more. And this is seen in the Sit-to-Stand and the Stand-to-Sit movements.

6.3 Vertical Arm Force X Gripping Force

An important point is the way that the gripping force increases during the movements and it belongs to the motivation for the development of this prototype. As the measurement of the gripping force is a groundbreaking analysis of STS tests, there was a perception of how the volunteers would exert this force while the motion was completed.

With this unknown behaviour of the gripping force, some questions were raised during the project such as if people who presented higher gripping force during the STSTS movement execute a more unstable movement, and if the gripping force and the vertical force raise nearly in the same proportion.

For the first topic, as all the volunteers are healthy students, the motions either for both the Sit-to-Stand and the Stand-to-Sit movements were stable movements, on what the individuals could even have completed the manoeuvre without the upper limbs’ assistance. So, to have a better view and/or analysis of the movements’ instability, it is necessary to expand the range of volunteers also for people in rehabilitation processes or who suffer from an impairment.

And when the gripping force exerted over the tests is compared to the vertical force resulting from the upper limbs’ assistance, it was expected to build a relationship between them. However, the results obtained, showed a different perspective.

Figures 6.13 e 6.14 show the data of the maximal gripping force, in percentage of the maximal vertical force for each subject. In the graphics on the figures, the volunteers were displayed from the smallest maximal vertical force to the biggest one, in other words, the volunteer 1 applied the smallest maximal vertical force and the volunteer 33 the biggest one. These forces, in movements done by healthy people, seem to be independent, in other words, even when the vertical force gets bigger, the gripping force can be very small, or the other way round can also happen. In Figure 6.13 and 6.14, the only relation that can be constructed is that when the maximal vertical force is smaller, the maximal gripping force, in percentage of the vertical force, is bigger than when the subject exerts a higher maximal vertical force.

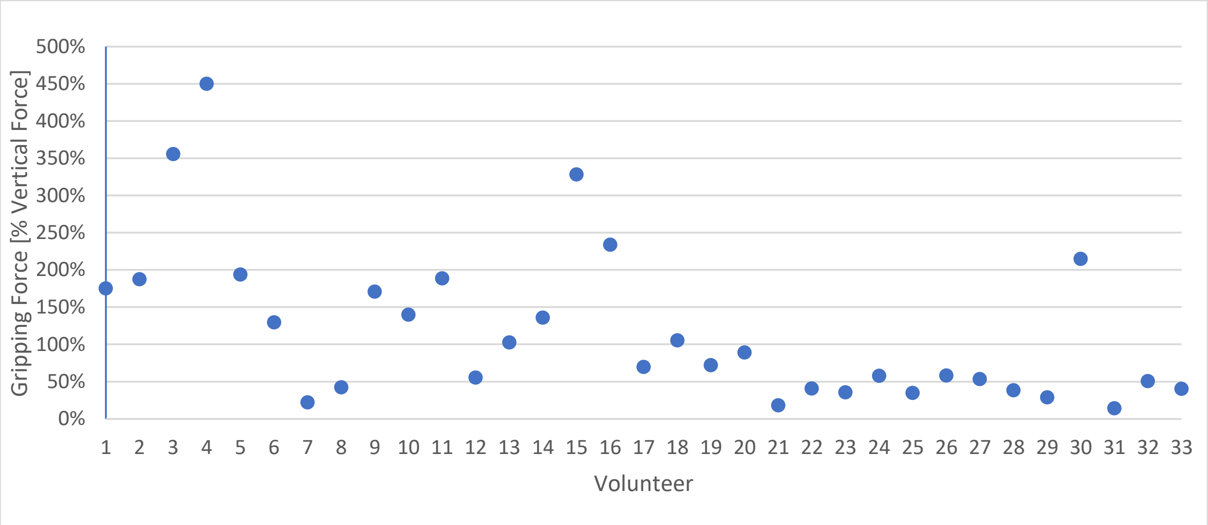


Figure 6.13: Graphic of Maximal Gripping Force in percentage of the Maximal Vertical Force for the right side during the Sit-to-Stand Movement.

