Analysis and design of an assistive and adjustable 3D-printed exoskeleton for disabled children

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Abstract

As the prevalence of musculoskeletal disorders increases throughout the world, the exoskeleton industry in the field of rehabilitative and assistive medical care has been rapidly growing. Upper extremity musculoskeletal disorders are one of the most concerning disabilities as mobility in the upper limbs is pivotal to perform basic tasks, and patients that suffer from these kinds of disorders often have a decreased quality of life. For children, upper limb mobility is crucial to gain independence and live a normal childhood. However, the limited number of commercially available upper limb assistive exoskeletons for children are not adaptable to their growth and are often inaccessible to underprivileged patients. In this dissertation, a 3D printed ergonomic passive upper limb exoskeleton that mitigates the problems mentioned previously is proposed. The design of the exoskeleton is based on the Wilmington Robotic Exoskeleton, a passive orthosis that uses elastic bands to counterweight gravity and provide a flotation sensation to the user, enabling arm movement. The redesigned exoskeleton is adjustable to a patient from 2 years old to adulthood and allows the user to perform the essential activities of daily living through fluid movements, without interfering with the environment and the comfort of the wearer. A prototype of the final design of the exoskeleton is completely 3D printed in polylactic acid, and the connecting elements to the body of the user are printed using thermoplastic polyurethane.

Keywords: Exoskeleton, 3D Printing, Musculoskeletal Disorders, Passive Exoskeleton, Upper Limbs

1. Introduction

According to the World Health Organization (WHO), approximately 15% of the world's population suffers from some form of disability. This percentage has been increasing as the world's population ages and chronic health conditions become more common. The prevalence of disability is higher in lower-income households and countries [1]. Musculoskeletal disorders (MDs), disabilities that cause limited mobility of the human body, are the leading contributor to disability worldwide [2]. Upper extremity musculoskeletal disorders (UEDs) affect the mobility of the upper arm, the forearm, or the hand, and are considered one of the most concerning disabilities, as lack of mobility in the upper extremity has a large impact on the quality of life of patients.

Exoskeletons are mechanical structures externally attached to the joints of the user that can serve both assistive and rehabilitative medical purposes, particularly for people that suffer from MDs. Furthermore, these devices can also be used to enhance physical ability in industrial and military settings. Exoskeletons can be classified as upper extremity exoskeletons, in case they are joined to the arms, shoulders, and torso, lower extremity exoskeletons, in case they offer support to the legs and hips, or as full-body exoskeletons. Additionally, devices that rely on an external source of energy are labeled as active while exoskeletons that rely on elements such as springs and elastic bands to store energy are classified as passive. The exoskeleton industry has been expanding in recent years, with projections pointing to a compound annual growth rate of the global exoskeleton market of 41.3%, from 2018 to 2025 [3]. It is expected that the development of this technology will focus on military and corporate applications, as well as in assistive exoskeletons for the elderly. However, the development of devices meant for children is still somewhat scarce.

In children, MDs can occur due to systemic conditions, orthopedic conditions, or trauma. Upper extremity disorders, in particular, are recorded in 2 out of 1000 live births [4]. Although these conditions are rare, lack of mobility in the upper limbs causes an inability to perform basic tasks and hinders the chance to live a normal childhood. Consequently, for these kinds of conditions, the treatment is usually aimed towards maximizing the limb's function through, for example, exoskeletons. However, the exoskeletons currently available for children are too heavy, large, or expensive.

With the introduction of 3D printing in the manufacturing process of exoskeletons, it is possible to rapidly construct highly customized and lightweight parts that can be used to assemble an exoskeleton. The Wilmington Robotic Exoskeleton (WREX), represented in figure 1, is an example of an assistive passive upper limbs orthosis for children that includes 3D printed parts. This exoskeleton was developed for children that suffer from multiple disorders that affect the strength of the muscles, particularly muscular dystrophies (MD) spinal muscular atrophy (SMA), partial spinal cord injury, and arthrogryposis. The WREX counters the force of gravity through elastic bands in order to decrease the effort the user has to perform to move their arm.

Figure 1: Wilmington robotic exoskeleton (WREX) [5]

However, the WREX suffers from several limitations. Although its upper arm link is adjustable to different arm lengths, the forearm link and several other features are custom-made for each user. Therefore, the exoskeleton does not follow the growth of the child nor is adaptable to several users. Furthermore, several clinical studies concluded that patients often find the WREX incommodious and cumbersome, interfering with their environment and not moving in concert with the user. Accordingly, the purpose of this thesis is to analyze and design an assistive 3D-printed exoskeleton for the upper limbs that is adjustable to the child's growth, following the anthropometric dimensions defined in table 1, comfortable and aesthetically pleasing. This exoskeleton must have five degrees of freedom (DOFs) to allow the user to perform basic essential activities of daily living (ADLs) presented in table 2.

