Title:
Hand Exoskeleton for Personalized Rehabilitation.

Authors:
Mirko Ciceri, mirko.ciceri@mail.polimi.it, Politecnico di Milano
Marco Gauterio, marco.gautiero@mail.polimi.it, Politecnico di Milano
Stefano Scaccabarozzi, stefano3.scaccabarozzi@mail.polimi.it, Politecnico di Milano
Jose Angel Santos Paz, mariaconcetta.carruba@unipegaso.it, Universidad San Pablo CEU, Spain
Rodrigo Garcia-Carmona, francesco.ferrise@polimi.it, Universidad San Pablo CEU, Spain
Beatrice Aruanno, beatrice.aruanno@ing.unipi.it, Università di Pisa
Mario Covarrubias, mario.covarrubias@polimi.it, Politecnico di Milano

Keywords:
Virtual Reality, Training, Special Education, Down Syndrome, Autism, Mental Retardation.

DOI: 10.14733/cadconfP.2023.31-35

Introduction:
The aim of the project is the complete design of a hand "exoskeleton" for rehabilitation purposes, able to actuate independently each finger by the means of linear actuators. The input is given by Arduino and have 2 possibilities: a sensed glove capable of acquiring the healthy hand's movements or by a virtual reality approach. In particular we present the design steps and actuation mechanics of a wearable exoskeleton for hand rehabilitation of post-stroke. It has been demonstrated that replicating the movements allows a faster rehabilitation. Our design method is focused on achieving maximum safety, comfort, lightness and reliability in the interaction. According to the United Nations, we are experiencing a social transformation: the world population is ageing [3]. A longer life brings new opportunities, but it can cause an increased incidence of diseases, such as stroke. According to the Global Burden Disease study, stroke is the third cause of disability [4]. Based on the medical definition [2], we can identify two principal types of stroke: ischemic and hemorrhagic. An ischemic stroke occurs when a clot or a foreign mass obstructs a blood vessel, reducing the bloodstream to brain cells. A hemorrhagic stroke occurs when a damaged blood vessel breaks and bleeds into the surrounding brain area. Wearable exoskeletons are targeting directly each human joint, but conversely they have greater mechanical complexity, weight and encumbrance, given the close interaction with the user. Approaching the human hand rehabilitation is very challenging due to its structure it offers a very limited space for physical interaction with external devices. Our intention is to realize an end point machine that is very light and comfortable to wear, so maintaining the actuation device detached from the patient's hand. For the seek of simplicity for the remaining part of the report we will continue to call our device exoskeleton even though effectively it is an end point machine. In this paper, we introduce our developed exoskeleton training device for hand rehabilitation. That anyway is not meant to be portable in the day life condition, but it is suitable for on-desk sessions with maximum ease of mounting and maximum lightness perceived by the patient. Here, we describe the mechanical design and different control strategies of the exoskeleton.

Proceedings of CAD'23, Mexico City, Mexico, July 10-12, 2023, 31-35

Concept

The fundamental concept behind this project is to improve the rehabilitation of patient's hand after a stroke. In particular people with neuronal diseases as Ictus that allows the patient of controlling half of its body. This limitation generally is only neuronal and it is a matter of capability of sending impulses to the muscles, that are not compromised as well as the nerve connections.
We are realizing a sensed glove able to acquire the motion of each single finger of the healthy hand, those sensors will be connected to an Arduino UNO able to elaborate those data and sending inputs to five different linear actuators. Those actuators will be connected to the hand exoskeleton by the means of metallic cables that would actuate the ladder, replicating the movements of the sensed glove. On top of that we are going to realize a virtual reality environment in which it is explained how to mount the machine and it is delivered a showcase of each single component. In the program will be also present an actuation interface able to communicate with Arduino and allowing also the software actuation of the exoskeleton. Here are located five different sliders allowing the independent actuation of each single finger and three different buttons actuation all the finger together, allowing three main basic movement that experts recommend for rehabilitation:

- Pinch
- Cylindrical Grasp
- Wave

Fig. 1: Pinch - Cylindrical Grasp - Wave

Passive exercise:

Together with medical experts from Villa Beretta rehabilitation centre, we defined four passive rehabilitative motions. According to the literature, performing these repetitive movements can prevent or reduce tendon retraction, spasticity and oedema [1].

- 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 afterwards flexed. It mimics the precision grip of a small object.
- Wave: it starts with the extension of all fingers. One finger per time is flexed and re-extended in order, from thumb to little finger and then in the other sense.

