Motion Evaluation of a Finger Exoskeleton for Rehabilitation

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Abstract. Stroke is responsible for a large number of injured limbs. The hand is of major importance for activities of daily living and any malfunction can result in difficulties to handle the simplest tasks. Current clinical strategies are still not close to fully restoring patients' limbs. During the past decades, several devices have been developed to assist in hand rehabilitation, although only a few are designed for finger rehabilitation. A prototype of a finger exoskeleton with one cable-actuated degree of freedom was developed. There are two different assemblies for the exoskeleton. In order to evaluate the device, the workspace and resulting angles of the fingertip, distal and proximal interphalangeal joints with respect to the metacarpophalangeal joint during free index finger flexion were com-pared to the same movements when the finger was actuated by the exoskeleton. Results showed that the device is capable to achieve more than 70% of free hand fingertip workspace during flexion.

Keywords: Exoskeleton · Rehabilitation · Soft-actuation

1 Introduction

Stroke is one of the leading causes of death worldwide. In 2010, there were 33 million events, which was responsible for 11.8% of total deaths in 2013. Among the survivors, an estimate of 102.2 million disability-adjusted life years (DALYs) were lost [1, 2].

Six months after the incident, more than one-third of the patients have a non-functional upper limb [3] and depend on assistance to manage activities of daily living (ADL) [4] and approximately 60% of the survivors present some impairment associated with their hand [5].

Despite health issues, rehabilitation is also important due to economic reasons, as DALY loss has an impact directly on productivity. The rehabilitation program begins in the hospital, right after the incident. However, hand recovery is not considered a priority. Its rehabilitation comes after the lower body, trunk, and upper arm, for example. When hand therapy begins, often the patient is not in the acute stage anymore [6], although

J. L. B. Marques et al. (Eds.): CLAIB 2022/CBEB 2022, IFMBE Proceedings, 100, pp. 509–518, 2024.
https://doi.org/10.1007/978-3-031-49407-9_51

intensive training in the first six months after the accident is determinant for better, or at least faster, recovery of functionality [7].

Current clinical rehabilitation methods are still far from restoring normal functions and quality of life in most patients [6] so, researchers have focused on the development of new methods for patients with motor disabilities [8].

During the last decades, robots have been designed to assist in motor training. Compared to other strategies in rehabilitation, robotic training offers several potential ad-vantages, including quantifiable performance measures, reduced load on therapists, repeatability, and intense and task-oriented activities [9]. Furthermore, it makes it easier to apply new constraints, optimizes required movement pat-terns, and allows patients to exercise independently.

Several studies indicate that robot training is, at least, as effective as current clinical treatments. However, the number of subjects is usually small. The most extensive trial involving an upper limb device for hand rehabilitation, the In-motion robot (MIT-Manus) involved 127 patients. The study provided evidence that robot training and high-intense conventional therapy produced similar results for a 36-h program [10].

Since the hand is the most important limb to perform activities of daily living (ADL), a great number of hand exoskeletons has been developed in the last two decades [11, 12]. Thus, this works aims to evaluate biomechanically a finger exoskeleton developed in the Image and Signal Processing Laboratory (LAPIS) from COPPE's Program of Biomedical Engineering at UFRJ.

2 Exoskeleton

The exoskeleton is a hybrid soft-rigid cable driven device which provides only one actuated degree of freedom (DOF) which is the distal phalanx. The middle and proximal phalanx are underactuated. Furthermore, the exoskeleton does not act on adduction and abduction movements while it does not constrain these movements either.

The actuator is a RobotZone HDA 10-50 linear servo that have a maximum piston extension of 25 cm, average velocity of 1.5 cm/s and are able to provide a force of 500 N. The actuation system is located away from the body which is important avoid load transfer to other parts of the musculoskeletal system [12]. Servo position is controlled through PWM signal.

Force is transmitted through Bowden-cables that move inside cable sheaths in order to provide the capacity of either pulling or pushing. The sheaths are fixed in the forearm, wrist, and MCP (metacarpophalangeal) joints in order to constrain any possible cable movement and guarantee that the force will be transmitted to the distal phalanges, where the end of the sheaths will be attached to provide the actuated DOF.