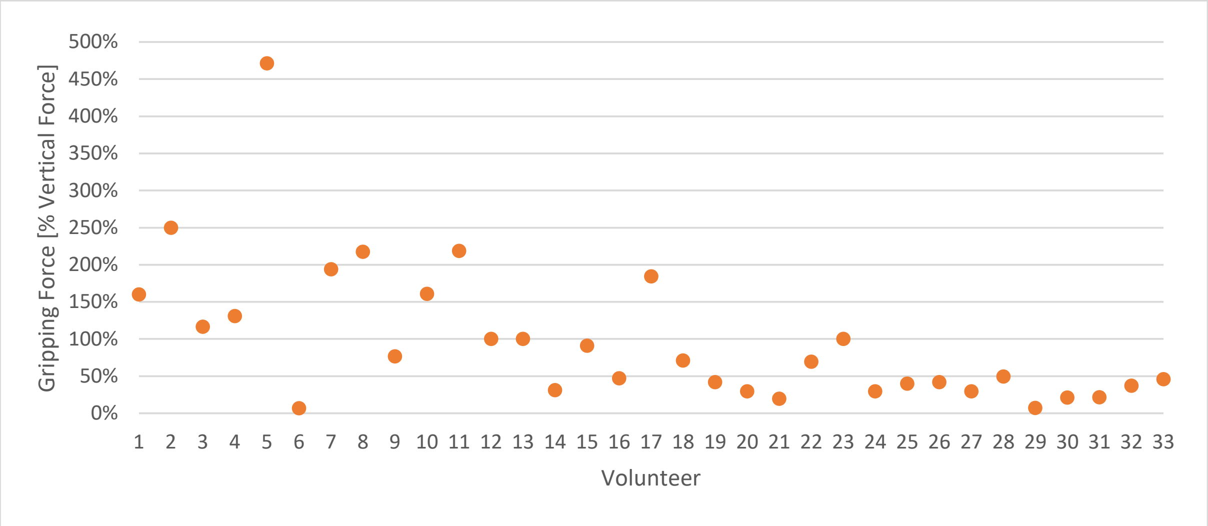


Figure 6.14: Graphic of Maximal Gripping Force in percentage of the Maximal Vertical Force for the left side during the Sit-to-Stand Movement.

Figure 6.15 e 6.16 have the data obtained for the maximal gripping force in percentage of the maximal vertical force for the Stand-to-Sit. As on the previous data analysed, the volunteers were arranged from the smallest maximal vertical force to the biggest one. Like the data for the Sit-to-Stand movement, in this motion, the maximal gripping force represents a higher percentage of the maximal vertical force for the volunteers who exerted less vertical force during the manoeuvre.

