Assistive hand exoskeletons: The prototypes evolution at the University of Florence

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N. Secciani, M. Bianchi, A. Meschini, A. Ridolfi, Y. Volpe, L. Governi, B. Allotta

Abstract - Robotic assistance to hand-impaired people represents an as difficult as important challenge. In this context, the research work of the Department of Industrial Engineering of the University of Florence (UNIFI) led to a tailor-made wearable device for rehabilitative and assistive purposes. In this paper, the synthesis of the development process, sequentially ordered, is given.

1 Introduction

The number of wearable robotic devices has been remarkably increasing during last years. Since the hand plays a key role in everyday life, much effort has been undertaken to help people who have lost their hand dexterity [1], [2]. One of the most challenging aspect in this field is represented by the users' acceptance of the device. The authors have tackled this issue by developing a compact and tailor-made device capable of accurately following the fingers natural trajectories. In this paper, the development process of a low-cost and fully wearable hand exoskeleton is discussed. Starting from the same kinematic architecture (Section 2), three different versions of the prototype have been sequentially developed to get closer to the user's needs. Sections 3-5 will describe the main accomplishments of each version.

2 Kinematic architecture

This Section describes the mathematical model of the system kinematics which has been exploited in each version of the exoskeleton mentioned in this paper. The accurate development of a novel mechanism, characterized by a single Degree Of Freedom (DOF) per finger allowed to precisely and comfortably reproduce the complex hand kinematics without being forced to use an equally complex robotic device. The choice of a single controlled DOF has led to reduced costs, weight and encumbrance, so that the whole system (mechanism, actuation and control) can be directly placed on the back of the hand. An in-depth analysis of the kinematics of the single-DOF finger mechanism is detailed in [3]. In the following, a brief overview is reported in order to introduce the mechanism kinematics. Fig. 1 shows the 1-DOF

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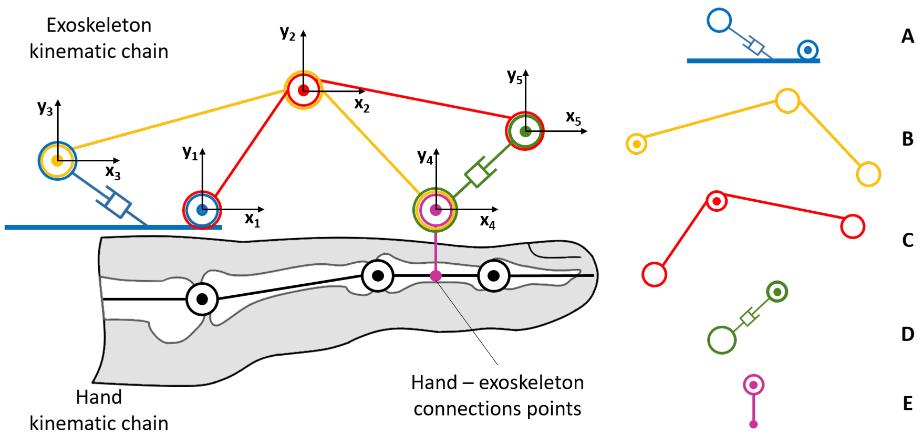

Fig. 1 Hand - exoskeleton kinematic model.

finger mechanism kinematic chain (reference systems 1-5 are respectively related to parts A-E). The forward kinematic model of the mechanism can be studied as follows:

$$\mathbf{0} = {}^{1}\mathbf{p}_2 + \mathbf{R}_2^1\,{}^{2}\mathbf{p}_1 \tag{1}$$

$${}^{1}\mathbf{p}_2 = {}^{1}\mathbf{p}_3 + \mathbf{R}_3^1\,{}^{3}\mathbf{p}_2 \tag{2}$$

$${}^{1}\mathbf{p}_4 = {}^{1}\mathbf{p}_3 + \mathbf{R}_3^1\,{}^{3}\mathbf{p}_4 \tag{3}$$

$${}^{1}\mathbf{p}_5 = {}^{1}\mathbf{p}_2 + \mathbf{R}_2^1\,{}^{2}\mathbf{p}_5 \tag{4}$$

