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Development of a standing disruptive Concept for the mobility of individuals with motor disability

Master's Dissertation
Integrated Master's in Biomedical Engineering

Work done under the supervision of
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October 2017

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Dissertation's title: Development of a standing disruptive concept for the mobility of individuals with motor disability

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Conclusion year: 2017

Master's designation: Integrated Master's in Biomedical Engineering

Area of expertise: Biomaterials, Rehabilitation and Biomechanics

Universidade do Minho, ___/___/_______

Signature:

____

ACKNOWLEDGMENTS

I would like to start by thanking both my mentors, Professor Alexandre Silva and Professor Paulo Flores as they were instrumental in the completion of the dissertation. I am grateful for every sage advice and the constructive criticism which helped greatly in developing the project. I would also like to thank the never-ending support, availability to meet in order to discuss the work and patience for the small and big delays that the project endured.

I cannot show enough appreciation for my whole family who were pivotal in keeping me in good spirits with their everlasting care for me. To my sisters who individual successes make me aspire for more, to my father who helped me in anyway he could in developing and improving the dissertation with his wise knowledge, and to my mother, both with her kind words of encouragement to keep me going and her merciless arguments to keep me from slacking. I also wanted to thank my uncle Jorge, who taught me how to handle the 3D printer and was always available should any problem arise.

To all of my friends who supported me through not only this year, but all the years I spent and will spend in the search of new knowledge. To João Leitão, who mastered the arts of sketching and lend me a hand whenever possible. I am thankful to my friend José Martins, who came through whenever I needed some technical help. To my oldest friend, Daniel Miranda, with his engaging and endless discussions about the gender of the angels who kept us arguing hours on end. A special thank you to Filipa Mota, a great friend with who I had countless adventures during the last six years and for providing for a good amount of laughs. Thank you all for the support, strength and mockery that helped me end this project.

Lastly, I would like to thank God who, although I strongly believe has a dark and twisted sense of humour, has provided my life with great opportunities and greater companionship.

May the thirst for knowledge never be quenched.

ABSTRACT

The present project intends to explore the idea of creating a new and better kind of mobility device, capable of transporting individuals who suffer of mobility impairments. The developments of the dissertation culminated in an explanatory prototype based of a set of requirements and of withdrawn conclusions of the state of the art of mobility devices. It is proposed a novel concept of vertical transport for the mobility impaired. The present idea allows the user greater agility than most mobility devices, improved self-autonomy and operating while in a vertical stance, reducing health risks which the mobility disabled are prone to, both mental and physical. Firstly, it is presented a literature review of the mobility devices targeted for the mobility impaired developed thus far. The analysis of the development throughout history and of the devices currently presented in the market allowed to understand which necessities of the mobility disabled are yet to be answered. Said knowledge is the foundation of a project intended to further improve the quality of life of whoever has such special needs. To counter the list of requirements and specifications, the complex engineering problem was divided in smaller subfunctions that could be more easily answered to. After presenting several solutions to each subfunction, the ones considered best were selected and developed. For designing the device, several steps were taken. For a broader triage of concepts, it was used sketching. Later, the best notions were recreated on the CAD software *SolidWorks,* which allowed for virtual testing of the would-be prototype. Once a design was deemed worthy, the pieces of the mechanism were 3D printed, creating a physical model of the final goal of the project. Thus, it was created the basis of a mobility device for the individuals who suffer from mobility impairments that can be used in the outdoors, reach running speeds and assists in maintaining a vertical stance, diminishing the risks of developing health problems triggered from prolonged times in a seated position.

Key words: SolidWorks, Mobility Device, Mobility Impaired, Vertical Stance, 3D Printing.

RESUMO

O presente projeto pretende explorar a ideia de criar um novo e melhor dispositivo de mobilidade, capaz de transportar indivíduos que sofrem de deficiências de mobilidade. A evolução da dissertação culminou num protótipo elucidativo baseado num conjunto de requisitos e conclusões retiradas do estado da arte de dispositivos de mobilidade. Propõe-se um novo conceito de transporte vertical para quem sofre de problemas de mobilidade. A ideia permite ao usuário uma maior agilidade do que a maioria dos dispositivos de mobilidade, auto autonomia aprimorada e ser operável em posição vertical, reduzindo os riscos de saúde a que os deficientes de mobilidade são propensos, tanto a nível mental como físico. Em primeiro lugar, é apresentada a revisão da literatura sobre os dispositivos de mobilidade desenvolvidos até agora para quem sofre de problemas de mobilidade. A análise do desenvolvimento ao longo da história e dos dispositivos atualmente apresentados no mercado permitiu entender quais as necessidades dos deficientes que ainda necessitam de ser respondidas. O referido conhecimento é o fundamento de um projeto destinado a melhorar ainda mais a qualidade de vida de quem tem tais necessidades especiais. Para a lista de requisitos e especificações, o complexo problema de engenharia foi dividido em subfunções menores que poderiam ser mais facilmente respondidas. Depois de apresentar várias soluções para cada subfunção, os considerados melhores foram selecionados e desenvolvidos. Para projetar o dispositivo, foram tomadas várias etapas. Para uma triagem mais ampla de conceitos, foram utilizados esboços. Mais tarde, as melhores noções foram recriadas no software CAD *SolidWorks*, o que permitiu testes virtuais do potencial protótipo. Uma vez que um design foi considerado digno, as peças do mecanismo foram impressas em 3D, criando um modelo físico do objetivo final do projeto. Assim, foi criada a base de um dispositivo de mobilidade para os indivíduos que sofrem de deficiências de mobilidade que pode ser usado no exterior, alcança velocidades de corrida e ajudam a manter uma posição vertical, diminuindo os riscos de desenvolver problemas de saúde desencadeados por períodos prolongados na posição sentada.

Palavras chave: SolidWorks, Dispositivo de Mobilidade, Deficiência de Mobilidade, Posição Vertical, 3D Printing.

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1 INTRODUCTION

1.1 MOTIVATION

In the current times, there has been a greater effort from society to favour and help the daily basis struggles of individuals that suffer from motor disabilities than ever before. By standard, these individuals find themselves tremendously debilitated about their self-locomotion, being required a movement-aid device of some kind to help with their most simple quotidian tasks. There may be many reasons why a person cannot move freely on its own, such as spinal injuries, amputation or motor control problems. Mobility devices have been extensively used along the years to help with such difficulties.

Mobility aid devices exist since the invention of the cane, although the most emblematic nowadays is the wheelchair. There have been several approaches to improve the wheelchair, from the use of lightweight materials, different geometries for easier usage or storage, more comfortable seats for long usage, as the employment of electrical motors to remove the physical effort required to propel the wheelchair [1, 2].

Nowadays, it is reported the increase of population around the world which is affected by some form of physical disability, subsequently affecting one’s locomotion. By the records of the World Health Organization, it was estimated that 130 million people live with physical handicaps, which corresponds to 2% of the world population. Of these numbers, above 4.3 million use a wheelchair or another movement-aid device on their day to day routines [3]. With the growth of the world population, one can assume that these numbers will only continue to raise. On a more local note, according to the 2011 Portuguese census, the population which declared walking difficulties corresponded to 4.5%, meaning that around 475 300 people in Portugal have movement impairments [4].

Still, an individual with distress or inability to stand will see itself in a sitting position for the large majority of its life. Since the human being is physiologically not adapted to stay seated for long intervals of time, being protracted in a sitting stance may originate new health conditions, both physical and mentally [5]. Due to most of the users of mobility aid devices having chronic health conditions, it is believed that the development of technology to facilitate or mitigate the gravity of the problem should increase. Some solutions to attenuate these problems exist, but they do not avoid them. The best resolution would be to eliminate the cause.

It has been proven through the years that, while in a resting position, a standing stance is more beneficial versus a sitting one. The medical benefits of standing include the improvement/maintenance of bone integrity, strengthen of the cardiovascular system, reinforce circulation and swelling reduction, bowel function improvement, as well as assisting in kidney and bladder functions. A standing position also helps with the management of trunk and lower limbs atrophy, decrease of joint and muscle contractures and reducing the risk of pressure ulcers through changing positions [5].

Additionally, a better conversational interaction, as simple as keeping eye contact during a conversation, helps to increase self-esteem, self-confidence and self-image, diminishing the risk of developing depression. Such a small thing, taken for granted by many, can be crucial for some.

Looking at the market, it is ruled by chaired devices, which propagates the sitting issue. Few help the person to move around in a vertical position, and those who do, can be slow and cumbersome. Most of the standing devices present restricted mobility, difficult usage and present a hybrid composition, still allowing one to sit, which should be reduced as much as possible. Although there has been increasing development of medical and rehabilitation devices for people without self-sufficient mobility, few to none help the individual to keep a standing position, move autonomously, for long periods of time and at a walking to running speed.

As such, it is believed that a new brand of mobility devices is required. Further development of movement technology for the motor disabled could bring great advantages, such as improving the autonomy, confidence, well-being and reducing health problems of individuals with the lower limbs chronically debilitated.

1.2 OBJECTIVES

Most of the mobility aid devices available are considered sitting devices, which means that the user will have a seated stance at all times while operating the mechanism. As discussed before, such practice should be avoided, at expenses of one’s own health risk. The existing devices, which allow the individual to stand, still have much possibility for improvement.

This dissertation has as objective to develop and create a new standing mobility aid device, offering to the user an easy to use mechanism, greater autonomy, more comfort and reducing health issues. It should inspire and stimulate the individual to improve its day-to-day routines. As such, it is proposed the adaptation of an existing mobility device, which can only be used by individuals with lower limbs fully functional, in the original state.

By establishing the objectives for a vertical mobility device for individuals with movement impairment of the lower limbs, it was concluded that the primary objectives would be the user safety, specific functionalities and characteristics, as well as a simple production and usage. These objectives should prove enough for a safe and simple ride of the device.

Beyond the primary objectives, the mechanism should be visually attractive, economic and comfortable for the user. It ought, as well, be durable, which can be achieved by the selection and appropriate combination of the picked materials, as well as its geometry. The device should be capable to surmount obstacles of small dimensions.

The device should be designed, if possible, in a way that allows to reduce the costs of fabrication. Such ambition could be achieved by the usage of normalized components, manufacturing procedures of low complexity and the adaptation of an existing mechanism, avoiding the necessity of creating something from scratch.

To adapt the mechanism to motor disabled people, some considerations are required. As such, it is proposed that the dissertation should answer to a set of questions which are associated to the development of such device, as:

I. What device should be selected as a basic platform to upgrade?
II. How to fixate the vertical device so the user can mount it?
III. How to mount the device?
IV. How to fasten the user to the device?
V. How to keep the balance of the device?

These are the main questions that this dissertation seeks to answer in a preponderant and reasoned way by developing a standing movement aid mechanism for the motor disabled.

1.3 STATE OF THE ART

Erect mobility devices for the motor disabled can be considered still in their infancy. Such devices do already exist, although not widely used. As such, the market is more specialized. The first record of such a device is from 1942 [6]. Erect mobility devices are built with ergonomics in mind, allowing the user to stay in otherwise unpractical or uncomfortable positions for the operator for a prolonged amount of time. However, depending on the design, one might require assistance of a helper to attain full mobility.

To answer the needs of the people with locomotion disabilities, devices with different geometries and faculties are sold. Still, even with a somewhat large array of choices, erecting mechanisms can be classified in two kinds: stand-up wheelchair and standing frames, as indicated in the examples in the figure 1.

A B

Figure 1- Different kinds of erect mobility devices: A - Stand-up wheelchair [7]; B - Standing frame [8].

1.3.1 Stand-up Wheelchair

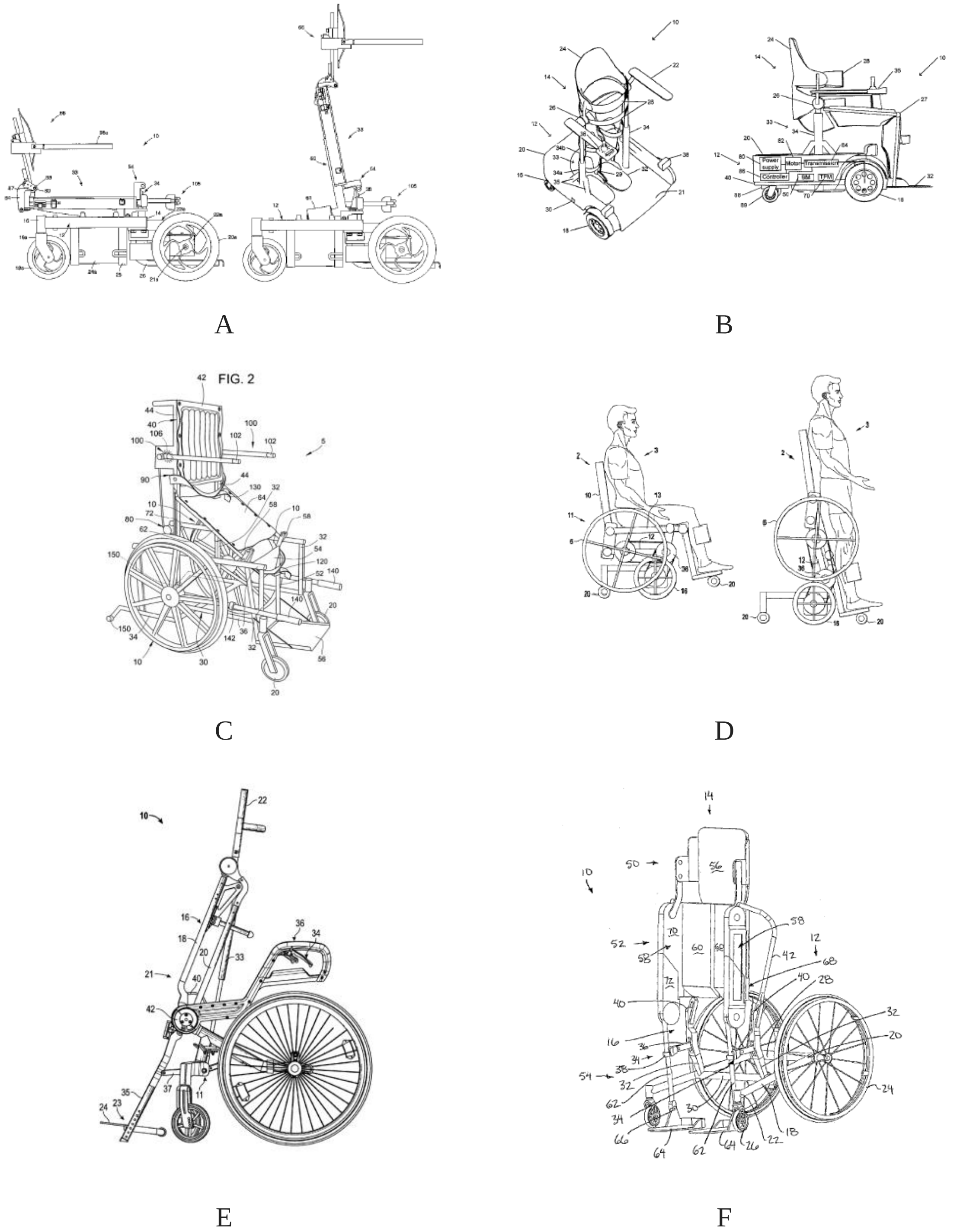
Stand-up wheelchairs are developed from common wheelchairs, granting the user two stances in which the individual can position himself in. It can remain seated, just as a regular chair, or adjust to a standing posture. This can be achieved by a mechanism which allows the mobility device to change between stances, as it will be shown later on. Such capability means that the user can choose a stance at own pleasure. However, one may fall prey to convenience, and use the mobility systems in a sitting position most of the time, not taking advantage of the therapeutic effects of remaining in a standing position [3].

As a general rule, these wheelchairs use a hinged structure comprising a back, a seat, and a footrest. Such an assembly is hinged, normally via the seat, about a front horizontal axis that is perpendicular to the vertical plane of symmetry of the chassis, and drive means are interposed between the chassis and the structure to enable the structure to be raised or lowered, and thus to occupy a sitting position or a standing position. The drive member may be controlled manual, electrical, or pneumatically [9-14].

The several cases studied in the making of the state of the art do indeed satisfy the intended stand-up objective, and in that sense they have undeniably provided improved well-being to users. However, in the stand-up position, such procedure has the effect of transferring the hinged structure and the stood-up user towards the front of the wheelchair, thereby increasing the load on the front wheels and reducing the load on the back wheels. Such forces give rise to instability, since the support is not uniformly loaded. That is why, as a general rule, additional support points are provided to stabilize the wheelchair when the hinged structure is in the stand-up state [9-14].

Although such a proposal, in the general sense, serves to provide a genuine factor of stability and safety for users, it nevertheless gives rise to a problem that is unavoidable when account is taken of the desire for wheelchairs to be movable even when the hinged structure is in the stand-up state. That corresponds to the perfectly understandable desire of users to be able to recover a lifestyle of independence. Reconciling such a desire with the present technique, appears to be incompatible with achieving good stability and, where appropriate, ease of handling.

Some of these devices have patents, such as the ones described in the figure 2.



A B

C D

E F

Figure 2- Different geometries of stand-up wheelchairs found in patents: A- US 6231067 (B1) [9]; B- US 9173792 (B2) [10]; C- US 9044369 (B2) [11]; D- US 7165778 (B2) [12]; E- US 9351891 (B2) [13]; F- US 2015/0283009 (A1) [14].

The device 2.A is an electrical moving mechanism, which allows the user to move without great effort. The standing wheelchair includes a base frame, a pair of front drivable wheels connected to the front end of the frame, and a pair of rear wheels connected to the rear end of the frame. A seat assembly is connected to the front end of the frame and includes a seat portion that is pivotable between a generally horizontal, seated position and a raised, angled standing position. An actuator is connected between the front end of the seat assembly and the rear end of the seat assembly to actuate the seat portion between the seated and standing positions.

The standing wheelchair 2.B was created with a harness assembly, which includes a plurality of braces to attach to the user’s body. The assembly is attached to an electrical wheeled base, which functions as a supporting surface. A lifting unit mounted on the base supports the hip joint of the harness assembly and is configured to be raised or lowered. When raised, the user assumes a standing position and when lowered, a sitting or reclining position.

The device 2.C is a manual wheelchair that allows the user to still move while in a standing position. Manual vertical wheelchairs usually are immobile due to safety mechanisms or lack of reach of the user to operate the wheelchair. In such case, due to the use of chains and gears, the operating system rises or lowers with the user when changing stances. Such invention allows full mobility, independent of the chosen stance.

The mechanism 2.D is a manually operable standing wheelchair with an actuator to transition the occupant from a sitting to a standing position. The lifting device includes a ratchet, cable, pulley and telescopic tubes, which allow the user to manually operate, shifting positions. The wheelchair is also equipped with spring loaded anti-tip front wheels that deploy when the user is standing.

The wheelchairs 2.E and 2.F are quite similar, as they are both made with a minimal design, allowing an easy usage but also presenting some tipping issues. Shifting between stances is achieved by the usage of levers. While standing, it is deployed anti-tipping legs, rendering the wheelchairs immobile.

From the study of these patents, one can examine the strengths and weaknesses of the designs. In terms of vertical mobility, only the devices from 2.A to 2.C allow the user to move by himself while on the standing stance. Only 2.A and 2.B are electrical, and their heavy features, such as the batteries, are used as an advantage, maintaining a low center of gravity. This makes the devices safer for the user, diminishing the risks of tipping over. On the other side, lighter devices such as 2.D, 2.E and 2.F, require an anti-tipping mechanism, rendering the user immobile while taking a vertical stance.

From the commercial viewpoint, these devices have the price range from 3.000 up to 15.000 euros.

Some of the top-selling stand-up wheelchairs can be observed in the figure 3.

A B

C D

Figure 3- Different geometries of stand-up wheelchairs found in the market: A- LEVO C3 Stand Up Wheelchair [15]; B- Karman Stand-Up Power Wheelchair [16]; C- Manual Stand-up Wheelchair LS – LIFESTAND [17], D- Comfort Manual-drive Standing Wheelchair LY-ESB140 [18].

From the figure above, we can distinguish the two types of stand-up wheelchairs on the market: the electric, such as 3.A and 3.B, and manuals, as 3.C and 3.D. Although the electric wheelchairs are more expensive, up to three times the price of manual wheelchairs, they can be controlled by the user with the use of a joystick, granting greater independence to the individual.

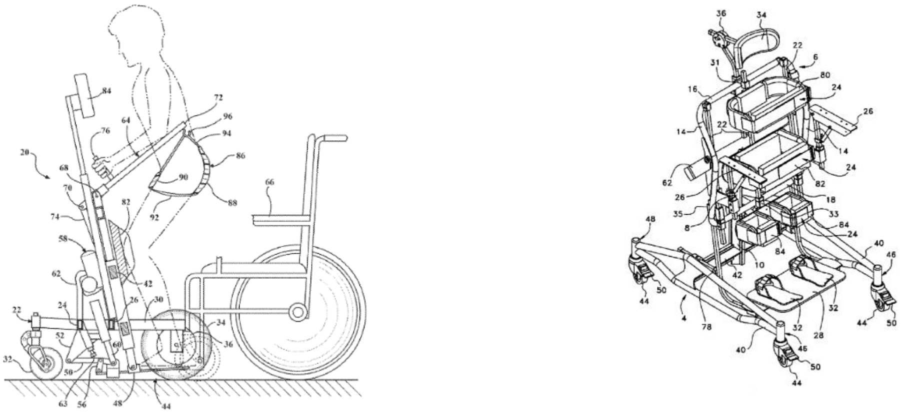
1.3.2 Standing Frames

Standing frames were invented as an alternative to stand-up wheelchairs. Although the later was an adaptation of the famous sitting design, it presented problems with the original scheme. Vertical wheelchairs are known for some shortcomings, such as arranging the wheels in such a manner that the device has an inadequate stability, limiting the ability to transport the users over a wide variety of terrain or in tight interior conditions.

