Actas de las XXXIX Jornadas de Automática, Badajoz, 5-7 de Septiembre de 2018
https://doi.org/10.17979/spudc.9788497497565.0015

# LOW COST 3D-PRINTED HAND EXOSKELETON CONTROLLED BY A BCI

Christoph Wilms
Faculty of Nature and Engineering, International Degree Programme in Biomimetics B.Sc.,
City University of Applied Science Bremen, 28199 Bremen, Germany, cwilms@stud.hs-bremen.de

Marisol Rodríguez-Ugarte, Eduardo Iáñez, José M. Azorín
Brain-Machine Interface Systems Lab of the Miguel Hernández University of Elche,
Avda. de la Universidad s/n, Ed. Innova, 03202 Elche, Spain,{maria.rodriguezu,eianez,jm.azorin}@umh.es

## Abstract

*The aim of this work was to build and design a low-cost active hand exoskeleton to be used in rehabilitation of post-stroke patients. The hand exoskeleton was 3D printer and it allowed an active flexion and extension of the fingers. The exoskeleton designed was powered by three servomotors which pulled tendons to shorten the distance over or under the joints. This produced a natural hand movement close to a biological one. The exoskeleton was controlled by a Brain-Machine interface (BMI) utilizing an EEG-cap for measuring the brain activity. This way, two subjects tested the whole system opening and closing the hand exoskeleton by using only their thoughts.*

**Keywords:** hand exoeskeleton, BMI, rehabilitation.

## 1 INTRODUCTION

An active exoskeleton is mainly used in two different application areas. The first one serves to support people that are able to move their limbs. In this case, they have no neuronal or muscular constraint and it is usually used for lifting heavy objects such as in military usage [11]. In the second case, it is employed by people that have suffered neuronal or muscular damage to rehabilitate the movement of the affected limb. In this case, some studies uses human brain activity, or electroencephalographic (EEG) signals, to control the exoskeleton [2]. This is known as Brain-Machine Interface (BMI) where the EEG of the subjects are registered through non-invasive methods [6].

In comparison to passive systems they are powered by a motor so that an active movement of the exoskeleton is possible. There are different ways of conveying the force from the motor to the exoskeleton and varying its size and/or complexity, the weight, the grasping force and the control of every joint is diverse. For example, there are designs relatively compact that can generate high forces. The main disadvantage of this design is the motors placed on the lateral of the fingers. Out of these reasons, this design is often used for the knee, placing the motors at the outside of the leg [8].

Current exoskeletons have several advantages as well as disadvantages [1]. Therefore, different exoskeletons are developed for different application areas where the disadvantages are less important. Heo et. al. [5] gives a good overview about the current hand exoskeletons for rehabilitation and assistive works. Especially in the last few years a change in the design can be noticed. More and more exoskeletons are based on flexible designs using gloves as a support structure. The power transmission is performed with cables/tendons routed by fixations at the glove. The advantage of this jointless design is adaptability to different hand sizes. A disadvantage is the palmar cable for closing the hand as well as the complete covering of the hand which could lead to a sweaty hand. Beyond this reason, Kang et al. developed a polymer-based version which covers only the finger particularly. Even so, they cannot relinquish palmar pieces for closing the hand [3] [7].

The aim of this work is to build and design a low-cost active hand exoskeleton to be used in rehabilitation of post-stroke patients. The design has different hand sizes to be adapted to several people and be able to comfortable perform flexion and extension of the fingers. Our hypothesis is that this low-cost 3D printed hand exoskeleton produces a natural hand movement.

## 2 MATERIAL AND METHODS

### 2.1 EXOSKELETON

A hand-exoskeleton was developed to be used in future works with post-stroke patients in rehabilitation therapies. The requirements for the exoskeleton were the following:

- Completely 3D-printable.
- Active exoskeleton for rehabilitation (flexion and extension).
- The control method was a BMI.
- Simple mechanics, easy to repair and cheap.
- Attachable to different hand sizes respectively finger length.
- As compact as possible, usage of less motors.
- Small grasping forces, lower than 10 N [10].

The exoskeleton design was low-cost focus and it was based on the previous requirements and the mind map of [4]. The main decisions taken were the kind of power transmission and the actuator type. The purpose and the intention sensing method was also predefined by the requirements. In addition, a servomotor was used to generate a torque which was conveyed by tendons. This power supply was chosen due to the low costs of the material and the maintenance costs. Furthermore, based on the tendon driven mechanism chosen, the exoskeleton was light in weight.

