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Rapid Prototyping in Engineering Education: Developing a Hand Exoskeleton for Personalized Rehabilitation

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Abstract. Nowadays, universities address topics like CAD modeling and additive manufacturing to teach students important aspects of engineering and design. However, the development of a prototype is an iterative process composed of different phases that range from the definition of the problem to the evaluation of the concept The paper describes how to integrate all these phases for active learning in the course Computer-Aided Design and Mechanical Prototyping, which is part of the Master's Degree in Mechanical Engineering program at Politecnico di Milano. The final project assigned as a case study to students consists in the development of a rehabilitative hand exoskeleton. The paper presents how students faced the different phases of the development process till the final prototype and its evaluation with healthy subjects and some post-stroke patients. The methodology applied to the course was really appreciated by students, in particular, the experience of designing different devices from scratch. They were challenged in different areas, like mechanics, electronics, informatics, and manual work, which allowed them to range widely during the design and manufacturing process and to extend considerably their knowledge.

Keywords: engineering education, hand exoskeleton, additive manufacturing, CAD modeling, interactive applications
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1 INTRODUCTION

Rapid prototyping is becoming a more and more relevant topic in universities. Engineers and product designers are required to learn and understand the concepts behind the development of proof-of-concepts and prototypes. Rapid prototyping is an agile methodology used throughout the product development process. With this method, designers and engineers may now generate prototypes directly from computer-aided design (CAD) data in previously impossible time frames and make rapid and frequent revisions to the models according to feedback acquired during the execution of real-world tests. Nowadays, several university courses address topics like CAD modeling and additive manufacturing to teach students important aspects of engineering and design. However, the development of a prototype is an iterative process composed of different phases that range from the definition of the problem to the evaluation of the concept, schematized in Figure 1.

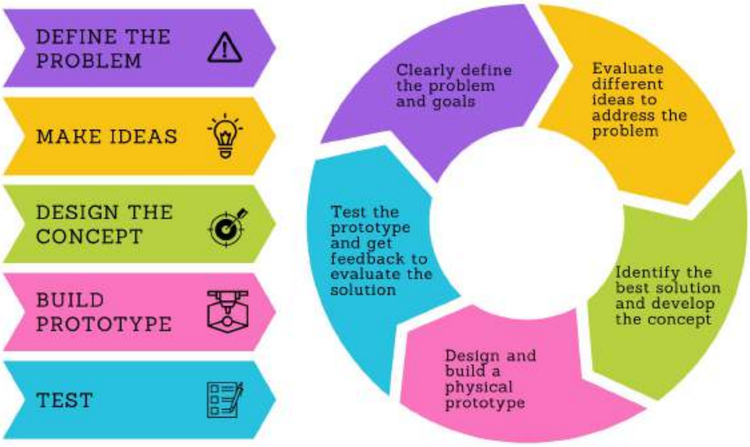


Figure 1: Methodology applied in the design of the Hand Exoskeleton for Personalized Rehabilitation.

The paper describes how to integrate all these phases for active learning in the course Computer-Aided Design and Mechanical Prototyping, which is part of the Master's Degree in Mechanical Engineering program at Politecnico di Milano. The most important topics in this course are related to Parametric Modelling, Additive Manufacturing, CNC Manufacturing, Virtual and Augmented Reality with Arduino Integration. The course has a strong orientation towards the problem-solving approach. It couples theoretical lectures and exercises in which students can play an active role in a multi-disciplinary laboratory setting. During the course, students are initially presented with the principles of the different technologies and methodologies involved in rapid prototyping. Then, students are divided into groups, and a social problem or need is given to them. Under the supervision of tutors and professors, they are requested to find a solution to the problem and develop a physical prototype following the different phases of product development and the topic studied during the course. The students have full access to both the Open Lab and the Virtual Prototyping and Augmented Reality Labs.

From the literature, it emerged that this type of active learning approach based on problem-solving showed a higher engagement and interest in the students. Students are more focused on different aspects of their prototypes, such as aesthetic, functional, and ergonomic compared to the conventional approach [6, 12].