Standing frames were created with a more indoors approach in mind. They occupy less area, making them more agile and easy to operate in close quarters, and has a more stable and lower gravity centred body.

These devices were also created with another purpose - as transfers. Moving a patient from a bed to a sitting or standing position is a significant source of injury to health care workers [19-21]. Manually lifting a person can cause serious strain on the back and shoulders of the aiders. Transfer devices have thus been developed to assist in the lifting and transfer function of handicapped users.

Some of these devices have patents, such as the ones described in the figure 4.



A B

Figure 4- Different geometries of standing frames found in patents: A- US 2012/0255118 (A1) [22]; B- US 7036512 (B2) [23].

The standing frame 4.A is a device, which includes a mobile base and a foot platform. Both are connected at an angle that is comfortable to the user, supporting during the procedure. The device supports the operator with straps and a harness. The mechanism has two arms that, in synchronization with an electrical motor, function as a crane for the individual. With the aid of the crane, the user can stand or sit without the help of another person, granting greater independence. Optional motors associated with one or more wheels of the device may be controlled by the user with a joystick for self-propelled standing mobility.

The device 4.B, on the other side, does not grant such independence to the user. Although it has a mounting assembly with upper and lower mounting elements connected to the carriage and the body support assembly, it has no way to help the user to enter the mechanism, unlike 4.A. It also has no system to propel itself, not even manually by the user. As such, it is required the help of an aider to move the user. This device can change between a vertical and a prone position, by the rotation of the assembly by an axis. Such observation helps to conclude that the machine was designed with the intent to transport patients, instead of giving them self-mobility.

From the commercial viewpoint, standing frames have the price range from 1.500 up to 6.000 euros. Some of the top-selling standing frames can be observed in the figure 5.

Figure 5- Different geometries of standing frames found in the market: A- Rifton K150 medium Mobile Stander [24]; B- EasyStand Glider [25]; C- Parapion Active [26].

From the figure above, it can be perceived that these three different devices can be used by the individual to move around manually. On another note, all of them use unalike systems to that effect. Device 5.A makes use of wheels big enough so the operator can turn them to move, just as a wheelchair. The mechanism 5.B allows the user to move by the support of the handles, which propel the device when pulled. Finally, 5.C uses a system of chains which transfers energy from the wheels that the user rotates to the lower wheels, thrusting the mechanism.

1.4 ORGANIZATION OF THE DISSERTATION

Being that the primary goal of the study is the development of a revolutionary way of mobility for mobile impaired individuals, the dissertation will be structured in the following manner:

In the chapter 2 it will be explained, under a literature review, the development of the most well-known mobility devices over the years. The knowledge acquired from the chapter will be useful to identify strong and weak points in each device, aiding in selecting over which type of mobility device should the project be based on.

Under chapter 3 it is demonstrated the reason behind why the final product was selected to be developed that way. The chapter explains the difficulties that the author believes should be answered by the final product, the possible solutions for each problem and, finally, single out the superior ones.

Chapter 4 describes the line of development of the concluding product, from sketches to the final prototype. It also includes the virtual testing and expected behaviour from the mechanism.

Chapter 5 debates the conclusions of a yearlong project and possible perspectives of continuous development of the project in the future.

1.5 CONTRIBUTIONS

Mobility devices can be found in widespread use around the globe. Some are used with recreational proposes, although the vast majority is used with therapeutically ends. As such, it is unfortunate that so many of the devices targeted to individuals with mobility impairments force the user to stay in a seated position, even more so if the target audience is the paraplegic public.

Although some devices have a vertical component, their intent is generally to stay immobile while standing or for indoor use only. Therefore, the project focused on a part of the mobility device market which the author believes is still unexplored: outdoors or even all-terrain mobility devices for individuals with unresponsive or dysfunctional lower limbs.

It is thus believed that the elaborated dissertation may, if marketed to the general public, improve the wellbeing and health of disabled individuals who can, once more, *stand* and *run.* The new-found autonomy, agility and speed which the device can provide can greatly benefit the self-esteem of one such person, as well as aid him in spending less time sitting, avoiding adverse events in one’s health.

CHAPTER 2 – LITERATURE REVIEW

2 LITERATURE REVIEW

For a better understanding of the struggles of the mobile impaired, a literature review was performed to the available mobility devices solutions that are currently being used to aid such individuals moving. The focus of the investigation was to help the author to understand the advantages and daily challenges that each type of mobility device offers to the user.

Such insight is helpful to better design a new type of device that might offer new advantages that none of the previous could. With this in mind, the information collected in the present chapter as well as chapter one will be used as guidelines in chapter three, Methodologies.

In chapter one, two types of mobility devices were already approached, the stand-up wheelchair and the standing frame. As such, these devices will not be addressed again in the present section. Instead, it will be discussed three more widely recognised devices: the wheelchair, the exoskeleton and the walker.

Each subchapter dedicated to a mobility device will cover its historic evolution, from the known invention to the current times, the more common uses, advantages and difficulties.

Ending the current chapter, there is a conclusion considering the strong and weakest points about each device and what kind of path should be followed to design a new mechanism that could address a gap in the current mobility device’s market.

2.1 WHEELCHAIR

The wheelchairs are one of the most ancient mobility devices. Moving ill or motor impaired people is facilitated if they are in an immobile position. As such, some of the earliest contraptions to move a conscious person uses a sitting stance. The earliest recorded device resembling a wheelchair was created in ancient Greece, as demonstrated in figure 6.A. This image was preserved in a vase dated back to the 6th century BC [27-30].

Similar to the Greeks, it was also discovered that in ancient China, around the year 525, a device was invented, adapted from the wheelbarrow to transport both the infirm and disabled people, as shown in figure 6.B [27-30].

Lost for a millennium, only in the end of the XVI century was such knowledge reinvented. Considered a lost technology, it only surfaced again in Spain, around 1595, built specifically for the Spanish king, King Phillip II (King Phillip I of Portugal). The design, as shown in figure 6.C, required help from an aid to move, as the user could not propel the chair on his own. Still, a throne fit for a king, with elaborate armrests and leg rests and adjustable backrest suggests that it was made with comfort in mind.

A B C

Figure 6- Ancient wheelchairs: A- Greek wheelchair [31]; B- Chinese wheelchair [32]; C- King Phillip II's wheelchair [27].

The first wheelchair that allowed the user to move independently was created in 1655, by Stephen Farfler, being himself motor disabled. A Nuremberg watchmaker by trade, Farfler was accustomed to wheels and cogs. With 22 years, the inventor created a three-wheeled chair that could be propelled with the use of hand cranks and cogs. The design, demonstrated in figure 7, could be the ancestor of the tricycle [30]. The device, although complex, was the first one to allow disabled people to move without the help of any aid, giving the user a sense of liberation. Still, such an invention was nothing more than the personal project of an ingenious man to meet one's own special needs, and the invention was not proliferated to other people with the same requirements. Only a century later would an inventor market such a device for the public.

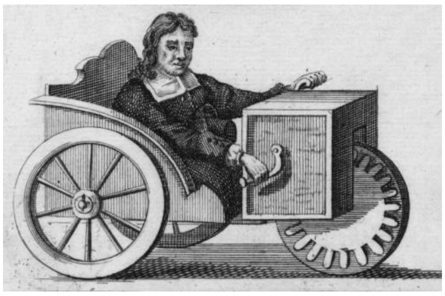


Figure 7- Farfler's wheelchair [33].

One of the first wheelchairs to be widely used was the Bath chair. Baptized by its place of origin, it was invented by John Dawson of Bath in 1783. Similar to a small carriage, the bath chair was an individual sited chair with three or four wheels, depending of the version. In later iterations, the front wheel could be steered by the user, as demonstrated in figure 8. This device required external help to be moved, meaning that an aid or some animal was needed so it could be propelled [27-30, 34, 35]. By the size of the mechanism, it can be safely theorised that it was created for the outdoors and not in-house usage. It also had the comfort of the individual in mind, with a padded sit and, in some cases, a retractable roof in case of sun or rain.

Figure 8- Bath chair [35].

The first patent of a wheelchair was created by A. P. Blunt and J. S. Smith in 1869. The first of the modern designs appeared after the American civil war, where the great demand for a mobility device was born after such a violent event. The main reason was due to the great number of lower limb amputations that resulted from the conflict. The chair was designed in such a way that the user could move the device by manually pushing the hind wheels that were proposedly big enough for reachability. As demonstrated in figure 9, it also presented a reclining back and leg rest, which meant that the user could stay seated or lying in the chair [36].

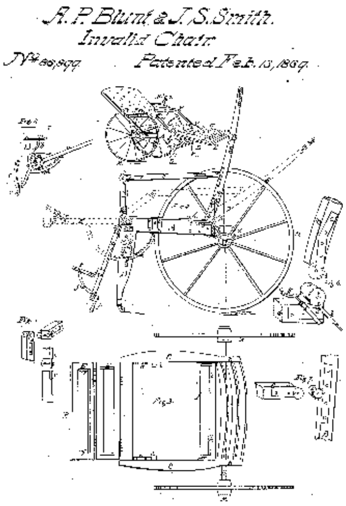


Figure 9- Invalid Chair, patent US 86899 A [36].

One of the great advances of the wheelchair was the folding wheelchair. In an effort to steer away from the bulky and heavy builds of the wheelchairs used at the time, Herbert Everest and Harold C. Jennings came up with a new design in 1933. The device, depicted in figure 10, was lightweight, made of tubular steel and was able to collapse, through a *x-brace* design, which made it easy for storage [37]. This device was so successful, that predominated the market throughout several years. Variations of such design are still used in the present days.

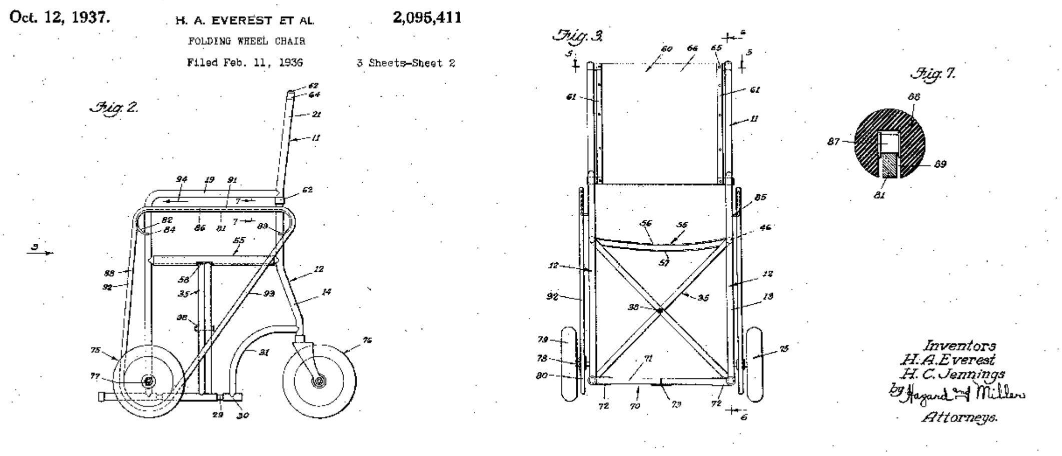


Figure 10- Folding wheelchair, patent US 2095411 A [37].

Although advances have been made, the users of a wheelchair were still fairly limited if the movements of the arms were not proficiently enough or an aid was not available. The consensus of who first invented a functional electric wheelchair is debatable, but it is believed that George Klein invented the Klein Drive Chair, the self-proclaimed first electric-powered wheelchair in 1953. The canadian invention had in mind the veterans in need after the World War II. In 1956, a similar chair was mass-produced for popular use by the same company that invented the folding wheelchair, Everest & Jennings. As demonstrated in figure 11, the wheelchair had the battery and electric motor under the operator's seat and the user could control the movement due to an armrest-mounted joystick. In the case of the individual was unable to use the joystick, an alternative was a sip-and-puff controller, were the movement of the chair was dictated by the user blowing air into a sensor [27,28, 30].

Figure 11- Klein Drive Chair [38].

The 20th century saw the evolution of wheelchairs, both manual and electric, in key concepts as manoeuvrability, comfort and reliability of the device. The individuals, who suffered systematically from pressure sores and other problems related to being immobile by long periods of time, saw their problems being taken into consideration by such devices. It also allowed people to participate in a more functional manner in social activities.

Still, there is room for improvement. The most recent concept applied to wheelchairs is mind control. In recent years, investigators have been researching technology to link the wheelchair and the brain of the user. With the use of BCI (Brain-computer interface), the goal has been achieved. Such technology allows people that cannot produce any movement, such as quadriplegics, to move without aid, regaining this way some independence. With some training, the computer incorporated in the chair can interpret a few basic functions, such as moving forward, backwards and turn, from the brain signals captured from sensors attached on the scalp of the user [39-42].

Figure 12- Mind control wheelchair [42].

2.2 POWERED EXOSKELETON

The powered exoskeleton has been in the global imagination of mankind for quite some time, as back as 1868, the year of the novel *The Steam Man of the Prairies* [43,44]. Still, due to several technological limitations, only in recent years advances in the area have taken place.

Such a device grants the power to the user to perform herculean tasks. Lifting heavy weights, rapid movements, repeat exhausting errands without tiring and helping the motor disabled to walk again. The feat of engineering can be achieved through the combination of electrical, pneumatics and hydraulics systems, depending from case to case.

One of the first patents for something similar to an exoskeleton was published in 1890 by Nicholas Yagn. It was an apparatus that facilitated walking by using compressed gas, as demonstrated in the figure 13.

The user of the device would use specialized shoes. In each stride, compressed gas would be pumped under the foot, helping the user to gain momentum [45]. Still, the operation of this apparatus was passive, as it required human power to operate. As such, the energy of the device was originating from the individual and not the machine. Its true intent was to augment the running speed and jumping height of the user. The concept never left the paper.

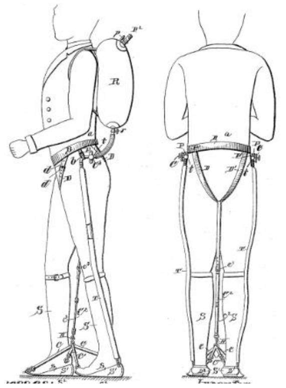


Figure 13- Apparatus for facilitating walking [45].

Only in the late 1960s, a prototype of a full-body powered exoskeleton was developed. The U.S. Office of Naval Research funded General Electric for the development, culminating in the dubbed *Hardiman* [46, 47] demonstrated in figure 14.

The first true exoskeleton integrating human movements enabled the lift of 110 kilograms with just 4.5 kilograms of lifting power by the user, amplifying the strength of the individual by a factor of approximately 25. Powered by hydraulics and electricity, force feedback enabled the wearer to feel the forces and objects being manipulated. Unfortunately, the impractical weight of the machinery -680kg-, slow response time and sluggish walking speed made the project unsuccessful [48].

Figure 14- Exoskeleton Hardiman [47].

The first successful powered exoskeleton was developed at the Mihailo Pupin Institute in 1969. Powered by pneumatic technology and cinematically programmed, the mechanism allowed the user to walk close to an anthropomorphic gait. Ongoing work throughout the 1970s-decade culminated in the *Active Suit*, demonstrated in figure 15, deemed a success from rehabilitation and research standards. Controlled by a microcomputer and electromechanically driven, it allowed an individual with affected gait to walk again normally [49].

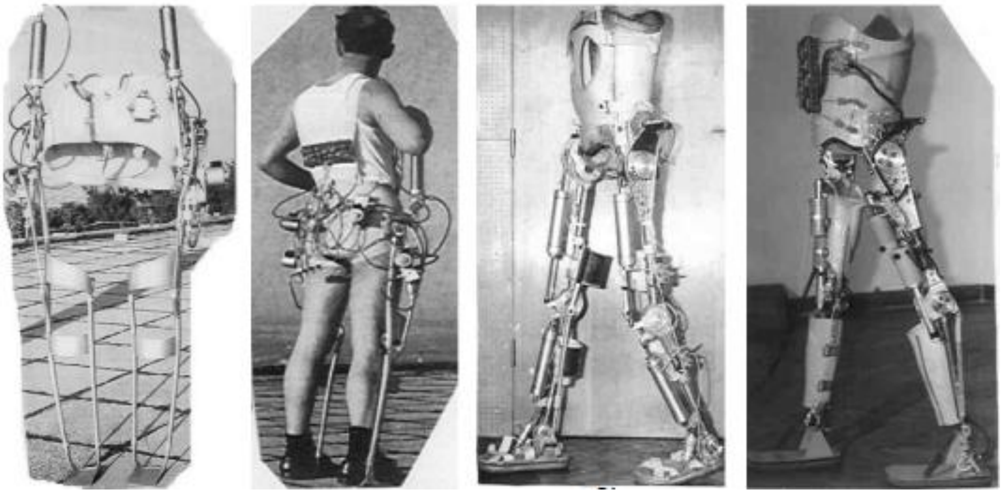


Figure 15- World's first walking active exoskeleton [49].

The first exoskeleton to be considered autonomous was the Berkeley Lower Extremity Exoskeleton – BLEEX, as demonstrated in figure 16. The device carries its power source, culminating in an original weight of 28kg, being later halved to 14kg due to improvements. BLEEX allows the user to have three degrees of freedom at the hip, one at the knee and three more at the ankle [50]. Originally, with the size in mind, the actuators of the device were hydraulic. However, further testing prompt the use of electric motor actuation, diminishing the overall power consumption. Later on, the culmination of the development ended in a hybrid between hydraulic and electric with portable power supply, resulting in a lighter actuation system with a hydraulic transmission [51-53].

Figure 16- BLEEX [50].

In the current days, there are some commercial exoskeleton models that are used with rehabilitation purposes, designed with the intent to re-train the user’s gait. Going a long way since the limited Exoskeleton of the Mihailo Pupin Institute, the new exoskeletons allow the user to carry out routine ambulatory functions, such as standing, walking and climbing stairs. Not every single one is so complete, although each has its own purpose. Some of the new lines of exoskeletons are the ReWalk, MindWalker, HAL, REX, eLEGS and the Vanderbilt's exoskeleton, as shown in figure 17.

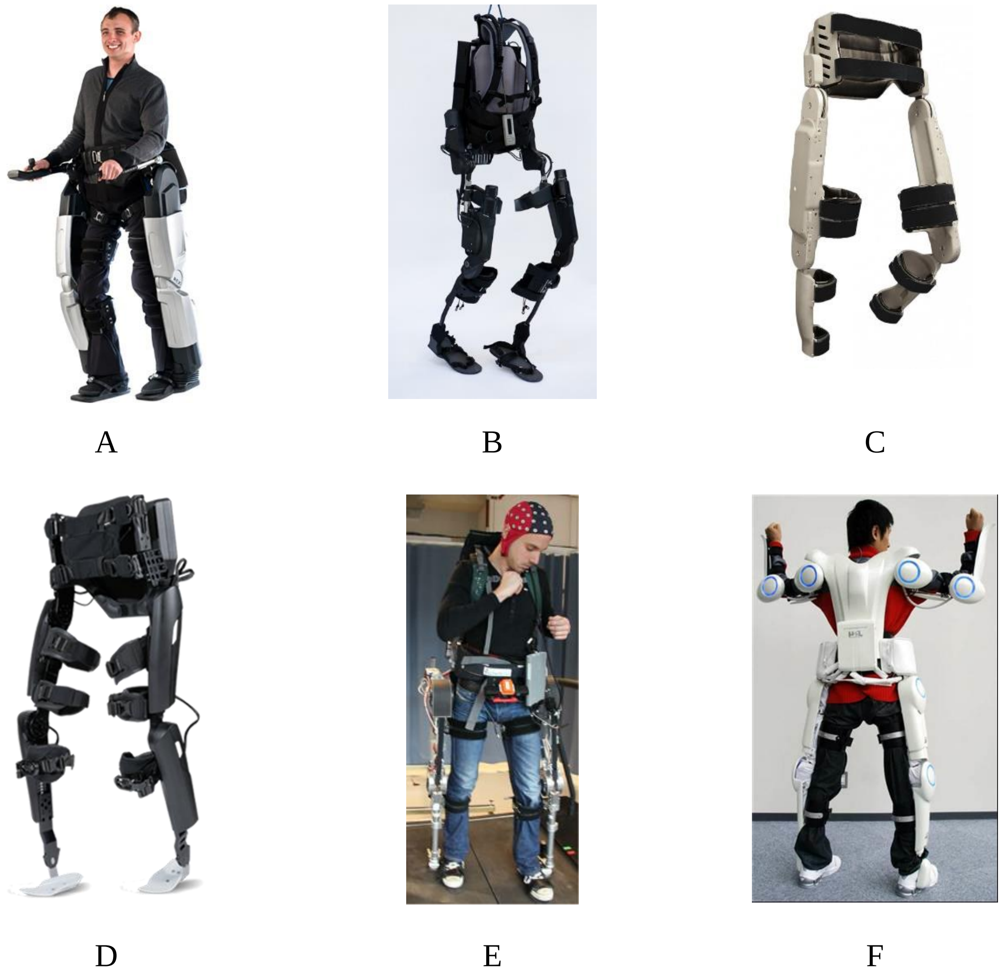


Figure 17- Models of rehabilitation exoskeletons: A- REX [53]; B- Elegs [54]; C- Vanderbilt's exoskeleton [55]; D- ReWalk [57]; E- MindWalker [58]; F- HAL [57].