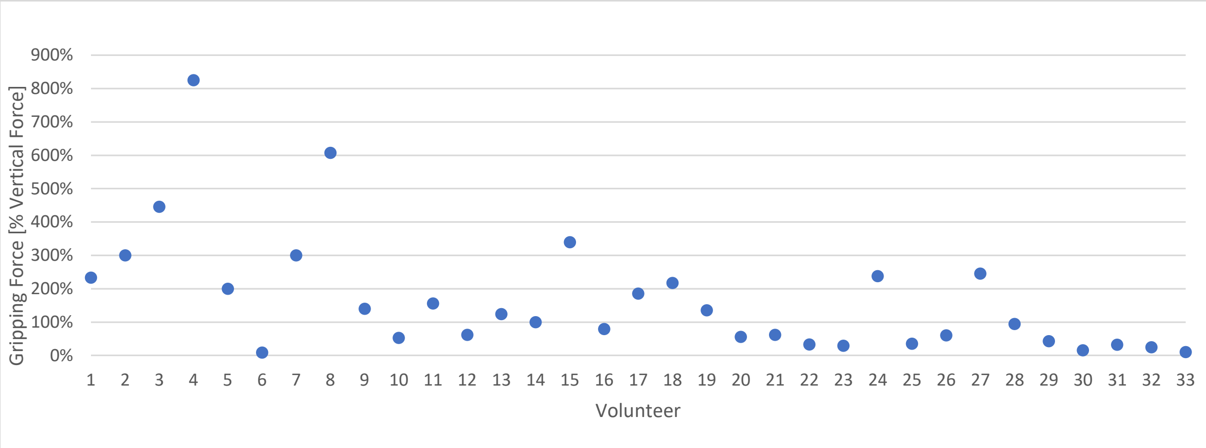


Figure 6.15: Graphic of Maximal Gripping Force in percentage of the Maximal Vertical Force for the right side during the Stand-to-Sit Movement.

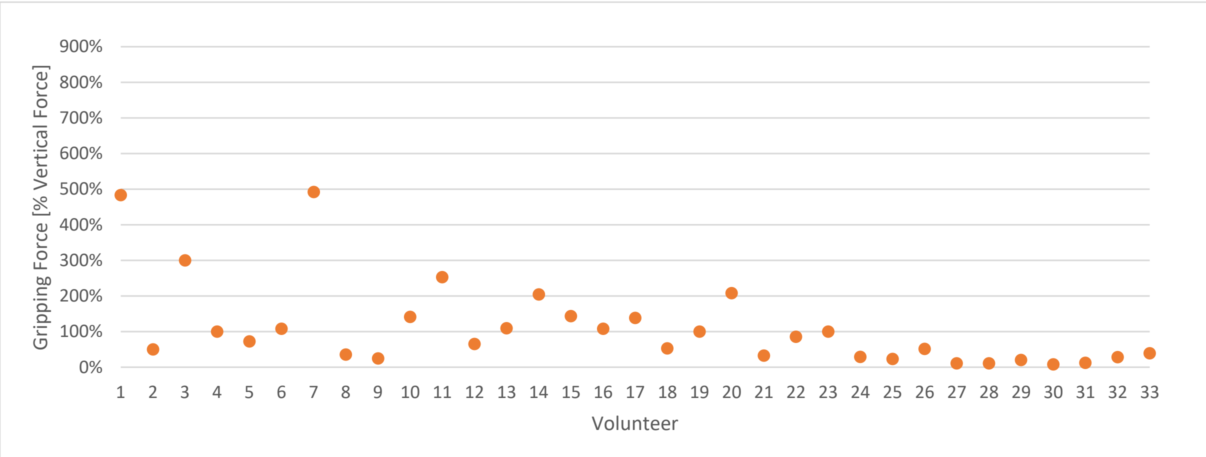


Figure 6.16: Graphic of Maximal Gripping Force in percentage of the Maximal Vertical Force for the left side during the Stand-to-Sit Movement.

6.4 Instability

One of the goals of this prototype is to identify possible unstable movements during the tests. However, this kind of motion is more susceptible for people who are in rehabilitation processes or elderly and people who suffer from an impairment. And, as the tests were done with healthy and young subjects, this instability could not be noted.

All the subjects involved were able to complete the movements just with the lower limbs' effort and it is seen for some volunteers who did not apply great loads for the vertical force. What was expected to be a signal of instability during STSTS movements is the high necessity of the upper limbs' assistance and the gripping force varying according to the instability of the motions.

6.5 Overview

Another analysis that is possible to do with the data acquired is the development of the forces over time. The graphic behaviour of the volunteers presents a similarity, even if the forces during the movement are different. It is possible to observe some symmetry between the sides and check when the peak of each force happens. So, the figures exposed in this sub-chapter shows the data from one volunteer but represents the general behaviour of the forces during the STSTS tests.

The first data analysed over time is the force exerted by the subject's feet, which is shown in Figure 6.17. There is a symmetry between the left and the right sides over the whole movement. As it was asked the individual to remove their hand from the prototype when they were stabilized in the standing position, it is shown a plateau on the force between the 2.8 s and 4.3 s. For the measurements during the STSTS motions, it is possible to observe a force peak in both situations, a peak between 1.3 s and 1.6 s on the Sit-to-Stand movement and another peak between 5.2 s and 5.5 s on the Stand-to-Sit motion.