This paper presents the active learning approach adopted in the course of Computer Aided Design and Mechanical Prototyping at Politecnico di Milano, in which has been assigned as a case study for the final project, the development of a hand exoskeleton for personalized rehabilitation. The presented prototype is the result of a four-month group project work in the course. The following sections will show the methodology that has been applied to this project.

2 HAND EXOSKELETON: PROBLEM DEFINITION

The theme of upper limb rehabilitation has been active in the literature for a long time. Numerous researches present possible solutions to address this topic. The field of rehabilitation robotics gained momentum in recent years thanks to its potential applications in the treatment of neuro-muscular impairments following spinal cord injuries (SCI), cerebral palsy, and stroke. The latter, in particular, is the third cause of disability according to the Global Burden Disease study [13]. Based on the medical definition [10], it is possible to identify two principal types of stroke: ischemic and hemorrhagic. The first occurs when a clot or a foreign mass obstructs a blood vessel, reducing the bloodstream to brain cells. The second arises when a damaged blood vessel breaks and bleeds into the surrounding brain area. The usage of robotic devices for physical treatment allows repetitive and long-duration therapy sessions and allows a quantitative evaluation of the treatment's outcome.

It was decided to propose this topic as a case study for the course considering the social relevance of the problem and the availability of ideas in the literature that could inspire students. Furthermore, it represents a multi-disciplinary project that allows students to practice all topics addressed in the course, ranging from CAD to additive manufacturing and virtual reality. The final project of the course asked students to "create a prototype of a personalized post-stroke hand exoskeleton using rapid prototyping and virtual reality technologies."

The first step students had to face was understanding the post-stroke patients' needs and performing a brief literature review to evaluate possible solutions available on the market. Two are the robotic approaches toward rehabilitation: end-point machines, and exoskeletons. The former are typically easier to design, control, and install, having only one point of interaction with the subject (e.g. the hand). However, they do not allow to control strictly the limb posture. Wearable exoskeletons target each human joint, but conversely, they have greater mechanical complexity, weight, and encumbrance, given the close interaction with the user. Approaching human hand rehabilitation is very challenging due to its structure; it offers very limited space for physical interaction with external devices [1].

3 MAKING IDEAS AND LITERATURE REVIEW

Many discoveries in basic neuroscience have provided stimuli for research in motor rehabilitation. Repeated motor practice and motor activity in real environments have been identified in much research as beneficial for motor recovery after a stroke. The use of rehabilitation training devices to provide motor therapy has shown great potential. With multidisciplinary integration and development, the product, especially the exoskeleton for hand rehabilitation, has made major strides.

Students particularly focused on some commercial devices and some of the most-cited works from the literature. Here are reported some of the solutions examined by the students.

- WaveFlex from Ottobock, which is a commercial continuous passive movement (CPM) device for physical therapy of the hand. An electric motor is used for actuation.
- Gloreha (IDROGENET, Italy) [7], is also a commercial CPM device for hand rehabilitation, and as with other modules, the glove-like device can make flexible and individual passive hand motor exercises according to the specific patient circumstances.
- The ExoHand [5], from Festo, can be used as an active manual orthosis. Together with a brain-computer interface, it allows a closed feedback loop to be established; many studies about hand motor training have made great progress [4].
- HEXORR developed by Schabowsky et al. consists of a finger module and thumb module. Each module is driven by an electric motor and the user's movement volition is sensed using a torque sensor [11].
- Chiri et al. proposed a wearable hand exoskeleton HANDEXOS for post-stroke rehabilitation, which has five independent modules for the fingers. The flexion and extension of the metacarpophalangeal (MCP) joint is driven by a slider-crank mechanism, while the other joints are driven by Bowden cable transmissions [3].

Starting from this preliminary literature review, students were asked to identify some relevant lacks in the proposed solutions and start making ideas about how to solve these issues.

The literature review on the existing products and systems pointed out that most of them have been demonstrated in a laboratory setting. Not all the devices can be applied effectively to daily life and in outdoor applications, e.g. only a very few can be used alone without a big drive system; even some exoskeletons are quite big and relatively heavy. For daily and outdoor use in particular, power source technologies and reliable wireless technologies must be resolved. Moreover, portability in a rehabilitation device can broaden its potential applications.