REX is an exoskeleton with the sole purpose of rehabilitation, although it can still be used for housework. It helps the user to do exercises, such as squats, lunges, stretches, among other movements. To move around, the user has a joystick, which can make the exoskeleton to move forward, backwards, sideways or turning. The motion is generated by ten linear actuators and the user must have a limit of 100kg. It uses carbon fibre to minimise weight and increase strength, and tethered straps for creating a comfortable hold of the legs. It has a double battery system, each one can power the exoskeleton for one hour, which means that the exoskeleton can have a continuous use if the batteries are changed [53].

eLEGS is an exoskeleton powered by a hydraulic system that helps paraplegic users to stand/walk with the aid of a support, such as crutches or a walker. The individual, with such device, can walk in a straight line, stand for an extended period of time, stand up from a chair and sit. It weights 20kg, can reach a top speed of 3km/h, has a battery of 6 hours and the interface uses 40 sensors to monitor the user's gesture and motion to interpret its intent actions and implements said movements [54].

The Vanderbilt's exoskeleton attaches to the user throughout a series of straps located at the torso, legs and feet. If the individual leans forward, the mechanism will start to walk in the same direction, by activating electric hip and knee joints that are controlled by computer. To keep balance, the user should use a point of support, such as crutches or a walker. The exoskeleton weights 12.25 kg, which facilitates the portability when not in use. It can be adjusted to the level of difficulty the user has to walk, meaning that the operator can use the exoskeleton to still maintain a degree of physical fitness instead of the exoskeleton doing permanently all the work [55, 56].

The ReWalk exoskeleton helps the user to stand upright, walk, turn, climb and descend stairs. More than used for rehabilitation, this device can be used at home and on the outdoors. Like the eLEGS, it senses the user's motions and responds accordingly. It needs another point of support, so a walker or crutches are advised [57]. The ReWalk uses DC motors at the joints, as well as rechargeable batteries, an array of sensors and a computer-based control system. All comprised in a wearable brace support suit.

The MindWalker is the most ambitious project of its kind. Instead of using a controller or using the individual's movement, it synchronizes with the brain signals of the user to determine what movement should it take. By using EEG signals from the brain or EMG signals from the user's shoulder muscles, the brain-neural-computer interface interprets to electronic commands, instructing the exoskeleton. The EEG signals can be differentiated enough to create commands such as standing, walking and making the exoskeleton walking faster or slower [58].

HAL is a full-bodied exoskeleton, meaning that along with the legs, it also supports torso and arms. It can be used to lift five times the weight the user could on its own. The newest model weights 10 kg and picks up small biosignals on the muscles (EMG) and changes of movement of the user in order to predict the movement it should take. The cycle of reference walking patterns is adjusted for the patient and the walking support based on the reference walking is achieved, synchronizing with the individual's intentions estimated by the algorithm. The algorithm successfully estimates mobility corresponding to a user's intention, but does not stabilize the operator’s body posture, meaning that to maintain balance, it is required the use of a walker or crutches [57].

2.3 WALKER

The walker, or walking frame, is a mobility tool widely spread in the modern time society. Although notoriously associated to the elderly, disabled people with partially functional lower limbs also use it. A paraplegic cannot use this device, since it requires some legwork in order to function. It requires an individual capable of standing to some point, only aiding as a moving point of support for the user [60, 61]. It can be also used as a rehabilitation tool. With the application of sensors and other devices, it can provide useful information of the development of the patient to the physiotherapist, helping to tailor its approach to the recuperation plan [62-64].

To use the walker, the individual should be in a standing position with the walker’s frame surrounding him. The hands provide support to the rest of the body by holding the top of the frame. Then, conventionally, the walker is pushed or picked up and moved ahead of the user. With the new gap between the individual and the device, the user can walk a short distance while still holding the frame. Once the distance is closed, the process can be repeated [60, 61].

The mechanism has a very recognisable design. As figure 18 demonstrates, a common walker consists of a lightweight chassis with four legs, preferably wider than the user and normally the height can be adjusted, which should be about waist high of the individual. In more extreme cases, there are varied sizes, such as paediatric or bariatric.

A B C

Figure 18- Different sizes of the common walker: A- Normal [70]; B- Pediatric [71]; C- Bariatric [72]..

Although these are the collective image associated with the walker, the concept has been in development since around the late 1940's. In 1949, Cribbes Robb William presented the first patent of any variation of the walker, dubbed *walking aid*, as demonstrated in figure 19.

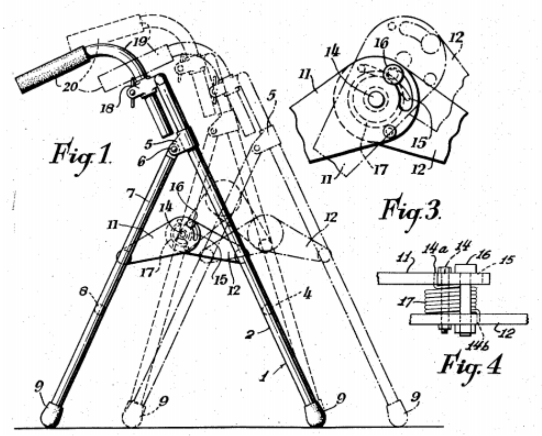
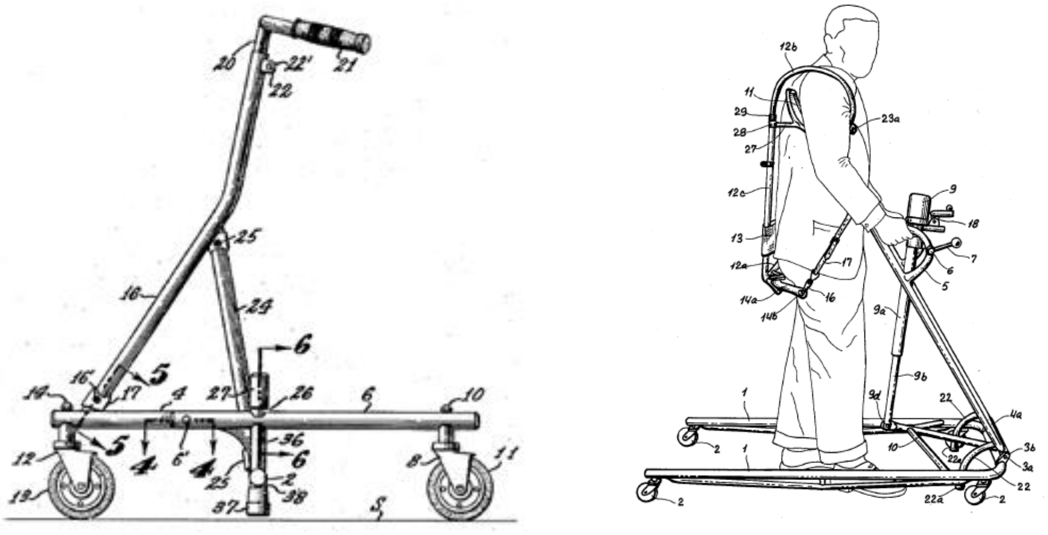


Figure 19- US 2656874 [65].

As proposed by the patent application, the device assists to walk again those who have fallen under illness or injury. The mechanism has four metal rods that work as legs and two handles where the user can hold for support. It is invented in such a way that can be closed and disassembled for better storage. The handles can be moved to better adjust the individual's height and the distance between the front and rear legs can be adjusted, granting the device a lower point of gravity if deemed necessary [65].

In 1957, two more patents were registered, although the more notorious addition was the wheels on the device, as demonstrated on figure 20.



A B

Figure 20- Depictions of wheeled walkers: A- US2792874 [66]; B- US2792052 [67].

The proposed use of wheels was due to the requirement of the user, a mobile impaired person, to lift the device. By adding wheels, the individual can push the frame forward without significant effort [66, 67]. Although an innovative idea, full-wheeled walkers are prone to keep the momentum, and if the user cannot force the device to stop, it can originate a fall. That is why the device shown in figure 20.B has an awkward apparatus to the user to wear, albeit preventing falls [67].

In figure 21, it is depicted a patent of 1965 that avoids sliding when the user moves forward or lifts the frame.

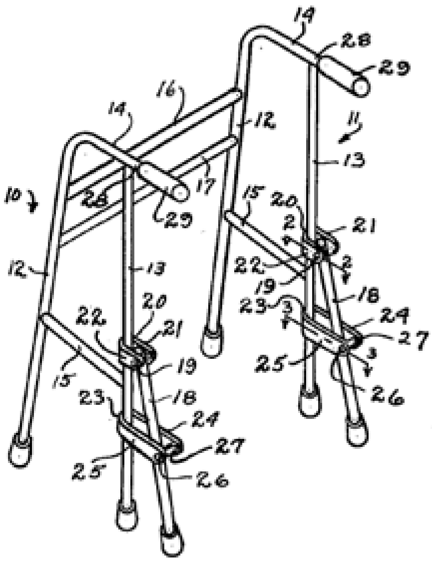


Figure 21- Anti-sliding design [68].

By adding an angled, smaller leg to the rear legs of the walker, there are four points of contact with the ground at all times. The walker has a system, which is pushed forward step-by-step by the user without sliding or lifting. This means that small obstacles such as obstructions or slightly higher elevations do not make the user lose control of the device [68].

In figure 22 it is shown the modern walker, which was first published in 1970 and invented by Alfred A. Smith [69].

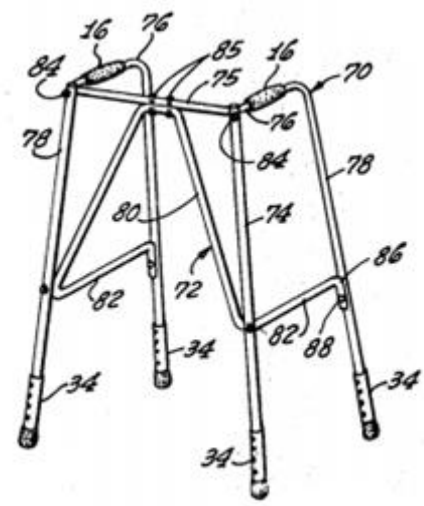


Figure 22- Invalid Walker [69].

The walker was invented as a perfected device from the previous ones, and more simplified [69]. That is why the device is so widely spread on the current days. Still some distinct kinds of walker geometries can be found in the market.

A B C

Figure 23- Different geometries of walkers on the market: A- Anterior Walker [73]; B- Posterior Walker [74]; C- Rollator [75].

The walkers represented on figure 23 are the top competitors to the common walker.

The first two walkers, anterior and posterior walkers, are used for therapeutic purposes. Each one is used to train and develop a different kind of gait, to which the user is incapable or inept to walk by himself.

The Rollator, on the other hand, is used as an everyday tool. Its big wheels can help overcome small obstacles that are expected of the outdoors and has installed a small bench in which the operator can sit when tired. It also has a shopping cart that can be used to store items, which can prove to be highly practical.

2.4 SUMMARY AND DISCUSSION

In retrospect, although presenting a wide array of choice, all the mobility devices analysed present strong and weaker points.

From the devices examined on the previous chapter, both the stand-up wheelchair and standing frame could sustain an user in a standing position, minimizing the health risks which could result from staying long times in a seated position.

By scrutinising the standing frame, one can conclude that it is an exceptional device for indoors usage, nimble and stable. On the other hand, the device is usually slow, presents difficulty in overcoming small obstacles and is not designed for the outdoors.

The stand-up wheelchair can give the user a greater mobility than the standing frame, although usually only in a seating position. By general rule, they are designed to function as a chair, allowing the user to stand if the need arrives, although normally it is required to stay still, rendering the operator unmovable and sacrificing stability.

The wheelchair is the most recognizable mobility device and with just cause. It is usually cheaper than most mobility device, reliable, safe and functional. The greatest downside of the technology is the requirement of the user to stay permanently seated while in use.

The exoskeleton might be the most evolved technology presented on the study. Able to help patients in recovering from traumatic events, allow the user to lift great weights or repeat movements without tiring and allow paraplegics to walk again. On the other side, it is extremely expensive, it can only reach walking speeds and still not widely used.

One of the most recent mobility device is, surprisingly, the walker. Cheap, therapeutic, simple and widely spread. Some iterations allow the user to sit, being thus able to rest if necessary. Still, the device can only be used by people with functional or partially functional lower limbs, as it requires the gait of the person to move.

The conclusion of the present study will be used on a later chapter, Methodologies.

CHAPTER 3 – METHODOLOGIES

3 METHODOLOGIES

3.1 DESIGN THINKING APPROACH

The development of products has acquired a special place in companies due to the competition and consumer requirements in the market, which have been forcing an improvement in excellence standards and quality levels, price and design time. Currently, the greatest challenge of business management lies in driving companies in an environment of increasing information, knowledge and proportional dynamics and turbulence, in terms of the correct and efficient approach to innovation. The recognition that the current business situation might be fragile and unstable leads to the study and search for strategic solutions that bring a base for innovation, promoting the sustainability of business strategies.

The development of a project is a complex and multidisciplinary process, that requires a close relationship between the client and the team that is in charge of developing the product, but also in the marketing, production, purchasing, quality control and sales sectors, consumers and suppliers in order to achieve the desired success.

Solving a complex engineering problem is usually achieved by dividing it into a set of smaller, more easily solved problems. Thus, in the development of any complex system, the function of the device is decomposed into several subfunctions so that the team can find solutions for each one. Such procedure simplifies the process and presents the possibility to work in parallel. In case of using a team, different elements of the project can be divided, working on solutions for different sub-problems in parallel, increasing the speed of the procedure. Although the advantages of this method make it quite attractive in design, defining the most appropriate set of sub-problems can be difficult.

In design, there is a process or a series of steps that transform a set of inputs into a set of outputs. In the procedure, there is a sequence of activities for the purpose of designing, developing and marketing a new product. Product development is the process of articulating market needs and opportunities to the technical and organizational possibilities which transform data about market opportunity and business possibilities into goods and information for the manufacture of a commercial product.

The development of the product corresponds to a series of activities organized with the objective of transforming an idea into a real final product, starting with the perception of a market opportunity and finalized with the production, sale and delivery of the product. The process of product development depends not only on the product that will be realized, but also on the organization for this purpose. Although development processes have characteristics that make them unique to each project, the phases of any development process can be categorized into a generic sequence for application in a variety of systems and organizations.

A well-defined and structured design development process can add advantages to the product such as: quality assurance, when all stages of a project and all the control parameters are well specified, it is possible to guarantee the quality of the resulting product; Coordination, a well-built development process will define the roles of each team member, enabling effective interconnection of all members and integration of all contributions into the overall project; Planning, a development process will define completion points at each stage allowing the design and control of a global time map of development; Management, the development process allows to identify, manage and solve possible problems that may occur; And finally evolution - careful documentation of the development process helps identify optimization possibilities contributing to constant evolution. There are models that are abstract representations of reality and are constructed, analysed and manipulated to increase understanding of reality. These contribute to good decision making, ensuring that the right people use the right information at the right time. The models related to the development of the project can be classified into two types: descriptive models, which describe and explain why and how a process works or occurs in a certain way and prescriptive models, which describe how processes should or can be carried out following norms and guidelines.

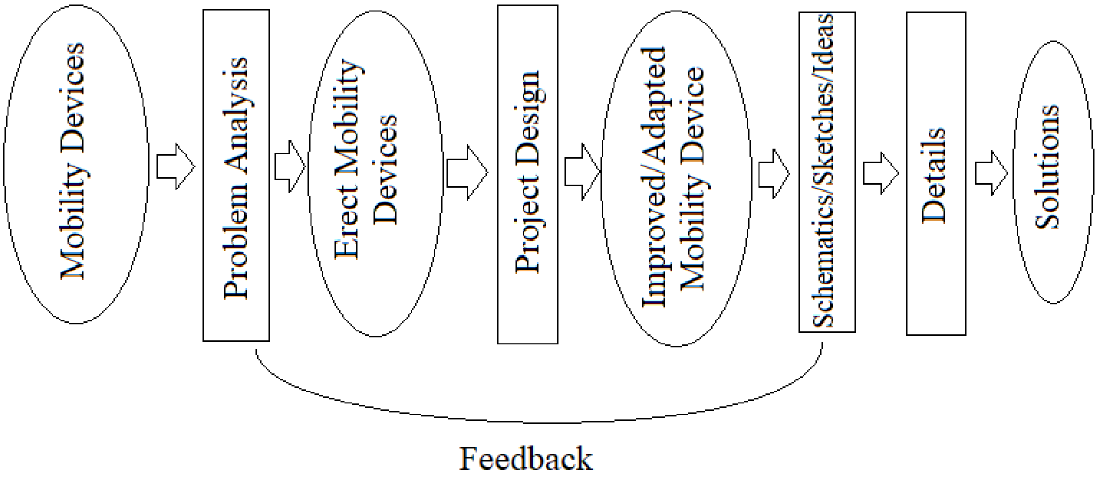


Figure 24- French's model of the project design.

The dissertation based the descriptive model on the *French* model, where the circles represent the goals to reach and the rectangles signify the activities in progress, as demonstrated in figure 24.

Prescriptive models are usually considered as tools, which provide a methodology to the project. A detailed model of this kind is the model of *Cross*, as demonstrated by figure 25.

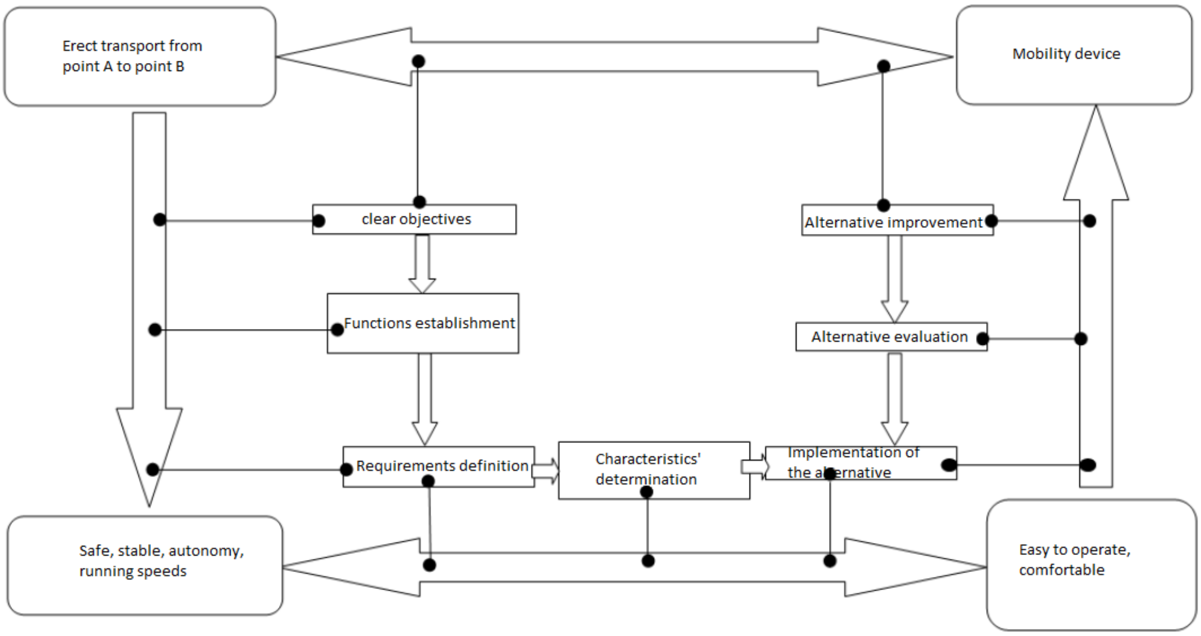


Figure 25- Cross' prescriptive model.

3.2 PERFORMANCE FEATURES IDENTIFICATION

3.2.1 Requirements

With the end goal of creating a new mobility device, some requirements from the user's end must be met. Still, these requirements must not compromise the objective of the project, which is to design a mobility device where the individual could travel in a standing stance and reach running speeds for a sustained period of time.

With the above stated, the requirements are then divided into two: the device's and the user's requirements. The device's requirements dictate what the mechanism must achieve for being declared functional by the dissertation's ideals. The user's requirements are more secondary than the device's. As such, these should be taken in consideration, although only if there is no impossibility to implement the device's requirements, which take priority. Still, every effort must be taken before excluding them.