A palmar cable was avoided to guarantee a better picking of things. The mechanism was related to the human finger, the cables were the tendons and the servomotor replaced the muscles (Fig. 1 (B)). That means that the mechanism was bioinspired, with the difference lest the joints were hinge joints. Conditioned by the design, the grasping force was relatively small, but in the application area of rehabilitation only small forces were needed. The grasping force could be increased by using bigger distance of the cable to the joint or by utilizing another servomotor with higher torque. But both ways result in a bigger exoskeleton.

The different pieces of the exoskeleton were constructed with the software Rhinoceros 5 (Robert McNeel & Associates, 1993 -2017, Seattle, USA). While designing, Marc/Mentat software (MARC Analysis Research) was used to calculate the stress of the pieces. Based on the results, material was added or removed at several positions. Furthermore, the software Z88Arion was used to do the same as Marc/Mentat albeit automatically to a defined material usage. The pieces were exported as .stl-files and they were converted into .gcode-files using Cura software provided by Ultimaker. These files can be printed by almost every rapid prototype printers. In this work, it was used the Prusa P3steel, but with the modification of a bigger bed. The modified bed was 160 mm x 280 mm with the result of a printing room of 6,994 * $10^3$

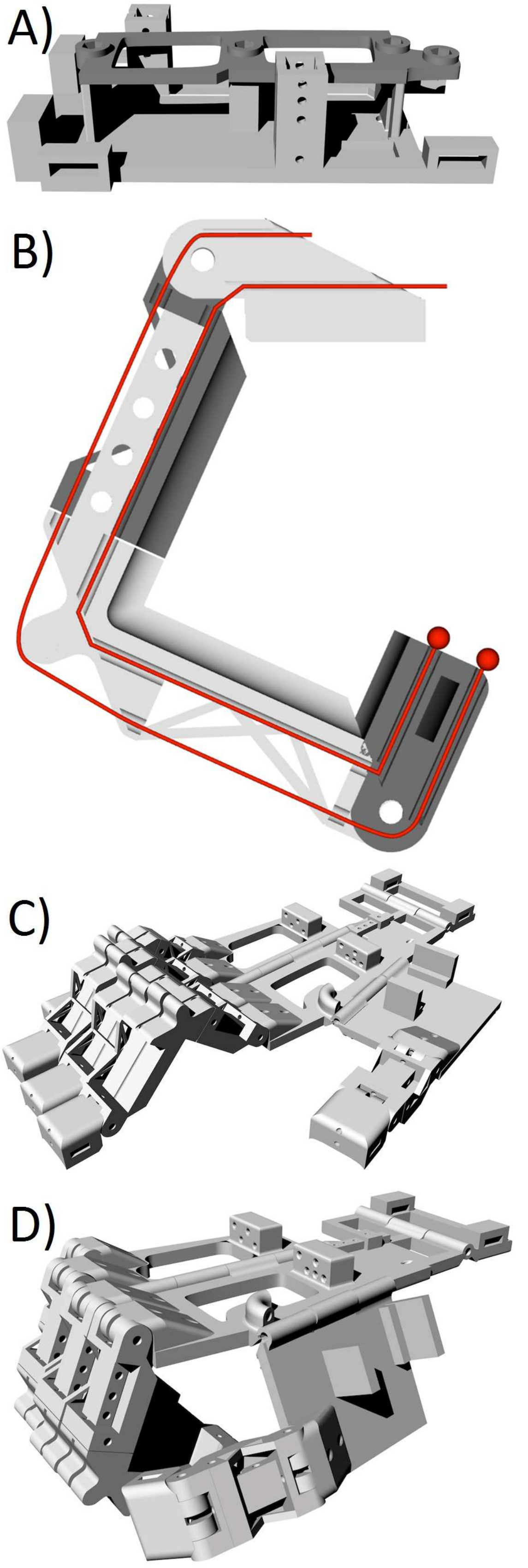

Figure 1: CAD-rendering of the exoskeleton hand. A) place for the servomotors. B) routing of the cables. C) opening position. D) closed position.

