

A Hand Exoskeleton with Flexion and Abduction Motion

Marco Fava, Vincenzo Parenti-Castelli, Ming Jiang, Yukio Takeda, and Nicola Sancisi

Abstract Strokes and other spinal cord disorders cause the loss of mobility in the hand fingers. The main impairments are flexion-extension and ab-adduction movements. While the first is always considered during the development of assistive devices such as hand exoskeletons, only a few solutions consider the ab-adduction movements. An new wearable, affordable and lightweight solution is presented, with a low number of degrees of freedom, which eases the mechanical design. It combines a multi-loop mechanism to drive the flexion-extension and ab-adduction of the proximal phalanges. The position analysis is presented to evaluate the decoupling between the two motions. Finally, an exoskeleton prototype is introduced to demonstrate the feasibility of the conceptual design.

M. Fava

University of Bologna, Department of Industrial Engineering. Viale del Risorgimento 2, 40136 - Bologna, Italy

V. Parenti-Castelli

University of Bologna, Department of Industrial Engineering. Viale del Risorgimento 2, 40136 - Bologna, Italy

M. Jiang

Institute of Science Tokyo, Department of Mechanical Engineering. 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

Y. Takeda

Institute of Science Tokyo, Department of Mechanical Engineering. 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

e-mail: takeda.y.2c40@m.isct.ac.jp

N. Sancisi

University of Bologna, Department of Industrial Engineering. Viale del Risorgimento 2, 40136 - Bologna, Italy

e-mail: nicola.sancisi@unibo.it

1 Introduction

Strokes and pathologies such as myelopathy [7] and hand-arm vibration syndrome [6] impair finger mobility in 60% of cases, affecting abduction-adduction and flexion-extension movements. Hand exoskeletons are devices mounted on the fingers that assist finger movements with external forces, thereby enhancing blood flow and nerve recovery, helping the user fully perform activities of daily living (ADL), such as grasping an object with sufficient strength, typing properly, etc. They can also be used in rehabilitation procedures to restore full mobility.

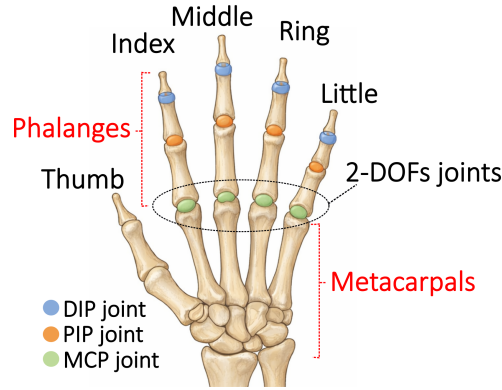


Fig. 1: Hand schematisation (modified from [10]).

Many different types of hand exoskeletons have been proposed [9], featuring rigid or compliant joints, or even jointless solutions [1, 4]. The latter are exoskeletons that use anatomical joints as exoskeleton joints, and are typical of soft robotics. Jointless solutions are generally lighter but rely on the patient's joints for guidance and load resistance. Referring to Figure 1, the Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints can be considered revolute joints that connect proximal, middle, and distal phalanges; Metacarpophalangeal (MCP) joints can be schematised with a Universal joint, and can perform ab-adduction (a-a) and flexion-extension (f-e) motion. However, most existing hand exoskeletons assist only f-e, and only a few solutions also include a-a, generally increasing mechanical complexity, although its importance for full recovery [3–5, 8]. Simple designs that can support all degrees of freedom (DOFs) of the fingers are crucial. In this context, an innovative hybrid exoskeleton solution that combines rigid and jointless mechanisms to perform f-e and a-a motions is presented for the index, middle, ring, and little finger. The rigid part helps to preserve and guide the patient's joints, while the jointless part reduces weight. The new solution drives the distal and middle phalanges via a jointless cable-driven mechanism, while the proximal phalanges are

driven by a rigid exoskeleton. The rigid part is presented in detail below, while the jointless part and the whole exoskeleton will be addressed in future works.