The following requirements must be executed by the device in order to be deemed a success:

-Being able to transport the user: As the primary function, the mechanism must be capable to move the user from point A to point B. To reach such effect, the source of energy required could be electric, with the use of batteries, or mechanic, namely by the arms of the individual;

-Aiding a mobile impaired user to maintain a vertical stance: A handicapped individual may have problems in maintaining a standing position, even incapable by its own means. As such, the device should have a system to lock the user in place, without requiring sustained effort from the part of the individual;

-Helping in sustaining a vertical position: A motor impaired person may have problems in maintaining balance. For that particular reason, in the off chance that equilibrium is lost during the usage of the device, it is required a countermeasure to avoid a fall and help to reacquire the lost balance;

-Reaching running speeds: the incapability of running again can cause great stress to a handicapped person. Most of the available mobility aid devices do not go further than reaching walking speeds, 5 km/h. As such, it would be considered a great addition and benefit for the user’s psyche if the device could reach higher speeds.

-Maintaining top speed for sustained periods of time: Although reaching running speeds is important, sustaining them has equal significance. The operator should be able to keep up with healthy individuals for better integration in mundane activities, such as going for a friendly jog. To reach such effect, if it is decided to use an electrical device instead of a mechanical one, the battery life should be taken in account;

-Personal autonomy: As a mobility device, personal autonomy is one of the main concerns. The device should be designed to require the minimal external assistance as possible. While using, the device is expected to help the user to get to places which other more conventional mobility devices are not made to reach, such as uphill or rough terrain.

The following requirements should be satisfied in order to grant the user with a comfortable, rewarding and fulfilling experience, while avoiding health complications:

-Comfort throughout the ride: While using the device, the user could be several hours in a stance that has potential to be physically rough if the proper measures are not taken. As such, and for increasing the operator’s will of continuous use of the mechanism, said problem should be addressed;

-Uncomplicated mounting and dismounting: Since the device has a target audience of mobile impaired individuals, several of the users may need assistance in transitioning from a seated to a standing position. Therefore, the mounting of the mechanism should be as user-friendly and safe as possible, avoiding significant efforts and complicated steps;

-Driving system: The driving system should be as user-friendly as possible. The device is expected to be easy to maneuver and be reliable. As such, it should be picked one type of system that comes naturally to the individual and simple to implement.

3.2.1 Specifications

For each distinct requirement, specifications must be made. The use of the device as a medical device also means that some regulatory specifications must be answered.

-Being able to transport the user: In the eyes of the project, the device is required to carry an individual with at least 90kg of weight. The value of 90kg was selected after analysing the average weight of several countries and none surpassed an average of 90kg [76];

-Aiding a mobile impaired user to maintain a vertical stance: To help such an individual to keep standing, it is necessary to be bond to the device. As such, it should be required that the bonds are as few as possible without putting the user in peril. In case of accident, the user should be able to remove himself from the mechanism by his own hands;

-Helping in sustaining a vertical position: The design of the device must be fall proof under normal conditions, and still keep the device with a high freedom of movement as possible;

-Reaching running speeds: Since the average person would change from walking to running gait at around 6-7km/h, it is considered that a good cruise speed could be 10km/h, possibly going higher if the user so choses;

-Maintaining top speed for sustained periods of time: If the propelling force depends of batteries in the device, the minimal time of highest usage should be expected to be an hour- as such, the battery must resist as long;

-Personal autonomy: In flawless practical terms, the user should be able to mount, use and dismount the device on his own, without difficulties, granting so autonomy from third parties;

-Comfort throughout the ride: While in a vertical posture, the device should grant enough points of support to avoid unnecessarily painful pressures and other attentions, such as using soft and smooth surfaces/fabrics in contact with the individual. Ergonomics should be taken in consideration;

-Uncomplicated mounting and dismounting: The mounting mechanism of the device is required to hold the user on a sitting position for small periods of time, allowing the user to change to a chair while dismounting;

-Driving system: Although abundantly clear by the content of the project, the driving system cannot rely on the feet of the user to function.

Table 1- Specifications metrics and target values.

Subfunction	**Importance (1-5)**	**Metrics**	**Desired value**	**Acceptable value**
Transport user	5	Weight	>90kg	>80kg
Aid the user maintain stance	5	Binary	Yes	-
Help sustain vertical stance	4	Binary	Yes	-
Running Speed	4	Velocity	>10km/h	>6km/h
Maintain Top Speed	3	Time	>1h	>0.5h
Personal autonomy	4	Binary	Yes	-
Comfort	2	Binary	Yes	-
Uncomplicated mounting	3	Binary	Yes	-
Driving System (user-friendly)	2	Binary	Yes	-

A range of devices capable of moving healthy individuals while in a standing position already exists. The most recognized line of personal transportation vehicles, although competition exists, is the brand *Segway*. After deliberation, it was concluded that such a device would be perfect as a basis for the mechanism designed for the project, as it is already designed to transport individuals vertically. Still, it does not answer to all the requirements listed above, and as such, it needs adaptations.

If the mobility device previously described was to be accepted in the open market as a medical device, it would have to be categorized in the first place. The mechanism is designed to only enter in contact with the unharmed skin of the user. It is not intended to enter in contact with injured skin, storing or modifying bodily fluids, diagnostics, emitting ionizing radiation, administer medicine nor any kind of invasive procedure. The European

Commission classifies the medical devices in four classes, from lowest to the highest level of risk, Class I, IIa, IIb, III. Following the guidelines for medical devices [77], the mobility device designed in the current thesis falls under the classification I. By the application of rule 1, all non-invasive devices are in Class I, unless another rule applies [77]. After intense scrutiny of the other rules, rule 9 - active therapeutic devices intended to administer or exchange energy, came to close attention. The rule claims that active therapeutic devices which have intentions to have energy transfers with the human body should fall under classification IIa or IIb, depending on the case [77]. As the mobility device is required to maintain the user’s body in a standing position, mechanical energy will be transferred. Although there is energy transfer, this is not considered *potentially hazardous*, allowing the mechanism to stay in Class I.

3.2 MORPHOLOGICAL MAP

To explore a novel solution by combining new elements, along with brainstorming, a morphological map is an interesting tool to be used. Such an approach allows to identify several possible combinations of individual elements that can include already existing conventional solutions and brand-new ones that can lead to innovative solutions which are more personalized for the problem that is being tackled.

As such, the elaboration of the morphological map starts by listing all the essential sub-functions that the device should execute, which have been already identified before. Afterwards, it is catalogued the different means that were thought of to answer the needs of every sub-function identified, also known as sub-solutions. When combined, they form the global solution.

Later, it is created a table where, at the left, the sub-functions are listed and, for each line, the sub-solutions are identified for the respective sub-function. Such a concept allows for different answers for each problem, but ideally only one sub-solution for each sub-function should be picked. Each combination of sub-solutions found corresponds to a conceptual solution for designing the global function of the device.

In table 2 it is represented the matrix which enlists the sub-functions of the device and the respective sub-solutions, in which the prime function can be achieved. In the same matrix, marked in bold, are identified the blocks which are thought to allow creating the most promising combination, the global solution.

Table 2-Morphological map.

Sub-function/ sub-solution	**1**	**2**	**3**	**4**
Transport user	***Segway***	Stand-up Wheelchair	Standing Frame	-
Aid the user maintain stance	**Harness**	**Straps**	Suspended cords	-
Help sustain vertical stance	Anti-tipping feet	**Extra wheels**	-	-
Running Speed	**Electric motor**	Manual	-	-
Comfort	**Padded support**	Anti-allergic fabric	Suspension	-
Uncomplicated mounting	Harness with cables	Rigid frame	**Flexible frame**	Motor
Driving System	**Balance**	Joystick	Mind-controlled	-

As shown in table 2, after careful deliberation, for each sub-function it was enumerated a list of options that have the means to solve the problem at hand. From there, it was picked those which were believed to be the finest solution for the impending case. In some cases, two solutions may be selected, due to the fact that both do not interact with each other directly and give the user a better experience.

To the sub-function *Transport User*, after careful deliberation of the current market of mobility-aid devices, it was analysed in detail the possibility of creating or adapting and existing stand-up wheelchair or a standing frame. Alas, both present a problem to the present project: lack of top velocity and maneuverability at those speeds. Standing frames are more used indoors, not requiring the device to achieve more than walking speeds. Although stand-up wheelchairs are used outdoors, most of the times are used in a seated stance, only standing when the user needs to grab something out of reach, talk to someone or perform some task. When standing, the wheelchair still moves, but the low speeds are better suited for taking a stroll or as an indoor device.

When checking the market for mobility devices, Segway is the most recognizable brand. The most familiar device is a two-wheeled mechanism with auto-balance, which is piloted by the user by leaning or tilting to the direction the individual wants to take. Although projected for able people, it is believed that after some alterations, the device could support and be used by a motor impaired individual. Using the Segway device as a basis for the project already answers to some sub-functions discussed below.

To answer the sub-function *Aid the user maintain stance*, more than one optimal solution was found. Originally was thought using a combination of suspended cords linked to a frame and the user wearing a harness. The cords would be used to adjust the height of the user's waist, helping to transition from a seated to a standing stance. This idea was later discredited, due to balancing issues. If the user cannot use its legs to support himself, then suspended cords would result in a loose link between the hips of the individual and the mechanism. By having a loose link, a motor impaired individual could not use the hips to lean into the direction that he wishes to drive. As such, it was idealized a combination of straps in a frame, that will be later discussed, and the wear of a harness. The user, by wearing a harness with hip rings, would be tightly linked to a frame by its waist without any slack. The legs of the user would be hold in place by the straps located along the frame as demonstrated in figure 26.


A B

Figure 26- A- harness with hip rings [78]; B- leg strap [79].

The sub-function *help sustain vertical stance* refers to avoiding the user from tipping over in case of some unbalance. Although the Segway is very safe by itself, some extra precautions were taken due to the fragility of the users in case of some accident. Two solutions were discussed: anti-tipping feet or adding extra wheels. The selected solution was adding extra wheels, since anti-tipping feet can cause accidents if the device is moving. These are useful in stationary devices, but in moving ones, it can cause the mechanism to trip over. As such, adding extra, smaller wheels in front and back of the device was considered the best option to avoid accidents. The concept was already put in use by a partnership between Segway and General Motors, creating the PUMA (Personal Urban Mobility and Accessibility), as demonstrated in the figure 27. The device is a two-wheel with two seats vehicle, intended for urban use.

Figure 27-PUMA [80].

To achieve the sub-function *running speed*, the Segway device already can achieve those speeds. It can go up to 20km/h, although that speed is more than enough for the project. In fact, it may be too much, and can be limited by an inbuilt controller. After careful deliberation, from the different models presented by the brand, it was considered that the best model to be incorporated in the project was the Segway X2 SE, as demonstrated in figure 28.

Figure 28- Segway X2 SE [81].

The model, the all-terrain variation of Segways, has rugged, large tires, which are made to transpose a large array of obstacles in the wild, meaning that the user can drive in the streets without worries of accessibility. As other Segways, it can reach up to 20 km/h, above the required velocity for the project. The exterior of the model also has great durability and stamina, meaning that heavy-duty usage is not a problem.

The sub-function *comfort* is achieved by using padded straps and a padded harness, which can improve the comfort while using the device for a prolonged amount of time. Using anti-allergenic fabrics were considered, but the straps and harness are to be used above the trousers of the user, rendering the contact between the device's fabrics and the user's skin highly improbable. Using suspension on the extra wheels can help having a smoother experience when passing above some small obstacles, although it may also create tipping problems if it were to malfunction.

Relatively to the sub-function *uncomplicated mounting*, it is in the user's best interest to mount the device without unnecessary difficulties. As such, different approaches were taken to help the individual to change from an initial sitting position to a vertical, riding position. It was thought that it could be used a harness with cables, a rigid frame, a flexible frame or a motor to help the user transition and maintain a standing stance.

As explained before, a harness with cables would result in a slacked link between the user and the device, complicating the driving of the mechanism. A rigid frame could have as consequence the motor impaired individual requiring someone's aid to transition from a seated position to the vertical position, due to the fact that the rigid frame, although more stern, could not bend. Using a motor to help the user to rise was thought in detail, but the cost and maintenance of such a mechanism would deter buyers.

The best solution to the function was a flexible frame. A frame that would maintain the user in place, but also could fold when required, under the own weight of the user. With the use of hydraulic cylinders, the frame would go from folded to straight with small effort, just as in the car trunks (figure 29), but when straight, it could not fold unless a string was pulled, due to a safe mechanism, which was developed in the next chapter.

Figure 29- A trunk pneumatic mechanism, the inspiration for a smooth transition between stances [82].

3.3 SUMMARY AND DISCUSSION

In the present chapter was discussed the methods that the author took when selecting the best approach for developing a new device.

First it was picked the requirements and specifications essential for the mechanism. This line of thought helped in pinpointing which goals were necessary to achieve and which ones were more vital, establishing a line of priorities were, if possible, all were to be included, if there was no overlapping.

Afterwards, it was used a morphological map which assisted in defining all the sub-functions which the device must do in order to be deemed functional by the author. To every sub-function was answered a several solutions. From these, the most appropriated one was then picked for each case and, in some instances, more than one could be used without overlapping, creating a more complete device.

This chapter was critical to identify all the potential necessities of the users of the device, which it must answer to.

Although the guidelines to answer each individual sub-function are now selected, they must now be crafted, tested and implemented in order to achieve the final goal of the project, a functional vertical mobility aid for mobile impaired individuals. This will be discussed in the next chapter, *Technical Development.*

CHAPTER 4 – TECHNICAL DEVELOPMENT

4 TECHNICAL DEVELOPMENT

4.1 DEVELOPMENT APPROACH

In the pursuit of developing a new calibre of mobility devices for the motor impaired, the challenges were divided and answered with potential solutions in the preceding chapter. In the current section, such ideas will be expanded upon, leading to its growth and development into the final prototype.

In order to progress in the design of all the components, on most occasions it was taken the same path. The intended solution for each sub-function was first sketched to the form which was believed to be the best shape for the device. Sketching allows to explain a better understanding of the designer’s idea to third party members, without spending too much time. This way, the concept can be easily criticised and improved upon rapidly without spending too much resources. The skill also allows to indulge in out of the box ideas, which would otherwise be shelved due to spending too much time by being developed in later stages.

Later, the sketched piece would be designed in SolidWorks, creating thus a 3D model of each part planned. SolidWorks was selected over other CAD software due to being easy to draw, intuitive to use, presence of in-built test tools and, lastly, the familiarity the writer already had with the program. After designing each part, they were assembled and subjected to test forces, in order to access if the design was sturdy and capable enough to support a grown human being.

After testing, the pieces were 3D printed, creating the prototype. Bringing the digital solution that was built in SolidWorks to reality by prototyping can generate great advantages before full-scale production. Such a technique allows the creator to understand potential problems that were oversighted until then. Having a physical entity of the project helps to recognize potential flaws and improvements which can be overcome with low costs, in comparison to later phases, such as full-scale production or sale distribution. By having a prototype, the project can also be better explained to the public which is not inside the mindset of the designer. Using two 3D printers, the WitBox and XPIM, the diverse parts of the mechanism were created using the thermoplastic PLA. Two prototypes were intended, with different scales. A smaller one, with 17.5% of the original size, was created as a practical example to better demonstrate the ideas to assist the motor disabled. The bigger one, with 67% of the original size, could be used as a final example of the project. The prototypes have small differences between them, which will be discussed further on.

Even with all the input and calculations present in the sketch period, some pieces, and even concepts, were considered flawed while being design in CAD. Would it be by failing a test, dimensioning or realization of a more approachable scheme, such ideas were sent back to the sketch stage. Such reimaginations resulted in different 3D designs, with some being later demonstrated and explained why they were not used.

4.1.1 Sketching

In the project, sketching was used not only to assist in creating a general concept, but also to develop more intricate ideas, such as the foot rest and the knee of the apparatus. Some drafts were erased from the dissertation due to straying too far from the solution which were picked in the previous chapter.

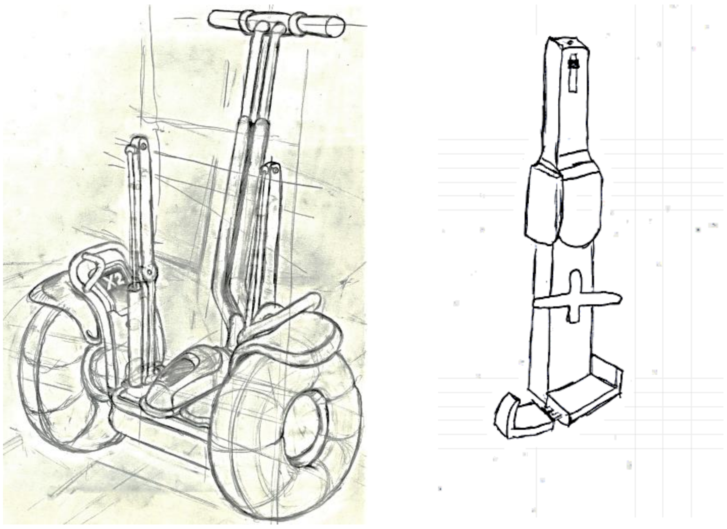


Figure 30- Original Concept.

In the sketches in the figure 30, one can observe that the adaptation is waist-high, were it is meant to attach the user to the Segway by the hips, lower legs and feet. While wearing an harness, the individual would be fastened to the pillars mounted on the Segway. The straps on the lower legs would help maintain balance and the feet rest are present so some of the weight of the user is transferred to the Segway through them, avoiding some unnecessary stress in the adaptation mechanism.

Some concepts took more thought than others, due to the potential of different approaches that could be taken, such as the foot rest and the knee lock.

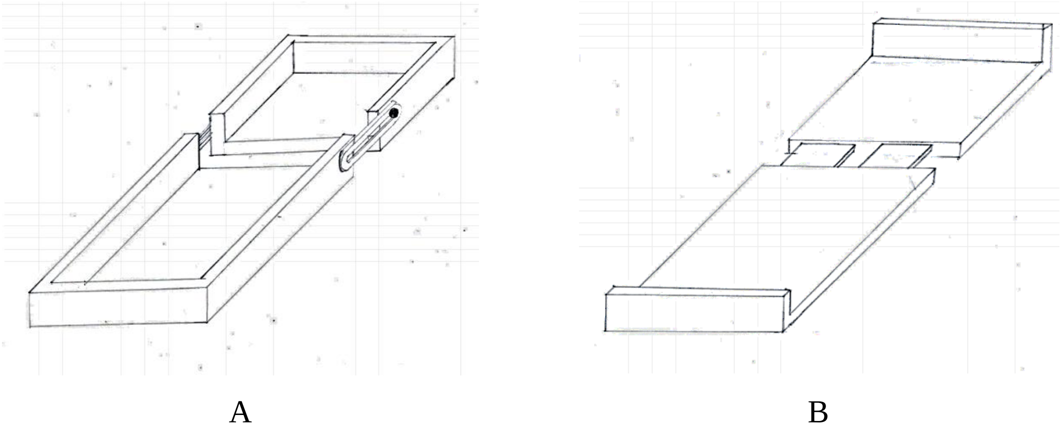


Figure 31- Foot rest concepts: A- original; B- improved.

The foot rest had two original designs, as pictured in figure 31. The first one had borders all around the foot, with the intent of better accommodate the foot, avoiding it slipping. For adjusting the length of the foot, it was thought a side slide with a bolt and nut lock. Although a safer approach, the strategy was too bulky and occupied extra space that the Segway's floor did not have. Such a lock was also quite impractical and time consuming when adjusting. Due to the enumerated complications, the later design did not use side borders and the length lock is friction based. These modifications resulted in a foot rest more compact and user-friendly. For good measure, a strap can be implemented encompassing the instep, avoiding vertical movements of the feet.

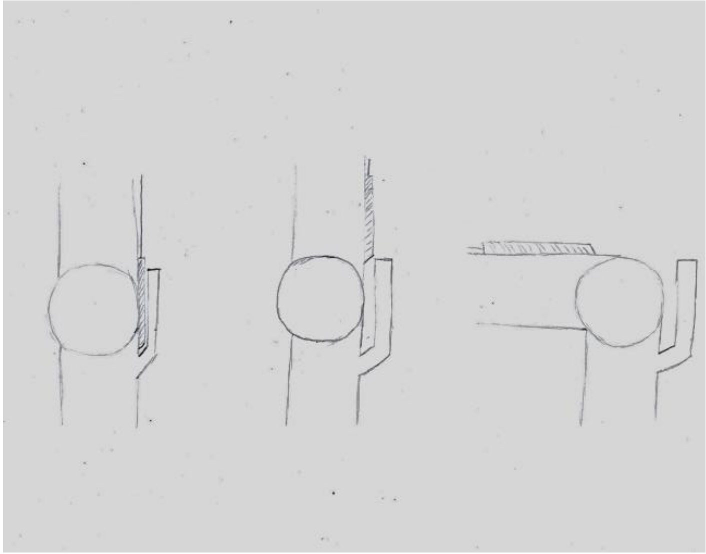


Figure 32- Knee lock concept with patella.

For the knee lock, there were three approaches to the solution. They all revolved around different ideas for locks. It was thought that such a device was required for avoiding losses of balance or even a collapse of the mechanism during use. The first one revolved about the idea of an external patella, as seen in the figure 32 above. The patella would be fixated on a pair of rails which would be vertically oriented. The part would be attached to an external string that would be connected to the user's hand. When the string was pulled, the patella would slide upwards, removing movement restrictions and unlocking the knee. On the other side, when the string was to be released while on the vertical stance, the patella would be embedded in the knee, preventing any rotational movement. The patella lock was eventually shelved due to the dependence of exposed parts which could jam easily, relied on gravity for locking and would only lock in a vertical stance.

