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PROTOTYPING ROBOTIC MEDICAL REHABILITATION DEVICES

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ABSTRACT: This paper will be presenting research and development stages of robotic rehabilitation devices. The focus of rehabilitation are aimed for the human hand, mainly for regaining motor functions by the aid of robotics. As part of the project a series of parts were designed around anthropometric measurements were used from previous work to design the prototype parts in the robotic rehabilitation device. In this paper non conventional fabrication methods were used such as fused filament fabrication to obtain the prototype parts. Research was done on materials to determine the optimum filament material for the application. Testing and configuration of the fabrication process was done gradually with the final result being presented in this paper.

KEYWORDS: Fused filament fabrication, robotic rehabilitation device, robotic exoskeleton.

1. INTRODUCTION

Taking a brief look at the history of technological innovation, we will see that science and technology has provided us with major advancements in the industrial and economical sectors of activity. As we continuously develop new technologies we are expanding the potential for nonconventional technologies in key fields such as engineering, medicine, space exploration etc. In a way we can safely assume that ground-breaking, new and nonconventional technologies of today may be the standard of tomorrow.

In this paper I will discuss the application of fused filament fabrication (FFF), commonly known as 3D printing in prototyping and development of medical robotics, mainly assistive rehabilitation devices.

Advancements in technology has brought us closer to a world where hard labour, repetitive, and difficult tasks are replaced by high-tech autonomous machinery [1]-[4]. Advancements that ended some job areas and opened others, enabling us to focus on intellectual activities such as design, programming, and engineering. Although we have made significant progress in the sectors mentioned above, some areas such as medical robotics are still in need of development and advancements [2], [11], [12].

The research presented in this paper is to be used for rehabilitation of the hand grasping motor function for people who have suffered from stroke or cerebrovascular accident with the aid of robotics [3].

The focus of this paper is merely a step in developing a device that can aid physiological rehabilitation and enhancement of the human body.

Nature's design as we know it, involve complex shapes and the human hand is no exception, modelling and fabrication the required parts would have not been possible without using nonconventional fabrication techniques such as 3D printing [4]. As such the prototyping of robotic system was vital for the project’s starting point. Factors such as bone structure, joint and ligaments, muscle actuation and degrees of freedom were researched in order to mimic the natural movement of the biological hand, in essence reverse engineering and collecting data for designing a robotic exoskeleton.

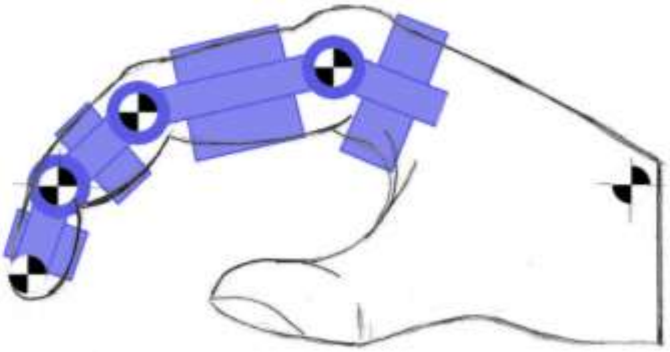


Figure 1. Exoskeleton sketch for the human hand

Angular limitations and anthropometric dimensions were observed and recorded of the human hand in a previous paper regarding the anthropometric parameters needed for the first prototype.

In order to retrain and recover the gasping motor ability the fingers need to be moved externally by trained personnel or robotic exoskeleton [5], [9], [10], [13], [14] similar as seen in the sketch presented in figure 1.

Stages of development and fabrication of the parts necessary for the first robotic exoskeleton prototype for this project is presented further in this paper.

2. MATERIAL STUDY AND RESEARCH

The concept of 3D printing or Fused Filament Fabrication (FFF) (Also known as Fused deposition modelling (FDM)) is not new but the recent advancements in commercial grade 3D printers has made it a viable and low cost technology used in prototyping. We can say that this new technology has opened the door to a wide variety of applications with complex shapes, for example medical rehabilitation robotics. Although it is tempting to think that by 3D printing we can generate any shape or structure it does have some limitations. In this section of the paper we will discuss about the material aspects of 3D printing, in table 1 we will take each material and research general aspects such as advantages, application use, print difficulty, print temperature and also heat bed temperature.