$$a_1\,{}^{1}p_3^x + b_1\,{}^{1}p_3^y + c_1 = 0 \tag{5}$$

$$a_2\,{}^{4}p_5^x + b_2\,{}^{4}p_5^y + c_2 = 0 \tag{6}$$

where, referring to Fig. 1, the position of the origin of frame i with respect to frame j has been denoted by the vector ${}^{j}\mathbf{p}_i = \left({}^{j}p_i^x\;{}^{j}p_i^y\right)^T \in \mathbb{R}^2$ (the component on $\mathbf{z_i}$ axis has been omitted as the proposed mechanism acts on a plane), and a_1, b_1, c_1 and a_2, b_2, c_2 are respectively coefficients of Eq. 5 and Eq. 6, which represent the two linear constraints of the mechanism. Finally, $\mathbf{R}_i^j$ represents the orientation of reference system i with respect to frame j, which, in this case, results in a rotation about $\mathbf{z_i}$ axis through an angle α_i. Referring to Eq. 1-4, the state of the system is represented by the vector

$$\mathbf{q} = \left[{}^{1}\mathbf{p}_2\;{}^{1}\mathbf{p}_3\;{}^{1}\mathbf{p}_4\;{}^{1}\mathbf{p}_5\;\alpha_2\;\alpha_3\;\alpha_4\right] \in \mathbb{R}^{11} \tag{7}$$

and depends on the control variable α_2. The dependence of the state of the system by the set control variable can be obtain by solving Eq. 1-4. Details are reported in [3]. All geometrical parameters of the mechanism can then be collected in vector $\mathbf{S} \in \mathbb{R}^{14}$:

$$\mathbf{S} = \left[{}^{2}\mathbf{p}_1\;{}^{3}\mathbf{p}_2\;{}^{2}\mathbf{p}_5\;{}^{4}\mathbf{p}_3\;a_1\;b_1\;c_1\;a_2\;b_2\;c_2\right]^T, \tag{8}$$

They are all completely known and depend on the design of the exoskeleton parts. The direct kinematic model $\tilde{\mathbf{q}} = \mathbf{f}(\alpha_2, \mathbf{S}) \in \mathbb{R}^{10}$ (see Eq. 9) of the mechanism results in a function of α_2 and $\mathbf{S}$, where $\tilde{\mathbf{q}}$ is the unknown part of the state vector $\mathbf{q}$:

$$\tilde{\mathbf{q}} = \left[{}^1\mathbf{p}_2 \; {}^1\mathbf{p}_3 \; {}^1\mathbf{p}_4 \; {}^1\mathbf{p}_5 \; \alpha_3 \; \alpha_4\right]^T = \mathbf{f}(\alpha_2, \mathbf{S}). \tag{9}$$

The motion is completely defined since ${}^1\mathbf{p}_2$, ${}^1\mathbf{p}_3$, ${}^1\mathbf{p}_4$, ${}^1\mathbf{p}_5$ and ${}^1\mathbf{p}_6$ trajectories can be described with respect to the fixed reference system 1. The three mechanical solutions reported in the paper embody such a kinematic model leading, in the final version, to an adaptable and ergonomic solution for different patients' hands.

3 First prototype: manufacturability assessment

The first version of the hand exoskeleton prototype (Fig. 2, [4]), produced by the Department of Industrial Engineering of the University of Florence (DIEF), represents the first embodiment of the kinematic model reported in Section 2. A patient affected by Spinal Muscular Atrophy (SMA) was the first user of the device, specifically developed for him.

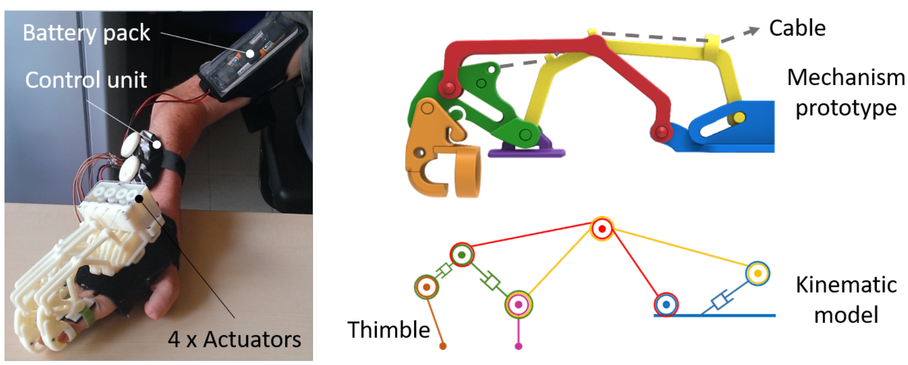

Fig. 2 First version of the exoskeleton prototype by the DIEF.