Table 1: Average anthropometric dimensions in centimeters (cm) [6, 7, 8]

Measurement	2-year-old child	Adult
1 - Shoulder-Elbow Length	17.3	36.6
2 - Mid-arm circumference	16.1	33.8
3 - Elbow-Hand Length	22.9	41.7
4 - Sagittal abdominal diameter	15.0	22.8
5 - Waist circumference	48.3	94.8
6 - Torso length	24.4	52.0

Table 2: Activities of daily living according to [9]

Tasks	Hygiene	1. Reach to the opposite axilla
		2. Reach to opposite side of neck
		3. Reach to the side and back of the head
	Feeding	4. Hand to mouth
		5. Eat with a spoon
		6. Drink from a mug
	Everyday	7. Answer the phone
		8. Brush hair
		9. Raise a block to shoulder height
		10. Raise a block to head height

2. Background

2.1. Historical Overview

Although the term exoskeleton originated in the field of zoology, to describe external structures that are usually observed in invertebrate species, for the purpose of this thesis, an exoskeleton is defined as a mechanical structure that is externally joined to the human body. The first model of a device that resembles a bionic exoskeleton was patented in 1890. This patent described a lower-body passive exoskeleton that intended to enhance the performance of the user when running or jumping [10]. In the second half of the 20^{th} century the first active exoskeletons appeared, mostly targeted towards military purposes to enhance soldiers' performance, and for rehabilitative applications. However, as these exoskeletons were heavy and the inadequate technology available at the time made them unfeasible, exoskeletons became commercially available only in the 21^{st} century with the development of research fields like robotics.

Most of the assistive devices available today are designed for paraplegic patients, allowing the user to move without a wheelchair. However, exoskeletons targeted towards military applications also have been developed in the 21^{st} century, mostly by the United States Army, such as the XO Max, that allows the user to lift up to 90kg of weight for eight hours [11]. Nevertheless, these exoskeletons are still not fully prepared nor developed for a close combat environment and warm and humid climates, as they impair the agility and comfort of the user. Therefore, most military exoskeletons are currently being used for applications outside of direct combat, such as to help soldiers transport armaments.

On the other hand, in recent times, the number of exoskeletons developed for industrial applications has been exponentially growing. These exoskeletons are usually passive and have the objective of relieving the user of loads or of their own body weight.

Currently, the exoskeleton industry still faces many challenges in the commercial implementation of these structures. It is necessary to decrease the weight of exoskeletons and enhance their design to provide a satisfactory experience for the user and, for active exoskeletons, it is crucial to develop light-weight and efficient power systems. Soft-bodied exoskeletons offer a solution to these problems, as these devices use textiles to simulate the biomechanics of the human body, eliminating the need for a rigid structure. These exoskeletons provide fewer constraints and interference with the user and their surroundings, a reduction in the weight of the structure, and have less inertia, reducing the energy necessary to power the exoskeleton. Furthermore, as wearing a soft structure is easier than fitting a rigid one, soft exoskeletons offer adaptable and size-flexible structures, removing the need for individual customization. However, there are some disadvantages that come with soft-bodied exoskeletons. Whereas rigid exoskeletons have a hard structure, soft systems rely on the user's skeletal system, limiting the force that can be applied and increasing the difficulty to mount sensors, motors, and actuators in the soft structure. Consequently, mostly pneumatic actuation is used, due to its lightweight characteristics. To overcome the limitations of both rigid-bodied and soft-bodied exoskeletons, systems that combine both approaches, placing rigid elements parallel to the bones and soft elements in the joints of the user, are being implemented [12]. One example of the fusion of soft and rigid structures is tendon-driven exoskeletons, mechanisms that are driven by tendons that can keep a positive tension [13]. In the future, it is also expected that the integration of nanotechnology in this industry will allow for exoskeletons to become an integral part of the user and treat diseases such as obesity [10]. Another recent development in the exoskeleton industry is the introduction of 3D printing, which allows for rapid prototyping and lightweight devices. Therefore, this technology can decrease the cost of exoskeletons and expand their applicability.

The following section focuses on exoskeletons in the healthcare industry, as these are the most relevant for the present thesis.

2.2. Medical Exoskeletons

The market of exoskeletons targeted towards treating medical conditions has been significantly growing, with forecasts pointing to a growth rate of 35.15% between 2020 and 2027, and the market is expected to account for 1600 million euros by 2027 [3]. Healthcare is also the industry with the largest share in the global exoskeleton market, accounting for more than half of the market size [3].

Exoskeletons play an important role in assisting and rehabilitating patients affected by musculoskeletal disorders that cause people to lose limb mobility. These patients are often forced to rely on the assistance provided by caregivers, losing their independence and overall quality of life. For rehabilitative purposes, exoskeletons have the function of performing physiotherapy while the user executes task-based occupational or physical therapy in an active or passive mode. Assistive exoskeletons, on the other hand, improve the quality of life and the overall psychological and physical state of the patient by allowing them to move and perform tasks they otherwise would not be able to.

