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Low-Cost 3D Printed Exoskeleton for Post-Stroke Hand Rehabilitation

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Abstract. Strokes can lead to the paralysis of one or more parts of the human body and so stroke survivors more than often require rehabilitation to regain muscle coordination, for instance when trying to perform finger movements. For such an objective, an external device like an exoskeleton can be used. This paper presents a low-cost 3D printed hand exoskeleton with high flexibility degree to fit different hand, wrist, and finger sizes.

Keywords: Stroke, Post-Stoke Rehabilitation, Hand Exoskeleton, 3D Printing
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1 INTRODUCTION

Stroke is the second worldwide cause of death (about 5.7 million fatalities each year) and can lead to considerable disability in stroke survivors. As the average population age increases constantly thanks to the increasing life expectancy, strokes are going to become a more and more relevant issue due to age being the most relevant stroke-inducing factor, besides chronic conditions [7, 8]. One of the consequences of a stroke is the impossibility of having a coordinated muscle activity which leads, for instance, to a disability of the hand. A part of the rehabilitation process is a gradual recovery of muscle coordination by repeating the movements which are commonly associated with our hand by means, for instance, of an exoskeleton.
As mechatronics has seen significant developments in the last few decades, devices for hand rehabilitation (referred to as hand orthoses) are becoming more and more common and successfully used. Exoskeletons rely on different technologies, which also determine the cost and the complexity of the system [2, 5]. Some solutions are based on the combination of pulleys and cables [9] or cables only [4], while other ones are based on apposite mechanisms [1, 6].

Most solutions feature expensive components which may prevent the devices from becoming large-scale rehabilitation options. Having a low-cost exoskeleton that is also quite easy to use may then represent a viable option for future developments.

1.1 Objectives and Requirements

In any rehabilitation device must meet some requirements, that can be used as objectives of the project. The requirements which are most commonly found in the research works are:

- Wearability: the device must fit the patient's hand and forearm as well as maintaining the wanted position during the rehabilitation exercises
- Ergonomics: the exoskeleton must be comfortable and its components must fit on the patient's limb without being too tight
- Adjustability: the device must fit different patients and be flexible enough to be used for a variety of rehabilitation exercises
- User-friendliness: both control software and exoskeleton must be intuitive so people with different backgrounds can use it
- Price: most commercial devices are supposed to be found in hospitals or rehabilitation centers, mainly due to the high cost. If however most of the device parts can be 3D printed with a domestic 3D printer at a low cost, the possibility of having a home rehabilitation device can be achieved
- Durability: the performance of the device must be stable in time as long as possible
- Compatibility: the control software should be compatible with most computer brands and operating systems

2 DEVICE DESIGN DESCRIPTION

Even though the prototype is referred to as hand exoskeleton, there is no wrist activity but finger movements only. Such movements are obtained employing steel cables, driven by electric actuators.

To have optimal comfort, the part of the device which is in contact with the human body is designed based on a hand-forearm solid model.

The exoskeleton is placed on the limb from above and is then secured using Velcro stripes running through specific slots on the sides of the gauntlet (Figure 1). Velcro shall be tight enough to secure the device while making sure to avoid the risk of limiting the blood flow. This part is made of two modules that are connected utilizing bolts and nuts. This allows replacing one of the two parts if the patient's anatomy requires it.

Despite this, aiming at having an adaptable (flexible) device, the surface of the device in contact with the skin is covered in foam (Figure 2): with this solution, the prototype can fit different hand, wrist and forearm anatomical dimensions. This solution turned out to be successful during the testing phase since the very same exoskeleton was tested on thirteen volunteers without changing any part.

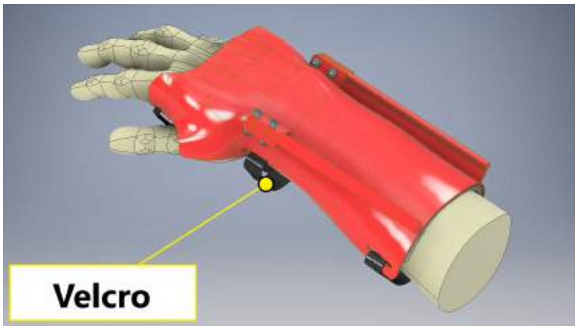

Figure 1: Exoskeleton 3D printed arm support.

