STRAHAND: Rehabilitation-Oriented Exoskeleton for the Hand

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Abstract. Rheumatoid arthritis (RA), a chronic autoimmune disease, affects a significant portion of the elderly population and often poses challenges in performing essential activities of daily living. Simple tasks such as grasping an apple or holding cutlery can become arduous and painful for individuals with this condition. Consequently, many of them require rehabilitative procedures to re-establish the functionality of their hands.

In this context, the implementation of a glove-based solution that incorporates pneumatic technology holds promising potential. By harnessing the power of pneumatic action, this innovative glove can provide valuable assistance in facilitating the squeezing movement of the hand. This assistance can prove immensely beneficial for individuals struggling with the debilitating effects of (RA).

The primary objective of this project is twofold. Firstly, it aims to directly support patients in their daily activities by alleviating the challenges associated with hand movements affected by rheumatoid arthritis. The glove, through its pneumatic action, can enhance grip strength and provide the necessary support to perform tasks that were previously difficult or impossible.

Moreover, the project strives to help patients regain lost mobility and independence. By actively assisting hand motions, the glove encourages engagement in rehabilitative exercises, contributing to the gradual restoration of dexterity and motor function. The dual purpose of this innovative glove is to not only offer immediate relief and assistance but also serve as a rehabilitative tool, fostering the long-term recovery of patients.

Keywords: hand exoskeleton, rehabilitation, CAD modeling, rheumatoid arthritis
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1 INTRODUCTION

The world population is ageing very quickly [29], causing a social trasformation. However, new opportunities and a longer life caused an increased incidence of diseases, such as rheumatoid arthritis. It affects in particularly women (3 times more), and the number of cases increases with the age. The main critical issues related to this desease are the heating of the interested zones, together with pain and also difficulties in movements that require strength in hands. [27]

Rehabilitation is defined as management of the consequences of disease. In patients with rheumatoid arthritis (RA), the consequences of the disease such as pain, deformity and loss of physical function have been recognized since its earliest descriptions. As none of the current therapies for RA are capable of inducing long-term remission in all persons, patients are likely to continue to experience disability due to their disease in the future. In last years different methods have been introduced to the treatment of RA; in this paper we will focus the attention of one of the most used: Exercise Therapy.

The objectives of exercise therapy in patients with RA are restoration, preservation or increase of joint range of motion, muscle strength or cardiovascular condition. About 70% of patients with RA are involved in any type of exercise. Range of motion (ROM) [22] exercises are intended to maintain or improve joint range of motion and flexibility and can be executed either active, assisted or passive.

- Active angular movement of the joints by the patients themselves is thought to be important for maintaining range of motion. If patients are too weak or otherwise unable actively to move their joints, assisted ROM exercises may be carried out, with the patient moving the joint through its maximal ROM and the therapist assisting with the terminal stretch.
- Assisted ROM exercises can also be performed with automated machines for continuous passive motion (CPM). These latter techniques are used, for example, after knee joint arthroplasty. In a systematic review of CPM after total knee arthroplasty, it was shown that, in the short term, a faster gain of range of motion can be attained in comparison with the control treatment; however, the effect on functional ability remains unclear.
- Passive ROM exercises are undertaken by a physical therapist, and are indicated for joints that are incapable of moving and at risk for development of contractures, with the aim of stretching peri-articular structures.

People affected by illnesses that limit the hand mobility (as hand dyskinesia), can find benefits in performing assisted ROM [18] exercises with the aid of an exoskeleton like ours. To regain dexterity, patients have to undertake as soon as possible a rehabilitative therapy. It can be a long process that usually requires the patient to move to the rehabilitative clinic periodically and frequently to perform exercises. It has a high social and economic impact on the patient and his/her family. In the long-term, it can lead to the abandonment of the therapy. Moving the rehabilitation to the patient's home, when it is possible, could allow greater flexibility and increase the sense of autonomy of the patient.

2 STATE OF THE ART

In recent years, the use of hand exoskeletons is in a rapid expansion of mechatronic devices for hand rehabilitation (also called hand orthosis), as can be seen in recent research studies and reviews [5, 21, 26, 1]. However, the number of commercial robotic devices is limited [19] compared to the number of prototypes developed in recent decades. Hand orthosis can be categorized according to numerous parameters, such as application field, mechanical mechanism and transmission, actuation, control strategy. [5]. This work considers only robotic devices for a medical purpose, discarding the ones used for military [17], or industrial applications [9].