$cm^3$ based on a printing height of 155 mm. Polylactide (PLA) material was used, therefore, the preferences applied in Cura were a filament with 1.75 mm of diameter (Ingeo Biopolymer 3D850, NatureWorks, Minnetonka, USA).

For generating the force, two different types of servomotors were utilized: HiTec Hs-422 and HiTec Hs-81. Fig. 1 (A) shows the space for the servomotors. HiTec Hs-422 has higher torque (0.41 Nm) than HiTec Hs-81 (0.3 Nm), hence, Hs-422 powers two fingers at once while Hs-81 was used to move only the thumb. The torque was generated at a voltage of 4.8 V which was provided by an Arduino microcontroller to the three servomotors.The servomotors were analog, hence, they were controlled via a PWM-signal (pulse-width modulation) which was supplied by the Arduino for 6 different channels. Additionally, the Arduino and the BMI were controlled by a custom design program developed in Matlab (MathWorks, Massachusetts, USA).

The gap between the joint center and the cables amounted 5mm and the angle of the 3 finger joints for a complete closed hand was about 270° with respect to an open hand 0° (except the thumb which reached only 180°). Equation 1 represents the length of the arc or the length of the cable (b).

$$b = \pi * r * (\alpha/180^\circ) \tag{1}$$

where r is the radius in mm and $\alpha$ is the angle of the arc in degrees. With 3 mm of radius, which is the distance between the cable and the rotation axis of the joint, the total cable length is about 15 mm. Therefore, the cables are fixed at a distance of 7.5 mm to the center point of the servo axis. With this configuration, a complete movement of the servomotor is performed allowing opening and closing the hand completely.

The main advantage of mounting the cable in this way was that the pull was not uniform. The beginning and the end of the open and close hand movements were smooth, having the maximum acceleration at 90°. Furthermore, several screws and threaded rods with the associated nuts were used as axis for the joints.

The control of the hand was performed at most with the Arduino-code. This code controlled the servomotors by sending them the angle which should carried out. The variation of the movement speed was executed by changing: the delay between the increments or the size of the increment itself. The opening and closing of the hand was performed by modifying the minimum and maximum angle of a continuing movement e.g. for stopping the movement. Considering this, the minimum and maximum angle was set at the same value as the current one. As already mentioned, this exoskeleton was controlled via Matlab. Therefore, the connection was carried out by a serial port communication. Based on the EEG-signal detected, an associated number to open or close the hand exoskeleton was sent to the Arduino.

### 2.2 BMI-EXPERIMENT

The participants seated in front of a screen while their EEG signals were recorded in order to control the hand exoskeleton. The screen provided two mental tasks to perform: ‘Relax’ and ‘Imagine’. Each session consisted on 7 runs and each run had 10 ‘Relax’ and ‘Imagine’ periods. They appeared alternatively with a ‘+’ signed between every period. Each mental task period lasted between 6 and 7.4 seconds and the ‘+’ signed lasted 3 seconds. During ’Relax’ periods, subjects had concentrate in their breath and being as relaxed as possible. During ‘Imagine’ periods, they had to imagine opening and closing their hand continuously. The first 4 runs were used to train a support vector machine classifier (SVM) and the other 3 were used to test the performance of the BMI by means of the accuracy achieved.

The EEG-signals were registered with the StarstimR32 from Neuroelectronics using 30 electrodes of the 10-10 International System at a frequency rate of 500 Hz. EEG signals were processed in Matlab based on Rodriguez-Ugarte et al. [9] algorithm as described next. Signals were processed in epochs of 1 second each 0.2 epochs. The algorithm was composed by:

1. 4th order Butterworth filter: high-pass (0.05 Hz) and low-pass (45 Hz)
2. Notch filter (50 Hz)
3. Electrode selection: CZ, CP1, CP2, C1, C2, C3, C4, FC1, FC2 For each electrode selected it was computed:
    - The power at each frequency from 6 to 35 Hz (step of 1 Hz)
    - Normalization
    - Selection the frequency that represent the maximum power difference between ‘Relax’ and ‘Imagine’ state
    - Select the power at that frequency as feature

As it can be seen, in each epoch there were 9 features. One for each electrode which was the power at the frequency which represented the maximum