The next two concepts made it to the CAD virtual modelling phase. As such, the reasons as which one was selected will be discussed in the following subchapter.

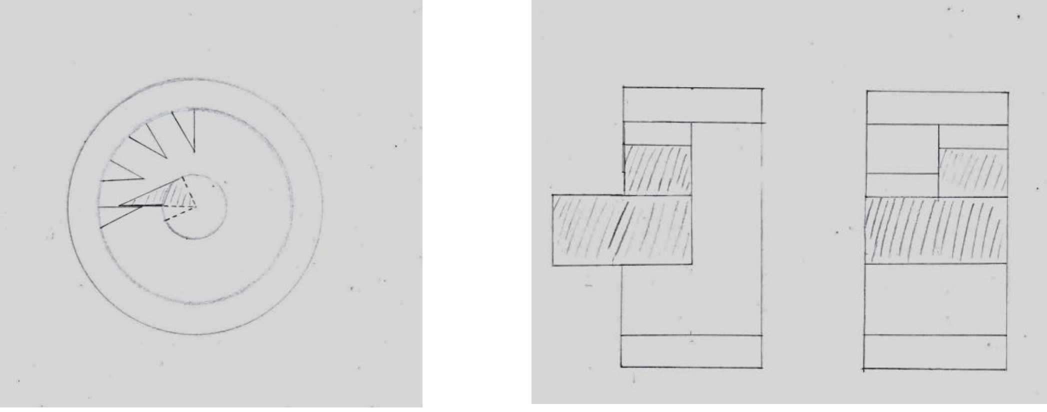


Figure 33- Knee lock concept based of handbrake mechanism.

The second lock idea was based of the handbrake lever present in cars. It was thought of a geared bracket attached to the lower part of the device and a pawl connected to the upper part of the mechanism, as in figure 33. As such, when the upper leg rotated at the knee with the lower leg, both the geared bracket and pawl would enter in contact. The geared bracket would allow the pawl to move freely in one direction -from seated to vertical position-, but would stop it from coming back, locking thus the device. The configuration would prevent the user from falling back, in case of loss of strength when standing. To unlock and allow the user to sit again, a button would be placed at the knee which, when pressed, would disconnect the pawl from the geared bracket in a horizontal motion, thus allowing the knee to rotate in the desired direction. When released, the pawl would go back to the original position with the assistance of springs.

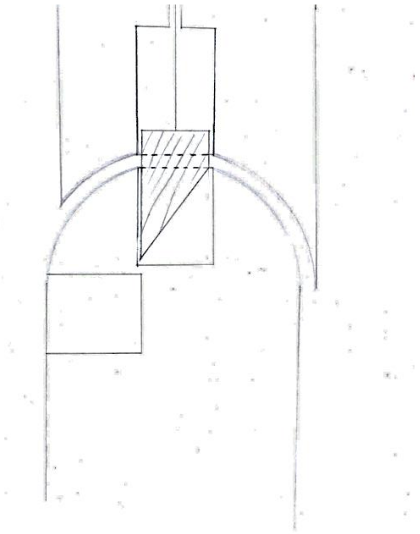


Figure 34- Knee lock concept with a pin.

The third and final lock concept would be the simpler one (figure 34). It uses a pivot pin as the locking mechanism. The spring-loaded pin is angled in one of the sides and attached to a string which connects to the user's hand atop the leg. The pin has two positions where it can be deployed, seated and vertical. In both stages there is a pit were the pin gets embedded in the respective pit and forbids the device from moving further in the anti-clockwise direction. To move in such direction, the mechanism must be first unlocked by pulling the string, removing thus the pin from the pit. Due to the pin being angled, it allows clockwise movement even if the catch is locked, allowing then the user to stand freely, but not to sit without pulling the string first.

4.1.2 CAD Virtual Modelling

At the present stage, it was required to estipulate an user's height so that the project could be designed in accordance. As such, it was concluded that the average height of an adult male in Portugal is 173.9 cm [83, 84]. Being the writer an healthy adult male with an height of 175 cm, this was the targeted measurement, although changes were made so the device could accommodate diverse heights.

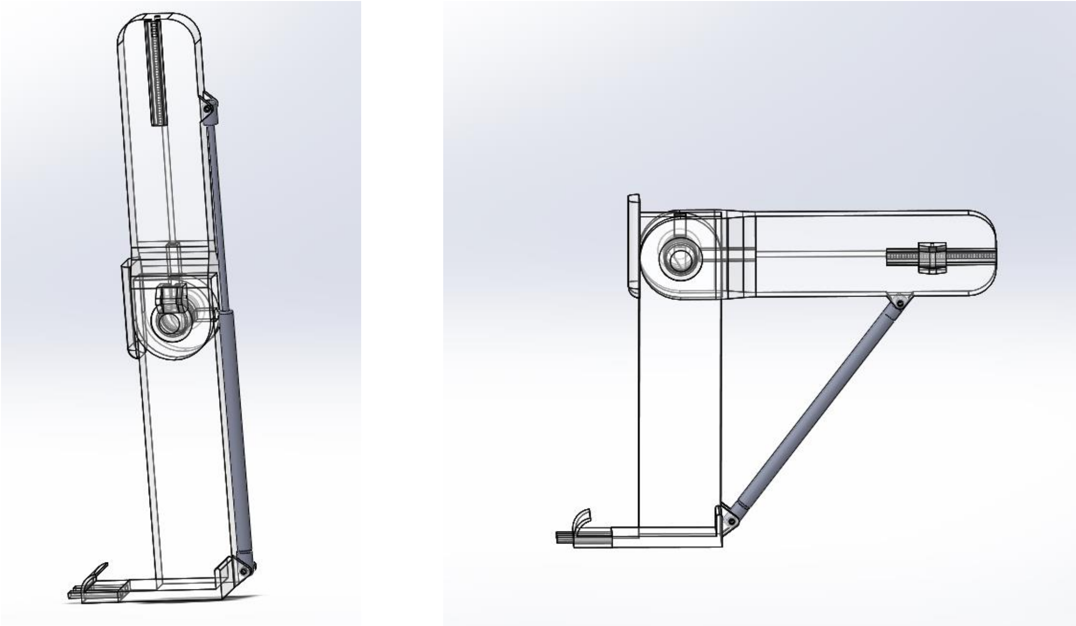


Figure 35- Model of the supporting structure.

The final model, shown in figure 35, has a sole with an height of 2.0 cm, foot length ranging from 25.5 cm to 33.5cm, due to the extendable sole. The distance from foot to knee is 50.0 cm and at standard user height -no hip adjustments- from foot to waist is 100.0 cm. The total height of the device is 109.5 cm.

All the parts of the device will be listed in three views in the Annex B.

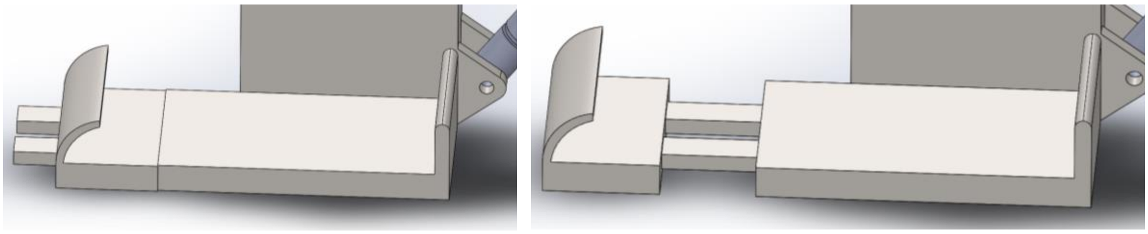
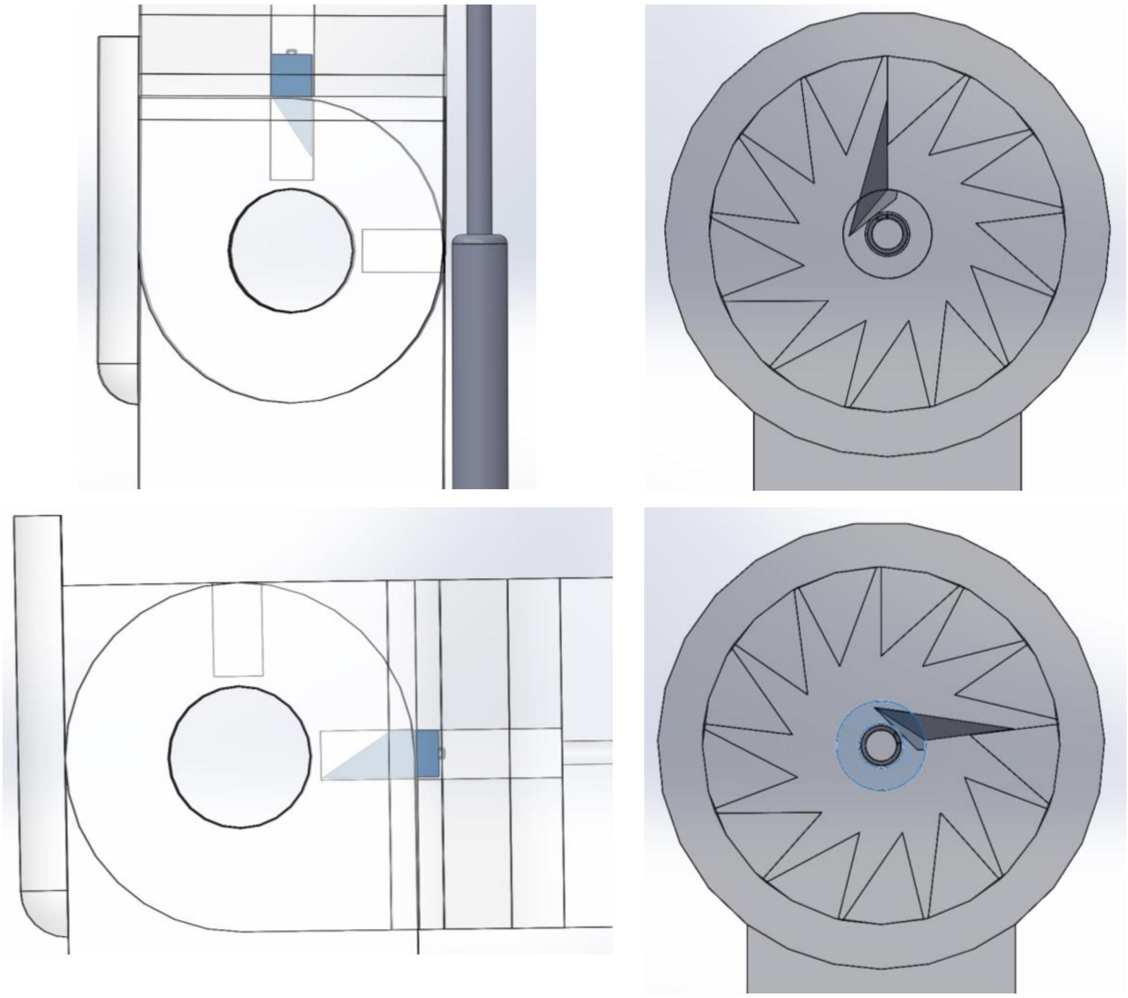


Figure 36- Foot rest model.

Entering now in more detail, the foot rest was modelled in a minimalistic way. As stated before, the pictured design allows for a slimmer and compact component. Still, there were implemented two walls, one at the heel and another at toes, as depicted in figure 36. The borders and the strap allow for a safer user, avoiding skids in any horizontal direction. The foot rest is easy to slip in and the strap is simplistic enough for anyone to use. The length of the foot rest is adjustable due to a split between the front and the back of the foot rest. With an on-rails connection, length is effortlessly regulated and has no complicated locks, having the on-rails connection enough friction to avoid slides even in use. Previously, the foot rest would be a part on its own, but to save precious space, it was implanted in the lower leg of the device.



A B

Figure 37- Knee lock models: A- pin lock; B- handbrake based.

As stated before, two knee locks made it to the CAD virtual modelling stage. Both showed promise, although ultimately only one could be picked. The knee based of a car’s handbrake, figure 37 B, only made it to the first stages of modelling due to two reasons: the discovering of a simpler lock and a design flaw. The design flaw was that the lock release button was at knee height, which would mean that the user would have to bend over, activate both buttons in order to be able to sit again, all while maintaining balance. Although feasible, it would require unnecessary degrees of effort and concentration for a task which should be effortless.

The pin lock, figure 37 A, while only has two locking positions, does not need to be unlocked to enable the standing movement –just as the above lock could- due to a cleavage in the locking pin, which allows one sided motion. It is considerably easier to produce and is not afflicted by the design flaw above stated, due to the unlocking string being located at waist high.

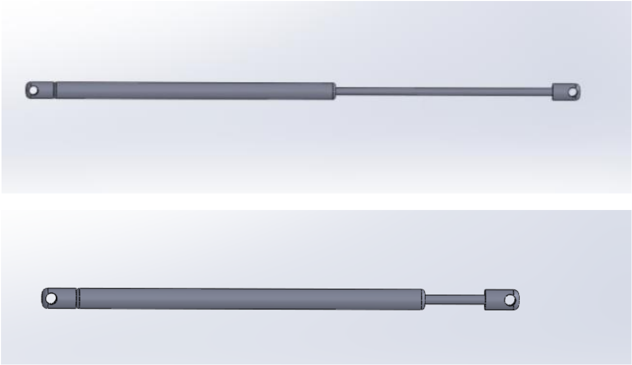


Figure 38- Pneumatic cylinder model.

In order to assist a motor impaired individual to use the device, it was thought that the implementation of pneumatic cylinders, as shown in figure 38, would be helpful to transition from seated to standing stance, without great effort. The cylinders should be dimension in a way that they should help, not lift the person on their own, or else excessively strong pneumatic cylinders would result in difficulties in lowering the user back to a seated position. The dimensioning of the cylinder strength is later discussed in the next subchapter.

The cylinders are designed to be connected between the upper and lower leg of the device, avoiding more connections to the Segway. Such placement allows the device to be more practical, speeding up the process of assembling or disassembling the mechanism to the Segway, should it be used to another end.

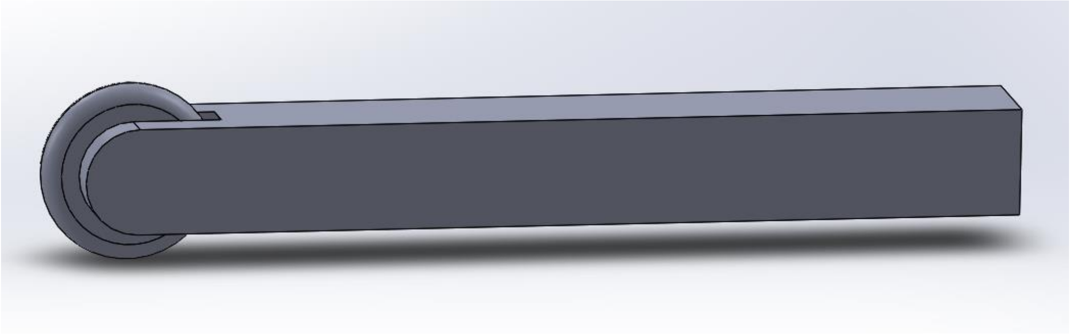


Figure 39- Extra wheels models.

The extra wheels are simple in design, as demonstrated in figure 39, as they are not meant to be used as the main wheels of the Segway. The function of these wheels is to help the user to regain balance in the off chance that the Segway would become too much tilted. Segways are programmed in a way that how more tilted they are, the faster they go. Such behaviour means that if the users lose control, they could end up speeding up and ramming against some obstacle, endangering themselves and others surrounding them. The extra wheels would avoid critical tilting, maintaining the balance of the user and the device, only touching the ground when such occasion arrives. Although top speed can be regulated in the Segway controls, the extra wheels would also avoid falls. While safer, the wheels limit the true potential of freedom that can be bestowed upon the user. As such, the wheels should be used only as training wheels until the individual can feel confident enough to ride on his own.

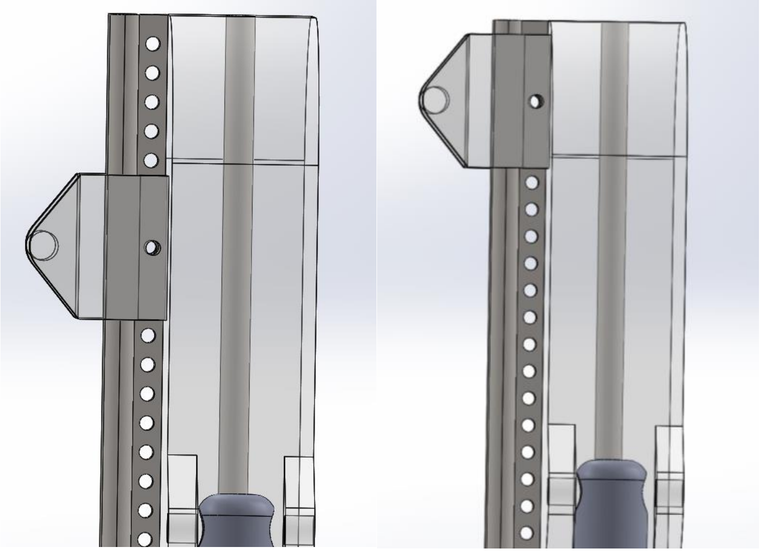


Figure 40- Height lock model.

The height lock depicted in figure 40 is a feature to help regulate the height for different users. Different approaches were discussed, such as a sliding system used in crutches, were the size of the upper leg could be extended or collapsed on itself by having two shapes sliding on one another and locking by a spring-loaded pin. Ultimately, the design was dismissed as the pneumatic cylinders connections would also need to be relocated every time the upper leg was resized.

As a result, the upper leg core was not modified for the feature, but the harness connection instead. By placing the harness connection -connection between the harness and the upper leg- on a rail system, the harness can be placed at different heights, accommodating shorter and higher people, all in an universal device and simple to adjust.

It was selected a rail system instead of a pin system due to the weight of the user being distributed homogeneously by a wider area, decreasing the stress on the system inherent in such a feature. The only pin present on the mechanism would be to maintain it in place, locking it.

Figure 41- 3D full model.

After all the parts were dimensioned, they were implemented in a 3D model of a Segway X2 SE, as demonstrated in figure 41, in order to better understand the final concept.

All the testing done in dimensioning the project shall be explained in the next subchapter.

4.1.3 CAD Analysis and Testing

After measuring and creating the intended leg support, it must be tested, in order to access if the support can keep up with the eventual forces that will ultimately be put upon it.

As a starting point, first was necessary to calculate the maximum force which will strain the mechanism. As stated before, the device is for the use of individuals up to 90 kg of mass. Converting into gravitational force, the value translates to 882.9 N. Still, the value needs to be halved, has it is being divided by both leg supports. Therefore, it is determined that 441.45 N shall be the force used in the study of the mechanism.

For the study of the forces applied to the device, it was considered that a leg support was a parallelepiped which had the dimensions of 50 mm hide, 150 mm across and 1100 mm of height. It was considered that the force would be applied at the top with an angle of -45º or 315º, as shown in figure 42. As such, it was calculated that the force of 441.45 N would have a vertical force of -312.15 N and a horizontal force of 312.15 N, as demonstrated in the following calculations.

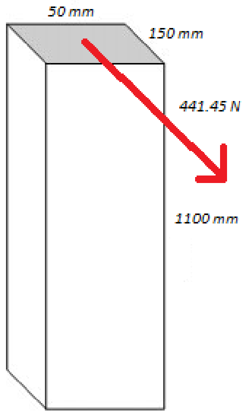


Figure 42- Descriptive force model.

$$\sin(315) \times 441.45\ N \cong\ -312.15\ N$$

$$\cos(315) \times 441.45\ N \cong\ 312.15\ N$$

For selecting which material should be used for a final prototype, mechanical properties were required in order to narrow potential candidates. As such, Young modulus, shear stress, shear strain and shear modulus were calculated. It was considered that the leg support should not deform either vertical or horizontally more than 20 mm, and even that value should be as minimalized as possible.

Young Modulus

$$E = \frac{\frac{F}{A}}{\frac{\Delta L}{L_0}}$$

$$E = \frac{\frac{312.15\ N}{0.15\ m \times 0.05\ m}}{\frac{0.02\ m}{1.1\ m}} \cong 2.29 \times 10^6 Pa$$

Shear Stress

$$\boldsymbol{\tau} = \frac{F}{A}$$

$$\boldsymbol{\tau} = \frac{312.15\ N}{0.05\ m \times 0.15\ m} \cong 41620\ Pa$$

Shear Strain

$$\gamma = \frac{\Delta x}{h}$$

$$\gamma = \frac{0.02\ m}{1.1\ m} \cong 0.09$$

Shear Modulus

$$G = \frac{F.h}{A.\Delta x}$$

$$G = \frac{312.15\ N \times 1.1\ m}{(0.05\ m \times 0.15\ m) \times 0.02\ m} \cong\ 2.29\ \times 10^{6}\ Pa$$

After obtaining mentioned mechanical properties of the desired material, it was necessary to cross-reference with a material library, in order to select the optimal material. As such, it was used the CES EduPack, a reliable and easy-to-use database which has the physical proprieties of hundreds of materials, allowing the user to do an informed choice of the best suitable material for the desired project.