Regarding the mechanical design of hand orthosis, they are usually differentiated in end-effector and exoskeleton devices. End-effector devices are connected to the patient hand only in its most terminal part [19]. They are usually coupled to or grasped by the patient's hand, such as the AMADEO® [28] and the InMotionARM/HAND™ [4] respectively. The principal advantage of an end-effector is its structure. It is mainly independent of the size and the proportions of a patient's hand. In the beginning, it allows a faster design process and set up in a clinical environment. However, the control of the position of the user's joints can be puzzling. All the other joints of the upper limb are moved indirectly by the device. Therefore, the device does not control directly the force applied to them. One advantage of end-effector devices compared with exoskeletons is that they can fit different hand sizes and are usually ambidextrous. On the other hand, proximal joints training seem to transfer limited benefits to distal parts highlighting new opportunities for exoskeletons [1].

Exoskeletons overlay the patient's hand. Examples of commercial exoskeletons are the Hand of Hope [25], the ExoHand [12], the CyberGrasp [8], and the Gloreha [15]. Due to their direct coupling with the hand, exoskeletons need to be designed keeping in mind some anatomical aspect of the upper limb, more than required for end-effector. One concern is the coincidence of the centre of rotation of the device with the fingers' joints [14]. A subclass of hand exoskeletons derives from soft robotics. It is a section of robotics that deals with soft materials [26]. Examples of soft hand exoskeleton are the Harvard Glove 2.0 [23] and the NUS Glove [30]. One of the main advantages of soft robots is their ability to adapt their shape to complex bodies. Furthermore, compared with exoskeletons based on rigid linkages, they seem to be more lightweight and compact [26]. Many of them use pneumatic actuators, which require an external pressure reservoir that generates force by inflating air in the flexible bodies.

Several mechatronic devices for rehabilitation have been developed, facing many challenges of different natures. We decided to summarise them here.

- Comfort. A painful or annoying device will be unlikely used with perseverance and desire. Especially for rehabilitation, a hand exoskeleton should be comfortable for the user [10]. These devices have to be worn for long periods. One cause of discomfort is the misalignment between the orthosis and the human hand. It can damage skin and tissue [5].
- Lightness. Even though there are examples in the literature of lightweight devices [24], they are still a limited number. During the development process of an exoskeleton, lightness must be considered a high priority [14].
- Validation. Several studies demonstrate the devices only in a laboratory setting. Usually, not all components are developed enough and packed to be easily transported and used in clinics or daily life situations. Challenges also involve reliable power source and wireless technologies [14].
- Cost. Even though numerous devices are technically advanced, there is still the need to reduce the cost of home-based devices that allows therapy based on activities of daily living [19]. 3D printing technology could be a possible solution to build customized devices [21].
- Appearance. McConnell et al. state that: "if a machine appears intimidating, it may affect the patient's progress or desire to use the device". It is usually an underestimated concept. A solution that can prevent this negative consequence is to include therapists and patients into the design process [21].
- Portability. One further big open challenge highlighted in numerous reviews is that many exoskeletons in literature lack portability, while they should be portable to allow home and personal use [6].
- User involvement. In literature, there are pieces of evidence that the development of a medical device requires considering the needs and capabilities of its users. This process appears difficult because it requires inevitably time and financial resources for the development team, patients and therapists [20].

This research aims to develop a pneumatic portable hand exoskeleton for rheumatoid arthrisis patients. This solution meets the users' needs and addresses the current open challenges in the literature. A further objective consists of coupling the prototype with engaging exercises to reduce the high therapy abandonment rate.