4 CONCEPT DESIGN

According to the aspects that emerged from the brainstorming about the literature and market review, students defined the concept and decided to focus on a portable exoskeleton for hand rehabilitation that was suitable for on-desk sessions with maximum ease of mounting and maximum lightness perceived by the patient. The aim was to realize a lightweight and comfortable device. So, it was decided to maintain the actuation system detached from the patient's hand. The prototype would have been created starting from a 3D scan of the patient's hand and then created using additive manufacturing technologies.

The fundamental concept behind the project was to improve the rehabilitation of a patient's hand after a stroke. This limitation generally is mainly neuronal, and it is a matter of the capability of sending pulses to the muscles that are not compromised as well as the nerve connections. In particular, post-stroke patients can present hemiparesis, in which a patient loses control of a half side of the body. Furthermore, some scientific evidence is present regarding bilateral rehabilitation. It presents benefits in restoring the neural connections by replicating the movements of the healthy hand to the injured one. To exploit this possibility, also following the example of some commercial solutions [7], students decided to create a sensed glove able to acquire the motion of every single finger of the healthy hand. Those sensors will be connected to an Arduino UNO board able to elaborate on those data and send inputs to five different linear actuators. Those actuators will be connected to the hand exoskeleton by means of metallic cables that would actuate the ladder, replicating the movements of the sensed glove.

To define the concept design of the exoskeleton, it was necessary to identify which rehabilitative movements a post-stroke patient needs to perform. It was organized an informal interview with some therapists, bioengineers, and medical experts from the Villa Beretta rehabilitation centre sited in Costa Masnaga, Lecco. With their help, students defined three passive rehabilitative motions:

- Grasp: from the resting position, all fingers simultaneously flex (like a fist) and then extend. It simulates the cylindrical grip.
- Pinch: all fingers are in a neutral position. Then, the thumb and index finger are extended and afterward flexed. It mimics the precision grip of a small object.
- Wave: after extending all fingers, the movement replicates the opposition of the thumb with all other fingers. It flexes and re-extends the thumb and one other finger per time.

According to the experts and the literature, performing these repetitive movements can prevent or reduce tendon retraction, spasticity, and oedema [2].

On top of that, students decided to realize a desktop virtual reality (VR) application. Firstly, it will explain to the patient how to mount the exoskeleton. Then, it will allow a therapist to control the exoskeleton by a personal computer using a graphical user interface (GUI). Otherwise, the patient can control the exoskeleton with a sensorized glove placed on the healthy hand. The GUI will be intuitive, with only five sliders allowing the independent actuation of each single finger and three different buttons actuation all the fingers together according to some main basic movement that experts recommend for rehabilitation: pinch, cylindrical grasp, and thumb opposition (here also called as Wave movement) depicted in Figure 2. This way, considering that each patient is different, a caregiver can set the range of movement of each finger, the number of repetitions, and the speed of the movement.

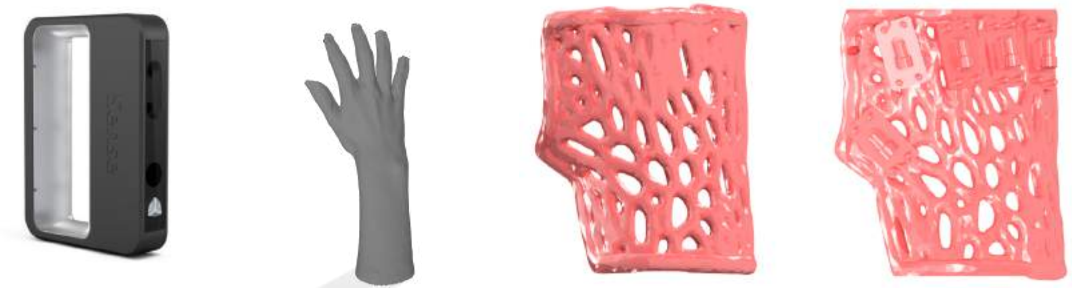
Figure 2: Pinch - Cylindrical Grasp - Thumb opposition (Wave)

5 BUILDING THE PROTOTYPE

The development of the physical prototype can be divided into four different parts: design and manufacturing of the physical hand exoskeleton, realization of the sensed glove, controlling the hand's movements through Arduino, and implementation of the desktop application using Unity to control the actuation also from a PC. Each part will be described in the following subsections.