Figure 6.18 shows the data of the vertical force over time and it is also possible to observe a peak force on both motions of the STSTS movement. The peak force on the Sit-to-Stand manoeuvre is between 2.2 s and 2.5 s, which is the same moment of the valley presented on the foot force exerted, in Figure 6.17. For the Stand-to-Sit motion, the peak force happens between 4.6 s and 4.9 s, which also matches the valley present in Figure 6.17. The fact that the peak force of the upper limbs' vertical force is coincident with a smaller foot force suggests that this is the moment when the individual uses the upper limbs' assistance. In Figure 6.18, between 3.4 s and 4.3 s there is no force exerted, being the time that the subject is stabilized standing.

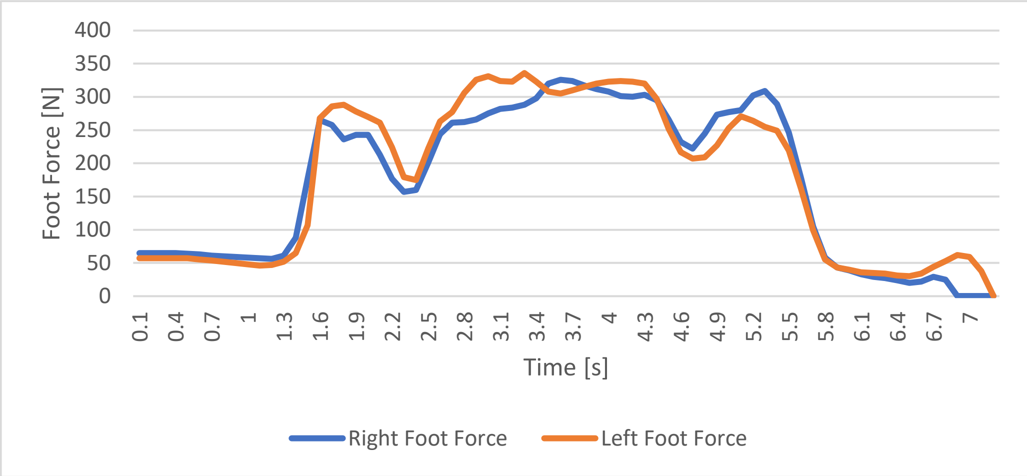


Figure 6.17: Graphic of Foot Force versus Time during the STSTS movement.

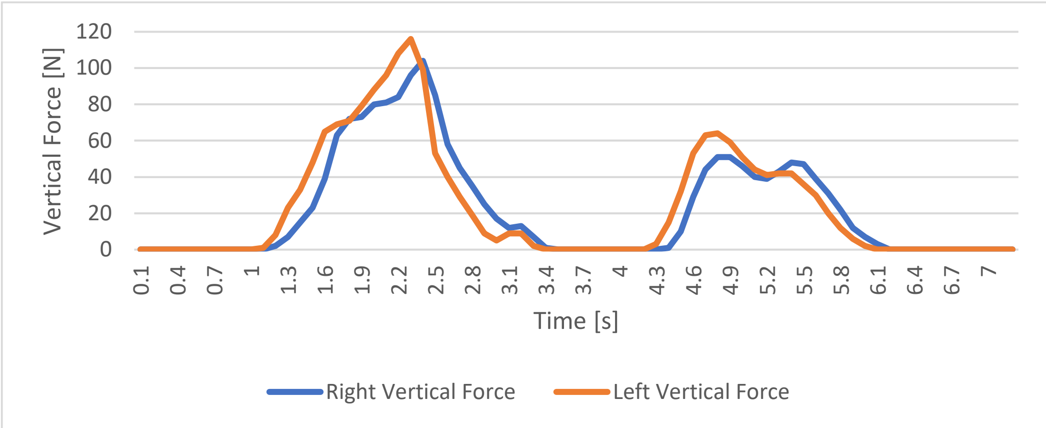


Figure 6.18: Graphic of Upper Limbs' Vertical Force versus Time during the STSTS movement.