2.2.1 Upper Limb Exoskeletons

The upper extremity of the body consists of the hand, wrist, forearm, elbow, arm, and shoulder complex. Excluding the movement of the hand and fingers, the arm has seven degrees of freedom. When designing the exoskeleton, the anatomical range of motion (ROM) of the arm joints will be considered, as represented in figure 2.

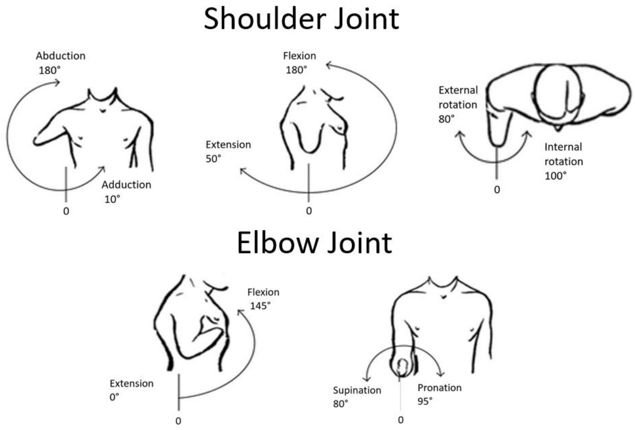


Figure 2: Range of motion of the human arm [14, 15, 16]

2.2.2 Upper Limb Active Exoskeletons

There are various commercially available upper limb active exoskeletons. In these types of exoskeletons, the energy is sourced via either pneumatic or hydraulic fluid pressure, or through electric current. The energy source dictates the type of actuation used.

The MyoPro exoskeleton, for example, is a powered orthosis commercialized by Mmyomo and originally developed at MIT with Harvard Medical School, in the early 2000s. This device functions in conformance with myoelectric signals received from the surface of the skin of the user, that activate electric motors that move the limbs according to the patient's intentions. The MyoPro is highly customizable and involves multiple fittings with the patient to ensure maximum comfort and effectiveness, and costs around 8500 € [17].

Contrary to the Myopro, the REALIVE power jacket is a soft medical exoskeleton for rehabilitation of the upper-limb movement of patients with one-sided paralysis. This exoskeleton is actuated through compressed air and when the incorporated sensors detect the movement of the unaffected limb of the user, the movement is mirrored on the paralyzed arm. Although Panasonic intended to commercialize the exoskeleton in 2009, it never came to fruition and was discontinued. At the time of writing this thesis, there are no commercialized soft upper limb medical exoskeletons.

The HAL-SJ exoskeleton has the objective of supporting and assisting the user's bodily functions. This device assists in the flexion and extension of the elbow joint through a power unit placed in the elbow. The exoskeleton is lightweight, weighing only 1.5 kg, and can operate for up to 120 minutes. This device controls the movement of the elbow joint by monitoring bioelectric signals or through a small controller that allows the operator to alter the setting and the motion status. As the exoskeleton only has one degree of freedom, its assistance is limited and can only be used without other structures in the elbow joint. However, it has been successfully used for rehabilitative purposes [18, 19].

2.2.3 Upper Limb Passive Exoskeletons

As the exoskeleton industry is moving towards adopting softer and less mechanical-appearing exoskeletons, passive exoskeletons have become, in recent years, more appealing. Passive exoskeletons eliminate the need to incorporate actuators that require a large amount of energy to compensate for gravity and, consequently, increase the weight and the size of the exoskeleton. These exoskeletons compensate the force of gravity passively using either counterweights or elastic elements such as elastic bands or springs. Although elastic bands introduce non-linearities into the system, they are more compact than springs and add less mass and inertia than counterweights. Therefore, elastic bands are used both in the WREX and in the exoskeleton designed throughout this thesis.

WREX Exoskeleton

The main goal of the WREX is to reduce the dependence of its users on others for personal care. According to the manufacturer's website, two similar exoskeletons are available, one for children and one for adults. Both exoskeletons can be made to fit a custom-made bodysuit or a wheelchair. The WREX has two segments, one for the arm and another for the forearm, connected together through the elbow joint and the shoulder joint, each providing two degrees of rotation, as represented in figure 3. For both versions of the exoskeleton, both in metal and 3D printed, the material of the links is steel. For the upper arm link, there are two parallel links that ensure that the elbow joint remains vertical as it rotates. For the wheelchair-mounted version, this link is telescopic and, therefore, adjustable for several upper arm lengths, but not suitable to adapt to the growth of a child nor to multiple people. The forearm link is manufactured through a mold and customized for each user. The elastics placed on the joints have different levels of stiffness to accommodate individuals with different arm weights. Usually, the fitting and adjusting during the manufacturing process of the WREX require patients to be present on three separate occasions in the Jaeco Ortophedic laboratory [20]. According to the "NeuroRheab" directory, the price of a WREX ranges from 1700 to 4300 €.