2 Rigid Exoskeleton Design

The exoskeleton rigid part moves the proximal phalanges in f-e and a-a motions. Rigid elements connected by mechanical joints are located on the hand dorsum and on the upper part of the proximal phalanges. The rigid mechanism is composed of multiple spatial 4-link mechanisms and additional chains that connect them (see Fig. 2). The generic spatial 4-link mechanism is composed of URSU joints (U = Universal joint; R = Revolute joint; S = Spherical joint). The last U corresponds to the MCP joint, which connects the proximal phalanx to the body of the hand. The middle finger is assumed to be unable to perform a-a motion, which is very limited while performing ADL activities [2]. On this finger, the linked mechanism becomes planar; thus, its URSU mechanism transitions to an RRRR mechanism. The initial posture is defined as the hand resting flat on a table, with the fingers fully adducted and the middle finger aligned with the forearm. In order to simplify the mathematical expressions of the mechanism position analysis presented in section 3, without losing generality, the exoskeleton geometry represented in Figure 2 has been chosen.

Since all the finger kinematic chains are topologically the same (except the middle finger one), the analysis will be focused on the part of the exoskeleton involving the middle and index fingers. A kinematic scheme of this part is represented in Figure 3. Rigid links 1 (hand dorsum), 2, and 3 are connected to the proximal phalanx of the middle finger (link 4), defining the RRRR mechanism. Rigid links 1, 7, and 8 are connected to the proximal phalanx of the index finger (link 9), defining the URSU mechanism. The additional connecting chain of the fingers mechanisms is composed of rigid links 5 and 6, connected by an S joint, and respectively connected to links 2 and 7 by P (= Prismatic) joints. The overall mechanism has 2 DOFs, driven by the rotation of link 2 (θ_2) and the translation of link 5 relative to link 2 (d_{25}). The former produces f-e, while the latter produces a-a. However, these two DOFs are associated with coupled secondary motions: flexion generates a-a motion, and vice versa, in the index and the other fingers.

3 Kinematic Position Analysis

To quantify the coupling between f-e and a-a, the position analysis of the mechanism shown in Figure 3 has been conducted, though this could be extended to consider the other loops too. Velocity analysis, or the study of the Jacobian, which is also useful for force transmission, was also performed. However, since it is not essential in this type of system, it is not reported due to space constraints. In short, with the con-

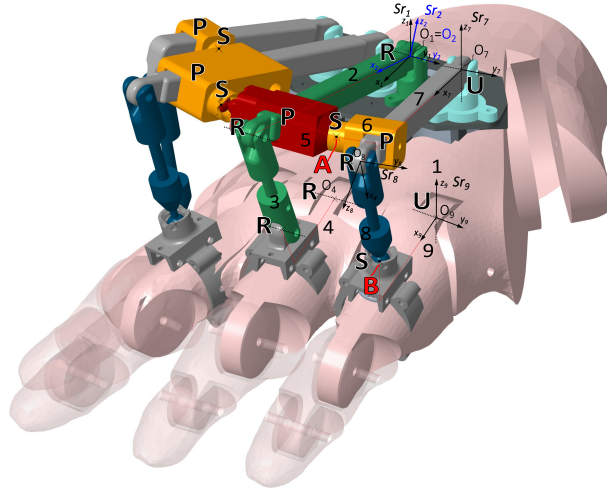


Fig. 2: Exoskeleton CAD model showing the joint locations.