Figure 6.19 shows the development of the gripping force over time. The peak of gripping force for the Sit-to-Stand movement happens between 1.3 s and 1.6 s, that is the moment that the volunteer starts to apply force with the upper limbs, as it is shown in Figure 6.18. And, for the Stand-to-Sit movement, the peak of gripping force happens between 5.3 s and 5.6 s, which is coincident with the moment that the individual starts to reduce the force applied by the upper limbs. Apart from a small force applied around 3.1 s, the time that the subject does not apply gripping force is longer than for the vertical force, which suggests that the gripping force is applied for a shorter period than the vertical force.

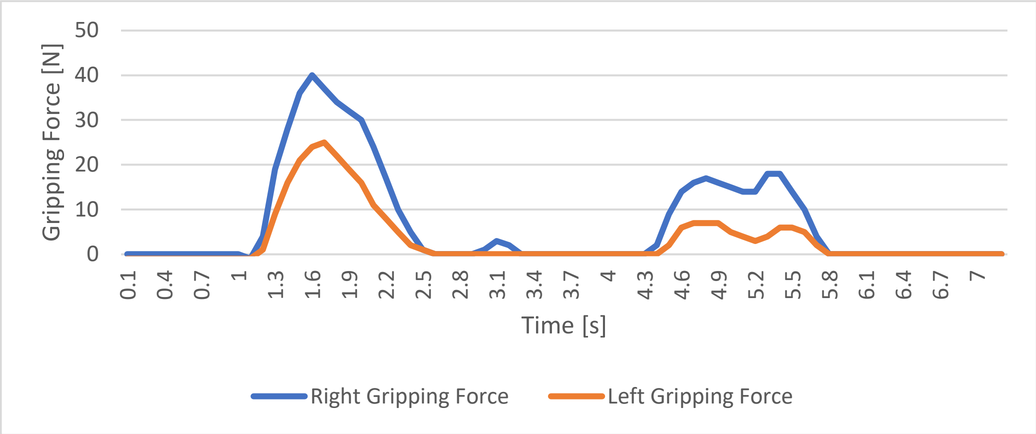


Figure 6.19: Graphic of Gripping Force versus Time during the STSTS movement.

7. Conclusions and Future Work

This master’s thesis was dedicated to the development of a prototype to contribute to the STSTS tests. After the literature review and the research, the first step was the design of the structure with the CAD software SolidWorks® 2021. It was decided that the device would be portable and suitable for any type of walker, which is an ordinary device for people in rehabilitation process or the elderly. After the design, the electronic system was developed with load cells, amplifiers, and Arduino. Then, 3D-printed boxes were manufactured to keep all the electronics protected and attached to the walker in a way that does not disturb the subjects’ movements.

The prototype had the desired behaviour and an adequate operation after several repetitions, allowing to obtain a parameter set that contributes to the assessment of the movement during the STSTS tests. In addition, the walker’s mechanism for height adjustment worked out very well for all the volunteers, allowing the handle of the prototype to be at the appropriate height.

After the data treatment, it was analysed the upper limbs’ assistance during the movement, the asymmetry, and the instability of the individuals. The biofeedback developed on the software Excel is another great advantage, once the individual could follow up the movement effort while the test is done.

At the beginning of the project, some research questions were raised to be answered after the tests were completed. One of the questions was if there is a relationship between the upper limbs’ assistance and the body weight of the individual. As the tests were made with healthy people, even if the person was heavier, it did not mean that these volunteers would use more of the arm to perform the movement. The debate if the gripping force and the upper limbs’ vertical force brought an answer that, for healthy volunteers and based on the results obtained, apparently, there was no straight relationship between these forces. A healthy person can apply the gripping and the vertical forces independently.

