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Design and development of a robotic system for hand's wrist-fingers rehabilitation

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Keywords

Robotically physiotherapy;
Stroke;
Hand;
Clinical trials;
Technical tests.

Abstract

Hand impairment, followed by stroke, causes significant deficits in performing different activities. Restoration of hand functions requires regular and repetitive therapy exercises. Although robotically physiotherapy systems have shown great promise in hand functions' improvements, they are not widely and effectively used, as the needs and expectations of patients and physiotherapists have been ignored. In this paper, a 4-degrees of freedom desktop-mounted robot is developed for four fingers and wrist rehabilitation, based on clinical observations. Hand-Robo-Hab provides the four mechanotherapy prevalent movements as follows: active, passive, active-assisted, and active resisted. In this study, the design and development of the robot are described. Then the efficiency and usability of the device are evaluated through two technical tests, and a preliminary clinical trial. The results of technical tests showed that Hand-Robo-Hab was able to cover the wrist range of motion of 99 to 203 degrees. Besides, the proposed device was capable of compensating its weight, which is a necessary step to accomplish the active modes exercises. In addition, clinical trial results showed that Hand-Robo-Hab was both operative and comfortable for patients with different hand sizes.

1. Introduction

Different neurological consequences such as motor sensory, cognitive, language, and emotional disorders are followed by stroke, which is the second cause of death worldwide. Although the mortality rate due to stroke has been decreased, it is still the main cause of long-term disability. Post-stroke survivors suffer from exacerbation of hand functions as the human hand is one of the most complex limbs in terms of functionality and Degrees of Freedom (DOF) [1–3].

The Stroke Alliance for European has declared that every 20 seconds a new stroke case occurs in adults. It has been predicted that the number of affected people by stroke will increase by 35% to 12 million in 2040 [4]. In the United States, about 800,000 subjects face stroke annually, among which 90% of the survivors are left with disability and 65% of them are not able to cooperate with their impaired hands in the different tasks even 6 months after stroke [5]. Furthermore, the exorbitant cost of rehabilitation plans and transportation, along with the lack of dexterity and strength of therapists have made the conventional methods difficult. The other drawback of conventional methods is time-consuming along with tediousness for both patients and therapists. Finally, quantitative and accurate data of the hands' performance improvements cannot be obtained [6].

Throughout the previous decade, Robot-Assisted Training (RAT), has been utilized to improve motor deficiencies in post-stroke survivors. In this regard, different

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models have been created. One of the most common groups of these devices is Exoskeletons, such as M3ROB which is a robotic platform for wrist and hand [7], a lightweight exoskeleton based on hand kinematic model [1], an exoskeleton for wrist-finger [8], a three-DOF exoskeleton [9], an exoskeleton for the thumb, index, middle and ring fingers [10], Flexor-Hand [11], a passive exoskeleton for wrist and forearm [12], a wrist exoskeleton [13], Hand Mate [14], a cable-driven exoskeleton [15], and a hand exoskeleton with series elastic actuation [16]. A wide range of these devices has been created just for fingers such as a finger exoskeleton [17], a linkage finger exoskeleton [18], a magnetic-force-based for paralyzed fingers [19], a portable hand rehabilitation finger [20] and a finger extensor [21]. Another group in this field refers to soft robotic devices which are often glove-shaped, such as Soft Exoskeleton Glove (SEG) [22], hand re-extensor with steel ribbons [5], mirroring glove [23], a soft rehabilitation robot which holds continuous passive motion mode [24] and a wearable exoskeleton glove [25]. The last introduced category refers to desktop-mounted models such as parallel robotic system [26], an end-effector bilateral rehabilitation system [27], end-effector type desktop robot [28], wrist-forearm desktop robot [29], and CUBE, a cable-driven parallel structured robot desktop [30].

Although there are a great number and variety of hand physiotherapy robots, only a few of them have been widely and effectively used. In other words, robot-assisted physiotherapy, which has shown great promise in hand-function improvements, has not yet replaced conventional physiotherapy. This problem has some reasons: First, the complexity of the robot configuration makes it unusable. Second, the needs of physiotherapists and patients have been ignored. This negligence would lead to creating a device with less effectiveness on the patients, and also not being very practical for the physiotherapists.