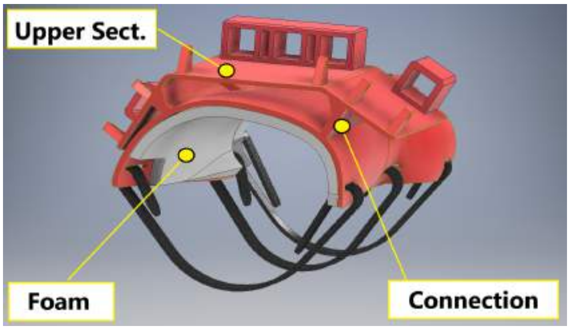

Figure 2: Rear view of the gauntlet.

To accommodate the actuators, an upper section is included. This section is glued to the lower one on two so-called connections (Figure 3).

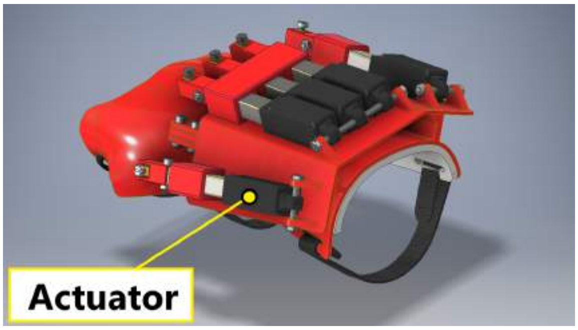

Figure 3: Gauntlet with the actuators.

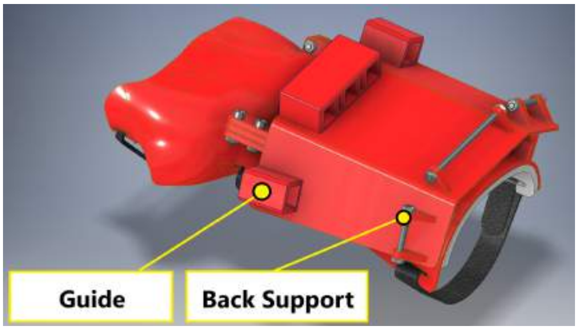

Figure 4: 3D printed support with the actuators.

The actuators are arranged as follows:

- On the central part of the upper section, three actuators are placed. These devices are responsible for the movement of index, middle and ring fingers
- On the left side of the upper section, one actuator is placed. Such device is responsible for the movement of the thumb
- On the right side of the upper section, one actuator is placed. Such device is responsible for the movement of the little finger

To constrain the actuators and keep them in their correct positions, the following parts are used (Figure 4):

- In the front, guides are used to prevent lateral movements of the actuators. In the central part of the upper surface a unique guide is used, while for the two lateral parts (thumb and little finger) two single guides are used
- In the back, six constraints are used. These parts feature holes so that, through bolts and nuts, actuators cannot slide back and forth

2.1 Inducing Finger Movements

To induce the movements of the fingers, five flexible TPU shells were 3D printed, where the idea is using reusable cable ties (Figure 6) to wrap and secure them around the fingers, inducing the movement of the latter ones. Proper infill is important during printing because it defines the flexibility of the shells: excessively low infill leads to low resistance with the risk of the part to fall apart, excessively high infill makes these parts too stiff and hence uncomfortable since they could not be wrapped around the fingers easily.

On top of such parts, PLA parts are glued to guide the cables and obtain the correct movements. Such parts are needed since cables can pull very well but cannot push unless properly guided and constrained laterally (Figure 5).

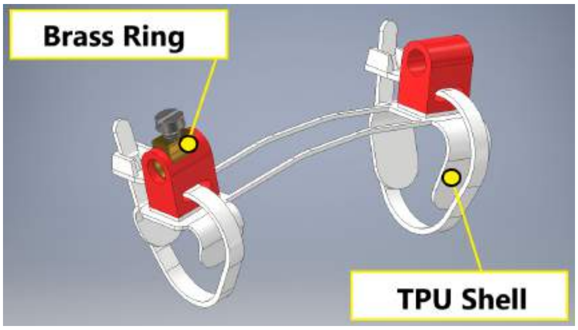

Figure 5: 3D printed TPU flexible shell.

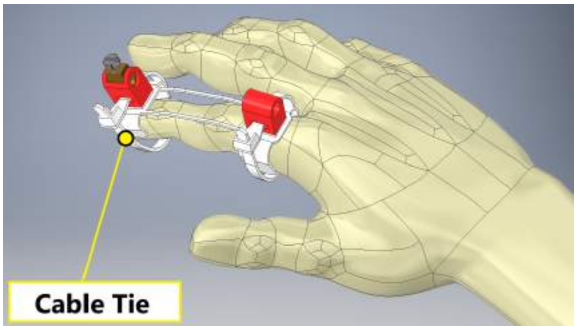

Figure 6: Shell on the right hand index.