As we can see in table 1 we have a large verity of materials to choose from when fabricating parts using 3D printing. The most common ones are PLA (Polylactic Acid) and ABS (Acrylonitrile butadiene styrene) and although there are numerous derivatives based on PLA and ABS such as PLA with carbon fibre particles they are not all mentioned here since their properties may differ from one manufacturer to another.

Table 1. General characteristics of 3D printing filaments

Filament	Based on	Advantages	Used In	Print Temp. (C)	Heated Bed – Temp (C)	Print Difficulty
PLA	Polylactic Acid	User Friendly	Consumer Products	180 -230	No	Easy
ABS	Acrylonitrile Butadiene Styrene	High Strength	Moving Parts	210-250	50-100	Moderate
PETG	PET+Glycerol	Hight Strength	Moving Parts	220-235	No	Moderate
Flexible TPE/TPU	Thermoplastic Elastomer	Elastic	Wearable's	225-235	No	High
HIPS	High Impact Polystyrene	Dual extrusion with ABS	Support Structure	210-250	50-100	Moderate
PVA	Polyvinyl alcohol	Dual extrusion with ABS	Support Structure	180-230	No	Easy
Nylon	Polyamide	High Strength	Moving Parts	220-260	50-100	Moderate
PET (CEP)	PolyEthylene Terephthalate	High Strength	Moving Parts	220-250	No	Moderate
Carbon Fiber	PLA+Carbon Fiber	High Strength	Moving Parts	195-220	No	Moderate
PC	Polycarbonate	High Strength	Temperature Resistance	270-310	90-105	Moderate
Conductive	PLA+Carbon	Conductive	Electronics	215-230	No	Easy
ASA	Acrylonitrile Styrene Acrylate	High Strength	Weather Resistance	240-260	100-120	Moderate
PP	Polypropylene	High Strength	Flexible Components	210-230	120-150	High

As seen in table 1 some materials are best used for support materials during the 3D printing process, such as HIPS and PVA while others are recommended for when high strength is required such as ABS, PETG, Nylon, PET, PC, PP and Carbon fibre (compound of carbon fibre and PLA).

Generally PLA is suitable for most applications and is preferred due to its ease of use compared to ABS, the other commonly used filament.

The next steps is to make a more detailed comparison between the two most commonly used materials for 3D printing using the FFF method, namely ABS and PLA materials.

As seen in table 2. we have the two materials comparing a few important properties such as density, tensile strength, strength to weight ratio and so on. While there ABS does have some superior mechanical properties in some situations PLA seems to be a more precise material overall with little variations. PLA is generally more rigid and has a very low coefficient of elongation at break, at about 6%, this means that parts manufactured with this material will bend very little before breaking.

One disadvantage for PLA would be its Glass Transition Temperature at approximately 60 degrees C, this means that while printing the deposited layers need to cool very fast before the next layer is added for the print to be as accurate as possible and without defects. But due to this low glass transition temperature we also have very low, close to negligible thermal expansion coefficient.

Is good to note that ABS plastic at high temperatures is toxic and should be used only with an enclosed 3D printer within a fume hood or well ventilated area due to toxic gas emanation during printing. Taking into consideration the eco friendly properties of PLA such as being biodegradable and non toxic, contrary to ABS, we will fabricate the first prototype using PLA filament [6].

Table 2. ABS and PLA characteristics

Material characteristics	Unite of measurement - Coefficient	PLA	ABS
Density	$\rho(Mg/m^2)$	1.25	1.01-1.21
Young's Module	E(GPa)	3.5	1.1-2.9
Elongation at break	%	6	3-75
Melting (softening) Temperature	T_m (°C)	160	88-128
Glass Transition Temperature	°C	60	100
Yield Stress	σ_y (MPa)	47-58	18.5-51
Tensile Strength	σ_{ts} (MPa)	36-55	25-50
Ultimate Tensile Strength	MPa	35	40
Thermal expansion	µm/m-K	-	83-95
Strength to weight ratio	kN-m/kg	40	31-80
Shear module G	GPa	2.4	-

3. DEVELOPING THE 3D MODELS

The 3D CAD modelling software used in the development of the mechanical parts is CATIA V5 by Dassault Systemes.

The robotic exoskeleton was designed attaches mechanically to the body via the orthetic shell structure together with a compliant material placed inside the shells that fits the human finger anatomy.