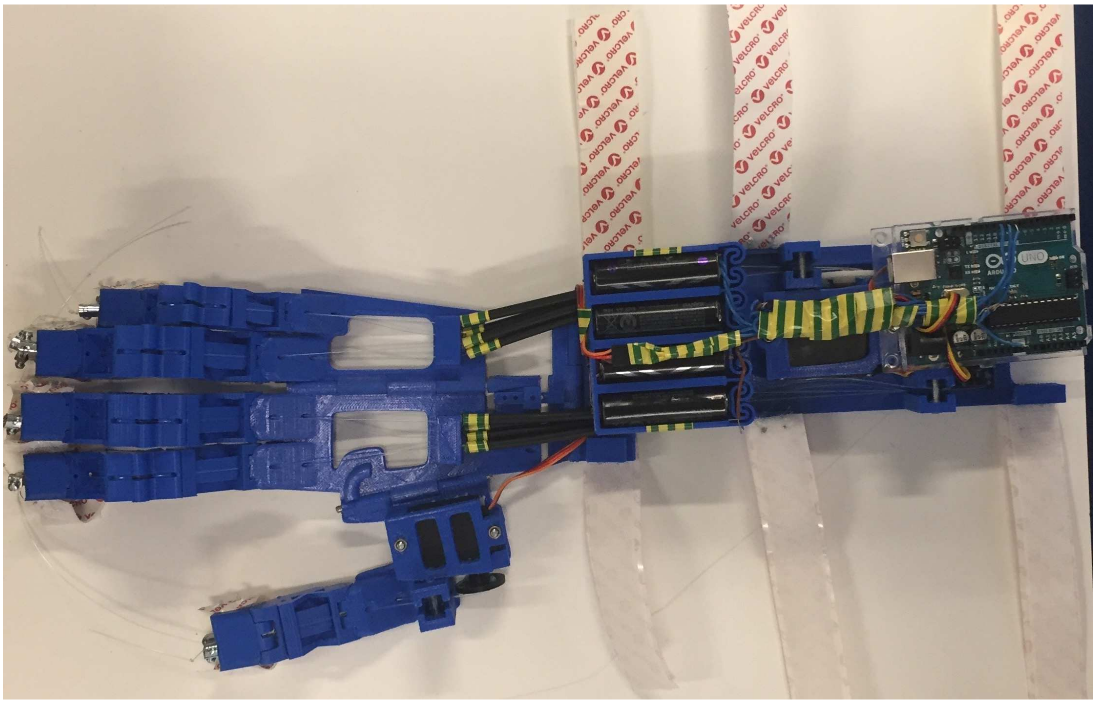

Figure 2: Real picture of the complete exoskeleton, ready to be attached.

power difference between the two mental tasks. Then, signals were classified using an SVM with radial basis function as kernel.

## 3 RESULTS

### 3.1 EXOSKELETON

Fig. 1 (C,D) shows the exoskeleton open and closed respectively. In this CAD renderings the cables are not shown. They run through the channels in the finger segments from the fingertip to the servomotors. As the servomotors were placed on the lower arm (Fig. 2), flexibility was needed between the servomotors and the hand. Hence, these cables were used as Bowden cables. Therefore, they had a plastic hull around it which was fixed on: the one end to the servomotor detent and on the blocks that were on top of the plate which was placed on the dorsum of the hand.

All printed pieces were reworked to remove the support material and small mistakes which were produced while printing. In this process, the most important aspect was to make the surface smooth to avoid injuries and to reduce the friction in the joints. Additional threads were cut into the outer part of the joints and were used to fix the axis. As the diameter of the inner part of the joint was bigger there was lower friction in comparison to the outer part. The axis could be removed with a screwdriver because this was a small slot as on normal screws. In this case, all joints were optimized for threaded rods with M3 of diameter (based on ISO 1502:1996-12).

For opening and closing the fingers, the cable length had to be changed. This was carried out by the servomotors turning their wheel. For that, first the finger had to go up to enable it. Then, the cable was pulled to shorten the length. That resulted in an open finger. For closing the finger the lower cable had to be pulled. As the length change of both cables wass the same and the movement was reverse, it was possible to attach the cables to one servomotor. Therefore, the attachments had to be on the opposite site, hence one cable was positioned at 0° and the other one at 180°. Through this configuration both cables had to be under the same tension.