To connect each actuator to its respective cable, five PLA actuator-cable connections are used (Figure 7). Such parts are connected to each actuator tip through bolts and nuts, while cables are secured using brass threaded rings both at each actuator-cable connection and at each distal phalanx cable guide (Figure 5). The flexibility of TPU allows adapting the flexible shells to different finger dimensions in terms of length while cable ties allow securing them to different finger thicknesses.

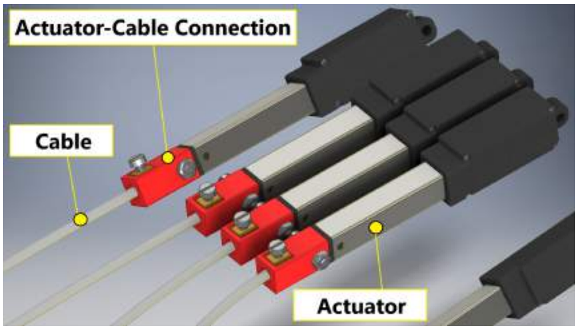

Figure 7: The actuator-cable connection.

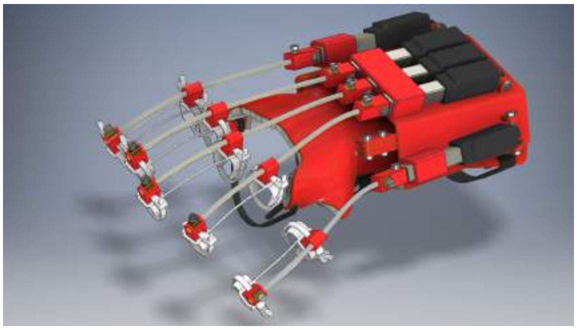

Figure 8: The complete device.

2.2 Controlling and Supplying Power to the Device

The actuator control signals come from an Arduino board, while the power does not come from the board but an apposite power supply. Both of these parts are hidden in an appositely 3D printed box (Figure 9).

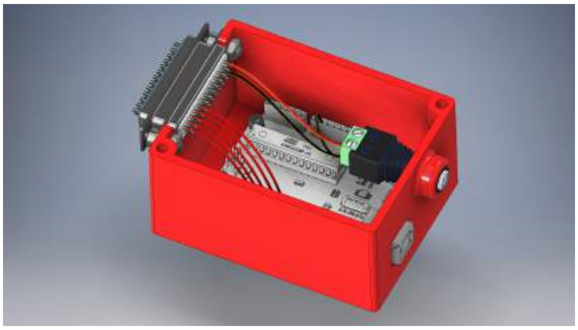

Figure 9: The electric part box with the Arduino board.

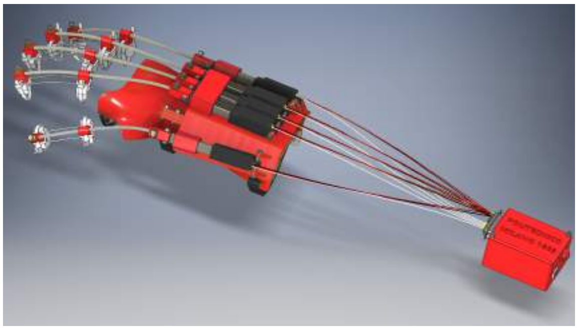

Figure 10: The device with the electric parts.

Figure 11: Real device (top view).

Figure 12: Real device (bottom view).

3 FINGER REHABILITATION MOVEMENTS

The three necessary movements to test the effectiveness of this prototype are:

- Grabbing: close the hand in a "standard" way
- Pinching: movement which leads to thumb and index distal phalanges touching
- Waving: create a wave-like movement with all the fingers except the thumb

4 DESKTOP APPLICATION AND COMMUNICATION WITH ARDUINO

The rehabilitation movements listed in the aforementioned section 3 can be induced by driving the cables through the actuator strokes and therefore, through the shells, the finger movements are obtained. A proper synchronization of the actuator strokes is necessary: such task can be achieved by controlling the actuators with an Arduino board and proper C++ coding.