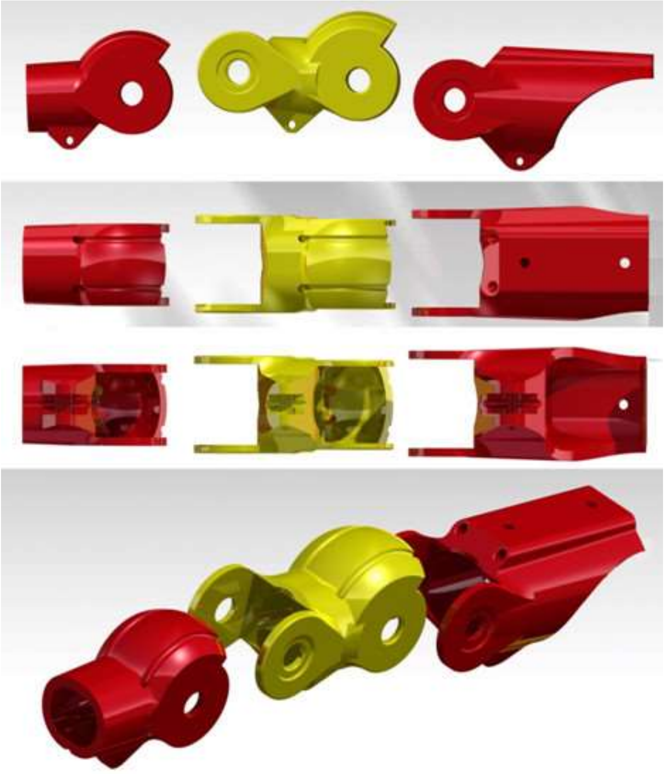


Figure 2. Finger exoskeleton elements

The exoskeleton parts match the centre of rotation of the human hand and provide flexibility.

All orthetic shell parts are 3D modelled using the anthropometric measurements collected previously and presented in [7]. The orthetic parts are divided into 3 separate categories: phalanx exoskeleton, metacarpal and forearm exoskeleton.

Each finger consists of three phalanges as a result three parts were modelled after the anthropometric dimensions, the resulting 3D model can be shown in figure 2.

The metacarpal region interfaces the palm region of the hand to the exoskeleton. The fingers are directly connected to this part via a circular guider that haves a remote centre of rotation coincident to the biological MCP joints.

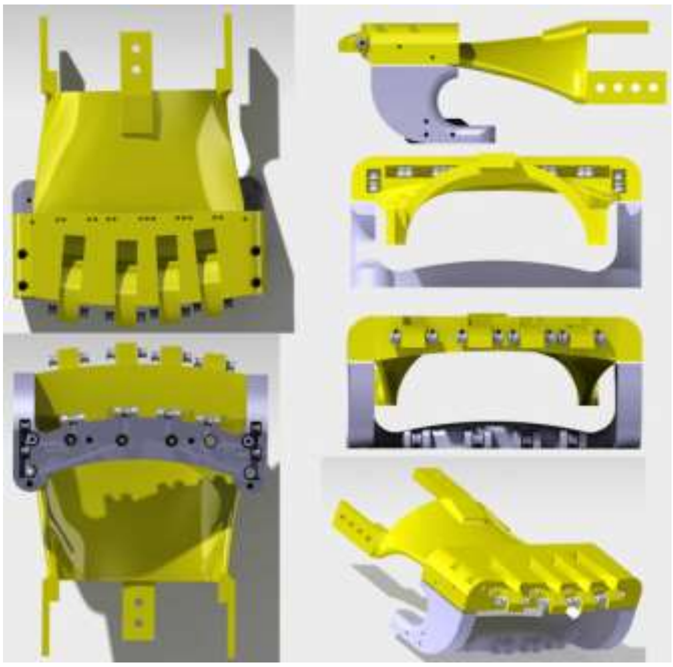


Figure 3. Metacarpal region exoskeleton parts

The wire is transmitted through this part via rollers mounted under and over the metacarpal parts. The metacarpal region part is seen in figure 3.

The phalanges exoskeleton include rollers in the dorsal area and cylindrical sliders for the wire transmission, the dimensions of the modules do not permit mechanically the joints to exceed the 0 - 90 degree angular limitation. This mechanical limitation is to avoid potential harm to the wearer of the exoskeleton. The limitations can be increased by placing addition spacers on the contact limiting surfaces of the phalanges.

The forearm exoskeleton interfaces to the arm of the wearer and holds the control electronics such as motors, drivers, microcontroller and battery. The orthetic shell of the forearm can be seen in figure 4 forearm exoskeleton parts.