There are two possible assemblies for the exoskeleton. By attaching the cable guide on the backhand (Free PP – Fig. 1), the actuation occurs mainly on the MCP joint.

Otherwise, when the cable guide is fixed in the proximal phalanx (Fixed PP – Fig. 2), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints are the only ones where the rotation takes place.

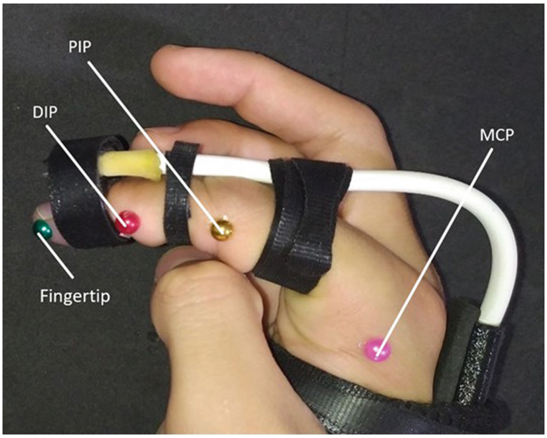

Fig. 1. Free PP assembly - the cable guide (black) is fixed on the backhand in order to allow MCP joint rotation

Fig. 2. Fixed PP assembly - the cable guide (black) is fixed on the proximal phalanx (PP) in order to constrain MCP joint rotation

3 Methodology

A total of 23 healthy individuals between 18 and 60 years were enrolled in this study. In order to match the inclusion criteria, the subject could not have had any neurological or orthopedic wound that limited finger motion. The trial was approved by the Ethics Committee CAAE: 29663120.8.0000.5257.

The experiment, similar to the one developed by [13], was designed in order to evaluate the hand workspace and joints angle displacement provided by the exoskeleton com-pared to the ones achieved by a free healthy hand.

3.1 Experimental Setup

The trial took place in a controlled environment. While sitting in a comfortable chair, the informed consent form was given to the participant and the instructions were explained by the author.

As four key locations were of interest: fingertip (FT), distal interphalangeal (DIP), and proximal interphalangeal (PIP) joints for trajectory analysis and metacarpophalangeal (MCP) joint for reference, markers of distinct colors were placed in those joints in order to allow the software (Kinovea) to track their motion. Each phalanx was measured in order to calibrate the system coordinates in post-processing. Index finger and referred markers are shown in Figs. 1 and 2.

3.2 Tasks

The experiment was divided into four tasks. The first and second tasks were performed with bare hands. In the beginning, the subject was asked to actively perform 10 cycles of right-hand index finger flexion and extension. Then, the next activity was to grasp and release a whiteboard marker pen. The only index finger was moved, the subject was instructed to keep the thumb at rest. There were performed 10 cycles of grasping/releasing.

For the next task, the subject wore the device and was instructed to remain in the rest position and not to perform any movement. The same 10 cycles right-hand index finger of extension/flexion, but the movements were entirely actuated by the exoskeleton. The experiment was repeated for an alternative assembly of the device.

All exercises were recorded by a fixed camera in 1080p resolution. Hand-free exercises were recorded at 60 frames per second (fps) and exoskeleton exercises were recorded at 30 fps. Tasks were executed in sequence to ensure that the exact same locations would have been analyzed (markers did not move).

3.3 Post-processing

Recorded videos were imported in open-source software Kinovea. Each marker was labeled according to the joint (MCP, PIP, DIP) it was placed or the fingertip (FT). The origin of the coordinate system was placed in the MCP joint at frame 1 (time = 0 s) and the length scale was calibrated for each subject.

The software automatically tracks the markers. However, sometimes an error might occur and the marker is lost. When such an event happens, it is necessary to perform a manual correction. When the video was fully processed, data was exported in XML format, which contains the coordinates and respective times for each joint.