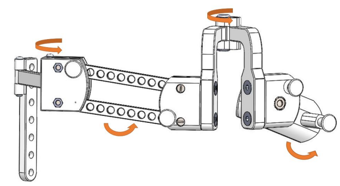


Figure 3: CAD model of the WREX and its four degrees-of-freedom

Focusing on the pediatric WREX model, several studies regarding patients' experience with this device have been performed. All articles conclude that, overall, the patients who use the WREX improve their performance of essential tasks and activities, and their satisfaction. However, there are still many limitations to the WREX. Most subjects report that the mounting and dismounting process of the exoskeleton is extensive and inconvenient and that safely transporting it to different locations is difficult. Furthermore, patients that suffer from ulnar deviation have difficulty using the WREX as it does not provide support for elbow pronation and supination [20]. For non-ambulatory patients, the process of removing and attaching the WREX to the wheelchair was impractical and required the help of another person, and the structure of the exoskeleton interfered with the joystick and the tray of the wheelchair. It was also referenced that adjusting the WREX to each individual was a task that required much skill and could only be done by professionals [21]. Another study noted that it is extremely important that the child has a parent or therapist available to tighten the screws and align the exoskeleton and that for active children the exoskeleton was incommodious and cumbersome [22].

Through the observations and conclusions drawn in the three studies described in the previous paragraph, there are several aspects that can be improved on the WREX. Firstly, as most disabled children live in lower-income households and countries and, consequently, it is likely that a device as expensive as the WREX paired with the trips required for the fitting sessions would be unattainable. Therefore, the exoskeleton should be obtainable for anyone with access to a 3D printer. Secondly, the entire exoskeleton should be adjustable to various users and to different ages and sizes without the need to attend laboratory sessions that entail the presence of many experts and the patient. Additionally, the exoskeleton should have an easy and intuitive assembly and fit that allows for anyone without any previous knowledge to be able to easily and rapidly mount it. On the other hand, the device should be comfortable enough for the user to wear it in any circumstances without risking damaging the parts. Furthermore, the joints should be less rigid and allow for fluid movement, and not interfere with the movement of the wrist unless necessary. Finally, the exoskeleton should be less mechanical-looking and more aesthetically pleasing, and move in accordance with what the user intends, and not interfere with the environment.

Although some of these challenges can be directly addressed through 3D printing, others have to be mitigated through a redesign of the exoskeleton. In the next section, solutions are provided and tested in order to improve the WREX in both these areas.

3. First Prototype

3.1. 3D Printing

Additive manufacturing (AM), also known as 3D printing (3DP), is a form of fabrication that consists of adding layers of a certain material to create a three-dimensional part. In comparison with traditional subtracting manufacturing, 3D printing allows for the manufacturing of more complex shapes while wasting less material, as it is not dependent on indirect consumables such as molds and fixtures. This technology is becoming increasingly more accessible not only for manufacturers but also for individual personal use, as in a study conducted by Reichelt Elektronik that surveyed 1000 UK consumers in 2018, 6% of the people claimed to own an AM system while 17% showed interest in acquiring one. Furthermore, as per the Wohlers report, around 550,000 desktop 3D printers were sold in 2018, almost twice the amount of the same sales in 2015, and in 2021 the 3D printing industry grew 7.5% despite the COVID-19 pandemic [23].

The manufacturing of 3D printed parts can be done through multiple processes, in which the material is deposited, joined, or solidified, while controlled by computer software for computer-aided design (CAD) and manufacturing (CAM). The most widely used 3D printing process, holding about a 69% share in 3D printing technologies [24], and the one used to fabricate the exoskeleton in the present thesis, is Fused Deposition Modelling (FDM). This process consists of heating plastic filament until plastified and depositing a layer in a heated bed through a heated extruder to build a 3D part according to the CAD data provided to the printer. Each layer quickly solidifies and bonds with the previous one.

In FDM, the parameters selected by the user, that are indicated to the 3D printer through a G-code generated by an appropriate computer software, strongly impact the properties and the quality of the final part. The infill percentage, in particular, has a great influence on 3D printed parts, as parts with a higher infill percentage have higher Young's modulus and ultimate tensile strength, but are more brittle. The adhesion between each layer is also an important factor when considering FDM parts and the bond strength between the different layers is lower than the base strength of the material. Consequentially, these parts are anisotropic: their strength in the z-direction is always lower than in the x-y plane. Therefore, the best mechanical properties are obtained when the deposition orientation direction is the same as the direction of application of the tensile load.

Although FDM can work with a wide range of materials, the most commonly used materials in FDM are thermoplastics such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). In the present thesis, both PLA and thermoplastic polyurethane (TPU) are used to build the exoskeleton prototype. The 3D printer used to manufacture the prototype is the Creality CR-10, a desktop 3DP with a non-direct extruder.