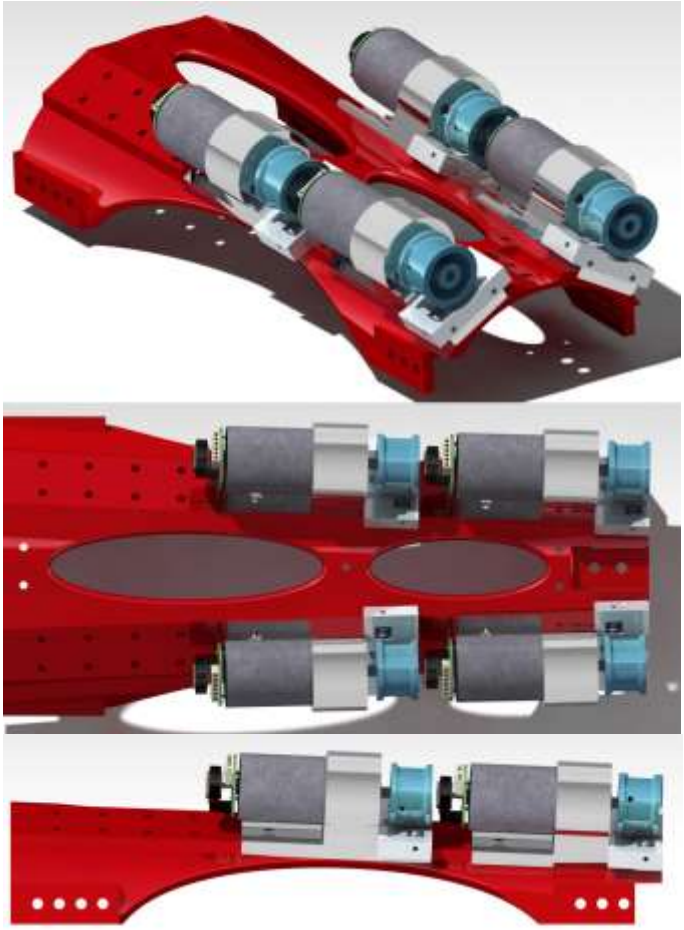


Figure 4. forearm exoskeleton parts

4. MANUFACTURING USING FFF

As stated earlier fused filament fabrication (FFF) was used to fabricate the parts for the prototype. The filament material used for was PLA and the 3D printer model was a Makerbot Replicator II clone seen in figure 6. The most notable characteristics provided by the manufacturer of this printer are:

- build size: 225 x 145 x 155 mm
- layer accuracy: 0.1mm - 0.5mm
- positioning Accuracy: XY axis 0.011mm
- input file type: stl, gcode
- nozzle diameter 0.4mm
- input method: USB2.0, SD Card

The CAM software used was the Makerbot MakerWare software as seen in figure 5, usually compatible with all Makerbot printers and most of their clones.

Factors such as speed and quality play an important role when fabricating 3D printed parts, the balance between these two factors usually is determined experimentally by observations [8], [15]. A reduced speed of printing usually results in a better quality print, on the other hand we need not reduce the speed some much that it renders the fabrication unpractical. For this printer the optimal speed parameters were determine as shown in figure 7.

Stages of printing that have high importance such as: *bridges, first layer, first layer raft* and *floor surfaces fills* are printed at slow speed to obtain the highest precision. For this prototype 10 and 20 mm/s was used for the high priority stages of printing. For the other non critical stages higher speeds were used, in this case 40, 50 and 60mm/s was consider a reasonable balance between speed and quality. By non critical stages we refer to those stages that do not impact the overall quality if the print such *infill*.

Another very important factor was the infill factor, depending on the component printed the infill ranged from 85% to 15%. Small parts such as the parts used for the fingers had higher infill to provide better structural integrity and bigger parts had less infill relying on the outer shell strength and the hexagonal pattern infill used [9], [10], [13].