Any translation performed by the hand was corrected by forcing the axes origin at the MCP. PIP, DIP, and FT coordinates were subtracted from MCP coordinates at the same instant. Angles were calculated using the coordinates at the beginning and end of each movement.

The workspace was obtained by determination of the area delimited by proximal, middle, and distal phalanges and the trajectory performed by the fingertip. For comparison, the area was divided by the finger length squared.

3.4 Data Analysis

The flexion movements were chosen to be analyzed since it is harder to perform finger flexion than finger extension with cables and at the initial position the finger is extended.

Data were divided into four groups: Free Hand; Pilot Pen Grasping; Exoskeleton - Free Proximal Phalanx and; Exoskeleton - Fixed Proximal Phalanx. Which was compared due to normalized workspace and relative angles for each finger joint.

Also, a Shapiro-Wilk normality test was performed in order to choose the most suitable multi-comparison test. The data was submitted to a Kruskal-Wallis test, with a significance level of 5%. A multiple comparison test was also performed in order to identify where the stochastic dominance occurs. The Bonferroni correction was performed.

4 Results

Data exported from Kinovea made it possible to analyze trajectories, angles, and workspace for the different tasks. The Exoskeleton - Fixed PP task failed for two subjects. Also, one subject performed only 9 cycles in the free hand experiment and another subject performed only 9 cycles in the pilot pen grasping experiment. Since there were 23 subjects in the trial, the number of flexions and extensions for each task is shown in Table 1. The data chosen to analyze the range of motion was from the flexion movements.

Table 1. Sample size for each task performed

Task	Number of data points
Free hand	229
Pilot grasping	229
Exoskeleton - free PP	230
Exoskeleton - fixed PP	210

The Shapiro-Wilk test concluded that neither of the sixteen samples is normally distributed. So, it was necessary to perform a non-parametric test (Kruskal-Wallis).

The first multiple comparison test performed was related to the workspace (Fig. 3). When the confidence intervals of two groups overlaid one another, it means that no significant difference was found between them. Therefore, data from groups 2 (Free Hand) and 4 (Pilot Pen Grasping) might be considered as they would have come from the same group.

Following tests compared the relative angles of MCP, PIP, and DIP joints between the four groups (Fig. 4). MCP mean angles of all groups significantly differ from one another. Still, it can be pointed out that the greatest similarities occur between groups 2 (Free Hand) and 4 (Pilot Pen Grasping).

The multiple comparison test resulted that groups 3 (Exoskeleton Free PP) and 4 (Pilot pen grasping) do not differ significantly from one another for the PIP angles (Fig. 5). Also, both of them present the lowest values, the latter being slightly higher.

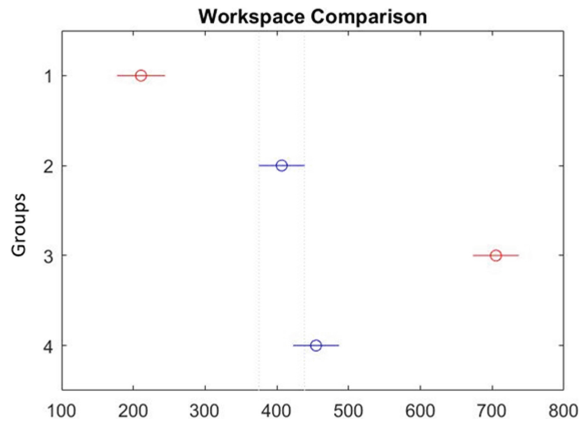

Fig. 3. Results of Kruskal-Wallis for workspace multicomparison between all tasks (group 1: exoskeleton fixed PP; group 2: free hand; group 3: exoskeleton free PP; group 4: pilot pen grasping)