5.1 Additive Manufacturing the Hand Exoskeleton

Firstly, students decided to make a custom-made hand prototype for the specific user. So, they captured the surface of a hand through a 3D scanner device (3D systems sense). Then, by means of the Sense 3D software, they obtained an .obj file of the scanned hand, as can be seen from Figure 3 (b). Starting from the 3D scan of the hand, students selected the dorsal part of the model and removed the remaining parts (the fingers, palm, and part of the arm). Then, they did an offset on the normal direction an thickened the model to obtain a solid body. To reduce the weight of the part and consequently, the material and printing time required by the additive manufacturing process, they used Meshmixer to generate the pattern visible in Figure 3(c).



(a) (b) (c) (d)

Figure 3: (a) 3D systems sense device - (b) Object obtained from the 3D scanning - (c) Edited mesh with Autodesk Meshmixer - (d) Refined version with knuckle joints

They edited the geometry on Autodesk Fusion and added some fundamental elements to the previous geometry as fixtures for the body of the fingers (called Knuckle joint, Figure 3(d)), holes for laces, and guide/fixing point for the cables. The Knuckle joints are designed with a particular geometry with four pins on the edges and a central guide properly designed to allow a snap fit with the body fingers and receive the sheath of the metal cables. The circular holes created on the top are meant to grant a fixture for an elastic cable, while at the bottom of the exoskeleton, two elongated holes are made in order to fit straps made of velcro.

For the realization of the structure for the fingers, students designed them in two main parts (Figure 4):

- The "Body finger" is distinguished by a specific structure that makes it more flexible, allowing for stretching also in the longitudinal direction, as well as several guides to properly drive and position the metal wire, and thus the finger. It is made of thermoplastic polyurethane (TPU). The elasticity of the material, combined with the model's specific structure, allows for the stretching of the part on top of the finger. As a custom-made device, the finger bodies are created based on the size of each individual finger obtained from the 3D scan of the hand. The lengths have been measured directly in the CAD software.
- The "Tip finger" has been realized according to the shape of each fingertip. On the upper side, there is a structure that allows blocking the wire with a snap-fit to the tip of a finger. In this case, students used the polylactic acid (PLA) material thatis stiffer than TPU.

Since the exoskeleton is meant to fit one particular hand, the possibility of using parametric CAD software is fundamental. As an example, the "Body fingers" have some locked parameters as the width and the two fixing parts: the one joining with the knuckle and the one fitting in the "Tip finger," where a hole also allows a mechanical joint with a bolt. Instead, the length of the core body is a variable, and the number of guides is adapted accordingly. The variable depends on the size of the user's hand and fingers' length. The same concept is valid also for the Tip fingers. They are adaptable in height, width, and depth, while the fitting parts of the cables and the body finger are locked.

(a) (b)

Figure 4: (a) Body finger with 10 guides for the wire - (b) Tip finger

The realization of all those pieces is done by us exploiting additive manufacturing, in particular with an Ender 3D Pro 3D printer. All PLA prototypes have been printed using Amazon basic PLA with an Extrusion temperature of $200°$, a bed temperature of $60°C$, and an extrusion speed of 50 mm/s. The TPU parts instead were made with E-Sun filament, an Extrusion temperature of $220°C$, a bed temperature of $40°C$, and an extrusion speed of 15 mm/s. Students generated the .stl files of all the designed parts and imported them in a slicer software (Ultimaker Cura) to obtain the .gcode files to be loaded into the 3D printer.

The only parts in the project that we have not designed and made are the metallic cables, the bolts, and the linear actuators. For our purpose, the metallic cables are simple bike cables. In Figure 5 is shown the result of the exoskeleton after the additive manufacturing and the assembly process of all the previously mentioned parts.