3.1 Mechanical design

This prototype has been primarily designed to test the manufacturability of the developed kinematic chain discussed in Section 2. All the mechanical parts have been 3D-printed in a thermoplastic polymer, Acrylonitrile Butadiene Styrene (ABS), since it represents a satisfying trade-off between good mechanical characteristics and low weight. The embodiment of the 1-DOF mechanism required several manufacturing choices (Fig. 2) leading to a real and practically manifacturable mechanical solution. In particular, referring to Fig. 1, component E, which represents the hand-exoskeleton interface, has been design to wrap only the back side of the finger phalanx not to reduce the sense of touch, while a Velcro held the finger tight achieving a solid connection. Also the distal phalanx was then connected to the mechanism through a idler thimble. Finally, the shapes of all the components have been modified to avoid contact with the finger during hand closure. A customization of the mechanism allowed to overall adapt the kinematic model to each patient's finger. Starting from a 2-D hand trajectories acquisition of the intermediate phalanges (performed exploiting open source Kinovea software), an optimization MATLAB-based algorithm minimized a constrained nonlinear multi-variable function [5] modifying the geometrical parameters and leading the mechanism to fit the acquired trajectories. The goodness of the solution of this first optimization algorithm was strongly dependable on the initial state, resulting in a low adaptability of the system when it was far from the first tentative shape.

3.2 Electronics and control

Since the whole system has been thought and developed under a low-cost concept, many solutions that could be found in the state of the art have been avoided due to their high costs. The reduction of the total mass, which was (and still is) one of the main requirements of the device, has led to the choice of high power density actuators to be directly mounted on the back of the hand. Four Savox SH-0254 servomotors, one per long finger, have been selected for their characteristics. These motors have been modified to allow for the continuous rotation of the shaft despite the resulting loss of position feedbacks. The control unit was based on a 6-channels MicroMaestro control board which has been chosen for its cheapness, its lightness, its small dimensions and because its six channel matched the number of external devices that had to be connected to the board: the aforementioned four servomotors and two buttons, one for opening and one for closure triggering action. The control unit and the actuators were powered by a compact 4-cell Lithium battery (@6.0 V). Regarding the control strategy, the system was controlled by a simple script, stored and running directly on the MicroMaestro chip-set. The code had to continuously check for one of the two buttons to be pushed and held down and then react by sending the corresponding command to the actuators. The bounds of the exoskeleton range of motion were manually managed by the user (keeping pushed or releasing the buttons) in order not to overcome their anatomical limits. All the long fingers were moved together.

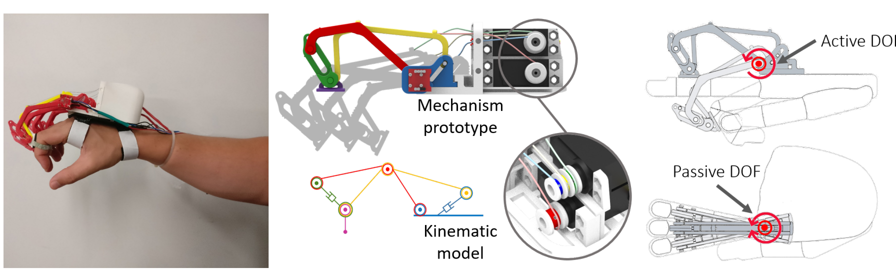

Fig. 3 Second version of the exoskeleton prototype by the DIEF.

4 Second prototype: ergonomic improvements

The second prototype was developed aiming to go beyond the limits of the first exoskeleton. Thanks to the experience gained during the testing phase of the former device, several modifications yielded a more lightweight and wearable system, fully adaptable to different users.

4.1 Mechanical design

This new version of the device presented important improvements. Firstly, the mechanical architecture of the finger mechanism was modified: according to user's feedback, the thimble has been removed to allow for objects grasping without tactile hindrance. An additional (passive) DOF was then added upstream of each finger mechanism to allow for the natural ab/adduction. In fact, when the exoskeleton structures replicate limb kinematics, rigid connections with the body may lead to a reduced mobility. In this case, ab/adduction movements resulted in a misalignment between the finger and the exoskeleton avoiding the mechanism to properly act on the hand. The introduction of the rotational passive joint allowed to act only on the finger flex/extension plane, passively following the finger ab/adduction gestures. Another important change was represented by the reduction of the number of motors from four to two (one for the index finger and one for the other three long fingers). Through the design of a particular pulley with three different diameters (highlighted in the central particular of Fig. 3), it was possible to actuate middle, ring and small finger mechanisms (which demand for different velocities) at the same time with the same motor. A totally new optimization-based strategy was finally developed: a Nelder-Mead based optimization algorithm has been used [6] achieving a straightforward adaptability to several users. Taking acquisition data (collected exploiting a BTS SMART-Suite MoCap System by BTS Bioengineering) and the kinematics of the mechanism as inputs, the implemented algorithm provides a customized geometry specific for each patient.

