Title:
Exoskeleton for Post-Stroke Hand Rehabilitation

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Introduction:

Stroke is the second worldwide cause of death, causing about 5.7 million fatalities each year, and can lead to consistent 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, since age is known to be the most relevant stroke-inducing factor, besides chronic conditions [1, 2].
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 the muscle coordination by repeating the movements which are commonly associated to our hand. Such result can be achieved by means of an external device, for instance an exoskeleton. Further improvements include tactile and eye-hand coordination exercises.

The continuous advancements in the Augmented and Virtual Reality worlds allow for an integration of such developments in the rehabilitation process. An Oculus Rift VR visor can be for instance used to improve the rehabilitation [3].
It must be underlined that even though the prototype is referred to as hand exoskeleton there is no wrist activity but finger movements only. Such movements are obtained by means of steel cables, driven by electric actuators.

System Architecture:

In order to design an anatomically comfortable exoskeleton, the hand geometry and dimensions can be well obtained with many available scanners which then create a solid hand model. Such model can be then used on many commercial solid modeling environments such as SolidWorks or Inventor.
3D scanning software do not even need a specific device for the acquisition but can be used by purchasing an accessory for tablets. Many nowadays devices even come with their own built-in three-dimensional scanners, even though the scanning quality may not be enough for applications such as this one.

Once the hand anatomy has been acquired, the surfaces of the model can be used to create the lower part of the device. The exoskeleton is placed on the limb from above and is then secured by means of Velcro stripes running in apposite slots on the sides of the gauntlet. Velcro shall be tight enough to secure the device while making sure to avoid the risk of limiting the blood flow.

Fig. 1: Hand model after scanning

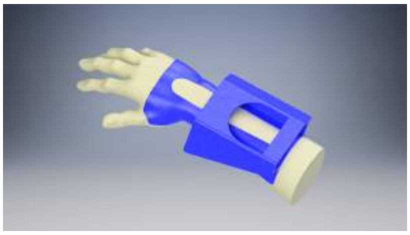

Fig. 2: Exoskeleton gauntlet

In order to have some at surfaces to accommodate the actuators, an upper section was created consisting of three different parts (Figures 3 - 4):

- 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

In order to constrain the actuators and keep them in their correct positions, the following parts are used:

- In the front, guides are used to prevent lateral movements of the actuators. In the central part of the upper surface a unique sleeve is used, while for the two lateral parts (thumb and little finger) two single sleeves are used
- In the back, six constraints are used. These parts have an hole so that, using bolts and nuts, such parts can constrain the actuators from sliding back and forth

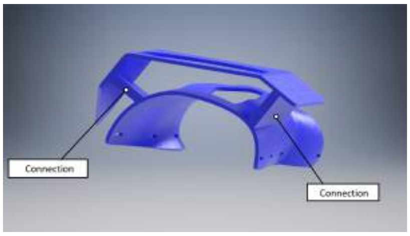

Fig. 3: Rear view of the gauntlet

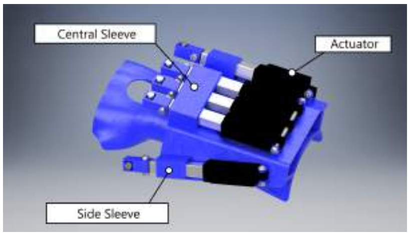

Fig. 4: Gauntlet with the five actuators

Inducing Finger Movements:

In order to induce the movements of the fingers, five 3D-printed flexible TPU shells were printed, where the idea is using Velcro to wrap them around the fingers. Proper infill is an important parameter during the printing process because it defines the flexibility of the shells: too low infill leads to a low resistance of such parts and then, there is the risk to fall apart. On the other hand, excessive infill leads to a higher stiffness and hence a bad wearability, because it would be very difficult to make them bend around the finger.

On top of such parts, PLA parts are glued in order to guide the wire and obtain the correct movements. Such parts are needed since a cable can pull well but cannot push with the same effectiveness.

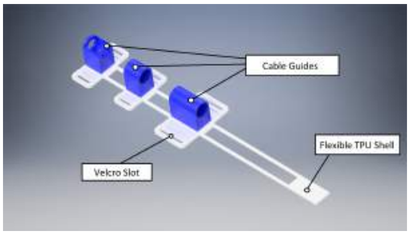

Fig. 5: Rear view of the gauntlet

Fig. 6: Gauntlet with the five actuators

In order to connect each actuator to its respective cable, five PLA actuator-wire connections are used. Such parts are joined to each actuators by means of bolts and nuts, while the cables are secured by means of brass threaded rings both at each actuator-wire connection and at each distal phalanx cable guide.

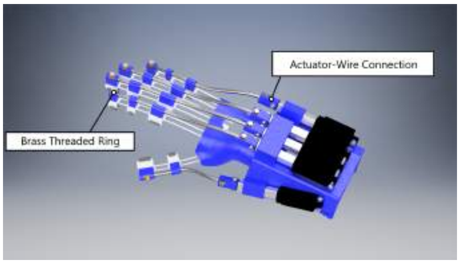

Fig. 7: The complete exoskeleton

The 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

Such movements can be induced by driving the cables and therefore, by means of the shells, the finger movements are obtained. A correct coordination of the actuator strokes is necessary: such task can be achieved by controlling the actuators with an Arduino board and codes. To see the renderings and the tests visit: https://1drv.ms/u/s!AoXkJge4QAcGZxQ4541y8d5JtCg?e=ECAYzT.