Figure 5. Makerbot CAM Software

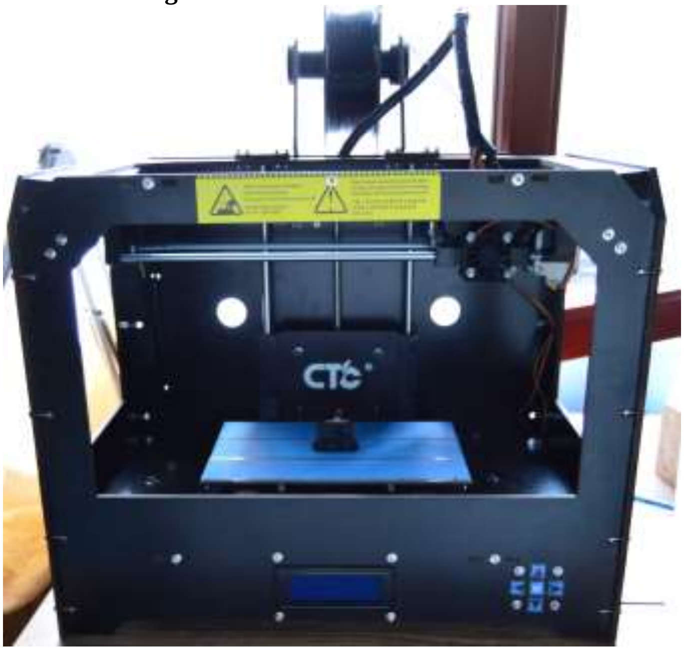
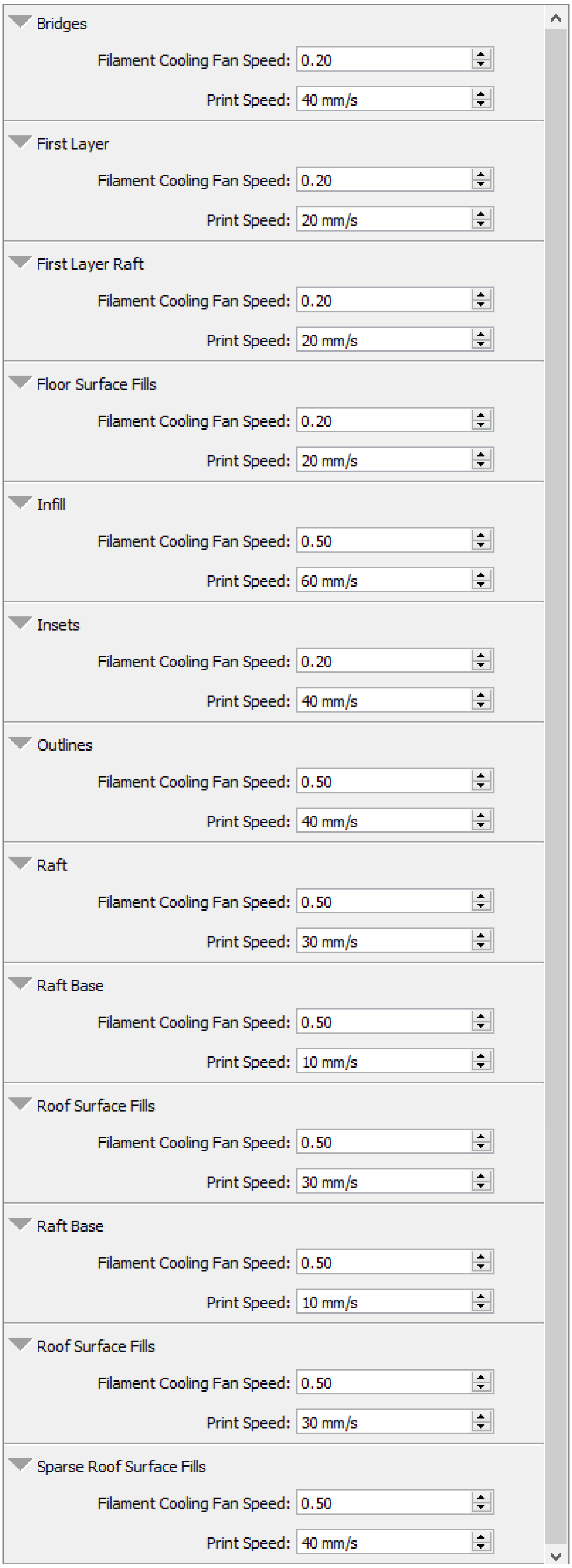