4.2 Electronics and control

The second version of the hand exoskeleton presented an electronics and a control strategy deeply modified and updated to solve some crucial problems highlighted by the tests conducted on the previous prototype. An issue that has immediately showed up was the high difficulty to prevent the four motors from acquiring more and more relative phase shift with the prolonged use. The number of motors has been halved and one motor has been connected to the index and the other one to the remaining fingers to mitigate this problem. The new performance required to the actuators were not reached by those presented in Subsec. 3.2 and they have been then replaced with HS-5495BH High-Torque Servo from Hitec. The actuators have been modified, as the previous one, to allow for a continuous rotation and a specific driver has been added to them. The Supermodified V3.0 for RC-servos from 01™Mechatronics consists of a DC motor controller and a 15-bit magnetic encoder and its exploitation has also allowed to overcome another problem: the lack of fingers' position and velocity feedback. These drivers have been, in fact, placed also on the knuckle joints of the index and little finger and their embedded magnetic encoder has been used to have continuous feedback on the state of the fingers, which was not available with the previous prototype. Another problem concerned the grasping of objects: without any information about the fingers' position or angular velocity, it was very hard for the user to stop pushing the close button as soon as an object was grasped. Being the fingers unable to close further because of the presence of the object and being the motors still running (even if for a very short time), the cable ended up coming out of the pulley seats and it twisted, making necessary an external intervention to rearm the transmission system. The new information provided by the Supermodified V3.0 has allowed for checking whether an object was grasped or the hand was moving freely. The basic idea for the new control loop was that the length of the released actuation cable, calculated both from the geometry equations of the mechanism for every configuration and from motors' data (i.e. angular velocity, pulley radius and running time), had to be the same if the hand was closing freely. When the difference between this two lengths overcame a fixed threshold it meant that the motors were still releasing cable while the hand was not further closing and, that is, an object was likely grasped. The new control code, including checking for a grasped object and for the reached limits of the range of motion, needed a more powerful processor to be run and a bigger flash memory to be stored. Hence an Arduino Nano has been chosen to be the embedded micro-controller of the system. This board offered the same ease of control of servomotors with improved performance, while still remaining a very cheap and small controller.

5 Final prototype: user-based control strategy

This current version of the exoskeleton is represented by fully portable, wearable and highly customizable device that can be used both as an assistive hand exoskeleton and as a rehabilitative one. Both mechatronic design and control system are developed basing on the patients needs in order to satisfy users' daily requirements increasing their social interaction capabilities.

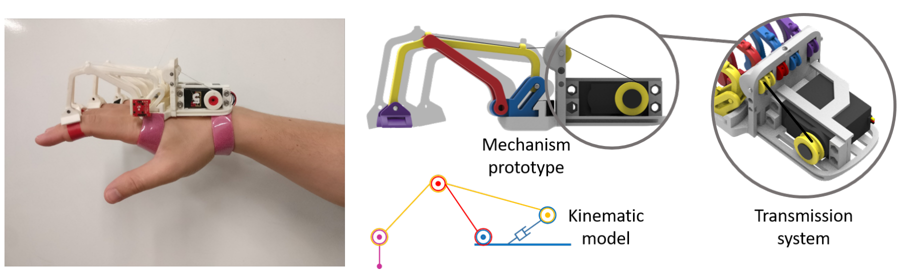

Fig. 4 Final version of the exoskeleton prototype by the DIEF.

5.1 Mechanical design

The mechanics of this last exoskeleton has been revamped to achieve a more lightweight solution and to improve its wearability without influencing the obtained results in terms of accuracy in replicating hand gestures. The new system is now actuated by a single servomotor and a specific cable driven transmission system has been developed to open all the four long fingers together at the same time. Different mechanisms velocities are obtained thanks to different pulleys diameters, which are calculated depending on users' fingers dimensions. The mechanism kinematic architecture is further modified by eliminating component D of Fig. 1.