Augmented Reality Application:

By means of Unity and Vuforia, an Android app can be developed. Such app exploits the smartphone camera to create an AR model based on the used marker. This allows showing a static view of the prototype or a static model of the exploded view, containing all the parts which compose the device.

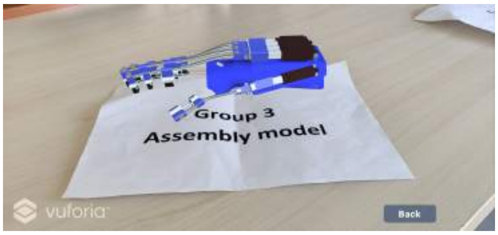

Fig. 8: Augmented reality (prototype assembly)

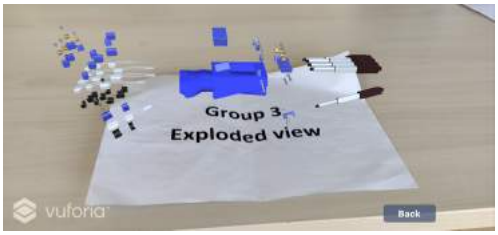

Fig. 9: Augmented reality (exploded view)

Virtual Reality Application:

In order to allow the patient to have a better understanding of the rehabilitation movements, a Virtual Reality (VR) environment for an Oculus Rift device was created with Unity.

This environment allows navigating through different scenes: one includes an assembly of the device, one includes a static exploded view and the last one allows to see the three rehabilitation movements in a sort of "virtual cinema". The navigation among different scenes can be obtained by means of the Oculus Controller or using the PC keyboard.

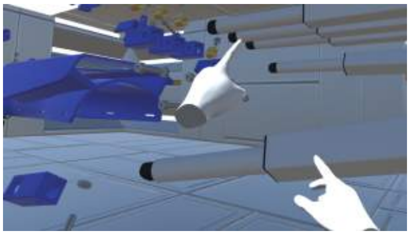

Fig. 10: VR room (exploded view)

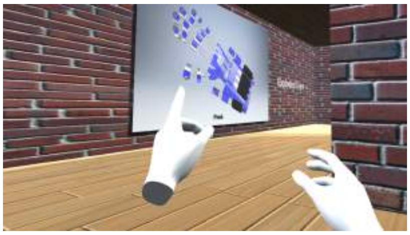

Fig. 11: VR room (movements)

It must be specified that in the beginning of the rehabilitation patients can only wear the Oculus visor since they cannot operate the controller, which is then operated by the physician. As the patients start to regain muscle coordination, they can start to operate even the controller for a more interactive rehabilitation process.

Desktop Application and Communication with Arduino:

In order to communicate with the Arduino board which controls the actuator movements, a Unity-developed Windows app is used. Such executable allows selecting the wanted movement among the rehabilitation ones (grab, pinch and wave) by clicking on the corresponding button.

User Study and Test Results:

The test of the physical prototype showed some issues related to:

- Time it takes to assemble the parts which induce the finger movements on the patient's hand
- Weight of the device due to the actuators
- In order to induce the finger movements by means of the flexible TPU shells, it was necessary to make them very tight around the fingers by means of Velcro, which actually led to an unpleasant experience for the tester since the fingers started to feel numb after long testing times

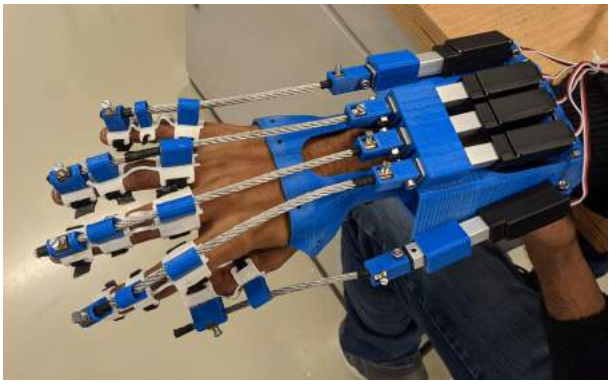

Fig. 12: The physical prototype

Conclusions:

Using higher diameter cables to induce finger movements allows overcoming all the issue related to low-diameter cables such as the instability which occurs when pushing, i.e. trying to get the movements such as grabbing, pinching and waving.

Despite the potentiality of the prototype, many improvements must be however carried out in order for the device to become a commercially viable option. One issue is adapting the device for different patients: even though the cost of the 3D printed parts is very limited, it does not seem reasonable to print a new gauntlet for each patient, which is time consuming and not environmental friendly. A solution could be printing a bigger gauntlet and using some sort of foam to obtain an optimal comfort.

Another issue relates to the flexible parts which induce finger movements: the parts used on this prototype are a very rough beginning which can lead to further future improvements which are currently being investigated.

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