3.2. PLA Filament

PLA filament is biodegradable and one of the easiest to print with as print temperature is lower than other materials such as ABS, enabling better surface details and features, and it is not as susceptible to warping and clogging. Additionally, PLA is available in a large range of different colors, which allows for easy customization of the exoskeleton according to the user's preferences.

The mechanical properties of the PLA filament used for the prototype are considered to be the same as the ones obtained by H. Gonabadi et al. for a 25% triangular infill and are presented in table 3 [25]. As the ultimate compressive strength can not be obtained through a uniaxial tension test, the value of this property was obtained through the information provided by MakerBot for a standard resolution and infill [26].

Table 3: PLA mechanical properties, considering a 25% triangular infill density [25, 26]

Ultimate tensile strength (MPa)	29
Ultimate compressive strength (MPa)	17.9
Ultimate tensile strain (%)	2.15
Poisson's ratio	0.31
Elastic modulus (GPa)	2.05
Failure strain (%)	3.4

3.3. TPU Filament

The parts that connect the exoskeleton to the wearer's body can not be manufactured in PLA, as their material must be flexible to adapt to the user's limb and its dimensions, and comfortable. Therefore, the parts in direct contact with the user's body must be printed using TPU, a durable and flexible thermoplastic elastomer that is smooth and comfortable on the skin and can be 3D printed with a standard desktop FDM printer. However, this material entails some difficulties as it is hygroscopic and its elasticity can cause clogging in non-direct extruders.

3.4. CAD Model

The CAD model for the 3D printing process was designed taking the WREX exoskeleton model as a starting point, and modifying its parts to tackle the limitations referred in section 2.2.4. The parts that were not 3D printed were modified to be able to be easily manufactured in PLA. Furthermore, various alterations were made to simplify or merge parts, and to create a flat surface in each one that facilitates the 3D printing process, improving the mechanical properties of the part. For example, the elastic support features were designed as individual parts to fit

Figure 5: 3D printed prototype of the exoskeleton being used while performing the ADL of brushing hair

into the structure, to provide a flat surface to serve as a base for the 3D printing process of the joints. On the other hand, several changes were made to reduce wear and friction of PLA parts.

Addressing the fact that the exoskeleton must be adaptable to several sizes, several options of extension and retraction of the upper arm link were considered. Various samples were also 3D printed to test structural integrity and analyze the ergonomics of each option. Finally, the design selected includes telescopic rails with a locking mechanism that allows the user to easily adjust the rails to the desired length. To adjust the exoskeleton to the forearm of the user, instead of using a custom-fitted mold, the 3D printed forearm link is connected and adjusted to the user through a TPU wide strap, that is adjustable to various sizes. As the customized vest should also be eliminated, a telescopic back link was introduced. This back link is strapped to the body of the user through a belt.

With the modifications mentioned previously implemented, the CAD model of the first prototype is represented in figure 4.

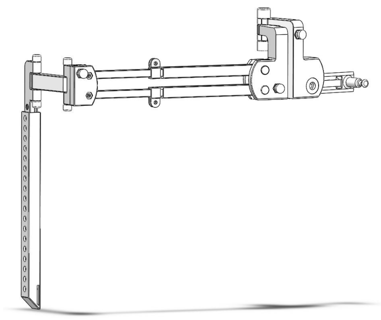


Figure 4: CAD model of the first prototype

Afterward, the CAD model was converted to G-code and 3D printed. The 3D printing process lasted 21 hours and 27 minutes and consumed 5.67 euros worth of filament. Through the prototype photographed in figure 5, various areas of potential improvement were identified.

3.5. Areas of Improvement

There are various areas to improve in the exoskeleton, relating to both the design and the 3D printing process. However, it is important to note that the prototype provides the range of motion necessary to perform all the ADLs defined in table 2. The exoskeleton was easy to put on by the user, albeit a second person significantly simplifies the process but the fit of the exoskeleton is cumbersome because of the fact that, when performing certain movements, the exoskeleton does not stay connected to the body as expected and the telescopic rails of the arm link would also disengage.

3.5.1 Design Aspects to Improve

The arm link composed by the telescopic rails does not lock in place when the user performs sharp and abrupt movements. In these situations, the arm link extends its length and it is necessary to untighten the bolt, reposition the outer telescopic rail in its initial placement and tighten the bolt again. This design flaw, although not completely impairing the usage of the exoskeleton, would be a great inconvenience for the user and must, therefore, be mitigated. For this reason, a groove was added to the inner telescopic rail and a tongue to the outer telescopic rail to hold these parts together during the usage of the exoskeleton, as represented in figure 6. The back link will follow the same design.