While choosing a material, it must also be taken into account what is the final use of the device. As a vehicle intended for outdoors usage, it should be resilient and must be able to be in contact with the elements. The weight of the overall structure should be minimal in order not to overburden the *Segway* and also the cost of the material, maintaining the project in a viable marketing stance.

Under the stated properties, the following study was carried out, depicted in table 3 and figure 43.

Table 3- Material study table.

Function	Support weight
Constraints	Elastic Modulus>2.29 MPa Yield strength> 2.29 MPa
Objective	Minimize cost and Density
Free Variable	Choice of Material

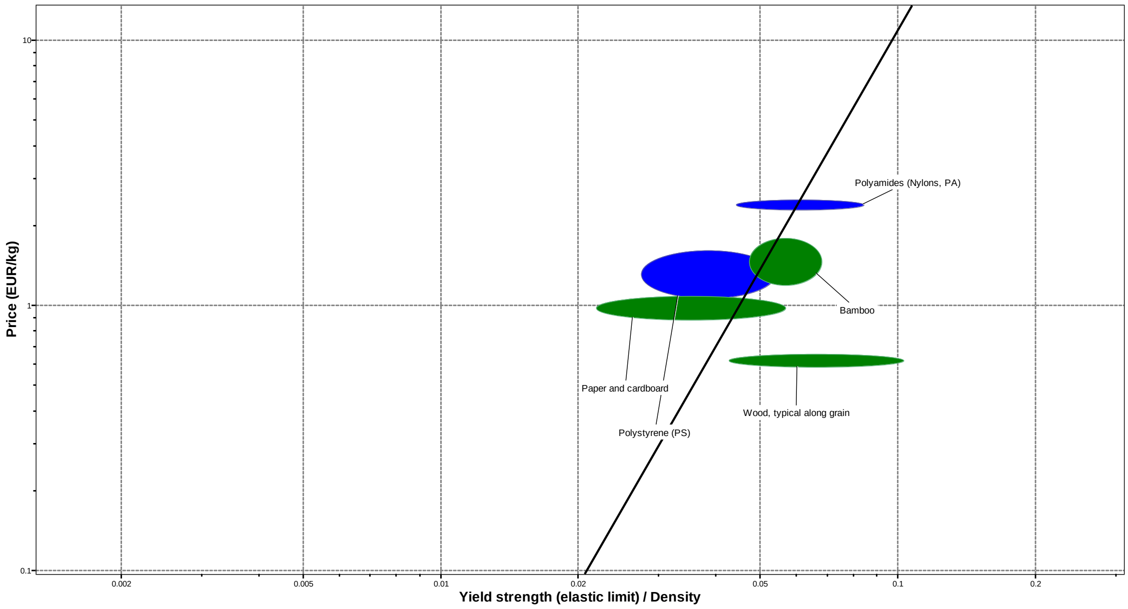


Figure 43- Fitting material options.

Since the choice of potential materials were still too many, the price was limited to 5€/kg and the material density to 1800kg/m^3. As such, the results were divided in two types of material. Biomaterials -such as *paper and cardboard*, *bamboo* and *wood*- and synthetics -*Polystyrene* and *Polyamides*. Although fitting the parameters, the biomaterials were discarded as they would require special treatment in order to be used in the outdoors, as humidity can easily swallow or shrink the materials, rendering the device useless if such an event happens. Left with polyamides and polystyrene, the polyamides were selected. Although more expensive, the yield strength to density ratio was superior that polystyrenes, making it the best choice.

According with CES EduPack, the different types of polyamides has a long array of uses, from filaments for garments, ropes, containers to chairs. The Young modulus can range from 2-62 to 3.2 GPa and the yield strength from 50 to 94.8 MPa.

A strong point for using a thermoplastic as polyamides, is that the processing techniques are considerably more accessible. Nylons have a large array of possible techniques, such as 3D printing, blow molding and compression molding. Models can be fast and mass produced with the right machinery.

With the material selected, now the device can be tested.

As the pieces for the Segway adaptation were created on *SolidWorks* software, the associated tools were used for the present step. Using *Solidworks Simulation* it is possible to generate resistance analyzes and stress tests in the modeled parts, as it is a CAE system (*Computer Aided Engineering*).

Firstly, it was used FEM, or Finite Elements Method. The idea behind the method is to divide the original model into smaller parts, simplifying a complex ordeal, creating a mesh. By dividing the piece in question in smaller parts, or elements, the *SolidWorks Simulation* can establish the equations, controlling the behavior of each element while it interacts with the surroundings. The elements in the mesh are connected by points that can be fluid in the direction X, Y and Z, granting three degrees of freedom.

The equations in *SolidWorks Simulation* links the unknowns, as displacements while analyzing tensions, just by evaluating the values of the material –from the inbuilt material library of the software- and the forces applied. Based on the parameters and the definition of the mesh created, the program will study the dislocation of every point and how it moves, showing later, when the information of all points is compiled, the deformation of the original piece.

The material selected in *SolidWorks* was *Nylon 6/10*, which, according to the software, has a Young modulus of 8.3x10^9 Pa, shear modulus of 3.2x10^9 Pa and a mass density of 1400 kg/m^3. According to the calculations made prior to the virtual test, these mechanical properties should achieve results inside the stipulated parameters.

After meshing the parts as finest as possible in order to achieve the most accurate results, an assembly of parts was tested. The results can be observed in the following figures.

Displacement

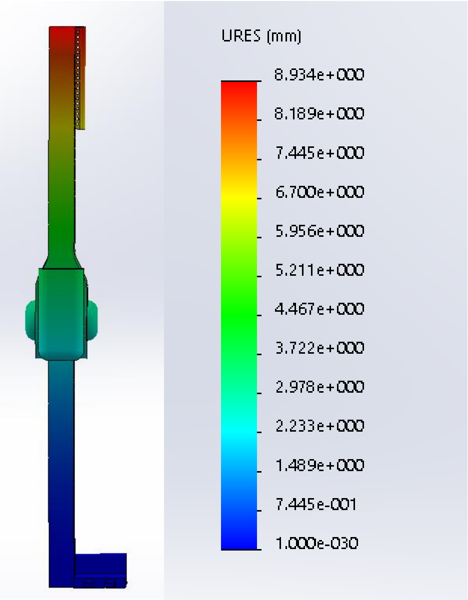


Figure 44- Static displacement study.

Calculating the displacement demonstrated in figure 44 allows the user to better understand where the model has displacements when the forces are applied.

After testing with the forces earlier calculated, the device registers a top displacement of only around 9 mm to the inside, being such value well under the parameters demanded.

Stress

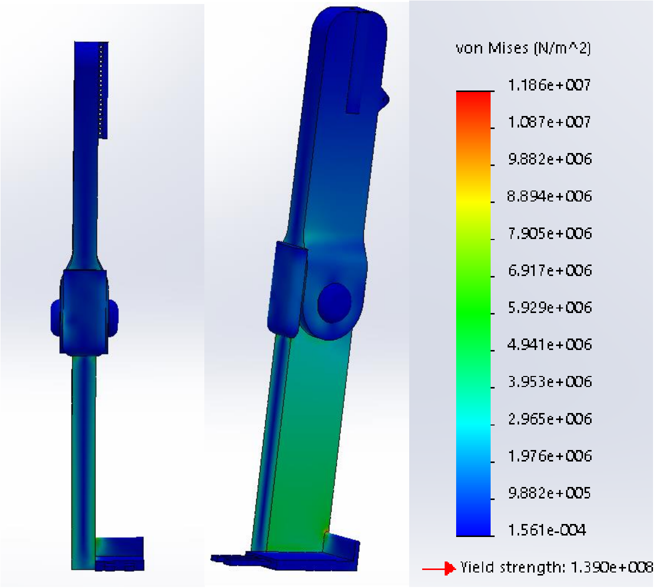


Figure 45- Static stress study.

Stress is the measure of internal pressures distributing within the system to cope with the forces applied to it.

While checking for stress placed on the structure, in figure 45, it can be easily understood that the lower part of the leg is where most of the stress is located. The highest point is between the contact of the lower beam and the foot rest which could be reduced with a slight change to the design. Still, the highest pressure applied is around 1.9x10^7 Pa, well under the Young and shear modulus of the material.

Strain

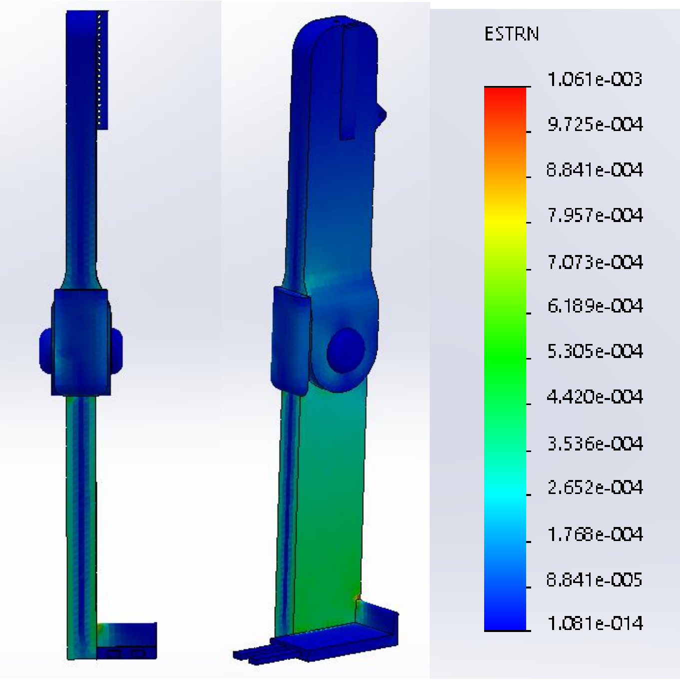


Figure 46- Static strain study.

Strain is a measure of the geometric response and the change in shape of the model due to the applied forces. Comparing to stress, visually is easier to understand.

As in the stress analysis, the most affected part of the device is on the lower part of the leg, depicted in figure 46. The same point of high stress, between the contact of the lower beam and the foot rest is, too, where more strain is accumulated. Still, following the equation of strain, the deformation can be considered minimal, rounding 0.1%.

$$\frac{\Delta x}{h} \times 100 = deformation\%$$

$$1.061 \times 10^{-3} \times 100 = 0.1061\%$$

Still, the device is not intended for being static. As such, it must be tested if it can handle the Segway breaking at full speed while transporting an individual. The top speed of the Segway is 20 km/h and it was considered that it should break in 2 seconds.

$$F = m\frac{v_f - v_i}{t}$$

$$249.75\ N = 90kg\ \frac{0\ m/s - 5.55\ m/s}{2s}$$

This force is now halved, as it is divided by each leg, meaning that each beam must support another 124.875 N as the figure 47 suggests.

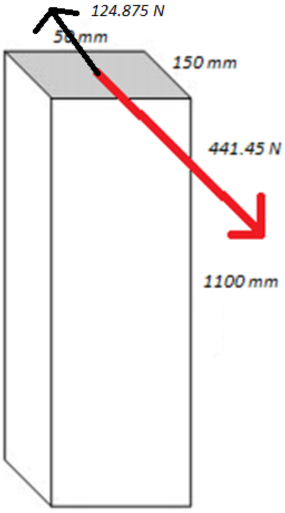


Figure 47- Stopping force model.

As expected, there is not much difference between the tests, passing both with flying colours, as shown in figure 48, 49 and 50.

Displacement

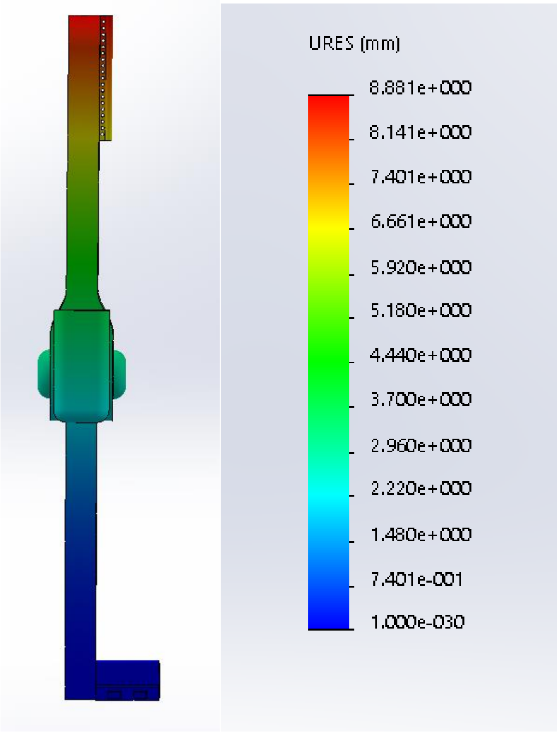


Figure 48- Moving displacement study.

Stress

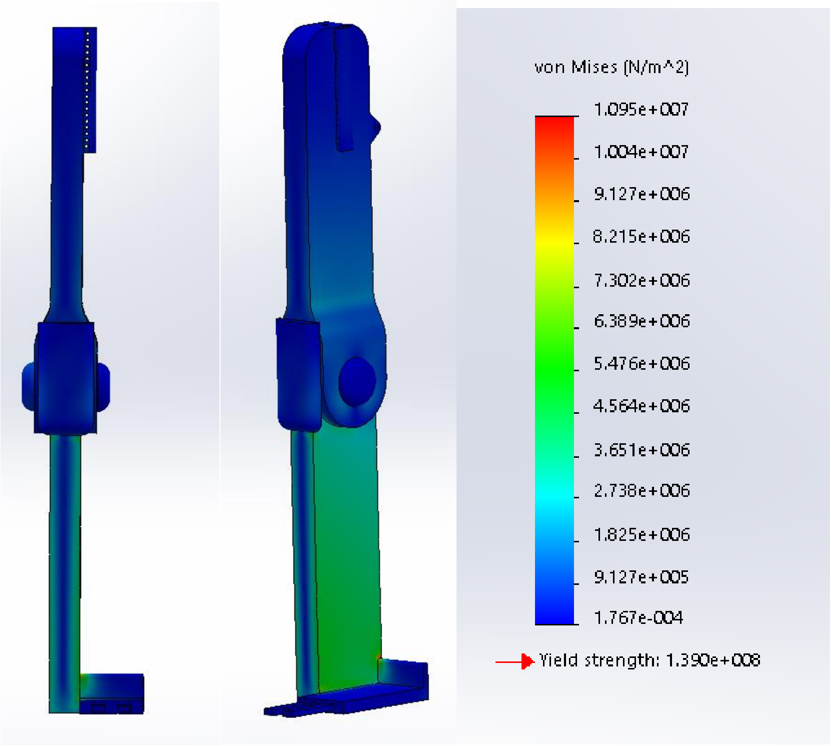


Figure 49- Moving stress study.

Strain

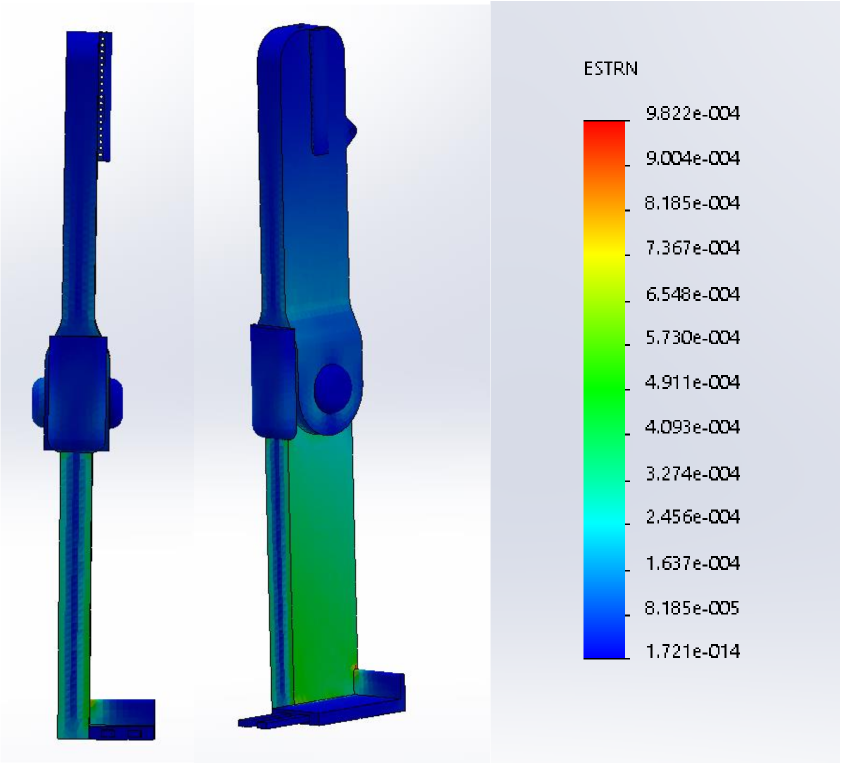


Figure 50- Moving strain study.

4.1.4 Prototyping

Creating a prototype is widely used to answer initial questions of the project, both to the team involved and to external parties. It can help in understanding if the original plan is feasible or it needs adjustments. It may also help convincing people unfamiliar with the project of its potential success and generate new input, instead of just presenting abstract ideas. As such, before entering mass production, all projects should create a prototype and test if the concepts generated theoretically hold up practically. The photos taken in greater detail of the individual parts shall be listed in the Annex A.

Figure 51- Final prototypes: 17.5% scale.

For the present project, two prototypes with different dimensions were intended to be created. The smaller one, in figure 51, with 17.5% of the original size was created as a proof of concept. It is quick to print and making it ideal to check for flaws of design. It was also possible to print by the author whenever necessary without using external assets, due to the easy access the author has to a 3D printer WitBox. It is a small, although precise, printer with the following work area: (*x*)297 x (*y*)210 x (*z*)200 mm. With the help of the printer XPIM, it was intended to create a larger model. Both 3D printers are depicted in figure 52.

A B

Figure 52- 3D Printers: A- WitBox; B- XPIM.

Due to its scale, it was possible to also print a scaled down model of the Segway X2 SE, picked from the *GRABCAD* library and assemble it with the prototype, giving a better understanding of the intents of the project, as shown in figure 53.

Figure 53- 3D printed model of Segway X2 SE.

Some liberties were taken with the *SolidWorks* version of the Segway X2 in order to simplify it before printing. Still, it was just for aesthetic proposes and should in no way influence the outcome of the final product.

Some alterations had to be made to the scaled down version of the prototype due to some components and gaps being too small for demonstrative use, but it does not affect the intended use of the prototype, which is to show case the ideas behind the project.

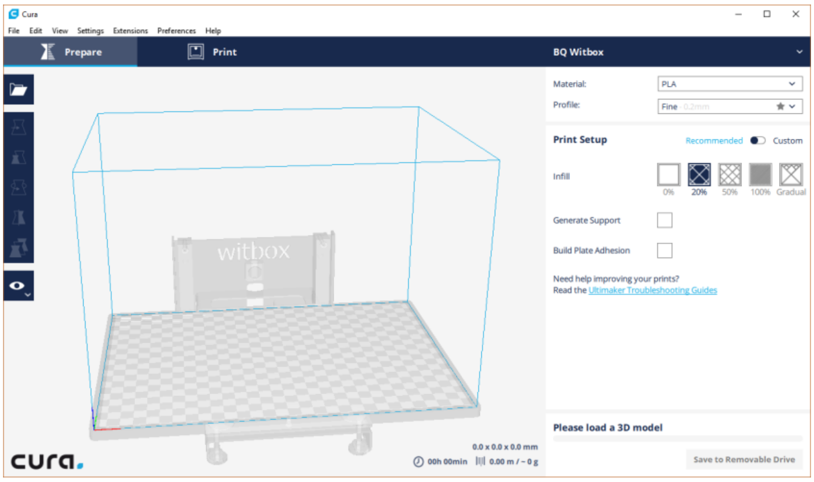
The larger prototype, with 67% of the original size was the final one, which would be created after all the modifications and adjustments were refined in the previous one. It takes considerably around 17 hours to print, and the scale was selected after acquiring an pneumatic cylinder, shown in figure 54. Being a difficult item to find a scaled down version of, the whole device was configured around the essential part. It was calculated that for a cylinder of that size, 60 cm -which can be compressed up to 35 cm-, the device would be 2/3 of the original size.

Figure 54- Pneumatic Cylinder.

Alas, the prototype cannot be used as a final product. Due to being 3D printed from a 1.75mm PLA bobbin, the most commercially available material for 3D printing, and not nylon, the material used was not up to standard with the requirements of the final product.

4.1.4.1 3D Printing

After designing and testing the final product, the prototype can be printed with confidence. However, first the project must be converted to *.gcode*, a type of file that the printer can read and start working. To do so, it was used the program *Cura*, depicted in figure 55, which is a free software with a fairly wide range of options of customization, ranging from printing speed, infill density, wall thickness, between others. The usual selected values were 0.1 mm for layer height, 20% of infill density, a printing speed of 220ºC and a printing speed of 40 mm/s.



Material: PLA

Profile: Fine - 0.2mm

Print Setup

Infill: 20%

Generate Support ☐

Build Plate Adhesion ☐

Need help improving your prints?
Read the Ultimaker Troubleshooting Guides

Please load a 3D model

0.0 x 0.0 x 0.0 mm

00h 00min 0.00 m / ~ 0 g

Figure 55- *Cura*.

Before even starting the printer, the plate must be cleaned with acetone, removing the residues from other prints that could still be present, as demonstrated in figure 56.