Another question was the possibility to link asymmetry with impairments or upcoming impairments, but, this case could not be analysed, once there were no volunteers with impairments doing the tests. And, in the end, the enquiry if an unstable movement brings a higher gripping force also could not be assessed, as there were no unstable movements among the volunteers who participated in the tests.

However, one perception of the data acquired from the tests was that, for the subjects involved, the foot and the vertical forces presented considerable symmetry during the STSTS motions. Meanwhile, the average maximal gripping force registered reveals an asymmetry, with the dominant side of the volunteers (the right side for the vast majority) applying more force than the other side.

So, these tests were important to validate the whole prototype and have a first view of how these six parameters analysed are linked. However, to have a more detailed database and build more connections between the efforts, these tests need to be expanded for a group of volunteers who present an impairment or the elderly. In this way, the questions according to the instability that were raised may be answered.

For future works related to this project, there are some ideas:

- Expand the tests for groups of people with an impairment or elderly;
- Implement the Bluetooth modulus and get the data from the Arduino with a wireless connection;
- Improve the data acquisition for a higher frequency;
- As the analysis of the data acquired in the project was descriptive, carry out a deeper and more detailed analysis of the efforts exerted by the volunteers.
- Add one more data acquisition for the force under the buttocks when the individual sits on the chair;
- Outside of the scope of the STS movement, remove the foot platforms and do different tests such as walking with the prototype and getting the measurements of the vertical force and the gripping force simultaneously.

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Appendix A – Main Code for the Arduino

```
#include "HX711.h"
HX711 scale;

uint8_t DOUT_1 = 3;
uint8_t CLK_1 = 2;
uint8_t DOUT_2 = 5;
uint8_t CLK_2 = 4;
uint8_t DOUT_3 = 7;
uint8_t CLK_3 = 6;
uint8_t DOUT_4 = 9;
uint8_t CLK_4 = 8;
uint8_t DOUT_5 = 11;
uint8_t CLK_5 = 10;
uint8_t DOUT_6 = 13;
uint8_t CLK_6 = 12;
HX711 scale_1;
HX711 scale_2;
HX711 scale_3;
HX711 scale_4;
HX711 scale_5;
HX711 scale_6;

float calibration_factor_1 = 87610; // Right Vertical Force
float calibration_factor_2 = -27750; // Right Gripping Force
float calibration_factor_3 = -22250; // Right Foot Force
float calibration_factor_4 = -21950; // Left Foot Force
float calibration_factor_5 = 86250; //Left Vertical Force
```

```
float calibration_factor_6 = -35750;  // Left Gripping Force


void setup() {
  Serial.begin(9600);
  Serial.println("Press T to tare");
  scale_1.set_scale(calibration_factor_1);
  scale_2.set_scale(calibration_factor_2);
  scale_3.set_scale(calibration_factor_3);
  scale_4.set_scale(calibration_factor_4);
  scale_5.set_scale(calibration_factor_5);
  scale_6.set_scale(calibration_factor_6);
  scale_1.begin(DOUT_1, CLK_1);
  scale_2.begin(DOUT_2, CLK_2);
  scale_3.begin(DOUT_3, CLK_3);
  scale_4.begin(DOUT_4, CLK_4);
  scale_5.begin(DOUT_5, CLK_5);
  scale_6.begin(DOUT_6, CLK_6);
  scale_1.tare();
  scale_2.tare();
  scale_3.tare();
  scale_4.tare();
  scale_5.tare();
  scale_6.tare();
}
void loop() {
  Serial.print((9.81 * scale_1.get_units()), 0);
  scale_1.set_scale(calibration_factor_1);
  Serial.print(',');
  Serial.print((9.81 * scale_2.get_units()), 0);
```

```
scale_2.set_scale(calibration_factor_2);
Serial.print(',');
Serial.print((9.81 * scale_3.get_units()), 0);
scale_3.set_scale(calibration_factor_3);
Serial.print(',');
Serial.print((9.81 * scale_4.get_units()), 0);
scale_4.set_scale(calibration_factor_4);
Serial.print(',');
Serial.print((9.81 * scale_5.get_units()), 0);
scale_5.set_scale(calibration_factor_5);
Serial.print(',');
Serial.println((9.81 * scale_6.get_units()), 0);
scale_6.set_scale(calibration_factor_6);

if(Serial.available())
{
  char type = Serial.read();
  if(type == 't' || type == 'T'){
    scale_1.tare();
    scale_2.tare();
    scale_3.tare();
    scale_4.tare();
    scale_5.tare();
    scale_6.tare();
  }
  if(type == 'S' || type =='s'){
    exit(0);
  }  }}
```