3 STRAHAND

The development of the STRAHAND device has seen the experimental approach as a primary aspect of the whole process. Some features must be taken into account in order to improve the comfort of patients in

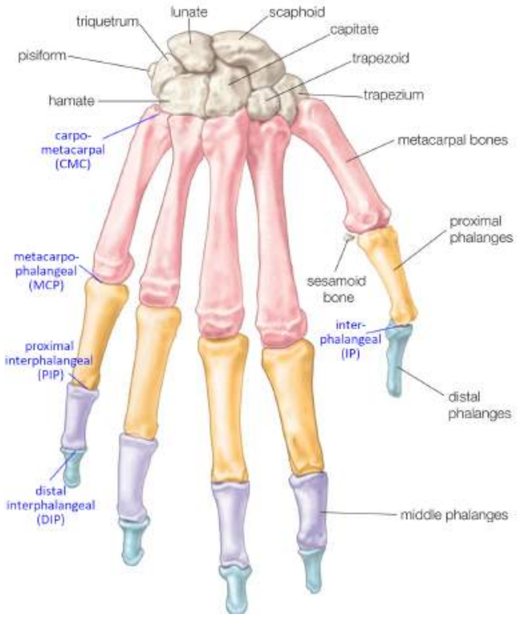

Figure 1: Names of the bones (black) and joints (blue) of a hand. Figure elaborated from [11]

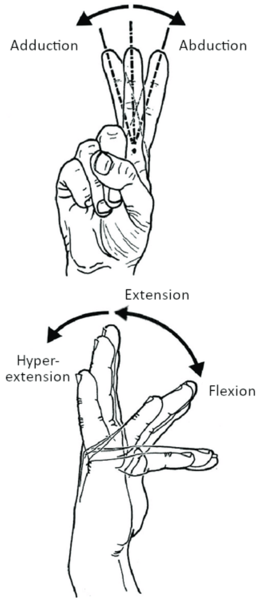

Figure 2: Main movements of fingers. Figure elaborated from [16]

the use of our device, following several sources from the literature and personal experience; among them the following are the most important:

- placement: the device should be placed on the dorsal side of the hand to permit the interaction with the environment
- weight: do not overpass approximately 500g on the hand. It is a rehabilitative device. The patient (usually elder with motor impairments) should undertake repetitive exercises for several minutes without feeling pain or fatigue.
- movement: the fingers extension is an essential movement to prevent the occurrence or aggravation of the spasticity. It is also important to avoid hyper-extension of the phalanges.
- cost: the device should be affordable to let the patient buy it or lease it from the rehabilitation centre, allowing the home-therapy.

Anatomy

3.1 Modelling of Hand

In order to develop an effective upper-limb exoskeleton the knowledge of the biomechanics and anatomy of the human hand is crucial. The human hands are extremely complex and adaptable body parts. They allow performing complex manipulations with various degrees of precision and force [7]. They are also a meaningful sensory organ. They have a large number of receptors, especially on the fingertips. Without these pieces of information, we could not perceive several qualities of an object, and it would be more complex to understand and interact with our surroundings.