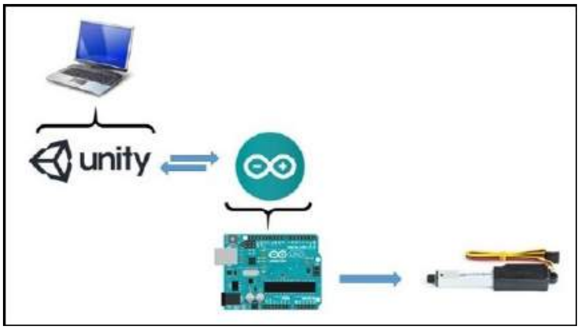

Figure 13: Control strategy.

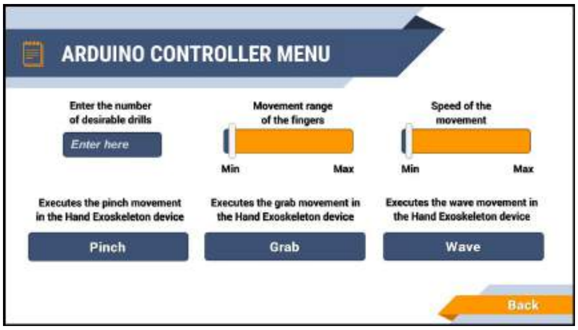

Figure 14: Arduino control window (Windows OS).

To have an intuitive communication with the Arduino board, a Unity-developed Windows app can be used. Such executable allows selecting (Figure 14):

- The wanted movement among the rehabilitation ones (grab, pinch and wave)
- The number of repetitions for such movement
- The movement range by controlling the actuator strokes
- The movement speed by controlling the stroke velocities

5 USER STUDY

Due to the ongoing Covid-19 pandemic, it was not possible to test the device on hospitalized patients who are recovering from strokes. In order to have anyway a reliable feedback, 13 users tested the right-limb as well as the left-limb version of the exoskeleton. All but one subject did not suffer from any stroke.

The tests do not aim at quantitatively measuring the improvements patients can obtain with a repeated and constant use of the system because having statistically significant data require long test runs as well as structured protocol. Furthermore, to observe the first results from the medical point of view, a considerable amount of time (months or even years) are needed. On the other hand, the goal of the tests is to evaluate the comfort and the user's willingness to use the device as part of their rehabilitation program. Even though a clinical trial is necessary for the future, these are preliminary and fundamental requirements for a rehabilitative device.

5.1 Testing Procedure and Results

The testing procedure is based on the standardized System Usability Scale (SUS) questionnaire [3] which features 10 statements to assess the comfort and the willingness to use the device. The questionnaire is based on the following procedure;

- The SUS questionnaire is based on a 1 to 5 Likert scale, where 1 means "strongly disagree" while 5 means "strongly agree" (Figure 15)
- Each answer is normalized based on a 0 to 4 scale (Table 1)
- For positively-worded questions (Questions 1, 3, 5, 7, 9 in Table 1), the score contribution is the scale position minus 1. For negatively-worded one, the contribution is 5 minus the scale position
- The final value is the sum of all contributions multiplied by 2.5, ranging therefore from 0 to 100

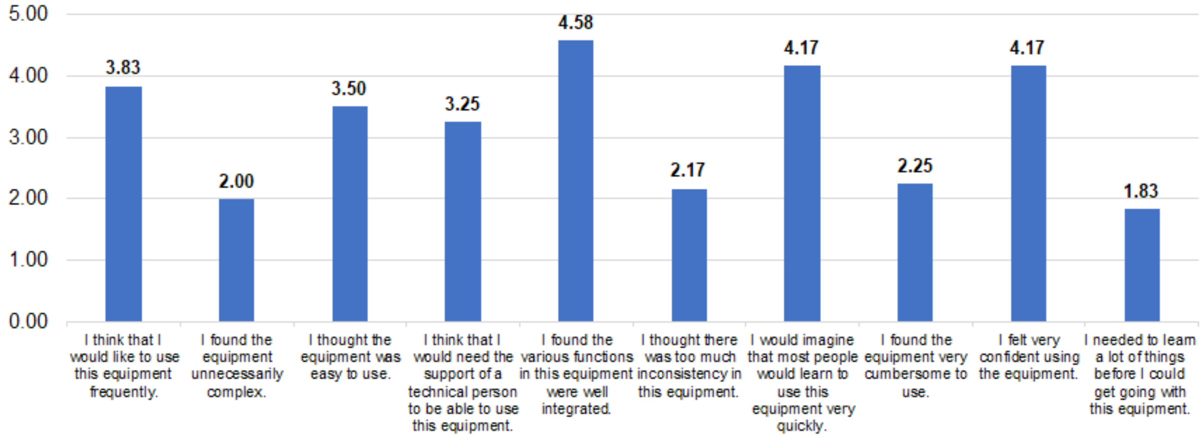

Figure 15: Likert scale feedback for the SUS questionnaire questions.