Figure 56- Cleaning the plate.

Afterwards, in order to avoid warping, which results in a weak adhesion between the part being printed and the plate of the printer, it was used a spray glue, easily removed with acetone, as shown in figure 57.

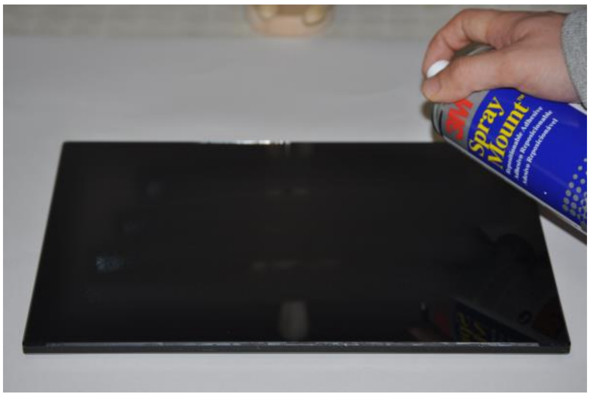


Figure 57- Applying glue.

Following the steps, the plate must be calibrated, the extruder must be heated to the desired temperature and then the printer begins to print the desired part. This is the most time-consuming process, which can range from minutes to days. Figure 58 depicts the 3D printer working.

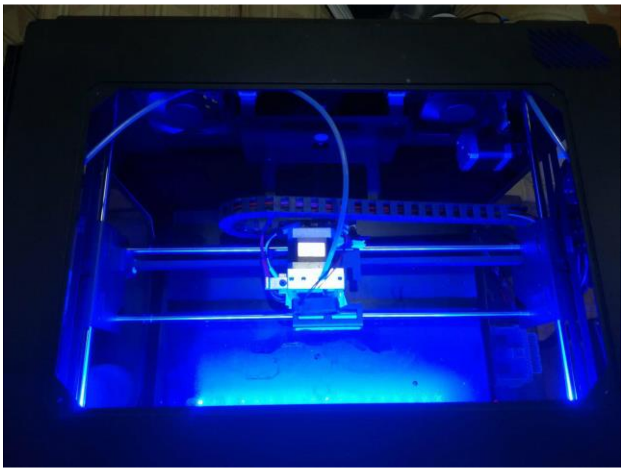


Figure 58- 3D Printing.

After the piece is finished, it must be extracted and the excess removed. In order to detach the gross of the surplus, as shown in figure 59, it was usually used a sharp knife. Still, some details had to be sanded and, for that purpose, it was used a drill modified with sandpaper.

Figure 599- Comparison between polished and raw printed parts.

After attaining the desired level of excellence, the device must be assembled. To maintain the mechanism in order without pieces coming out, it was used a plastic glue. The final prototype culminated in figure 60.

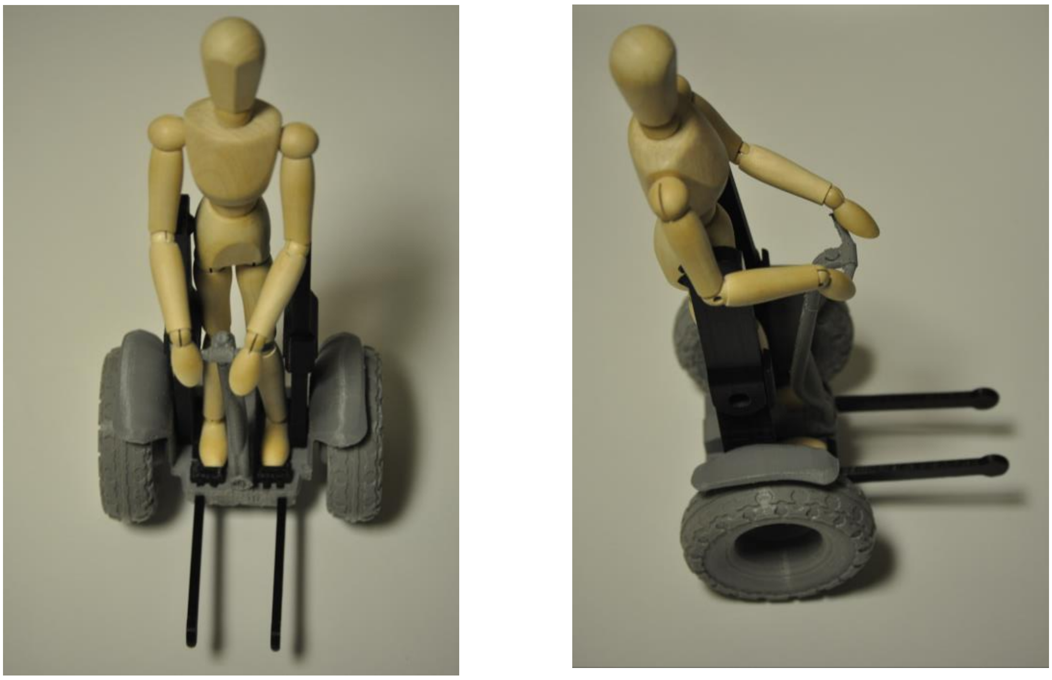


Figure 60- Final model.

4.2 SUMMARY AND DISCUSSION

The present chapter describes the procedure used for the development of the final model of the project. Firstly, it was introduced the sketches in mind for the device, and after reflection, the ideas were designed into 3D models in *SolidWorks*.

A study was conducted, with the assistance of the software *CES EduPack*, in order to access the best material for the device. In the end, it was selected Nylon 6/10, although other choices were available. The 3D model was then tested in *SolidWorks*, which passed with flying colours.

After testing, two real models were created via 3D printing. One had a scale of 17.5%, while the other had 67% of the intended size.

The present chapter was the culmination of all the work done to this point, allowing to design and develop a new mechanism with the propose of permitting disabled people to ride outdoors, at running speeds if so desired, while maintaining a vertical posture.

The printing of the device was not without mishaps. Some unfortunate events such as power shortage, lack material in the bobbin and misalignment while printing wreaked havoc in the schedule of printing the parts. Such misfortunes resulted in scars outside the walls, gaps, layer shifting or outright stopping the print, ultimately resulting in losing all progress that took hours to accomplish and, in some cases, days. Due to technical problems with the XPIM printer, unfortunately the larger model could not be printed.

CHAPTER 5 – CONCLUSIONS

5 CONCLUSIONS

After reflection of the overall development of the dissertation, and taking into consideration the innovative character of the project which could be relevant in the development of new types of mobility devices for the mobile impaired, some conclusions should be taken.

The study of the different mobility devices over the years of human history was taken in order to better understand the strong and weak points of each one, and thus, come up with a new concept that could answer the needs of individuals that are not yet quenched.

From the literature review, it was discovered a gap in the market for development of a vertical mobility device for people with reduced mobility.

After the assortment, sketches were created in order to flesh out the concepts. From these, 3D models were created using the software *SolidWorks*. Later, calculations were made to determine the best material for the product. The final model was then tested in order to access if it was viable for production. After validation, two prototypes were tried to printed in different sizes in order to better explain the concept and to find potential issues than can be fixed before potential mass-production. Alas, a larger model was not possible to create due to technical difficulties with the XPIM 3D printer.

After verification of the feasibility of the purpose of the work, it is believed that the project is valid for further development.

In conclusion, it is believed that the final concept answers to all the stipulated requirements, resulting in a success.

5.1 FUTURE TASKS

Although the achieved product can be considered a success by the author’s stipulated standards, it is believed that there is room for improvement.

There were not made studies in momentum transfer in the junction between the Segway and the designed mechanism. It is believed instead of gluing, fusing or bolting the mechanism in place, a new piece could be designed. The foot holder of the device and the foot placer of the Segway could be designed into a single piece, minimizing thus weak links.

The final product was considered functional, although somewhat bulky. An improved design could mean the use of lesser material, which means a lighter and perhaps cheaper product.

The device could be designed in such a way that otherwise deemed unviable materials could be used. If the mechanism was hollowed or even a different geometry was approached, minimizing volume, other denser, but stronger materials could be used, such as aluminium.

Another point of view could be instead of choosing an overall material, different ones could be selected for diverse parts, each one specialized for the different functions in the device. Some light metals could also be used on small parts were the weight would not be of significant importance and could smooth out the movements of the device.

If possible, the prototype should be as stable as possible due to the fragility of the intended users.

An intended step is the creation of a real scale prototype for testing with volunteers.

If feasible, a patent should be filled in order to protect intellectual property in order to study an entrance in the market.

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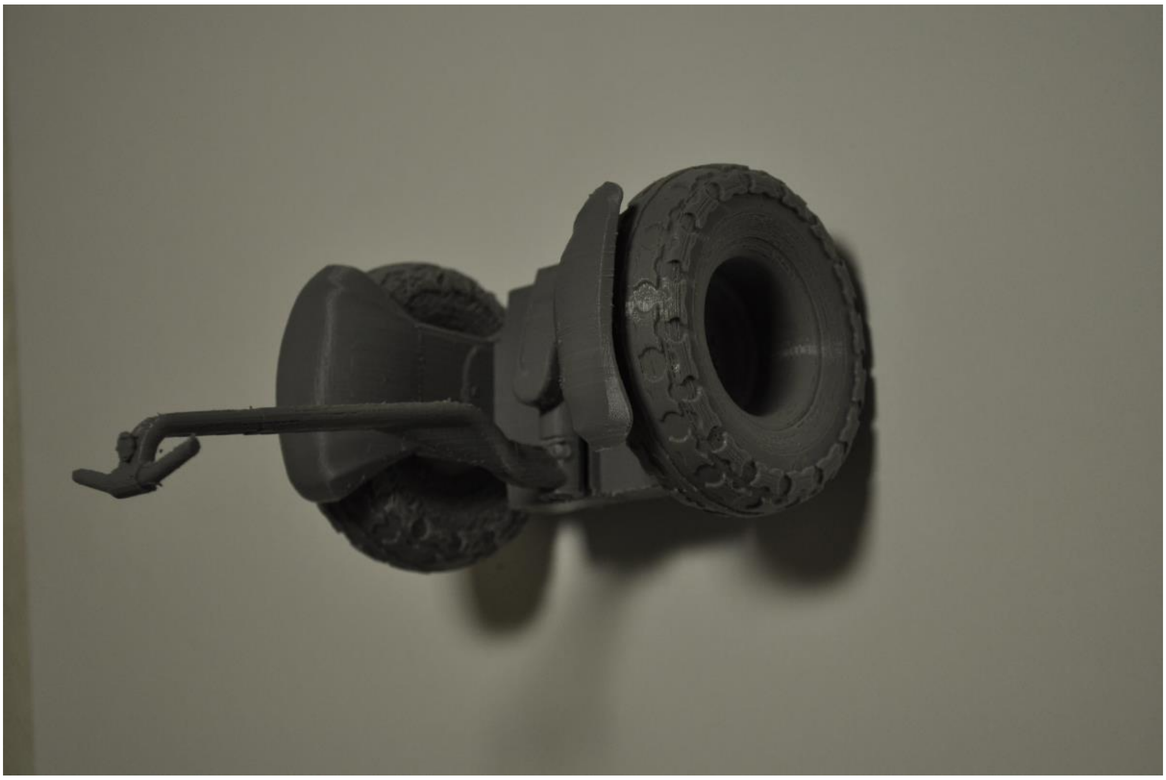
ANNEXES

ANNEX A

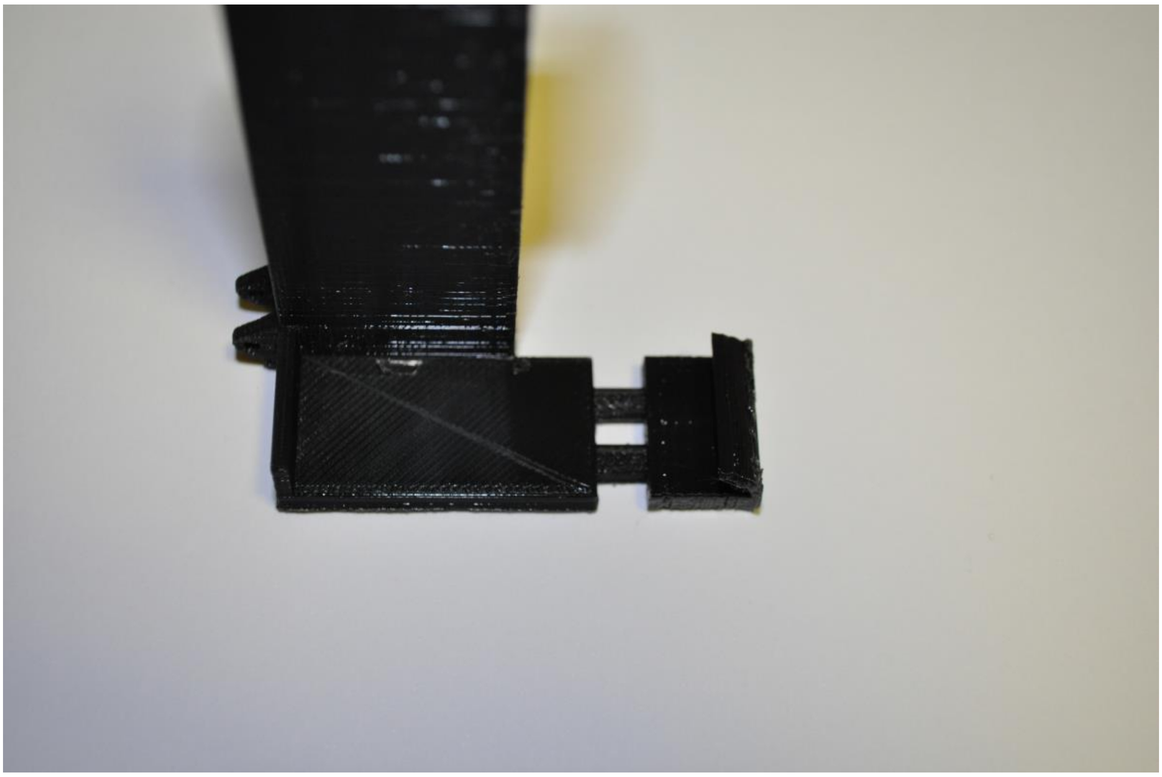
B.1 3D printed model of the Segway X2 SE.



B.2 3D printed model of the lower leg of the device (at a distance of 120cm with a 80x lense).

B.3 3D printed model of the front feet support (at a distance of 120cm with a 200x lens).

B.4 Visual explanation of the foot fitting.

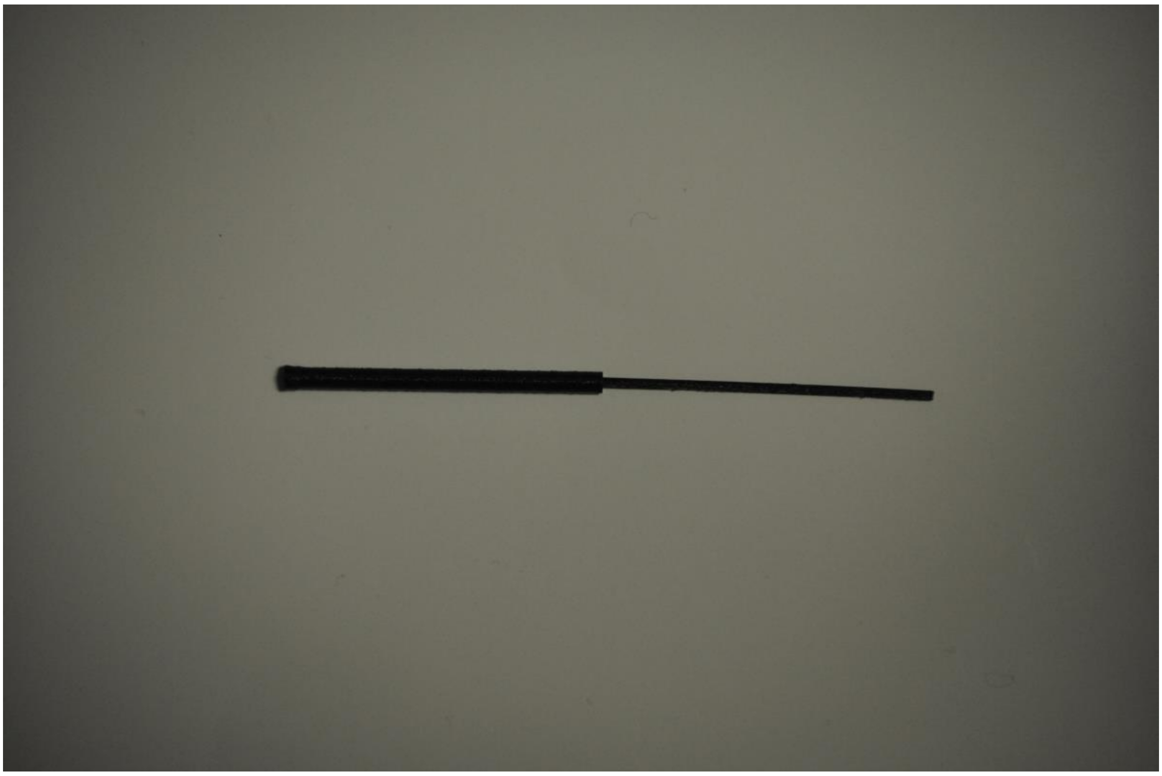


B.5 3D printed model of the upper leg of the device (at a distance of 120cm with a 80x lens).

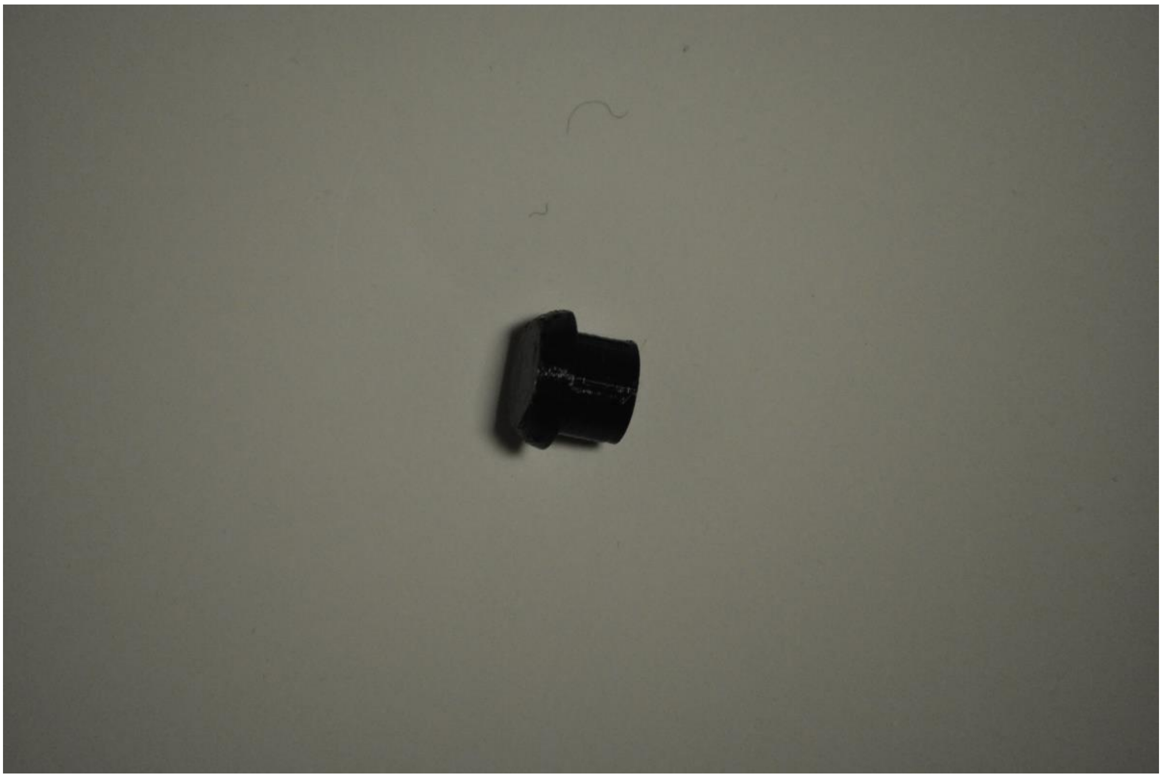
B.7 3D printed model of the lower leg of the device (at a distance of 120cm with a 80x lens).

B.8 3D printed model of the pneumatic cylinder of the device (at a distance of 120cm with a 80x lens).

B.9 3D printed model of the pneumatic cylinder of the device (at a distance of 120cm with a 80x lens).

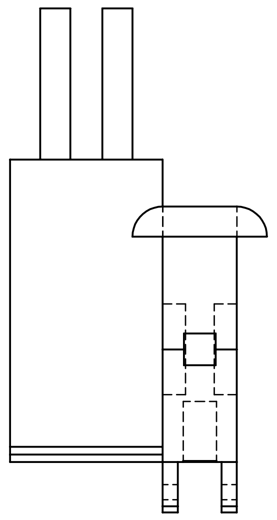


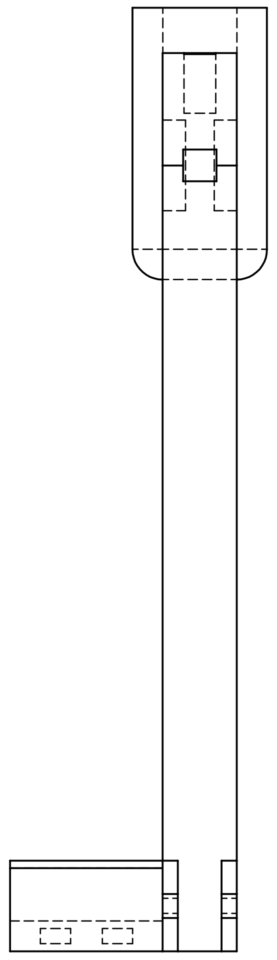
B.10 3D printed model of the rivet (at a distance of 120cm with a 200x lens).