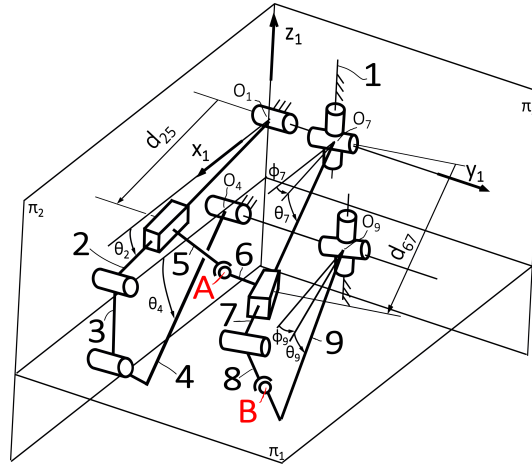


Fig. 3: Schematic of the exoskeleton involving the proximal phalanges of the middle (links 1,2,3,4) and the index (1,7,8,9) fingers, connected by the chain PSP (links 5,6).

figuration used, there are no singularities or critical conditions in the mechanism's operating range. In the present case, the mechanism shows three closed loops: one is a planar four-bar mechanism of type RRRR, involving the rigid links 1, 2, 3, and 4, that is, the geometrical representation of the middle finger proximal phalanx. This loop has one DOF. The second loop is a spatial five-bar mechanism of type RPSPU, involving the rigid links 1, 2, 5, 6, and 7 of the exoskeleton. The loop has two DOFs. The third loop is a spatial four-bar mechanism of type URSU that involves the rigid links 1, 7, 8, and 9, representing the index proximal phalanx. The overall mecha-

nism of Figure 3, considering link 1 as the frame (hand dorsum), has two DOFs. To control the mechanism motion, the angle θ_2 for f-e, and the linear position d_{25} for a-a as been chosen. The variable d_{25} has been chosen to lower the risk of motion locking. However, θ_2 also induces a-a of the index (ϕ_9), and d_{25} also induces f-e (θ_9) of the index. At this stage, no optimization was performed to reduce this coupling, but the kinematic position analysis was used to quantify it: if d_{25} is fixed and θ_2 varies, complete decoupling would imply ϕ_9 is constant; similarly, if θ_2 is fixed and d_{25} varies, θ_9 should be constant. The kinematic position analysis of the whole system is performed by sequentially solving the first, second, and third loops.

3.1 Kinematic position analysis of Loop 1

With reference to Figure 3, the plane π_1 is parallel to the horizontal plane of the hand-rest position and passes through the center O_4 which simulates the joint between the proximal phalanx of the middle finger and the dorsum. The plane π_2 is orthogonal to π_1 and passes through the axis of the middle finger. The plane π_3 is orthogonal to π_1 and passes through the center O_1 of the revolute pair between links 1 and 2. A Cartesian reference frame Sr_1 , (O_1 , x_1 , y_1 , z_1), embedded in link 1 is defined: the intersection of π_2 and π_3 defines the z_1 axis with direction upward, the direction of the revolute pair between links 1 and 2 defines the direction of the y_1 axis, while the x_1 axis is defined according to the right-hand rule.

The position analysis of the Loop 1, i.e., of the planar RRRR mechanism, is well known, so it will not be reported here in detail; only the results will be used, namely the corresponding values of the angles θ_2 and θ_4 , being θ_2 the angle between link 2 and the positive x_1 axis, and θ_4 the angle between link 4 and the positive x_1 axis, both measured counterclockwise.

3.2 Kinematic position analysis of Loop 2

Cartesian reference systems Sr_2 and Sr_7 are embedded in links 2 and 7 respectively as shown in Figure 2. Given the values of θ_2 and d_{25} , the position analysis of the RPSPU mechanism will return the values of θ_7 and ϕ_7 . Considering the reference frame Sr_1 , the angle θ_7 is the angle between link 7 and the positive x_1 - y_1 plane (parallel to π_1), while ϕ_7 is the angle between link 7 and the positive x_1 - z_1 plane (π_2). Let A be the center of S between 5 and 6. The closure equation of Loop 2 can be written by imposing that the coordinates of A with respect to Sr_1 are the same as those evaluated using the subchain of links 1, 2, 5 and the subchain of links 1, 7, 6, which leads to the following three equations in the three unknowns θ_7 , ϕ_7 , d_{67} , the latter being the position of 6 with respect to link 7:

$$\begin{pmatrix} d_{25} \cos \theta_2 - L_6 \sin \phi_7 - x_7 - d_{67} \cos \phi_7 \cos \theta_7 \\ L_5 - y_7 + L_6 \cos \phi_7 - d_{67} \cos \theta_7 \sin \phi_7 \\ d_{67} \sin \theta_7 - d_{25} \sin \theta_2 - z_7 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad (1)$$

obtained by:

$${}^2_1\mathbf{M} \begin{pmatrix} {}^2\mathbf{A} \\ 1 \end{pmatrix} - {}^7_1\mathbf{M} \begin{pmatrix} {}^7\mathbf{A} \\ 1 \end{pmatrix} = \mathbf{0} \quad (2)$$

where ${}^2_1\mathbf{M}$ and ${}^7_1\mathbf{M}$ are the homogenous transformations from Sr_2 to Sr_1 and from Sr_7 to Sr_1 respectively. ${}^2\mathbf{A}$ and ${}^7\mathbf{A}$ are the coordinates of A with respect to the local reference frame Sr_2 and Sr_7 . ${}^2\mathbf{A} = (d_{25} \ L_5 \ 0)^T$ and ${}^7\mathbf{A} = (d_{67} \ -L_6 \ 0)^T$. ${}^2_1\mathbf{M}$ and ${}^7_1\mathbf{M}$ are built as:

$${}^2_1\mathbf{M} = \begin{bmatrix} {}^2_1\mathbf{R} & \mathbf{0} \\ 0 & 0 & 0 & 1 \end{bmatrix}; \quad (3)$$

$${}^7_1\mathbf{M} = \begin{bmatrix} {}^7_1\mathbf{R} & \mathbf{O}_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

and ${}^2_1\mathbf{R}$ and ${}^7_1\mathbf{R}$ are the rotation matrices to pass from Sr_2 to Sr_1 (rotation of θ_2) and from Sr_7 to Sr_1 (rotation of ϕ_7 and θ_7) respectively. $\mathbf{O}_7$ are the coordinates of the origin of the reference frame Sr_7 with respect to Sr_1 : $\mathbf{O}_7 = (x_7 \ y_7 \ z_7)^T$.

3.3 Kinematic position analysis of Loop 3

Cartesian reference systems Sr_8 and Sr_9 are embedded in links 8 and 9 respectively as shown in Figure 2. Given θ_7 and ϕ_7 , Loop 3 analysis provides the angles θ_9 and ϕ_9 , i.e., the direction of the proximal phalanx of the index finger, relative to Sr_1 . Considering the reference frame Sr_1 , the angle θ_9 is the angle between link 9 and the positive x_1 - y_1 plane (parallel to π_1), while ϕ_9 is the angle between link 9 and the positive x_1 - z_1 plane (π_2). Let B be the center of S between 8 and 9. Similarly to what was done for Loop 2, the closure equation of Loop 3 can be written by imposing that the coordinates of B with respect to Sr_1 are the same as those evaluated using the subchain of links 1, 7, 8 and the subchain of links 1, 9, which leads to the following three equations in the three unknowns θ_9 , ϕ_9 , θ_8 , the latter being the angular position of 7 with respect to 8:

$$\begin{pmatrix} (x_7 - x_9) + \cos \phi_7 (L_7 \cos \theta_7 + L_8 \cos(\theta_7 + \theta_8)) + \sin \phi_7 (y_B \cos \theta_9 + z_B \sin \theta_9) - x_C \cos \phi_9 \\ (y_7 - y_9) + \sin \phi_7 (L_7 \cos \theta_7 + L_8 \cos(\theta_7 + \theta_8)) - \cos \phi_7 (y_B \cos \theta_9 + z_B \sin \theta_9) - x_C \sin \phi_9 \\ (z_7 - z_9) - (L_7 \sin \theta_7 + L_8 \sin(\theta_7 + \theta_8)) + y_B \sin \theta_9 - z_B \cos \theta_9 \end{pmatrix} = \mathbf{0} \quad (5)$$