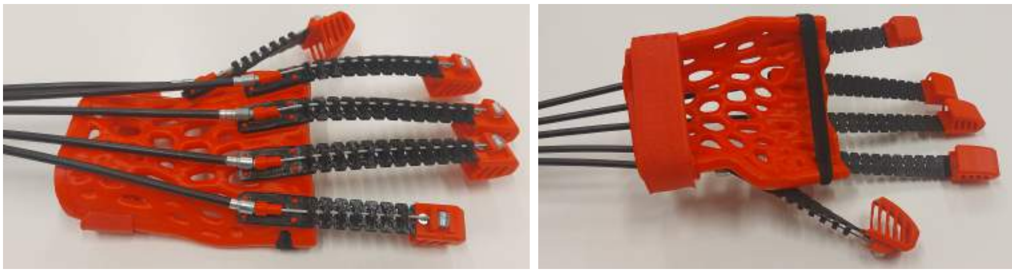


Figure 5: Physical prototype of the developed hand exoskeleton

5.2 Actuation Unit

The fingers of the exoskeleton are driven by bicycle brake cables connected both to the tips of the fingers and to the end of the linear actuator. The linear actuator holds the wire that can slide inside its sheath; due to this movement the pushing force generated at the tip of the finger, thanks to the flexibility of the finger, tends to bend it. In particular, for this project students have used five linear actuators from Actuonix (L12-R) with an internal position controller and a stroke of 100mm. The linear position of each actuator is set using the Arduino UNO board using a pulse width modulation signal.

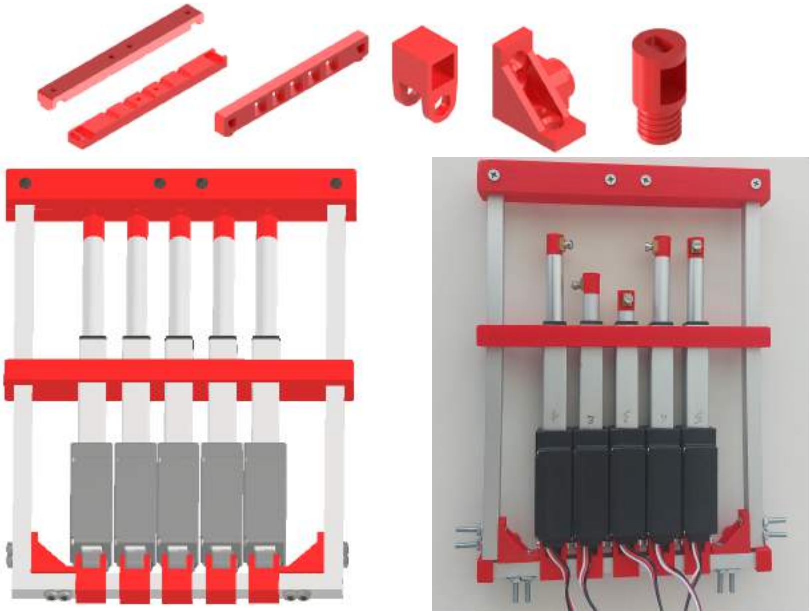


Figure 6: (Top) Detail of all components designed - (Left) 3D digital model of the assembly - (Right) Physical prototype

They designed a support for the actuators; each actuator is held in place separately by a support and a central guide. The chassis is made of aluminum and has been sawed and drilled by us with tailor-made dimensions. The angles, the central guide, and the cable holder have some feet in order to prevent the slipping of the whole structure. The cable holder part is made in 2 pieces allowing a snap fit with the end of the cable sheath, the aluminum chassis, and the other part of the holder. In particular, the negative of the metallic pin holding the cables has been debossed on both parts allowing the joint. To allow a proper constraint, 4 bolted connections have been designed; two of them pass through the chassis while the other two are meant to keep in their location the cables. In Figure 6 are shown all the designed parts that have been 3D printed in PLA, the digital 3D model of the assembly, and a photograph of the real assembled actuation unit. We would like also to point our attention on the end effector of the actuators. It was necessary to have minimal misalignment to reduce the bending of the metallic cables close to the actuation, so a particular component have been designed, able to tighten in the thread already present in the actuators and to allocate by snap fitting the cables.