To meet these challenges, a desktop-mounted physiotherapy system, “Hand-Robo-Hab”, is proposed in this paper. This device is introduced with a simple mechanical structure and can be used for the wrist and four fingers. To satisfy both physiotherapists’ and patients' needs, the design is based on clinical observations. The main novel features of the robot are summarized as:

- This device is usable for both right and left hands;
- The 4 DOF are created by using just one actuator;
- This device is provided with four mechano-therapy movements which are the fundamental treatments in physiotherapy;
- The proposed device can be used for the deformed hand, either. Therefore, it will be utilizable for a vast range of patients. To prove the robot’s features, technical and clinical tests are conducted.

The rest of the paper is comprised of six sections. In Section 2, the methodology including the mechanical structures and electrical components, is explained. The control strategy for four mechano-therapy modes is described in Section 3. In Section 4, the results of technical and clinical tests are described. The discussion and conclusion are stated in Sections 5 and 6, respectively.

2. Methodology

2.1. Clinical observations and design requirements

In the first phase, physiotherapy observations and movement analyses were done to identify impairments of the affected hand. Afterward, the appropriate movement therapy was selected to target these impairments. The results showed that hand spasticity was the main problem of stroke survivors. Spasticity keeps the wrists and fingers in flexion position; therefore, the therapist has to re-extend them regularly during each exercise which may interrupt the current task. This intermittent job is shown in Figure 1.

Figure 1. Spasticity compensation and forearm traction exercises.

Figure 2. (a) The CAD model of digit supporters and the side shafts, (b) real model of the finger cover and (c) the real model of side shaft.

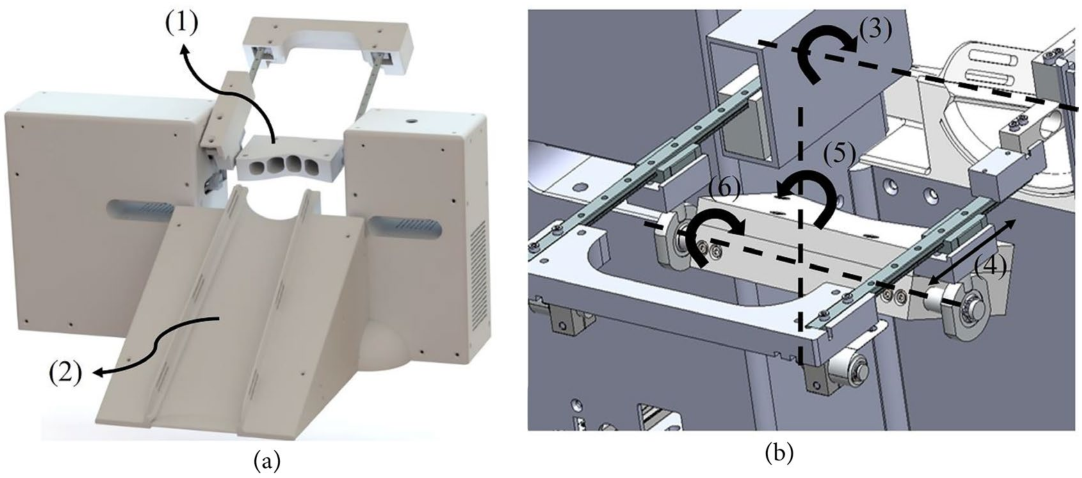

Figure 3. (a): (1) The finger cover, (2) the forearm placement and (b): (3) active degree of freedom created by the DC motor, (4) linear movement of finger cover, (5) rotation around the vertical axis (Yaw), (6) rotation of finger cover around the latitudinal axis (Pitch).

Due to the spasticity differences among the individual's fingers, hand re-opening is a tedious task for physiotherapists. To address this impairment using the proposed robotic system, exerting flexion-extension movements on the four fingers and wrist were chosen. Furthermore, stretching the flexor muscles in the forearm has a great impact on spasticity reduction. Thus, this movement is also considered as one of the aims of the proposed device. These selected movements will be achieved in all fundamental physiotherapy modes: passive, active-assisted, active and active-resisted.

2.2. Mechanical and electrical structure

The functional requirements, resulted from the previous phase, lead to the construction of the device with 1-active and 3-passive DOF to exert selected movements on the fingers-wrist. In this regard, the proposed device is composed of three main parts: 1-an adjustable finger cover and its side shafts, 2-a linear guide and 3-the driving unit.