### 3.2 BMI-EXPERIMENT

The function of the complete system was validated with two healthy subjects. The participants were previously informed about the experimental procedure and signed an informed consent according to the Helsinki declaration. The experimental procedure was approved by the ethics committee of the Miguel Hernández University of Elche (Spain). Both subjects carried out one session (Fig. 3). The experiments showed a well working system. During ‘Imagine’ periods, if imagination was detected, the exoskeleton hand opened or closed according to the previous state of the hand, otherwise no movement was performed. As the speed of

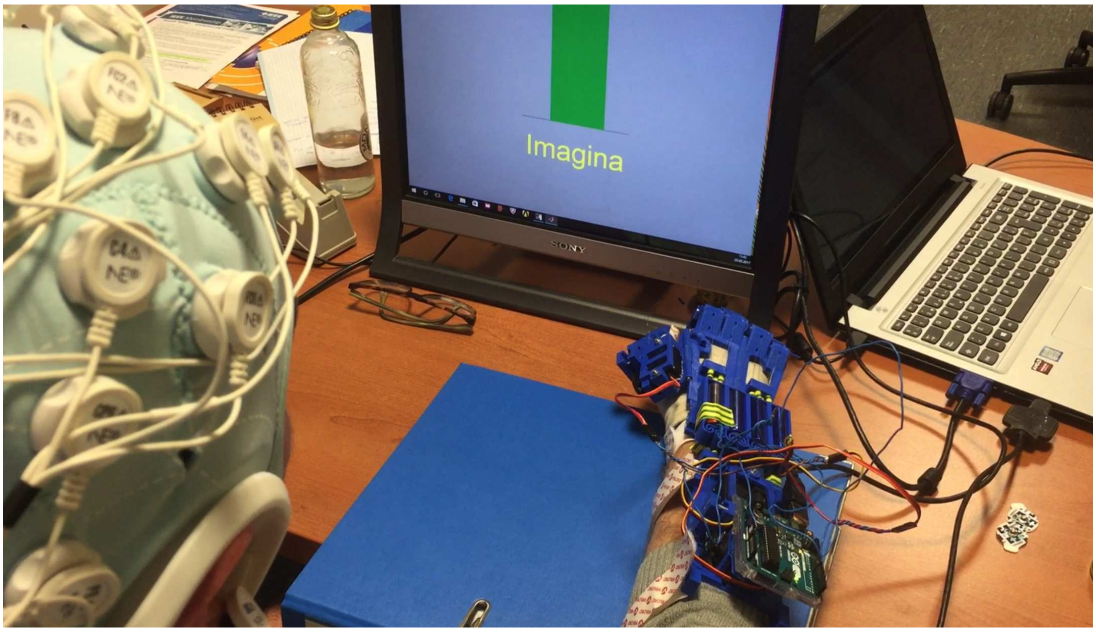

Figure 3: BMI-experiment with a healthy subject wearing the Neuroelectronics Starstim R32 cap to register brain signals. The computer on the right side recorded and analyzed the EEG signals and controlled the program, which showed the task on the screen. The exoskeleton hand was attached to the right hand.

the finger movement could be modified it was optimized for a complete movement in two seconds. This was at the same time as the '+' sign was shown on the screen. Two seconds were selected because the subject could concentrate better on the next task.

## 4 DISCUSSION AND CONCLUSION

A low-cost active hand exoskeleton was designed for future used in rehabilitation of post-stroke patients. Therefore, the exoskeleton was designed for flexion and extension of the fingers. One of the biggest advantages in comparison to other exoskeletons was the compact design of the hand, especially in the closed position. The cable used was a fishing line with 0.4 mm of diameter. Due to its small diameter and its high flexibility, it had a low friction in the routing which provided a good movement of the fingers, especially on the fingers tips. To control each finger on its own it will be necessary 5 servomotors. Because of the limited space on the lower arm three servomotors were selected for this exoskeleton. The control of the hand exoskeleton was performed by a BCI designed. However, this hand control was global instead of commanding each finger individually.