5.2 Electronics and control

The first important difference with respect to the previous system is that, as reported in Section 5, another motor has been removed. The motor model has not been changed, however the exploitation of just one actuator has brought with it some advantages: the total weight of the system has been remarkably reduced, the phenomenon of the phase shift has definitely disappeared and, finally, the control code results to be computationally lighter, not having to manage the coordination between motors. Another difference concerns instead the triggering system. Tests conducted on the second version of the prototype have stressed the importance for the user of being able to use both hands independently. For this reason the buttons-based triggering action had to be replaced with something which could allow for an autonomous control of each hand. An ElectroMyoGraphy (EMG)-based control system has been implemented following the most recent research trends in literature [7], [8]. Two MyoWare™Muscle Sensors (AT-04-001) from Advancer Technologies have been chosen for collecting EMG signals from the exoskeleton user's forearm muscles. Since the human hand can perform lots of different gestures and the corresponding muscles are very close to each other, a precise classification of every user intention usually requires the use of workstations, which is definitely far away from the idea of cheapness and wearability this project is based on. Hand opening, hand closing and hand resting have then been considered as the only possible users intentions to be classified, as they represent the basic hand motions for the Activities of Daily Living (ADLs). The classification phase is carried out by means of a ray-casting to the right algorithm called "Point-in-Polygon algorithm". This classifier is tuned during a preliminary training phase through a custom Qt Graphical User Interface (GUI) developed by the authors. It is a user-friendly tool which allows for collecting EMG signals and for displaying them on a 2D Cartesian plane, whose axis report respectively data from the first and the second sensor. Once the EMG data has been collected for all the three aforementioned gestures, it is possible to manually draw the geometric figures which delimit the data corresponding to the same gesture.

6 Conclusions

The paper describes the process which has led the researchers of the Department of Industrial Engineering of the University of Florence to develop a low-cost and fully wearable prototype of hand exoskeleton for assistive and rehabilitative purposes. Starting from a detailed study of the kinematics of a 1-DOF finger mechanism, which has been used as reference, three versions of the exoskeleton are presented in sequential order of realization. Changes and improvements have been made basing on the results of several intermediate tests, and users' feedbacks, allowing to embody the kinematic model each step closer to the patients' needs. The final prototype currently is at the heart of a new project funded by the University of Florence. Aims and future developments of this project, whose title is HOLD (Hand exoskeleton system, for rehabilitation and activities Of daily Living, specifically Designed on the patient anatomy), are a further improvement of the device ergonomics and usability, and the execution of a proper clinical trial with different patients.

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References

1. P. Heo, G. Gu, S.-J. Lee, K. Rhee, and K. J., "Current hand exoskeleton technologies for rehabilitation and assistive engineering," *International Journal of Precision Engineering and Manufacturing*, vol. 13, no. 5, pp. 807–824, May 2012.
2. M. Troncossi, M. Mozaffari-Foumashi, and V. Parenti-Castelli, "An original classification of rehabilitation hand exoskeletons," *Journal of Robotics and Mechanical Engineering Research*, vol. 1, no. 4, pp. 17–29, 2016.
3. R. Conti, E. Meli, A. Ridolfi, M. Bianchi, L. Governi, Y. Volpe, and B. Allotta, "Kinematic synthesis and testing of a new portable hand exoskeleton," *Meccanica*, 2017.
4. B. Allotta, R. Conti, L. Governi, E. Meli, A. Ridolfi, and Y. Volpe, "Development and experimental testing of a portable hand exoskeleton," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept 2015, pp. 5339–5344.
5. R. H. Byrd, J. C. Gilbert, and J. Nocedal, "A trust region method based on interior point techniques for nonlinear programming," *Mathematical Programming*, vol. 89, no. 1, pp. 149–185, Nov 2000. [Online]. Available: https://doi.org/10.1007/PL00011391
6. M. Bianchi, F. Fanelli, L. Giordani, A. Ridolfi, F. Vannetti, and B. Allotta, "An automatic scaling procedure for a wearable and portable hand exoskeleton," in *2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI)*, Sept 2016, pp. 1–5.
7. J. Lobo-Prat, P. N. Kooren, A. H. Stienen, J. L. Herder, B. F. Koopman, and P. H. Veltink, "Non-invasive control interfaces for intention detection in active movement-assistive devices," *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. 1, p. 168, Dec 2014. [Online]. Available: https://doi.org/10.1186/1743-0003-11-168
8. A. A. Adewuyi, L. J. Hargrove, and T. A. Kuiken, "Evaluating emg feature and classifier selection for application to partial-hand prosthesis control," *Frontiers in Neurorobotics*, vol. 10, p. 15, 2016. [Online]. Available: https://www.frontiersin.org/article/10.3389/fnbot.2016.00015