One of the main limitations of the design that students discovered during their first solution in the iterative design process was due to the buckling phenomenon of the cables and their management. When the linear actuator pushes the wire inside its sheath all the cables bend with them, preventing the desired effect on the tip of the finger. However, students are required to use the problem-solving approach throughout the course. So, to solve this issue, they fixed together all the cables with a new component (Figure 7). The same element was used to keep the cables in place on the hand when the linear actuators were pushing. They glued one of these components on the backhand and precisely cut each single cable to fix it into its knuckle location.

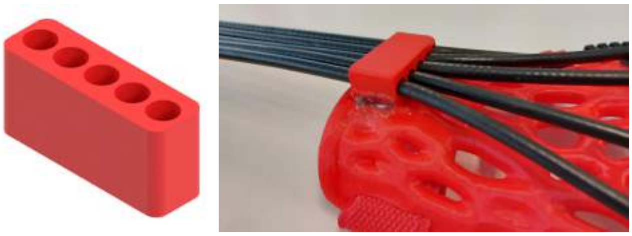


Figure 7: Constraint system for cables: 3D digital model and physical part glued to the dorsal side of the exoskeleton

5.3 Realization of the Sensorized Glove

Once the physical device has been realized, students focused on the acquisition of the "healthy" hand movement. A glove, designed to be worn on the user's healthy hand, has the function of sensing and measuring the flexion and extension of the fingers and communicating this information to the exoskeleton. The glove is composed of the following components:

- Bend Flex Sensors for measuring finger inclination.
- Tissue glove for wearing sensors.
- Arduino UNO board for controlling the system.
- LiPo Battery for the electric supply.
- Stripboard for brazing and connecting wires.

In order to acquire data from the healthy hand, they decided to use five flex sensors which behave like variable resistors. When they are bent their internal resistance change. The sensors are mounted on the fingers of the healthy hand, and they are able to detect when the patient flexes their fingers. The variation of resistance related to the bending angle of the finger is measured by an Arduino UNO board.

Also, the fixing of the flex sensors required brainstorming among the students. They designed a guide, where the flex sensors can slip and are able to slide inside. This case has some holes on the side that can be sewn on the glove to allow the fixing. This component has been 3D printed using the TPU material to be flexible. Figure 8 shows the sensorized glove (a), the guide (b), and a flex sensor (c). As can be seen in Figure 8 (d), a flexion of a finger in the sensorized glove activates the respective actuator, and it corresponds to a flexion of the same finger on the exoskeleton (Index finger in this image).

(a) (b) (c) (d)

Figure 8: (a) Sensorized glove - (b) 3D printed flexible guide - (c) Flex sensor - (d) Example of controlling the exoskeleton using the sensorized glove

The Arduino UNO board exploits a double function: the acquisition and elaboration of flexion data from the healthy hand and sending of the inputs to the prototype, and the connection with the VR application made with Unity, detailed in the following section.

To ultimate the prototype, a 3D printed box to enclose the electronic components has been manufactured having standard connections for the power source and an Ethernet connection for the sensed glove. Figure 9 shows the final result of the assembly, on top of the exoskeleton device and on the bottom of the glove system with the flexible sensors.