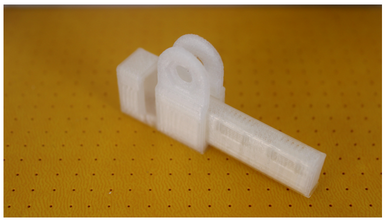


Figure 6: Sample the redesigned telescopic rail

During the usage of the exoskeleton, it was also noticed that the connection to the user's body was not enough to provide a stable and comfortable experience for the user. It was observed that this problem was predominantly evident in the elbow and shoulder joint, as when extending the arm the exoskeleton would not move as close to the body as supposed. Consequently, it is necessary to add a connection in the elbow link and another in the shoulder link. With these design modifications, four TPU straps are necessary to connect the exoskeleton to the user's body, and two additional ones, that can not be 3D printed in the Creality CR-10 due to build volume constraints, must be secured to the back link.

Another phenomenon observed was the wear that occurred in 3D printed parts when in contact with connecting elements. An article [27] published in 2020, where wear tests are performed on FDM 3D printed PLA samples, on a pin-on-disc tribometer with a steel disc, and a subsequent surface analysis concluded that the removal of material in the sample occurs due to both adhesion and abrasion. Therefore, it is probable that these wear mechanisms cause wear in the exoskeleton surfaces in contact with steel screws, particularly when there is rotation around these parts. It has been reported that the wear rate increases proportionally with layer thickness and the infill density [28]. Furthermore, a smooth surface finish of the component significantly reduces the wear suffered as the contact area is minimized [29]. The influence of these parameters is taken into account in the 3D printing process and in the selection of the parameters, to improve wear resistance whenever possible. Furthermore, when it comes to the design of the exoskeleton, unthreaded screws can be used to reduce the contact area between PLA and steel. The clearance between the bolts and the 3D printed parts' surface, for static components, should also be reduced to decrease friction between the parts. On the other hand, to reduce the wear between rotating parts and pins, a rubber O-ring can be placed between the top of the pins and the component.

3.5.2 3D Printing Challenges and Solutions

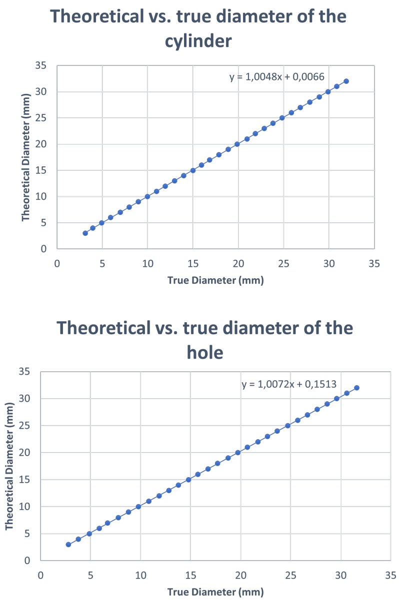


Figure 7: Graphs of the theoretical diameter of PLA 3D printed parts in function of the true diameter

When it comes to the 3D printing process, several issues ensued. Firstly, when 3D printing the prototype a problem that occurred recurrently was that certain parts did not fit within each other as expected and as modeled in SolidWorks. This issue ensued even though clearances were set for the necessary parts: 0.2 mm for parts that were fixed to each other, and 0.3 mm for parts that would have rotating or translating movements. For this reason, two thin plates were printed: one with cylinders and one with holes with diameters from 3 mm to 32 mm. The diameter of the holes and the cylinders were then measured using a digital caliper, and the dimensions obtained were compared with the dimensions initially modeled. The results of this test confirmed that the true diameter of the cylinders is always significantly larger than the true diameter of a hole with the same theoretical dimensions hence why many parts did not fit as expected. To mitigate this problem, the graphs presented in figure 7 provide the equation of the linear regression between the theoretical and the true diameter that will be used to estimate the dimension of the diameter to establish in the CAD model so that the intended dimension can be obtained.

Furthermore, the plate with holes was also used to determine which clearances should be used. It was concluded for that parts that need a tight fit, a transition fit of 0.2 mm should be set while parts that rotate or translate through each other should have a clearance fit of 0.3 mm.

Additionally, several problems arose when 3D printing with TPU, due to humidity absorbed by the filament. Consequently, to print the final prototype, the filament will be dried in an oven at 70 °C for one hour.

4. Engineering Calculation Notes

Through the Pugsley method, the safety coefficient is determined to be 2.3. If the value of the safety factor determined through the analytical calculations is inferior, the part does not comply with the safety criteria established.

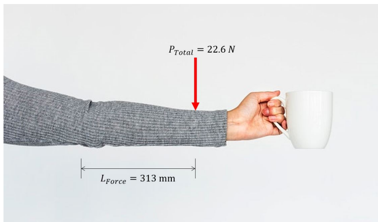


Figure 8: Loads applied in the forearm joint of the exoskeleton

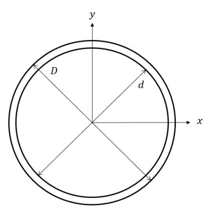
To determine the torque applied to each joint of the exoskeleton, the Denavit–Hartenberg Convention is employed to attain a kinematic model of the exoskeleton. As the exoskeleton is only attached to the limb of the user in the forearm, it is considered that the weight of the upper part of the arm is supported by the shoulder of the user. Therefore, the load exerted in the exoskeleton, without considering the elastic bands, comprises the weight of the forearm and the hand of an adult, $1.76\,kg$ according to [30], and a small object weighing $0.5\,kg$, that the user is holding. Therefore, the value of P_{load} is $22,6\,N$. As the momentum caused by a load is higher the larger the distance between the point of application and the center of mass of the link, the case where an adult is wearing the exoskeleton is considered, and the distance between the point of application of the load and the center of mass of the link is $313\,mm$, as represented in figure 8. It is also considered that the exoskeleton is fully extended, to maximize the torque in each joint.