	Statement	Average [0-4]	Std. Deviation
1	I think that I would like to use this system frequently	2.83	1.19
2	I found the system unnecessarily complex	3.00	0.85
3	I thought the system was easy to use	2.50	0.90
4	I think that I would need the support of a technical person	1.75	1.29
5	The functions in this system were well integrated	3.58	0.67
6	I found inconsistency in this system	2.83	1.11
7	Most people would learn to use this system very quickly	3.17	1.03
8	I found the system very cumbersome to use	2.75	1.05
9	I felt very confident using the system	3.17	0.94
10	I must learn a lot before I could get going with the system	3.17	0.83
	Total (sum * 2.5)	**71.88**	**13.78**

Table 1: SUS questionnaire questions and feedback.

As can be seen in Table 1, the outcome of the SUS questionnaires is 71.88 $\pm$ 13.78 points out of 100, giving a "good" usability result on the adjective-based rating of the SUS procedure.

Some users however expressed concerns regarding the weight of the device during the tests. Most of the weight comes from the actuators and is not related to the printed part themselves, so a different actuator choice for further developments should solve such an issue. Additionally, the parts which are placed on the fingers to induce the movements take long to fit and some users gave negative feedback in terms of their aspect, even though their functionality and robustness are undeniable.

6 Cost Analysis

In order to carry out a cost analysis, a G-code analyzer can be used. Once the filament quantity is known, the filament cost can be assessed based on the type of filament and its cost per unit length. The cost of the 3D printed parts as well as all the other parts featured in the device are reported in Table 2, while the cost percentages can be found in Figure 16.

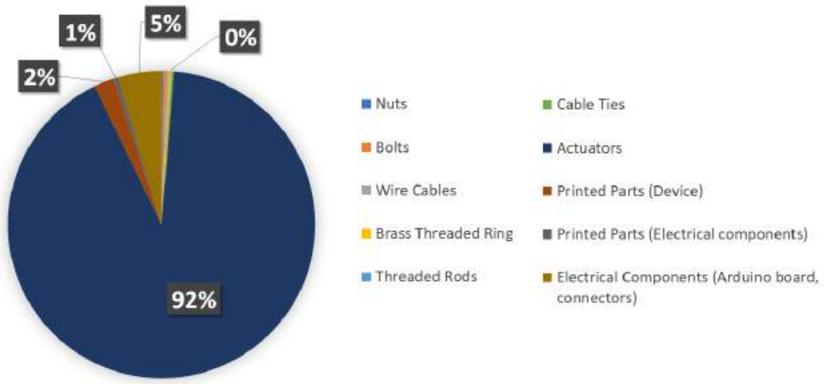

Figure 16: Costs of different parts of the device.

Part	No. of Parts	Unit Cost [$/unit]	Total Cost [$]
Nuts	17	0.06	1.02
Bolts	25	0.06	1.50
Wire Cables	5	0.30	1.50
Brass Threaded Ring	10	0.12	1.20
Threaded Rods	3	0.12	0.36
Cable Ties	10	0.12	1.20
Actuators	5	96.80	484.00
Printed Parts (Device)	26	-	11.01
Printed Parts (Electrical Components)	2	-	2.75
Electrical Components (Arduino board, Connectors)	3	-	24.16
Total	106	-	528.70

Table 2: Cost of the device parts.

Values in Table 2 and Figure 16 show that the highest costs come from the electrical components (Arduino board, connectors, and, most of all, the actuators) and not the 3D printed parts.

7 CONCLUSIONS

This paper presents a low-cost solution for hand rehabilitation that can be adapted to different patients thanks to some device features. The usage of 3D printed parts allows for optimal comfort and reduced weight as well as, maybe even more importantly, limited costs. A simple user interface that controls the device is also presented in order to have a simple but effective solution to achieve improvements in stroke patients.

Based on the test feedback, this prototype seems to be promising even though some visual improvements and weight reduction may be necessary.

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