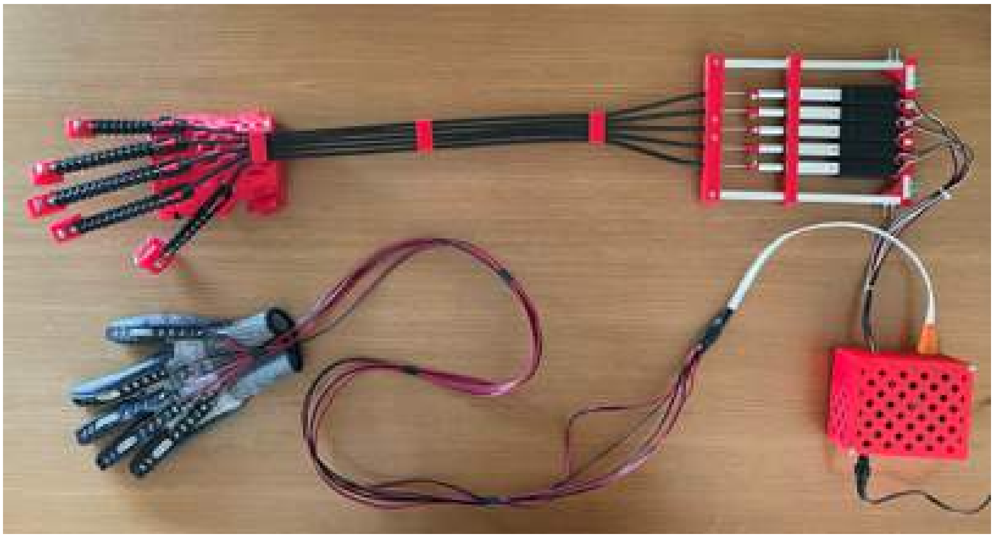


Figure 9: Complete assembly of the device

5.4 Implementation of Unity Application

Students have developed a desktop VR application on Unity. Unity is a multi-platform graphics engine that allows the development of video games and other interactive content, such as architectural visualizations or real-time 3D animations. The Unity development environment includes graphics and physics engines and a live game preview. The latter allows viewing a preview of the game in real-time during the development phase.

The developed application is composed of two different scenes. The first illustrates to the patient how to wear the exoskeleton using several animations and its working principle. The second, named "Actuation" proposes a scene in which a therapist can control the flexion-extension movement of the exoskeleton's fingers. The medical expert can control the exoskeleton by the GUI proposed by the application (Figure 10).

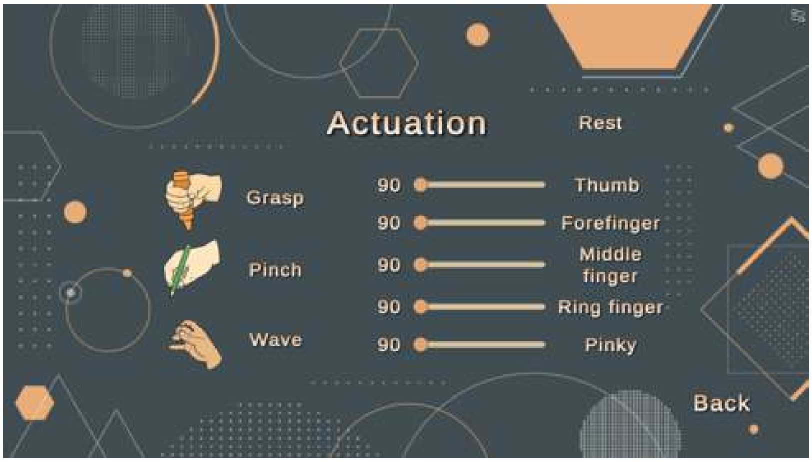


Figure 10: Actuation Menu

The scene Actuation has five sliders on the right side of the panel. Each controls the level of flexion of the related finger of the exoskeleton. The movement has been mapped linearly between the slider value and the actuator's position. On the left side of the GUI, there are three icons representing the passive movements suggested by the medical experts from Villa Beretta rehabilitation centre. Each icon is a button that starts the respective passive exercise. However, if the patient wants to control the exoskeleton in an active way, s/he can wear the sensorized glove, connect it to the Arduino UNO board and use it to perform a mirror movement between the two hands.

6 TESTS

The last stage of the project consisted of testing the device, which was useful for the students to understand how to manage users' evaluations and highlight the pro and cons of the prototype. The preliminary test was conducted with 10 voluntary healthy subjects (age 33.3 ± 14.16). The procedure observed during the test is the following:

1. Description of the device and its scope, explanation on how is expected to work.
2. Description of the exercise that is going to be tested.
3. It is shown how to wear the exoskeleton and how to activate it.
4. The test candidate wears the device, following instructions step by step.

5. Using the unity interface, the test is started.
6. Five grasp repetitions are performed.
7. Undress the device.
8. Questionnaire submission

The questionnaire was based on nine questions based on a five-point Likert scale giving a global view of the overall system (Table 1). For investigating different aspects, questions can be divided into four sections: ease of use (1, 2), fit and ergonomics (3, 4, 5), aesthetics (6), and effectiveness (7, 8, 9), .