Appendix B - Complementary Code for Calibration

```
if(Serial.available())
 {
   char type = Serial.read();
   if(type == 't' || type == 'T'){
     scale_1.tare(); //Reset the scale to zero }
     scale_2.tare();
     scale_3.tare();
     scale_4.tare();
     scale_5.tare();
     scale_6.tare();
   }
   if (type == 'z' || type == 'Z'){
     calibration_factor_1 += 100;
   }
   if (type == 'x' || type == 'X'){
       calibration_factor_1 -= 100;
   }
   if (type == 'c' || type == 'C'){
     calibration_factor_2 += 100;
   }
   if (type == 'v' || type == 'V'){
       calibration_factor_2 -= 100;
   }
   if (type == 'b' || type == 'B'){
     calibration_factor_3 += 100;
   }
   if (type == 'n' || type == 'N'){
```

```
      calibration_factor_3 -= 100;
    }
    if (type == 'd' || type == 'D'){
     calibration_factor_4 += 100;
    }
    if (type == 'f' || type == 'F'){
      calibration_factor_4 -= 100;
    }
    if (type == 'g' || type == 'G'){
     calibration_factor_5 += 100;
    }
    if (type == 'h' || type == 'H'){
      calibration_factor_5 -= 100;
    }
    if (type == 'j' || type == 'J'){
     calibration_factor_6 += 100;
    }
    if (type == 'k' || type == 'K'){
      calibration_factor_6 -= 100;
    }
    if(type == 'S' || type =='s'){
     exit(0);
    }
  }
}
```

Appendix C - Prototype Evaluation Sheet for Volunteers

Avaliação Funcional do Protótipo de um Dispositivo Biomecânico para Avaliação do Movimento “Sit-to-Stand”

Parte II - Questionário Final a preencher pelo voluntário

Assinale com um X a sua perceção para cada uma das afirmações, numa escala de 1 a 5, onde

1 - Discordo Totalmente; 2 - Discordo; 3 - Nem concordo ou discordo; 4 - Concordo; 5 - Concordo Totalmente.

1. Senti desconforto ao fazer o movimento sentar-levantar.	1	2	3	4	5

2. O dispositivo possui todas as funções necessárias ao procedimento (aplicação e quantificação da força ao executar o movimento sentar-levantar).	1	2	3	4	5

3. Considero que o dispositivo desempenha as suas funções de forma simples, correta e adequada.	1	2	3	4	5

4. Considero a ergonomia do dispositivo adequada (dimensões, geometria, tato).	1	2	3	4	5

5. Considero que a aplicação do sistema de medição num andarilho é uma mais-valia para o dispositivo.	1	2	3	4	5

6. Considero que os fios/cabos de ligação não representaram restrição de movimentos e/ou de maneabilidade do dispositivo.	1	2	3	4	5

7. A plataforma de colocação dos pés não perturbou a minha utilização do dispositivo.	1	2	3	4	5

8. Considero que a interface com a visualização das forças exercidas é adequada	1	2	3	4	5

9. (Facultativo) Clinicamente o dispositivo poderá ser uma mais valia no diagnóstico de pacientes que têm problemas de locomoção.	1	2	3	4	5

10. (Facultativo) Clinicamente o dispositivo poderá ser uma mais valia para pacientes que estão a passar por um processo de reabilitação nos membros inferiores.	1	2	3	4	5

11. Sugestões de melhoria do dispositivo.

____

____

Obrigado pela sua contribuição.