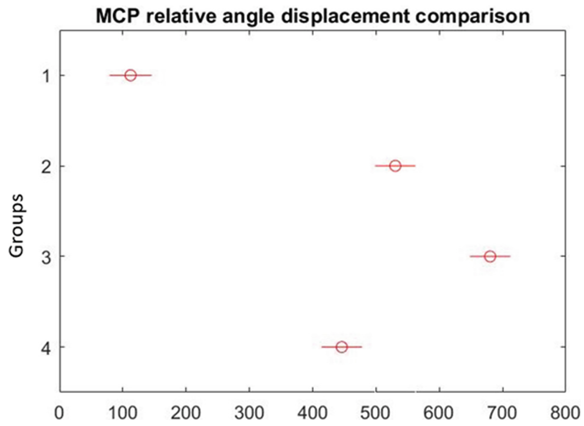

Fig. 4. Results of Kruskal-Wallis for MCP relative angle displacement multicomparison between all tasks (group 1: exoskeleton fixed PP; group 2: free hand; group 3: exoskeleton free PP; group 4: pilot pen grasping)

Figure 6 shows the results of the DIP joint comparison of all groups. All the means differ significantly from one another. Groups 3 and 4 possess the smallest differences among all of them.

The mean angles displacements provided for each joint in each exoskeleton assembly for flexion movements are presented in Table 2.

Comparison between the workspace provided by the exoskeleton and achieved when the subject was controlling the finger (exoskeleton was not worn) was done in terms of ratio. It is possible to notice in Table 3 that the Free PP assembly achieved 127% and 133% while the Fixed PP assembly achieved 77% and 81% of pilot pen grasping and free hand tasks, respectively.

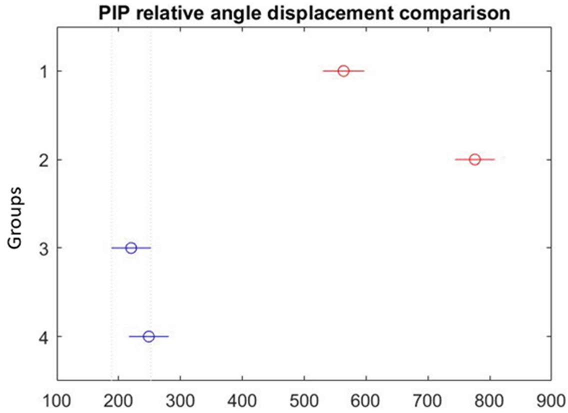

Fig. 5. Results of Kruskal-Wallis for PIP relative angle displacement multicomparison between all tasks (group 1: exoskeleton fixed PP; group 2: free hand; group 3: exoskeleton free PP; group 4: pilot pen grasping)

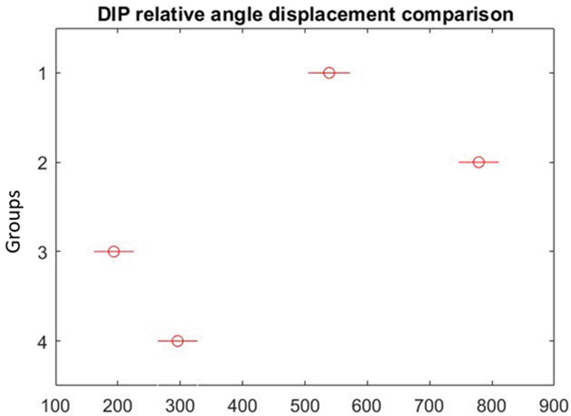

Fig. 6. Results of Kruskal-Wallis for DIP relative angle displacement multicomparison between all tasks (group 1: exoskeleton fixed PP; group 2: free hand; group 3: exoskeleton free PP; group 4: pilot pen grasping)

Table 2. Mean angles displacement for each joint for both exoskeleton assemblies

	MCP (°)	PIP (°)	DIP (°)
Free PP	63	14	11
Fixed PP	14	49	37

The same methodology was applied to compare the angle displacement for each joint when the exoskeleton was worn and when it was not. The ratios are present in Table 4.