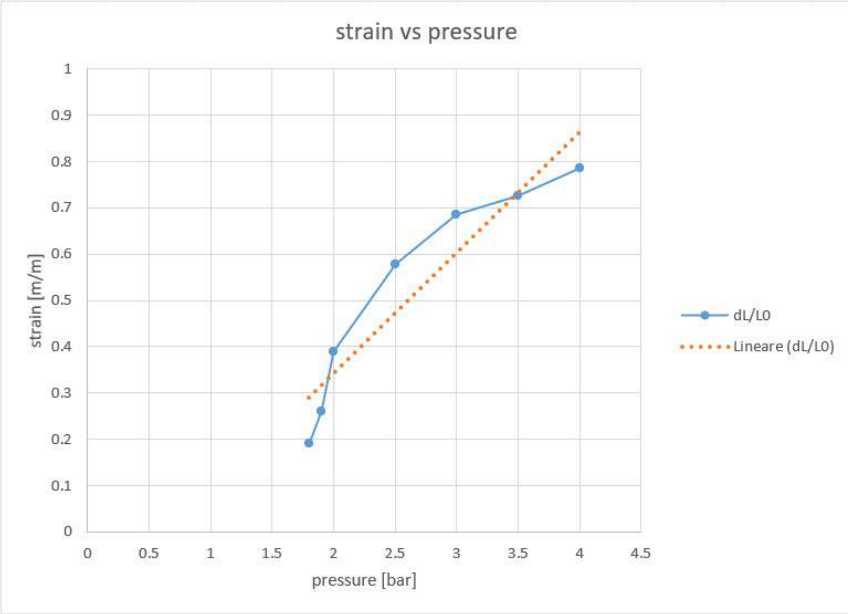

Figure 3: Result of the tests: relation strain/pressure

Behind the capability to perform a vast number of movements and activities, there is a complex structure of rigid and soft tissue. Figure 1 summarises the bones and joints of a hand, while Figure 2 the main movements of fingers. The skeleton consists of 27 small bones: 8 in the carpus, 5 metacarpals bones and 14 phalanges in fingers (5 proximal, 4 middle and 5 distal). Carpus and metacarpus are connected by five carpometacarpal (CMC) joints. The joints that connect metacarpals to proximal phalanges are called metacarpophalangeal (MCP). They are usually classified as ellipsoids. Both CMC and MCP have two degrees of freedom: flexion/extension and adduction/abduction movements.

Here illustrated at Figure 3 is the result of the tests performed on the elongable tubes, to tune the tubes length. It can be clearly seen the non-linear behaviour of the strain with respect to the applied pressure. Instead, the length of the tube does not influence the strain obtained of the tube itself given a certain pressure. It is then evident that, in order to achieve an homogeneous deformation of the fingers, a fixed, constant strain, must be tuned for every finger. Here are the chosen lengths, trying to find the best compromise for all the fingers [Figure 4].

3.2 CAD and Additive Manufacturing of the Exoskeleton

Based on the users' needs, STRAHAND has a pneumatic soul that, through deformable elements connected to the dorsal side of each finger, allows their movement. The pressurized air from the compressor is delivered through a single air-inlet tube. A sorter is present at the height of the dorsal part of the hand: it permits the ramification of the single air-inlet tube to the 5 finger-connected delivery pipes. For each finger, at the knuckles height starts the extendable tube that enable the flexion/extension movement of fingers, avoiding hyperextension. The conducts are fixed to the glove structure in multiple points, in order to limit the pipe's unwanted movements. Lastly, on the wrist, a sorter permits the passage from 1 flux in entrance to 5 fluxes (one per finger) in exit. STRAHAND aim is to help the patient in the grabbing mechanism of objects, so it

	Measured				Designed		
	L_{ini}	L_{fin}	ΔL	$\Delta L/L_{ini}$	L_{ini}	L_{fin}	$\Delta L/L_{ini}$
Little finger	9.8	11.8	2.0	0.204	10.0	12.0	0.20
Ring finger	12.2	14.6	2.4	0.197	12.0	14.4	0.20
Middle finger	13.3	15.8	2.5	0.188	12.5	15.0	0.20
Index finger	12.2	14.7	2.5	0.205	12.5	15.0	0.20
Thumb	10.1	12.2	2.1	0.208	10.5	12.6	0.20

Figure 4: Measured and design lengths of the fingers.

works on the finger's flexion movement.

We designed all CAD components using Autodesk Inventor® Professional 2022 [3]. STRAHAND is composed of several elements obtained by additive manufacturing (AM). The flexible ones lead and accompany movements of the human hand and have to adapt to its deformation. Others require more strength, for example, to fix the extendible pipes, and are rigid.

Figure 5: Final shape of STRAHAND

Looking at Figure 5, it is possible to notice that the core element of the assembly is the elongable tube. It spans all the user's finger lenght and is fixed to the hand by 3 different supports: a cap on the finger end, and two rings on phalanxes. Velcro is applied under the rings, in order to adapt STRAHAND to the specific user hand size, that can change the position of the joints to meet their needs. In the dorsal part of the hand 5 pneumatic joints are present, letting the passage to a smaller tube diameter; the smaller tubes are then collected into a sorter; from the sorter we are able to pass directly to the compressor.

All the sustain components (caps, rings, sorter support) and the plugs have been created using AM and can be seen in Figure 6 ; the process is based on the Fused Deposition Material (FDM) technology [2, 13].

The components have been printed using Sharebot One and Sharebot Next Generation. The technology used by these printers is the FFF (Fused Filament Fabrication): a wire of thermoplastic material (PLA) enters in the machine and is melted at about 210 Celsius degrees; the fused filament produced is then posed from a nozzle in the desired shape. This procedure assures good precision and a creation of quite complex shapes.