Through MATLAB's Symbolic Math Toolbox, the maximum torque at each joint and the position in which it occurs is determined, as represented in table 4.

Table 4: Maximum torsional moment in each joint and the position at which it occurs

Joint j	Maximum torsion (N.m)	θ_3 (°)	θ_5 (°)	θ_6 (°)
2	16.50	0	0	0
3	10.81	-	0	0
5	6.75	-	-	0

For the analytical calculations, the properties of the PLA filament defined in table 3 are considered. However, as mentioned in section 3.1.1, in FDM 3D printing, the parts are composed of an outer shell and an infill. As there are two outline shells and as the nozzle's diameter is 0.4 mm, the wall thickness of the 3D printed parts is 0.8 mm. For this reason, and to consider the worst-case scenario, formulas for thin-walled sections are applied, as represented in figures 9 and 10. However, in pure uniaxial tension, or compression, the formula considered is simply $\sigma_F = \frac{F}{A}$, as the material properties considered concern a tensile test performed on a specimen with a 25% infill density and a uniaxial compression test for a standard infill specimen.



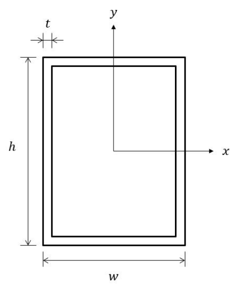
$$\tau_T = \frac{T}{2 \times t \times (\frac{D/2+d/2}{2})^2 \times \pi} \quad (1)$$

$$\tau_V = \frac{2 \times V}{((D/2)^2 - (d/2)^2) \times \pi} \quad (2)$$

$$\sigma_z = +\frac{M_x \times \frac{D}{2}}{I_x} - \frac{M_y \times \frac{D}{2}}{I_y} \quad (3)$$

$$I_x = I_y = \frac{\pi}{64}(D^4 - d^4) \quad (4)$$

Figure 9: Formulas to compute the stresses in a circular thin-walled part [31]



$$\tau_T = \frac{T}{2 \times t \times (w-t)(h-t)} \quad (5)$$

$$\tau_{Vx} = \frac{V_x \times Q_y}{2 \times t \times I_y} \quad (6)$$

$$\tau_{Vy} = \frac{V_y \times Q_x}{2 \times t \times I_x} \quad (7)$$

$$\sigma_z = +\frac{M_x \times \frac{h}{2}}{I_x} - \frac{M_y \times \frac{w}{2}}{I_y} \quad (8)$$

Figure 10: Formulas to compute the stresses in a rectangular thin-walled part [31]

Since the PLA filament is brittle, as the fracture strain is less than 5%, the effect of stress concentrations near discontinuities of the part must be considered in static loading conditions. Therefore, before comparing the maximum stress with the strength of the material, the nominal stress must be multiplied by the geometric stress concentration factor, K_t, obtained through Peterson's Stress Concentration Factors book [32]. Afterward, to compute the safety coefficient, the Brittle Coloumb-Mohr (BCM) theory is applied.

Employing the formulas presented previously, the stress and safety coefficient calculations were performed for each component. To assure that the parts comply with the safety criteria, besides several design modifications, the number of shell outlines was increased to 8, to provide a wall thickness of 3.2 mm.

Although the analytical calculations are completed and the exoskeleton was once again redesigned, it is not certain that the parts will not fail. Various assumptions were made in regards to both the behavior of the components and how the initial load is transferred throughout the exoskeleton. Additionally, most parts were simplified in the calculations and although mostly the material properties of a specimen with an infill of 25% were considered, it is printed with a different printer, parameters, and filament than the ones used in the present thesis. On the other hand, the anisotropic behavior of the material is not taken into account in the analytical calculations. For these reasons, to better understand the mechanical behavior of the exoskeleton and to confirm that it does not fail, a finite element analysis is performed in the next section.

5. Finite Element Analysis

The finite element analysis is performed on the software Abaqus and it is necessary to resort to a nonlinear analysis since the presence of an elastic material creates a nonlinear problem. To create the mesh, three-dimensional 10-nodes tetrahedral elements were employed. Hinge connectors were imposed on the joints, along with Multi-Point Constraints (MPCs), and the interaction between the elastic bands and elastic support features is simulated using surface to surface contacts. After the load and the boundary conditions were established, a dynamic analysis with a 0.1 s time was initiated. The main results of this analysis are presented in figure 11.