obtained by:

$${}^8_1\mathbf{M} \begin{pmatrix} {}^8\mathbf{B} \\ 1 \end{pmatrix} - {}^9_1\mathbf{M} \begin{pmatrix} {}^9\mathbf{B} \\ 1 \end{pmatrix} = \mathbf{0} \quad (6)$$

where ${}^8\mathbf{M}$ and ${}^9\mathbf{M}$ are the homogenous transformations from Sr_8 to Sr_1 and from Sr_9 to Sr_1 obtained according to the subchains above. ${}^8\mathbf{B}$ and ${}^9\mathbf{B}$ are the coordinates of B with respect to the local reference frame Sr_8 and Sr_9 respectively; ${}^8\mathbf{B} = (L_8 \ 0 \ 0)^T$ and ${}^9\mathbf{B} = (x_B \ y_B \ z_B)^T$. The matrices ${}^8\mathbf{M}$ and ${}^9\mathbf{M}$ are built as:

$${}^8\mathbf{M} = {}^7\mathbf{M} {}^8\mathbf{M} = \begin{bmatrix} {}^7\mathbf{R} & \mathbf{O}_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} {}^8\mathbf{R} & \mathbf{O}_8 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$${}^9\mathbf{M} = \begin{bmatrix} {}^9\mathbf{R} & \mathbf{O}_9 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

and ${}^7\mathbf{R}$, ${}^8\mathbf{R}$, and ${}^9\mathbf{R}$ are the rotation matrices to pass from Sr_7 to Sr_1 (rotation of ϕ_7 and θ_7), from Sr_8 to Sr_7 (rotation of θ_8), and from Sr_9 to Sr_1 (rotation of ϕ_9 and θ_9) respectively. $\mathbf{O}_7$ is described above (see section 3.2). $\mathbf{O}_8$ and $\mathbf{O}_9$ are the coordinates of the origins of the reference frames Sr_8 with respect to Sr_7 , and of Sr_9 with respect to Sr_1 respectively; $\mathbf{O}_8 = (L_7 \ 0 \ 0)^T$ and $\mathbf{O}_9 = (x_9 \ y_9 \ z_9)^T$.

4 Results

The exoskeleton geometry was defined by minimizing the size in z direction of Sr_1 while maintaining the fingers' f-e and a-a ranges for a generic male hand. This geometry allows 90° of flexion and about 27° of abduction. In particular, for the Loop 1, the lengths of links 2, 3, and 4 are $L_2 = 85$ mm, and $L_3 = 40$ mm, and $L_4 = 36$ mm, respectively. The link 1 length is determined by the coordinates of $\mathbf{O}_4$ with respect to Sr_1 , that are $\mathbf{O}_4 = (40 \ 0 \ -29)^T$ mm; for the Loop 2, the coordinates of A with respect to Sr_2 and Sr_7 , respectively, are ${}^2\mathbf{A} = (d_{25} \ 18.5 \ 0)^T$ and ${}^7\mathbf{A} = (d_{67} \ 9.75 \ 0)^T$ where d_{25} varies from 75 to 40 with 5 mm step, and the coordinates of $\mathbf{O}_7$ are $(0 \ 15 \ 0)^T$; for the Loop 3, the length of link 7 is $L_7 = L_2$, the coordinates of B with respect to Sr_9 and Sr_8 are respectively ${}^9\mathbf{B} = (30 \ 0 \ 20)^T$ and ${}^8\mathbf{B} = (40 \ 0 \ 0)^T$ mm (with $L_8 = L_3 = 40$ mm).