In order to provide suitable files to the printers, we used two slicing softwares: Slic3r for the Sharebot Next Generation and Continuum for Sharebot One. Including various tests that we have made and the final selected shapes, it took approximately 16 hours and 30 minutes for the production of all the models.

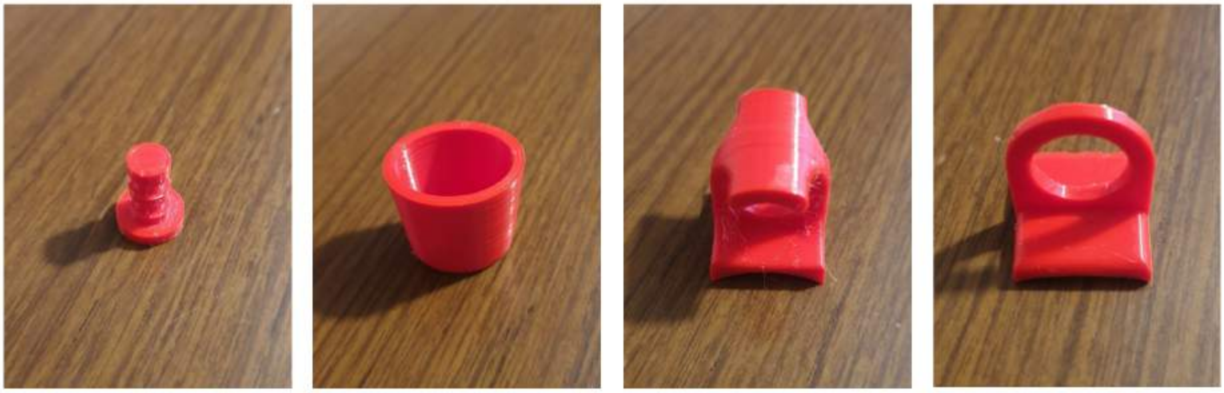

Figure 6: AM printed components

3.3 Final Assembly

STRAHAND is the union of multiple components. To better examine it, Figure 7 shows a drawing of the system with annotations. It includes the hand exoskeleton, pneumatic elements, fixing parts and joints.

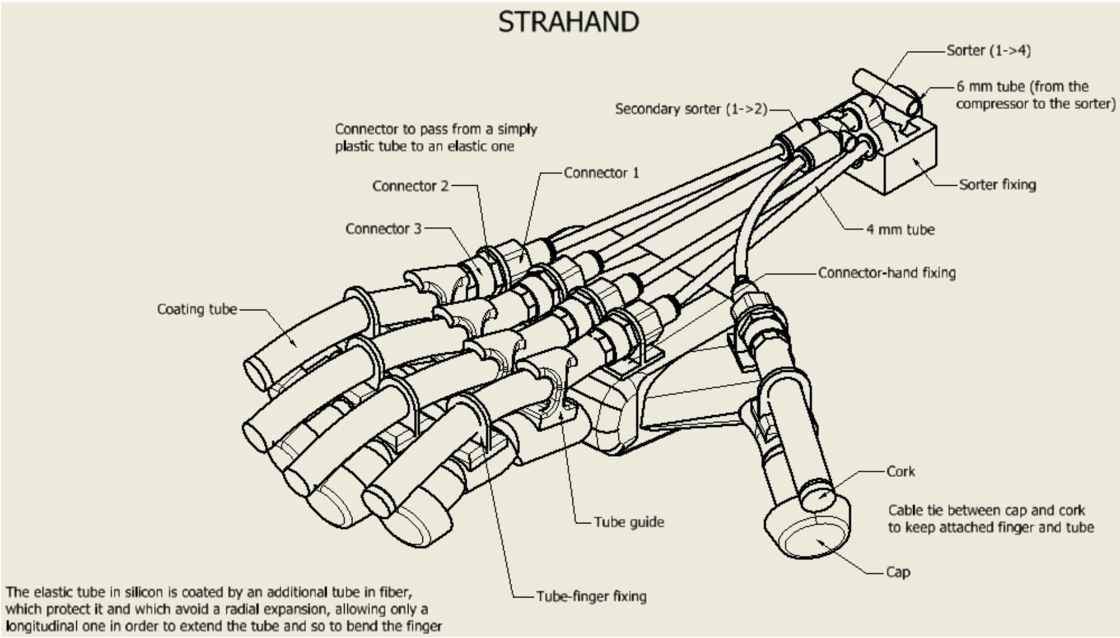

Figure 7: STRAHAND assembly

- Sorting system: the main 4-way sorter receives high pressure air from the compressor through a 6 mm tube, and separate the flow in 4 way; in the upper tube, there is an additional 2-way sorter in order to obtain 5 different flow, one for each finger; each tube has a diameter of 4 mm. This system is fixed to the glove through an apposite designed support, manufactured by a 3D printer