Another point to have into account was the connection of both cables between one finger and the servomotor because the length change of the cables was not exactly the same. The lower cable had a slightly smaller length change. The reason for this was that the upper cable follows the arc, but not the lower cable. It routs directly between the finger segments. Through the different cable routes, the length change had a difference of about 3mm. Thus, the cable being on the opposite to the finger position was under less tension. This implied a disadvantage during the movement because the finger could moved a little bit forward or backward. However, if the hand grabbed something or was completely open or closed this problem did not exist anymore. A possible solution for this could be a different cable routing in the joints or using more servomotors but this could lead to the same problem as above.

Two subjects tested the functioning of the complete system.Both subjects declared that the hand exoskeleton produces a natural hand movement close to a biological one. This fulfill our hypothesis. Nevertheless, two participants are not enough to validate the system for a long-time usage. That is why further experiments have to be performed. Especially, this concerns to experiments with patients who suffer from post-stroke symptoms. In addition, this exoskeleton should be used in more experiments, even with different interfaces using for example EMG signals of the upper limb muscles.

**Acknowledgments**

This work was supported by Brain-Machine Interface Systems Lab University Miguel Hernandez of Elche, Elche, Spain. C.W. thanks for financial support by the Erasmus+ Programme.

## References

[1] Barrios, L. J., Minguillon J., Perales F. J., Ron-Angevin R., Sole-Casals J., Mañanas M. A., (2017) “State of the Art in Neurotechnologies for Assistance and Rehabilitation in Spain: Support Technologies, Technology Transfer and Clinical Application”, *Revista Iberoamericana de Automática e Informática Industrial*, 14(4):355-361.

[2] Barrios, J., Hornero, R., Perez-Turiel, J., Pons, J. L., Vidal, J., Azorín, J. M., (2017) ” State of the art in neurotechnologies for assistance and rehabilitation in spain: fundamental technologies”, *Revista Iberoamericana de Automática e Informática Industrial*, 14(4), 346-354.

[3] Biggar, S. Yao, W., (2016) “Design and Evaluation of a Soft and Wearable Robotic Glove for Hand Rehabilitation”, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, pp(99):1.

[4] Fontana, M., Dettori, A., Salsedo, F., Bergamasco, M., (2009) “Mechanical design of a novel Hand Exoskeleton for accurate force displaying”, *In Robotics and Automation, 2009. ICRA ’09. IEEE International Conference on*, pp 1704–1709.

[5] Heo, P., Gwang Gu, G., Lee, S., Rhee, K., Kim, J., (2012) “Current hand exoskeleton technologies for rehabilitation and assistive engineering”, *International Journal of Precision Engineering and Manufacturing*, 13(5):807–824.

[6] Hortal, E., Planelles, D., Resquín, F., Climent , J. M., Azorín, J. M., Pons, J. L., (2015) “Using a brain-machine interface to control a hybrid upper limb exoskeleton during rehabilitation of patients with neurological conditions”, *Journal of NeuroEngineering and Rehabilitation*, 12(1):1–16.

[7] In, H., Kang, B. B., Sin, M., Cho, K.J., (2015) “Exo-Glove: A Wearable Robot for the Hand with a Soft Tendon Routing System”, *IEEE Robotics Automation Magazine*, 22(1):97–105.

[8] Mavroidis, C., Nikitczuk, J., Weinberg, B., Danaher, G., Jensen, K., Pelletier, P., Prugnarola, J., Stuart, R., Arango, R., Leahey, M., Pavone, R., Provo, A., Yasevac, D., (2005) ”Smart portable rehabilitation devices”, *Journal of NeuroEngineering and Rehabilitation*, 2(1):1–15.

[9] Rodríguez-Ugarte, M., Angulo-Sherman, N., Iáñez, E., Ortíz. M., Azorín, J.M., (2017) “Efecto de la estimulación tDCS en la corteza motora y el cerebro-cerebelo para la detección de imaginación motora del pedaleo mediante señales EEG”, *In IX edición del Congreso Iberoamericano de Tecnologías de Apoyo a la Discapacidad (IBERDISCAP).*

[10] Smaby, N., Johanson, M.E., Baker, B., Kenney, D.E., Murray, W.M., Hentz, V.R., (2004) “Identification of key pinch forces required to complete functional tasks”, *2004 Journal of Rehabilitation Research and Development.*

[11] Walsh, C.J., Paluska, D., Pasch, K., Grand, W., Valiente, A., Herr, J., (2006) “Development of a lightweight, underactuated exoskeleton for load-carrying augmentation”, *In Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, pp 3485–3491.