2.2.1. Finger cover

The finger cover consists of two separated up-down segments called digit supporters, in which two phalanxes of the four fingers can be placed. The digit supporters are adjustable in length and thickness to fulfill the biomechanical compatibility with different fingers' sizes. On the other hand, the digit supporters can be used for both left and right hands. This will be achieved by rotating the finger cover structure 180 degrees. Two shafts are screwed at both sides of the finger cover. The hand cover, digit supporters, and the side shafts are shown in Figure 2.

The shafts are inserted in articulated bearings, which are connected to the linear guide wagon set via a connecting piece. The articulate bearing allows rotation of the shafts around the endpoint of the shaft, which is perpendicular to the palm.

2.2.2. Linear guide

Two linear guides and wagons are connected to the digit supporter's side shafts, which can provide both linear and rotational movements of the fingers. This mechanism would create three passive DOF: a translational movement of finger cover along the linear guide, the rotation of shafts around their longitudinal axis, and a rotation around the vertical axis.

2.2.3. Driving unit

The driving unit is comprised of a DC motor (Maxon, 118755, Switzerland), a position controller (Maxon, Encoder MR type ML), a power supply (QUINT-PS/10-2866763), and an amplifier (Dynamic strain Amplifier, DN-AM100 DACELL, South Korea).

The DC motor provides an active DOF which is a rotation of the mechanical arm around the sagittal axis. The overall DOF created by the device and the displacement of fingers and forearms are depicted in Figure 3.

Furthermore, the robot is equipped with a force sensor, (Loadcell Zemic 1-S-B, Netherlands), to control the robot. To counteract the spasticity differences in the fingers, a constant

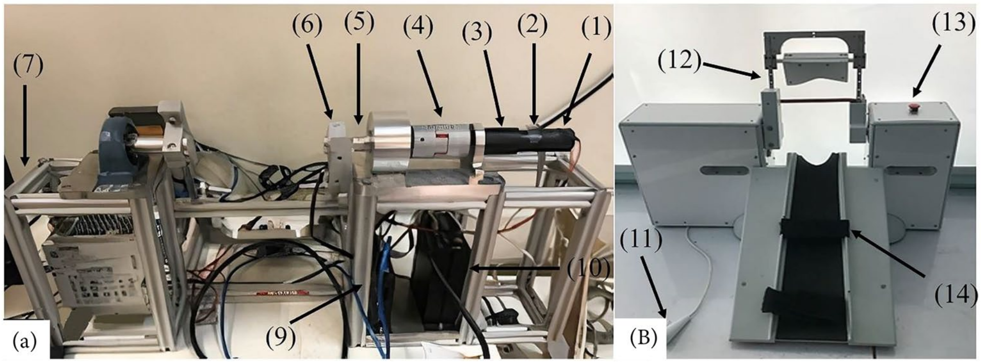

Figure 4. The robot platform (a) 1. encoder, 2. DC motor, 3. reduction gearbox, 4. coupling mechanism, 5. ball bearing, 6. loadcell, 7. mechanical structures, 8. power supply, 9. position controller, 10. amplifier and (b) 11. emergency stop, 12. linear Guide, 13. an emergency stop button, 14. handset.

force spring is used on both linear guides that pull the finger cover to fit the palm size.

To keep the patient in an ergonomic position, a specific design is made on the forearm part of the device, in which the forearm can be placed at an angle of 30 degrees to the horizon. This angle is determined based on clinical observations. For safety considerations, an emergency stop and an emergency button are utilized which can be used by the therapist and the patient, respectively. Based on the findings, some designs were depicted in SolidWorks 2015 (Dassault-Systems, France, 1995). Then the best prototype was selected and manufactured. The hardware platform is shown in Figure 4.

3. Control strategy

The control system was developed in such a way that the robot exerted the movements in all four mechanotherapy movements: passive, active-assisted, active and active-resisted. To make the controller user-friendly, the Graphical User Interface (GUI) was created by C# in the visual studio program, (Microsoft Cooperation, Washington, United States). In the Figure 5, the GUI, for the proposed device is shown.