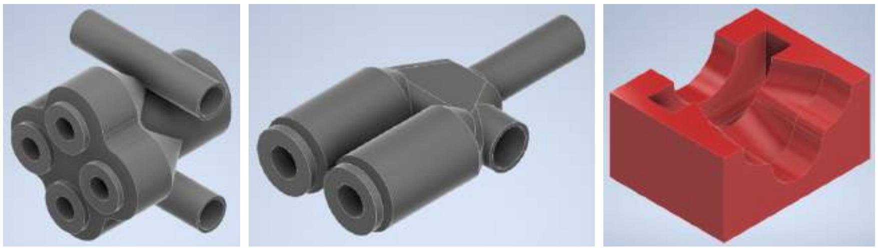

Figure 8: Sorters

- Connector system (x5): each of them receives the 4 mm tube from the sorter and keep the elastic tube in position through an apposite joint. The coating tube is kept in position by means of a cable tie, placed around the output part of the connector. Between the input and the intermediate part of the connector system, is placed the 3D printed part which fix the whole system in the right position on the hand

Figure 9: Connectors

- Coating tube: to avoid the elastic tube from expanding in all directions as a balloon, it is coated by an additional fiber tube, which prevents a radial expansion, in order to obtain only a longitudinal one. But the tube is attached to the finger, therefore this expansion result in a bending of the finger, so obtaining the closure of the hand.

Figure 10: Elongable tube

- Fixing system : morevover to the 5 connector-hand fixing systems, each one of the 5 tubes also present a similar component to keep the tube attached to the finger. Except for the inch, the other 4 fingers present also an addition 3D printed component as tube guide to keep it adherent to the finger

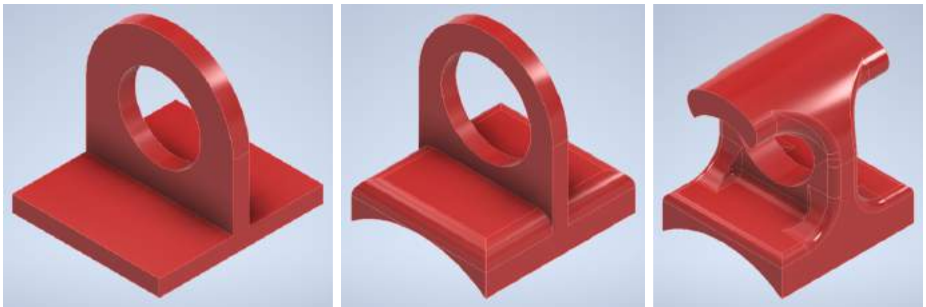

Figure 11: Fixing Elements

- End clamping system : each elastic tube is closed at the free end by a shaped cork, which engraving allow the placing of a cable tie. The free end of each coating tube is burnt in order to melt the component and seal the axcess to the elastic tube. At each finger tip there is a cap, which is fixed to its tube by means of another cable tie.

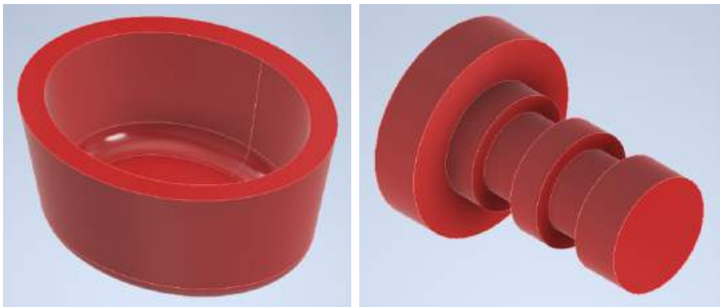

Figure 12: Cap and Cork

Moreover, every fixing element is connected to the glove by means of velcro, in order to permit to each patient to adapt the dimensions of STRAHAND to his own hand dimensions.
When we developed the project, we designed it under ideal conditions: if there isn't any loss, the compressor keep pushing and this may result in damage of the tubes or of the components. However, even if we set 10 bar in the fingers as compressor target, due to losses and pressure drops, the pressure will never reach this value, but it will stabilize around 3 bar. So, the valve sistem original designed is abandonend because not necessary, but also harmful (additional weight and cost).