The FEA results obtained are acceptable, as the behavior of the parts is reasonable, although more accurate in the initial steps when the elastic is countering the gravitational force. As, initially, the elastic is not being extended, it is not exerting any tension in the exoskeleton and does not fully simulate the actual behavior of these elements. Nevertheless, the first increments are considered to correctly depict the behavior of the exoskeleton and, when the total load is applied, it is possible to identify possible critical sections and the stress distribution through the exoskeleton, although presenting lower values, is in accordance with the analytical analysis. Additionally, to reduce computation time and cost, the parts were simplified, potentially erasing possible critical sections. The parts are also considered solid. Moreover, the anisotropic behavior of the material is not simulated, neglecting the effect of build orientation on the resistance of a part to certain loads. Nevertheless, the FEA performed provides valuable information regarding the stress distribution and the load transfer of the exoskeleton, that corroborates the assumptions made in the analytical calculations.

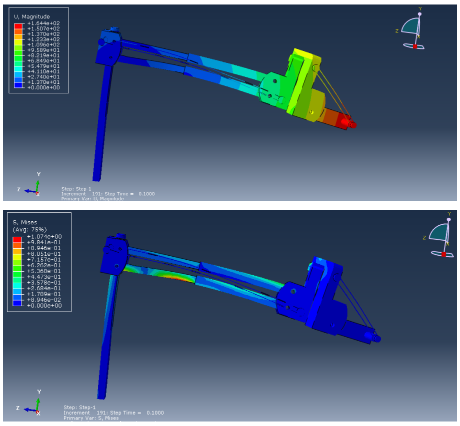


Figure 11: Results of the FEA for the displacement (top) and Von-Mises stress (bottom), at the final increment

6. Final Prototype

The 3D printing of the final prototype, with an infill of 25% and an outer shell thickness of 2.8 mm, took a total of 47 hours and 49 minutes to print. The final prototype is represented in figure 12. The full assembly of the exoskeleton is extremely lightweight, weighing only 0.47 kg with all the connecting elements and straps included. It can also be folded into a compact position, without any dismount necessary, that allows for easy transportation. When worn, the exoskeleton provides a flotation sensation where the upper limbs feel weightless. The structure can also be used comfortably for several hours throughout the day. The exoskeleton also permits that the user performs all essential ADLs defined in the first section. The joints are not rigid and the movement of the exoskeleton is smooth and fluid. As various connections to the body were added, the structure moves in accordance with the user's natural movement and is extremely compliant. For the same reason, the exoskeleton has minimal interference with the environment and it is possible to write or use the computer while wearing it. Overall, the exoskeleton provides a satisfactory, and even enjoyable, usage experience, and the main limitations of the WREX regarding patients' experience with the exoskeleton are mitigated.

Through a cost analysis that takes into account not only the filament cost but also the cost of the electricity consumed, the price of the connecting elements, and the elastics, it is possible to determine that the total price of manufacturing the exoskeleton is 20.25 €. This figure represents a decrease of 98% in comparison with the cheapest version of the WREX.

Figure 12: Final prototype of the exoskeleton

7. Conclusions

7.1. Accomplishments

During the course of this thesis, various exoskeletons in multiple areas were analyzed which served as a basis for the design of a new and improved passive upper limb assistive exoskeleton. The final exoskeleton fulfills the objectives stipulated at the beginning of the project. The exoskeleton that can be used throughout the childhood of the patient until adulthood, has an ergonomic design, with a focus on the patient's comfort, while efficiently assisting upper limb movement. The exoskeleton is easy and rapid to put on and take off, but commodious enough to be used regularly in day-to-day tasks and activities. Since the exoskeleton designed and manufactured in this thesis can be replicated by anyone with access to a 3D printer, at a minimal cost, this project expands the availability of these devices to a significantly larger number of people and, particularly, to disadvantaged patients.

7.2. Future work

To further ensure the structural integrity of the exoskeleton, the behavior of the exoskeleton when subjected to cycles of fatigue could be analyzed. Additionally, as through analytical methods, the computation of stresses often implies various assumptions and simplifications, an in-depth FEA where the microstructure of the components is modeled would culminate in an analysis that closely simulates the real behavior of the exoskeleton.

As reported in [20], children with ulnar deviation are unable to eat when using the WREX. Future versions of the exoskeleton can include a mechanism to allow these patients to correct their hand position so that feeding-related tasks can be performed. Furthermore, as several children with upper limb musculoskeletal disorders suffer from paralysis that extends to the wrist and the hands, a redesign of the exoskeleton can include an extension to encompass the wrist and the hand. Moreover, as the exoskeleton was only tested on able-bodied people, relevant and pertinent analysis and study of the experience of disabled patients with the exoskeleton was not performed.

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