At the beginning of each exercise, the robot should be homed to make sure it would start moving from a pre-defined position, Figure 6(a) shows the home position of the robot arm. Since, in the active modes the patient would displace the robot arm by his strength, the weight of the robot arm must be compensated and not imposed on the patient's hand. On the other hand, the angle of the robot arm would change while moving, which is illustrated in Figure 6(b), therefore the portion of robot arm weight which would be sustained by the hand, changes constantly. A calibration stage was done to determine the weight of the robot arm at any angle. The aim of this calibration is to find the relation between the force corresponding to the robot's weight torque and its position (the robot angle).

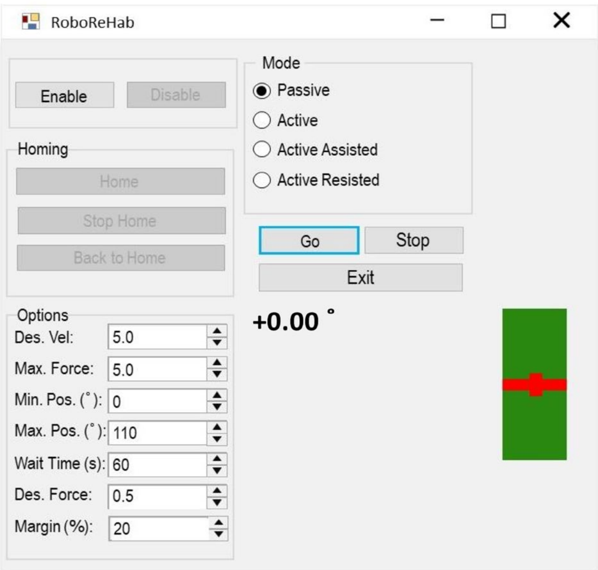

Figure 5. The GUI of the device.

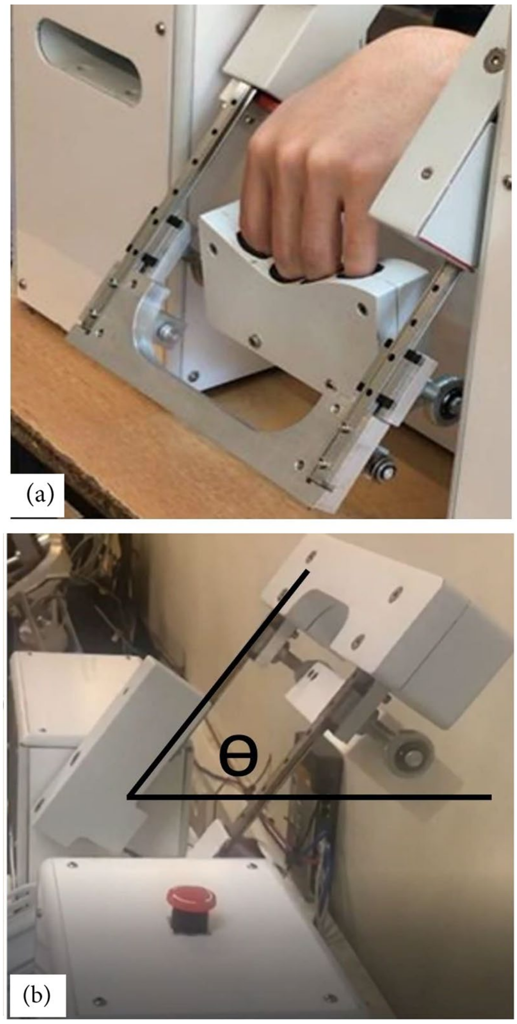

Figure 6. (a) Home position and (b) the angles of the robot at which its weights are measured.