4 CALIBRATION

In the project also, a part of testing has been covered: by trivial and error procedure, we tried some different solutions for every problem that we faced: for example, different types of fixing systems and caps have been developed before converging to the final shape. Several tests on the glove itself has been performed too; the ideal pressure for STRAHAND work is about 3.5 bar; it is a pressure that assures a good elongation of the flexible tube, permitting the right exercise for the patient. All of the fingers are homogeneously deformed, showing a very accurate and fast dynamics. Also the release of the pressure is optimal for our application, infact is as fast as the inlet process. Though the compressor that we have purchased, even if assured a fixed and controlled pressure (for example 3.5 bar up to a maximum of 10 bar), has a poor flow with respect to our needs, and is not able to guarantee the right feed to our glove. A bigger and more powerful one has been used for the tests involving the completed exoskeleton.

5 PRELIMINARY TEST

Last stage of the project consist in testing the device, which is useful to understand highlights and weakness of the prototype under different points of view. The preliminary test is conducted in healthy people and consist in wearing the exoskeleton and performing five repetitions of grasp excersise at maximum intensity level. The procedure observed during the test is the following:

1. Description of the device and its scope, explanation on how is spected to work.
2. Description of the exercise that is going to be tested.
3. It is shown how to wear the exoscheleton 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, has been drawn up referring to the System Usability Scale (SUS), a valuable evaluation tool, developed by Digital Equipment Co. SUS is a Likert scale, consisting of ten items, giving a global view of subjective assessments. Each statement has a 5 point scale, indicating agreement and disagreement. Items are selected so that the common response to half of them is strong agreement and the other is strong disagreement, in order to prevent response biases. In this case it is adopted for receiving a feedback of the overall system. For investigating different aspects, it is divided in four sections. These actions have been defined according to the requirement at the beginning of the project. Each section has a different number of statements. This allows to give different weights in the score calculation:

- Effectiveness: 40%
- Wearbility and Ergonomics: 30%
- Ease of Use: 20%
- Aesthetics: 10%

The average score of the test is 81%. In table 2, average score of each section is shown.
Effectiveness reached a fair score, even if the second statement did the lowest score. This item, asked if the fingers are sufficiently moved. This suggest that the exoskeleton would need to reach a wider range of motion. The worst section was ***Ergonomic and Wearability***, in particular due to the sixth question, regarding the simplicity to wear the device. Comfort and weight were instead appreciated. The highest score is reached in the section ***Ease of Use***, which take into account intuitiveness of Unity Interface and the simplicity to use 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 aesthetic point of view.

6 CONCLUSIONS

This work describes a rehabilitation system for the hand designed to assist patients during their rehabilitative therapy towards the process of regaining their autonomy. Improving the hand capabilities permits performing activities of daily living and interact with the environment. STRAHAND shows itself as a simple, agile and reliable exoskeleton. Anyway, this must be considered as a first prototype, from which several improvements can

Table 1: Questionnaire results in healthy people

Candidate	Age	Total Score
1	44	80
2	42	82.5
3	23	77.5
4	23	80
5	20	87.5
6	20	92.5
7	47	72.5
8	61	90
9	27	72.5
10	26	74

Table 2: Questionnaire results in healthy people

Section	Average Score	Percentage Score
Effectiveness	12.7/16	79%
Ergonomics	8.8/12	73%
Ease of Use	7.5/8	94%
Aesthetics	3.4/4	85%

be implemented, starting from its main drawbacks: the use of a rechargeable lung would make the exoskeleton perfectly autonomous and easy to carry, with no limitations due to the compressor. The automation of the control instead, comprehends the use of an Arduino board to control an electrovalve, that can manage the air flux and control the opening/closing of the device. Rehabilitation and object grabbing would be much easier.

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