- Opposition: after extending all fingers, the movement replicates the opposition of the thumb with all other fingers. It flexes and extends the thumb and one other finger per time.

Considering that each patient is different, the caregiver can set the range of movement of each finger, the number of repetitions and the speed of the movement.

Realization of the physical hand exoskeleton:

First of all we decided to realize a custom-made hand prototype for the specific user. So, in order to do that, we started bringing a 3d scan of the patient's hand through a scanner device (3D systems sense). Then, by means of a software called Sense 3D, we were able to obtain file .obj of the scanned hand. By the software mesh mixer we generated the topological optimization of the rough hand mesh.

For the realization of the structure for the fingers we designed them in two main parts, also in this case having a geometrical fit, on Autodesk Inventor Professional:

- The body of finger that is characterized by a particular structure which make it more elastic giving the possibility of stretching also in the longitudinal direction and with a great number of guidance in order to lead the metal wire, and consequently the finger, in a proper way. The material used for its realization is TPU which is elastic and the intrinsic material elasticity together with the particular structure allows the stretching of the part on top of the bending. Being a custom-made hand, also the finger bodies are realized according to the lengths of each own fingers.

- The tip of finger that is realized according to the shape of each tip finger. On top of it there is a structure that allows to block the wire with a snap fit to the tip of finger. In this case we used the PLA material that, in contrast to TPU, is rigid and allows a proper functioning of the structure.

The only parts in this 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 2 is shown the result of the exoskeleton after the 3D printing and the assembly of all the previously mentioned parts. At this point we can affirm that the design of the exoskeleton is solid and the fit is quite comfortable.

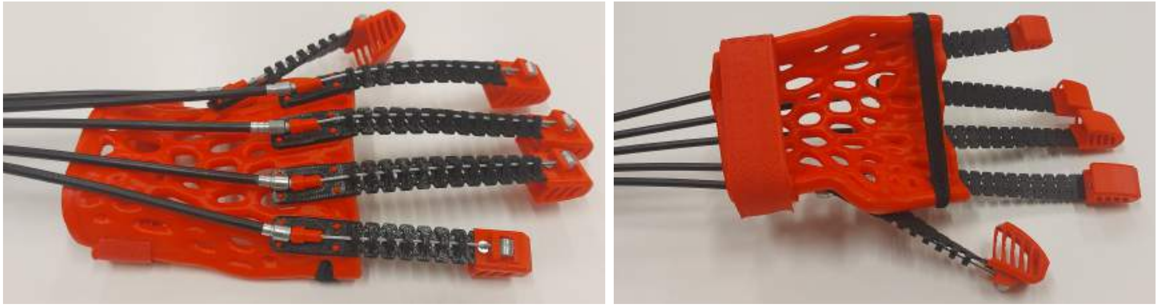

Fig. 2: Real prototype

Actuation unit:

The fingers of the exoskeleton (Figure 2) are driven by some bicycle brake cables connected both to the tips of the fingers and to the end of the linear actuator. The linear actuator hold the wire that can

Proceedings of CAD'23, Mexico City, Mexico, July 10-12, 2023, 31-35

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 we have used 5 linear actuators from Actuonix with a stroke of 100mm. Also in this case we have designed a support for the actuators, each actuator is hold in place separately by a support and a central guide. The chassis is made in aluminium and has been sawed and drilled by us with tailor-made dimensions. The angles, the central guide and the cables holder have some feet in order to prevent the slipping of the whole structure. The cables holder part is made in 2 pieces allowing a snap fit with the end of the cables sheath, the aluminum chassis and the other part of the holder. In particular the negative of the metallic pin holding the cables have been debossed on both parts allowing the joint. To allow a proper constraint 4 bolted connections have been designed, two of them are passing through the chassis wile the other two are meant to keep in their location the cables.

In Figure 3 is shown the final result of the assembly, on top the rendering and on the bottom the real prototype.