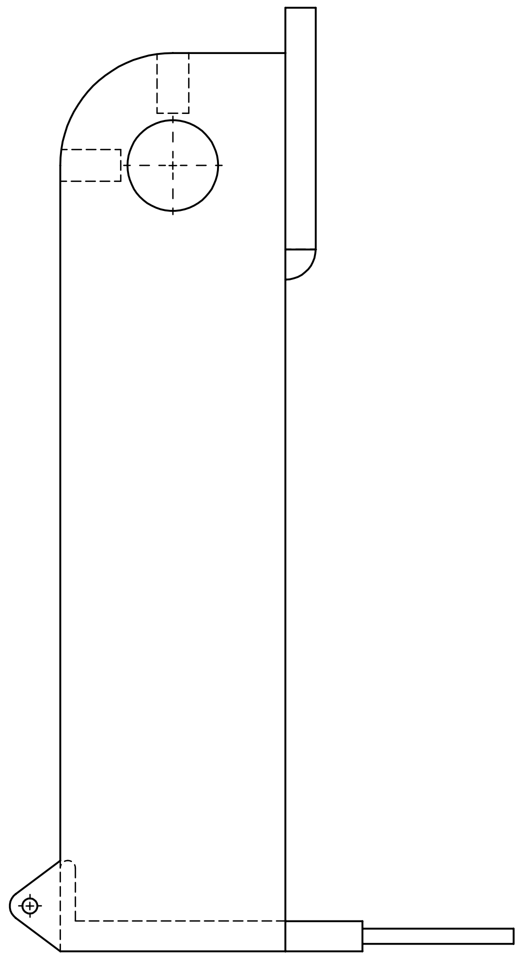


B.10 3D printed assembled model of the full leg (at a distance of 120cm with a 80x lens).

ANNEX B







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
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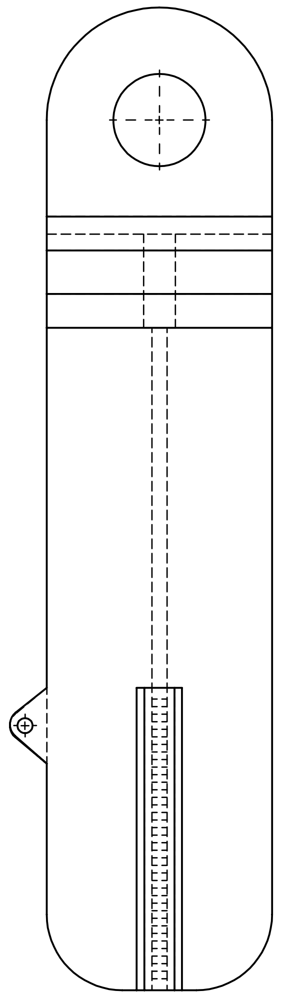
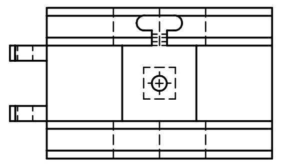
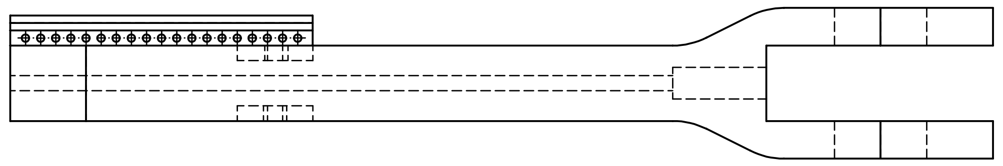
SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
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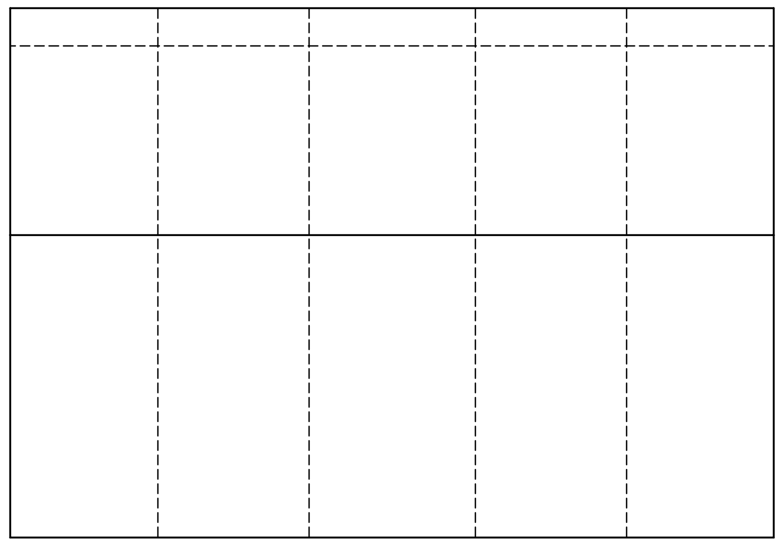
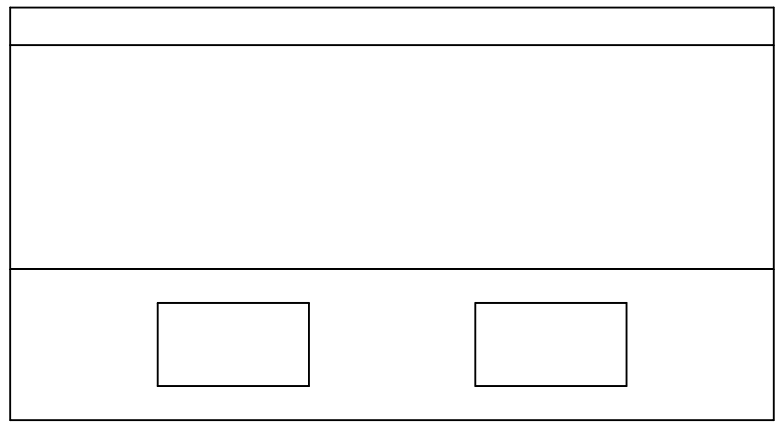
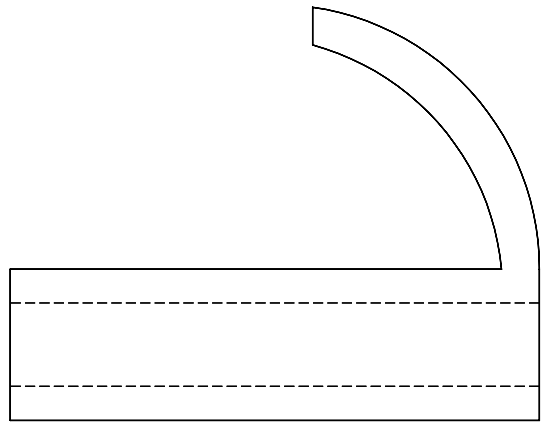
SHEET 1 OF 1







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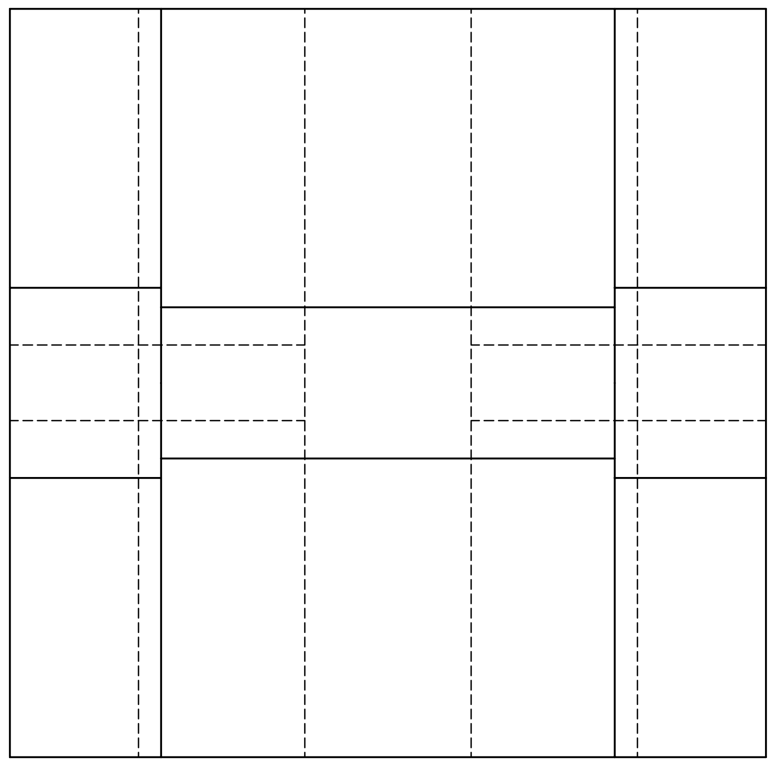
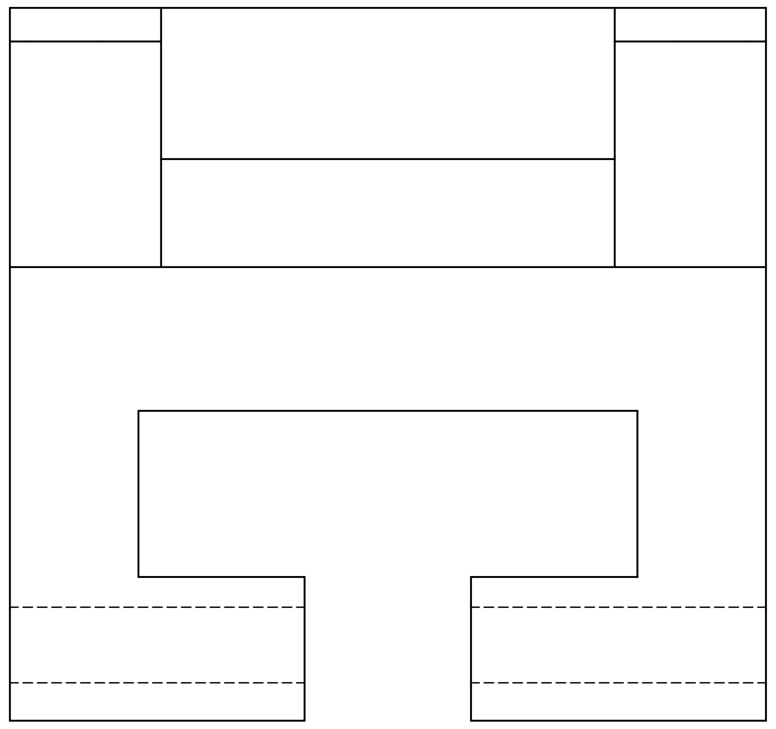
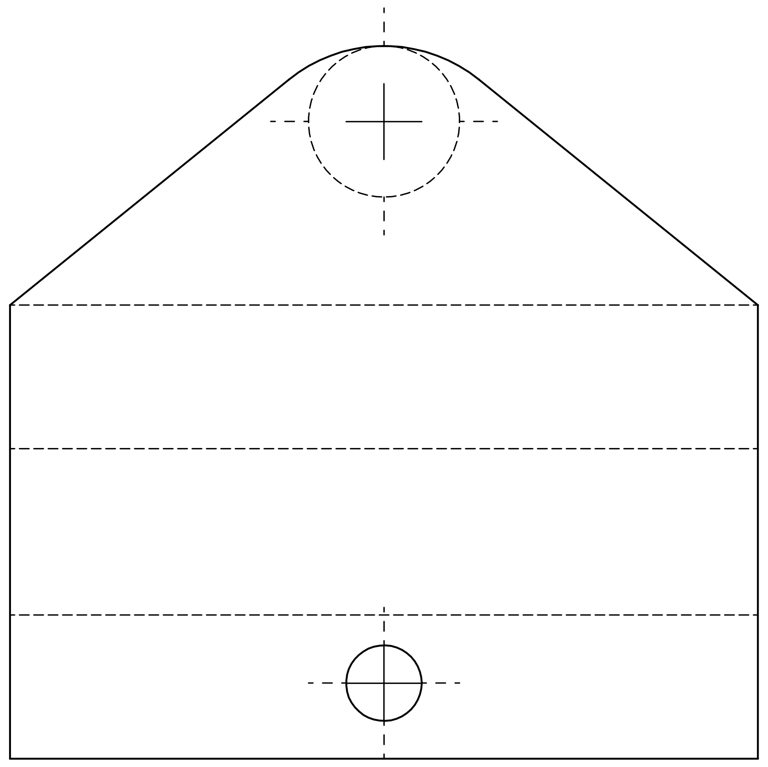
SHEET 1 OF 1







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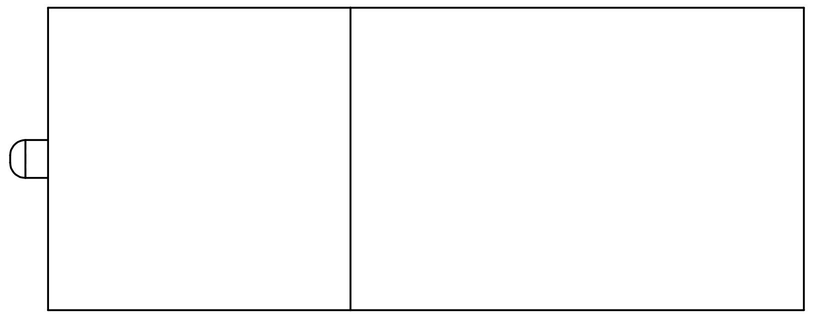
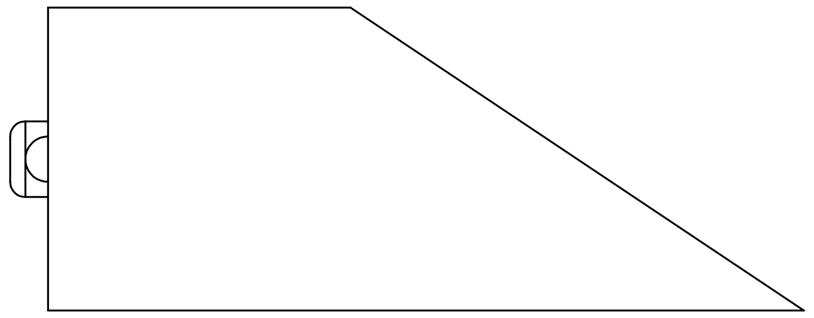
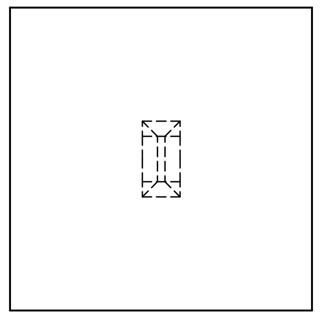
SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
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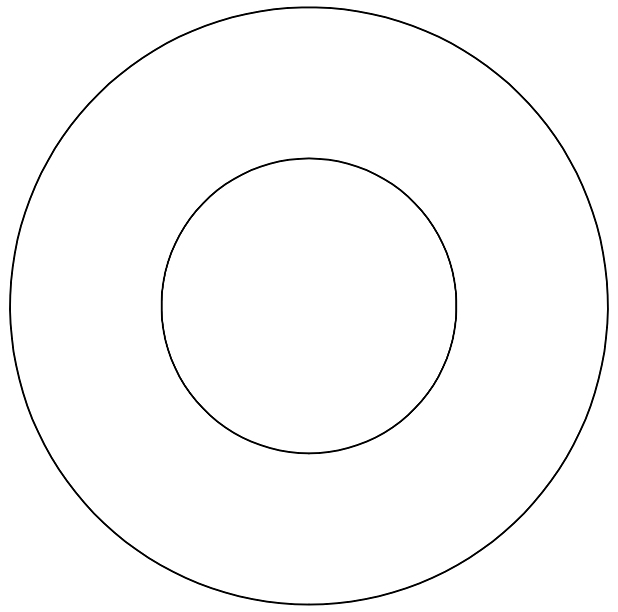
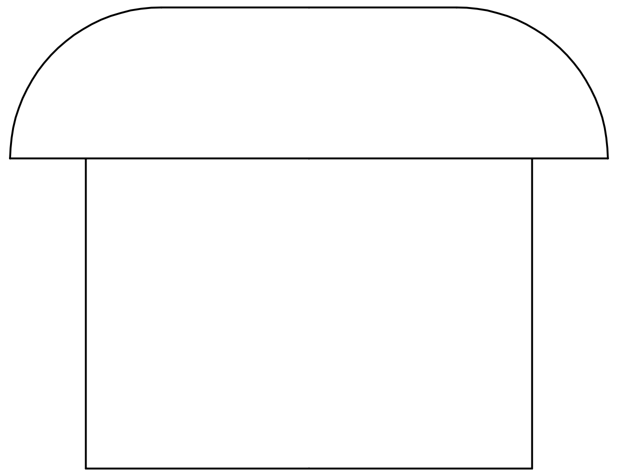
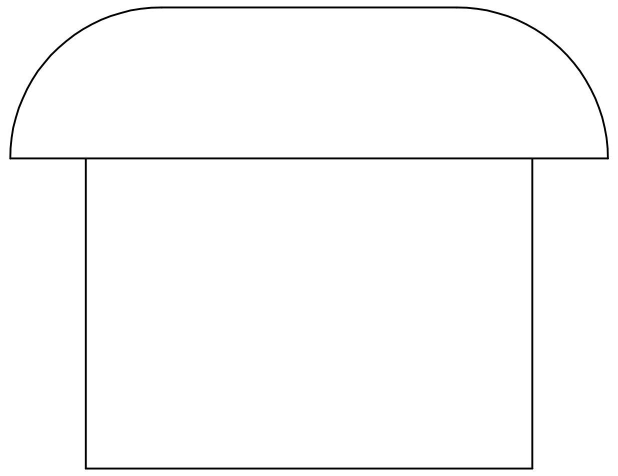
SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
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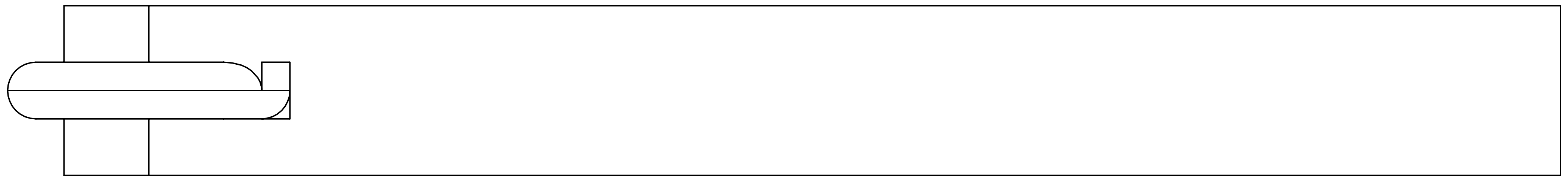
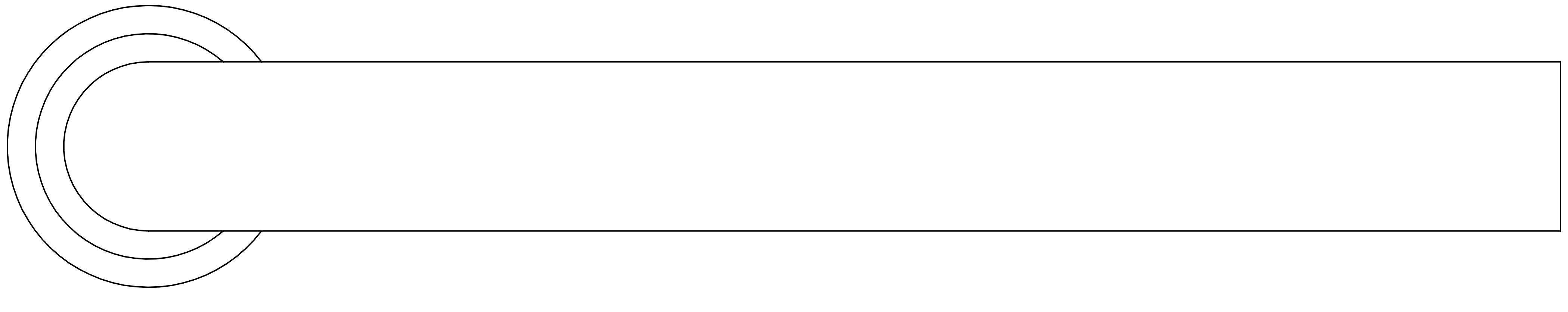
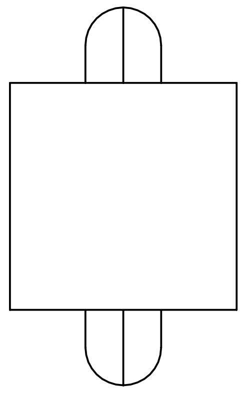
SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

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SHEET 1 OF 1