Table 3. Workspace ratios between exoskeleton assemblies and bare hand tasks

Tasks	Workspace ratio (%)
(Fixed PP)/(free hand)	77
(Free PP)/(free hand)	127
(Fixed PP)/(pilot pen grasping)	81
(Free PP)/(pilot pen grasping)	133

Table 4. Angles displacements ratios between exoskeleton assemblies and bare hand tasks

Tasks	MCP joint ratio (%)	PIP joint ratio (%)	DIP joint ratio (%)
(Fixed PP)/(free hand)	27	65	61
(Free PP)/(free hand)	120	19	17
(Fixed PP)/(pilot pen grasping)	32	338	214
(Free PP)/(pilot pen grasping)	138	96	60

5 Discussion

Concerning any mistakes that might compromise the study, some movements might have had motion in the z-axis. However, either the camera or Kinovea are able to detect only planar motion. Therefore, any displacement in the z-axis was neglected. Also, any hand displacement was corrected by considering the MCP joint as the axis origin in each frame.

Workspace achieved by the Exoskeleton - Free PP assembly was the greatest. It is fair to point out that this result occurred because the subjects did not achieve the maximum workspace when they performed finger flexion and extension with bare hands. It would happen if the MCP joint rotation achieved its maximum amplitude with the finger extended, and only then the PIP rotation starts and DIP after that. The results from MANO [13] report that the exoskeleton achieved 70% of the workspace compared with the bare hand. It is fair to indicate that the movement with-out the device might have been performed in a way to maximize the workspace as explained, which did not happen in this study.

Lin et al. 2021 [14] designed a hybrid soft-rigid hand exoskeleton (HSRexo) for poststroke rehabilitation with a similar design of MANO [13] and the device evaluated in this study. The HSRexo [14] is capable of providing maxi-mum angles displacements of 32°/61°/34° for the MCP/PIP/DIP joints, which provide a greater ROM for the patient hand when compared with the mean angles (63°/14°/11° and 14°/49°/37°) achieved by both exoskeleton assemblies used in this study (Table 1). Surprisingly, the Fixed PP assembly is the one which provides more similar angle displacements although the HSRexo assembly does not limit the MCP rotation.

The workspace comparison is one parameter to compare motion similarity but it should not be the only one, as multi comparison test between the free hand flexion/extension and the pilot pen grasping tasks rejected the null hypothesis. Therefore, a narrowed investigation must include the angle displacement for each joint.

The resulting finger trajectories of the pilot pen grasping experiment were quite similar to the ones provided by the Exoskeleton - Free PP assembly. However, the Kruskal-Wallis tests found a significant difference for the workspace, MCP, and DIP joints. One explanation for this discrepancy is that the movement was limited by the object in one task. This assumption is supported by the fact that in the exoskeleton experiment the workspace is significantly higher. Also, in both cases, the MCP joint had the greatest angles and again, it was higher when wearing the device. For the PIP joint, there was no significant difference and, in the DIP joint analysis, despite that the means significantly differed from one another, they were the closest ones.

6 Conclusion

One of the exoskeleton assemblies (Free PP) achieved a greater workspace compared to both barehand movements. In addition, the Fixed PP assembly achieved 81% of the workspace in the pilot pen grasping task.

Also, the Free PP assembly provides a quite similar trajectory for the index finger compared to when the subject tried to perform the pilot pen grasping since there was no significant difference between both angle displacements for the PIP joint. The greater values achieved for the workspace and MCP joint are explained because the pilot pen acted as an obstacle in one task but there was no limitation when the device was actuating the index finger.

The presented exoskeleton is still in development. However, it is already able to perform repetitive hand opening/closing and to measure cable tension with a load cell. Intention detector methods such as sensors and a hybrid brain-machine interface (electroencephalography and electromyography) are to be implemented. Furthermore, the main goal is to apply the device in injured individuals for rehabilitation.

Acknowledgment. This research received financial support from the national council for scientific and technological development (cnpq - grant 312592/2020-5), carlos chagas filho foundation for research support of the state of rio de janeiro (faperj - grant e-26/202.587/2019), and the coordination of superior level staff improvement (capes – grant 23038.008788/2017-27).

Conflict of Interest. The authors declare that they have no conflict of interest.

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