Table 1: Device's comfort and willingness to use questionnaire

	Statement
1	With the help of a caregiver, the device is worn quickly
2	The weight of the device on my hand is excessive
3	The device frame is comfortable
4	The device is very noisy
5	The device caused me discomfort or pain
6	I like the aesthetic aspect of the device
7	I think the device could help me improve
8	If I had access to the device exoskeleton, I think I would use it
9	If I could use the device at home to do my exercises, I think I'd use it

The average score of the test with healthy subjects was 81%. In Table 2, the average score of each section is shown. Effectiveness reached a fair score, even if the second statement had the lowest score. This item asked if the fingers were sufficiently moved. This suggests that the exoskeleton would need to reach a wider range of motion. The worst section was 'ergonomics,' in particular due to the custom-made nature of the design. Some users had significantly different sizes of hands compared to the 3D scans. This aspect was important for the students to learn. They had to balance the customization level of their prototype according to the final usage of the device (e.g. selling the device to the patient for home-therapy). Comfort and weight were instead appreciated. The highest score is reached in the section 'ease of use', which takes into account the intuitiveness of the Unity interface and the simplicity of using the device alone. Comments about this category were positive, especially for the interface. A single generic statement was about 'aesthetics', which asked if the device is appreciable from an aesthetic point of view.

Table 2: Questionnaire results in healthy people

Section	Average Score	Percentage Score
Ease of use	7.5/8	94%
Ergonomics	8.8/12	73%
Aesthetics	3.4/4	85%
Effectiveness	9.4/12	79%

Then, an informal evaluation was performed also with two voluntary post-stroke patients with the collaboration of the Villa Beretta rehabilitative center. Both therapist and student showed great enthusiasm in performing the evaluation with real patients of the project developed during the course. About the comfort, the prototype is lightweight on the hand (only 210g), permitting repetitive rehabilitative exercises without fatigue. Its design prevents mechanical misalignment between the device and fingers, unlike some experimental and commercial devices (such as [14, 9, 8, 7]).

7 CONCLUSIONS

This paper describes a case study of developing a hand exoskeleton for personalized rehabilitation, which was assigned as a final project in the course Computer-Aided Design and Mechanical Prototyping in the Mechanical Engineering master's degree program at Politecnico di Milano, Lecco Campus.

The course methodology was designed to teach students engineering concepts such as CAD modeling and rapid prototyping technologies such as additive manufacturing, Arduino, and virtual reality. This approach, however, includes some soft skills such as teamwork and problem-solving. This is possible due to the adopted method, which begins with the definition of a problem/need and requires the evaluation of various ideas based on the literature and market review. The students are then asked to identify their solution and create a working prototype. Finally, a simple test session enables students to comprehend the advantages and disadvantages of their design.

The project's development began with a field study to better understand stroke phenomena and their impacts. The state-of-the-art review provided suggestions for the design phase and suggested which characteristics were required. Furthermore, the design of the exoskeleton was informed by research into the mechanical behavior of the hand. The solution discovered is a system having two modes of operation. The exoskeleton is attached to a computer and conducts passive workouts determined by the therapist in the first method. The second approach is an active one, in which the patient's healthy hand wears a glove with flex sensors and drives the actuators of the exoskeleton, which moves the damaged hand in the same way as the healthy one.

Users include both therapists and post-stroke patients, who were actively consulted throughout the development process in collaboration with the Villa Beretta rehabilitation center. During the construction of a prototype, this partnership allowed for the emphasis on several features that had previously been missed in the literature.

Student were satisfied with their work. They are aware that the developed device is still a prototype and has some limitations. On top of the fact that the fingers can bend only in a progressive way and the fact that the device can exert a great force only when pulling so when the fingers are opening. However, the project has numerous improvement possibilities, also in the software environment. As an example of possible future works, they would have to include also visual feedback of a virtual hand resembling the real movements or the possibility of introducing augmented reality or the automatic switch between the two possible operation possibilities.

The students particularly appreciated this type of project work, especially the experience of designing several devices from scratch. It is challenged in several areas such as mechanics, electronics, informatics, and manual labor, allowing them to range extensively during the design and manufacturing process and significantly expand their knowledge.

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