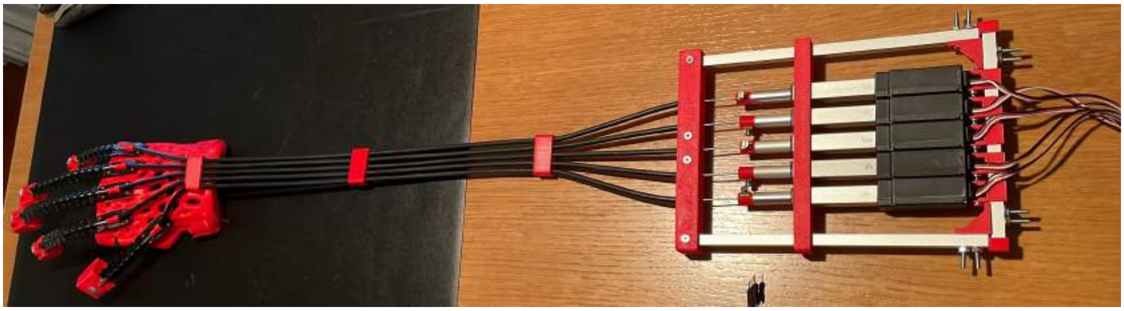

Fig. 3: Complete assembly of the device

Acquisition of data from healthy hand:

In order to acquire the data from the healthy hand we decided to use some components called flex sensors which behave like a potentiometer. So when bent their internal resistance is changed. They are mounted on the fingers of the healthy hand and they are able to acquire the signal, so the variation of resistance related to the bending of the finger and by a proper electronic circuit send the signal to Arduino. Also the fixing of the flex sensors is not an easy task because they are not flexible in the longitudinal direction and if glued directly on a glove they would prevent the bending of the fingers. So we have designed a sort of case, where the flex sensor can slip in and is able to slide inside. This case have some holes on the side that can be sewed on the glove to allow the fixing. This component have been printed in TPU material in order to be flexible.

Results:

Some patients undergo the validation session of the prototype. One has an ischaemic stroke in the chronic stage with left hemiplegia. Also, the second has an ischaemic stroke, some others have a concussion followed by a coma that caused hemiparesis. This means that the system is not only for post-stroke people.

Analyzing the SUS, we need to consider that two patients have little knowledge about interacting with computers. It is a preliminary qualitative evaluation of the system, and it would need a more exhaustive assessment with more participants. However, the positive first outcomes obtained seem promising.

Table 1: Device's comfort and willingness to use questionnaire. Mean values ranges from 0 to 4 and negatively worded items have been normalized. The device obtained 30.50 / 36

	Statement	Likert Scale (1:5)	Normal Mean (0:4)	Std. Dev.
1	With the help of a caregiver, the device is worn quickly	4.33	3.33	0.58
2	The weight of the device on my hand is excessive	1.00	4.00	0.00
3	The the device frame is comfortable	5.00	4.00	0.00
4	the device is very noisy	1.50	3.50	0.50
5	the device caused me discomfort or pain	1.00	4.00	0.00
6	I like the aesthetic aspect of the device	4.33	3.33	1.15
7	I think the device could help me improve	4.67	3.67	0.58
8	If I had access to the device exoskeleton, I think I would use it	4.67	3.67	0.58
9	If I could use the device at home to do my exercises, I think I'd use it	5.00	4.00	0.00
	Sum		**30.50**	**2.11**

Conclusions:

This work describes a rehabilitation system for the hand designed to assist post-stroke 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.

The system involves several innovative aspects designed keeping in mind the users' needs compared to the literature. Users are both patients and therapists, and both have been actively consulted during the whole development process collaborating with the Villa Beretta rehabilitation centre. This collaboration allowed emphasizing some aspects overlooked in the literature during the development of a prototype.

Acknowledgement:

We are grateful to the staff of Aspoc College. A special mention goes to Gianni Colombo and Chiara Colombo for collaboration in understanding needs and technical requirements.

References:

[1] Borboni, A.; Mor, M.; Faglia, R.: Gloreha-Hand Robotic Rehabilitation: Design, Mechanical Model, and Experiments. Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME, 2016. ISSN 15289028. http://doi.org/10.1115/1.4033831.

[2] Sacco, R.L.; et al.: An updated definition of stroke for the 21st century: A statement for healthcare professionals from the American heart association/American stroke association. Stroke, 44, 2064–2089, 2013. ISSN 00392499. http://doi.org/10.1161/STR.0b013e318296aeca.

[3] United Nations, Department of Economic and Social Affairs, Population Division: World Population Prospects 2019: Highlights. ST/ESA/SER.A/423. Tech. rep., UN, 2019. https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html.

[4] Vos, T.; Lim, S.S.; Abbafati, C.; Abbas, K.M.; Abbasi, M.; Abbasifard, M.; Abbasi-Kangevari, M.; Abbastabar, H.; Abd-Allah, F.; Abdelalim, A.; et al.: Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. The Lancet, 396(10258), 1204–1222, 2020. http://doi.org/10.1016/S0140-6736(20)30925-9.