Figure 6. MakerBot Replicator II clone



Bridges
Filament Cooling Fan Speed: 0.20
Print Speed: 40 mm/s

First Layer
Filament Cooling Fan Speed: 0.20
Print Speed: 20 mm/s

First Layer Raft
Filament Cooling Fan Speed: 0.20
Print Speed: 20 mm/s

Floor Surface Fills
Filament Cooling Fan Speed: 0.20
Print Speed: 20 mm/s

Infill
Filament Cooling Fan Speed: 0.50
Print Speed: 60 mm/s

Insets
Filament Cooling Fan Speed: 0.20
Print Speed: 40 mm/s

Outlines
Filament Cooling Fan Speed: 0.50
Print Speed: 40 mm/s

Raft
Filament Cooling Fan Speed: 0.50
Print Speed: 30 mm/s

Raft Base
Filament Cooling Fan Speed: 0.50
Print Speed: 10 mm/s

Roof Surface Fills
Filament Cooling Fan Speed: 0.50
Print Speed: 30 mm/s

Raft Base
Filament Cooling Fan Speed: 0.50
Print Speed: 10 mm/s

Roof Surface Fills
Filament Cooling Fan Speed: 0.50
Print Speed: 30 mm/s

Sparse Roof Surface Fills
Filament Cooling Fan Speed: 0.50
Print Speed: 40 mm/s

Figure 7. forearm exoskeleton parts

The fabricated and assembled parts can be seen side by side with the 3D rendered model in figure 8.

Limits such as build dimensions were taken into consideration when designing the printable parts. Parts that exceeded the build area of 225 x 145 x155 were split in two parts and assembled or glued after printing. The direction of the print also influenced the support material needed for the fabrication process, ideally the less support material needed the better the final result. For parts that needed supports, the same material was used and were printed to be easily break of the fabricated part, this type of support is commonly known as break away support.

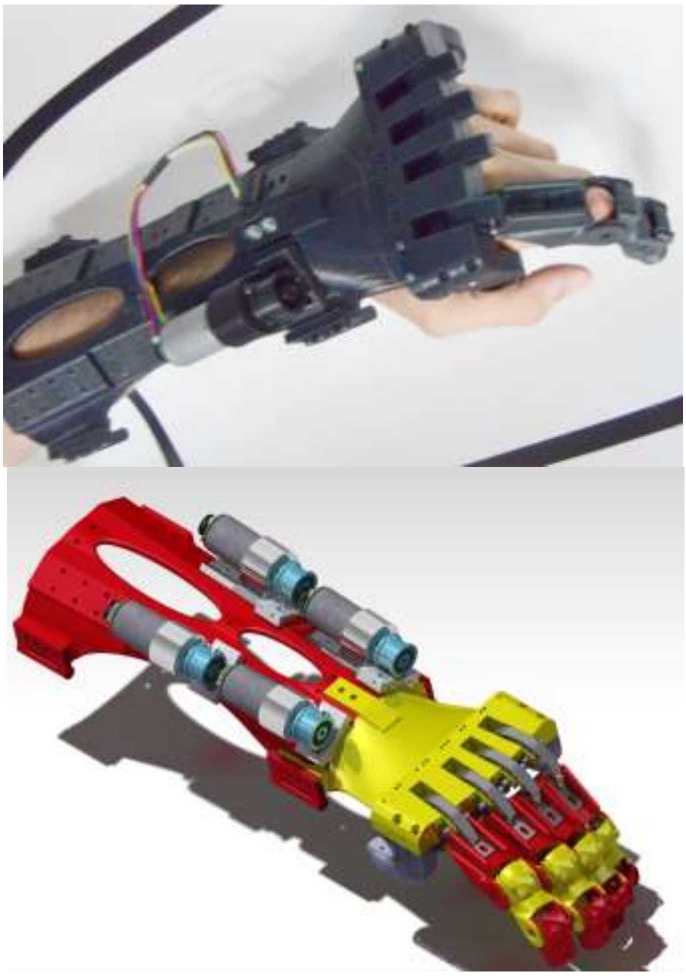


Figure 8. Fabricated and assembled prototype and 3D model

Mechanical transmission of motion from the motors to the fingers is a vast subject on its own and will be discussed in another paper dedicated to that particular chapter of the project later on.

A 3D render compared to the printed assembly is presented in figure 8.

5. CONCLUSIONS

Using 3D printing technology opens up new possibilities in numbers areas, in this case its proves to be very effective for prototyping robotic rehabilitation devices, and taking into consideration the affordability of commercially available 3D it can also be considered an option for producing customized devices based on patients needs.

As of this date the project is ongoing and is in continuous development.

6. ACKNOWLEDGEMENTS

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