The most interesting cases for coupling analysis are when $\theta_4 = 0$ and d_{25} is varied, thus performing abduction, and when d_{25} is held at its maximum value, so the initial ϕ_9 is at its minimum, and the flexion is performed. Figure 4a shows θ_9 changes when d_{25} is varied. In this case, the coupled flexion θ_9 is lower than 0.5° with an achieved abduction (ϕ_9) lower than 17° , and reaches its maximum (1°) when ϕ_9 is at its maximum value (27°). Similar results are obtained for different values of θ_4 : the variation in θ_9 remains under 1° .

Similarly, if link 5 is fixed at a specific position d_{25} , and θ_4 is varied, ϕ_9 varies from approximately 1.2° for flexion of 65° , up to 3.2° for a flexion of 90° (see Fig.4b). For different values of d_{25} , the maximum variation of ϕ_9 is still approximately 3° , but occurs at different flexion angles. The coupling has been judged low for this solution. Thus, based on the positive results, a prototype was built to demonstrate the feasibility of the conceptual design, consisting of 3D-printed components,

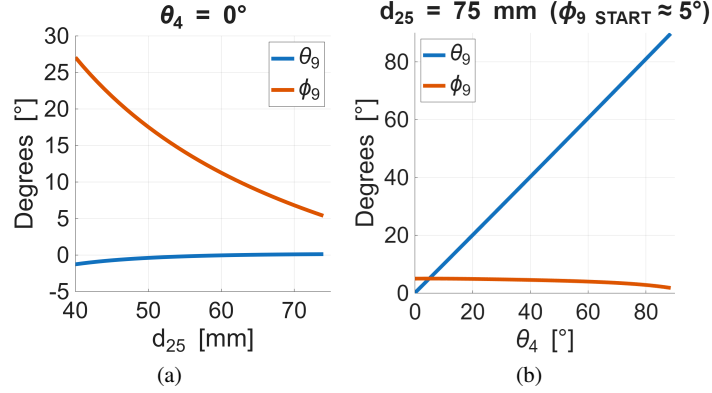


Fig. 4: Kinematic position analysis: abduction motion while θ_4 is a constant (a), flexion motion while d_{25} is in its maximum value, i.e. the initial value of ϕ_9 is minimum (b).

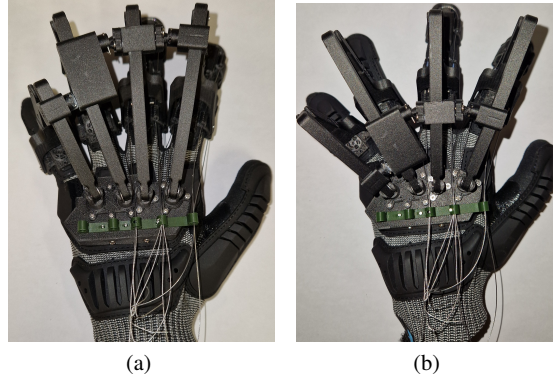


Fig. 5: Prototype top view: adducted position (a), abducted position (b).

dowel pins, and steel balls to fabricate the joints. It was built on a reinforced glove and tested on an articulated fake hand (see Fig. 5).

5 Conclusions

This work introduced the importance of addressing both flexion-extension and abduction-adduction in the design of hand exoskeletons for post-stroke and post-spinal cord injury rehabilitation and activities of daily living. A simple mechanical solution that provides support for all necessary movements to facilitate effective hand recovery was presented. It is composed of a jointless and a rigid part. The former was not addressed in this work, whereas the latter was analysed using kine-

matic position analysis, enabling a comprehensive study of its behaviour and movement capabilities. Although promising, the proposed solution can still be improved. In particular, it shows minimal, negligible coupling between flexion and abduction when performed individually. The kinematic study will be extended to all fingers of the hand, and the exoskeleton's geometry will be optimised to minimise movement coupling. A prototype of this exoskeleton has been built, and its evaluation in real rehabilitation scenarios will be the subject of future work.

Acknowledgements The contribution of MUR through Next Generation EU - PNRR funding is gratefully acknowledged. The study has been co-funded by Tech Srl, Villanova di Castenaso (Bologna).

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