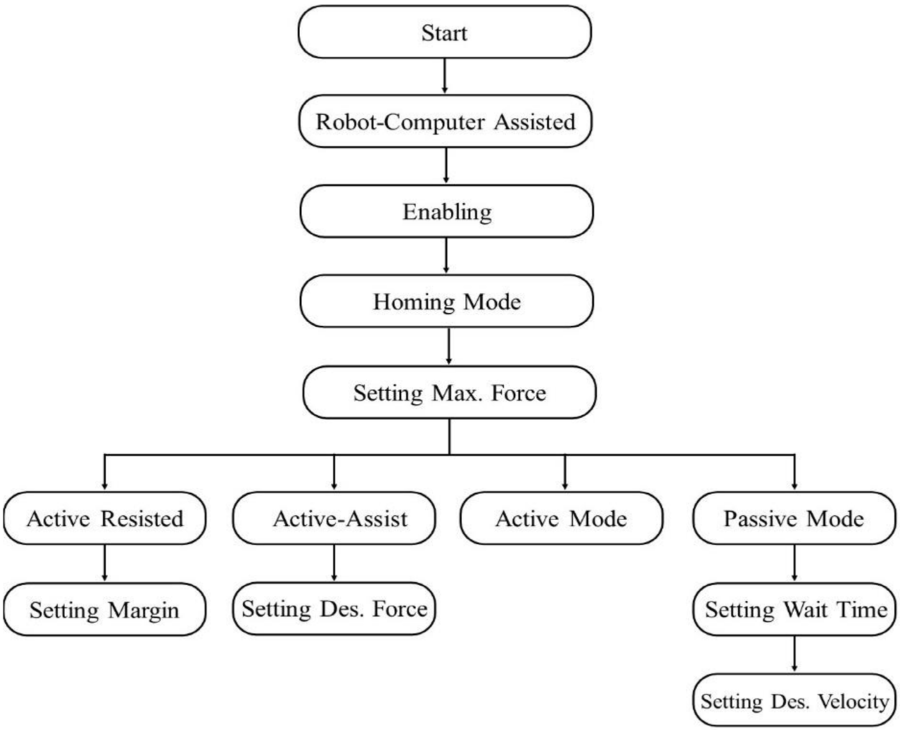

Figure 7. The procedure for utilizing the device.

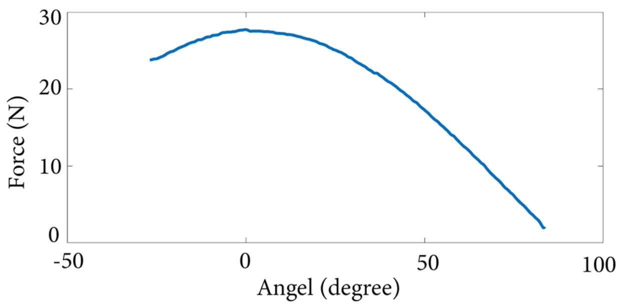

Figure 8. The force corresponding to the weight torque at each angle.

The calibration stage and control algorithm for each mode is explained in the following sub-sections. Figure 7 shows the procedure for utilizing the device.

3.1. Calibration

For the calibration, the robot moved in a quasi-static mode, at a very slow speed without carrying the user's hand. In such condition, the load cell would measure the torque resulting from the pure weight of the robot in any direction. The robot angles were also recorded using the encoder. By dividing the measured torque by the torque arm, the obtained force corresponding to each robot position is plotted in Figure 8. To extract the relation, the curve fitting tool of MATLAB was used and Eq. (1) was obtained:

$$F_{wt} = 22.64 \sin((0.020 \times Angle) + 1.701). \qquad (1)$$

3.2. Passive mode

In this mode, the motor moves the robot arm with a constant velocity specified by the user, until the current position is the same as the final position. Figure 9 illustrates all the control algorithms. After that, the direction of the motor rotation is reversed and the robot arm comes back to its home position. To stretch the flexor muscles in the forearm, the robot arm can be stopped in the maximum position, by means of setting the stopped time. For more safety, a Max. Force option is suggested which if set, the robot would stop immediately when it reaches the force set value. The robot's range of motion can be adjusted by the min. pos. and max. pos. options on the GUI.

3.3. Active mode

To perform the active mode, the device calibration data is used to compensate the robot's weight. The motor moves with a velocity commensurate with the weight obtained from the calibration based on the current angle. As the user changes the robot's position by applying a force, its weight changes. The new weight is read using the calibration formula and the new motor velocity is calculated.

3.4. Active-assisted mode

In this mode, the difference between the force shown by the load cell (F_L), and the robot's weight corresponding to the current position is calculated, (F_u). F_L is the summation of the robot weight (F_W) and the user's force. According to this difference, the motor moves with a velocity proportional to F_W, or it moves with a velocity proportional to F_u.

3.5. Active-resisted mode

To run this mode, the motor produces the torque, opposite to the hand movement direction with the help of the current control mode. The value of the motor velocity is proportional to F_u.

4. Clinical and technical tests

4.1. Technical tests

4.1.1. Passive mode test

A technical test is performed on the passive mode to check the capability of the device in covering a standard wrist range of motion. To this end, a healthy subject trained with the

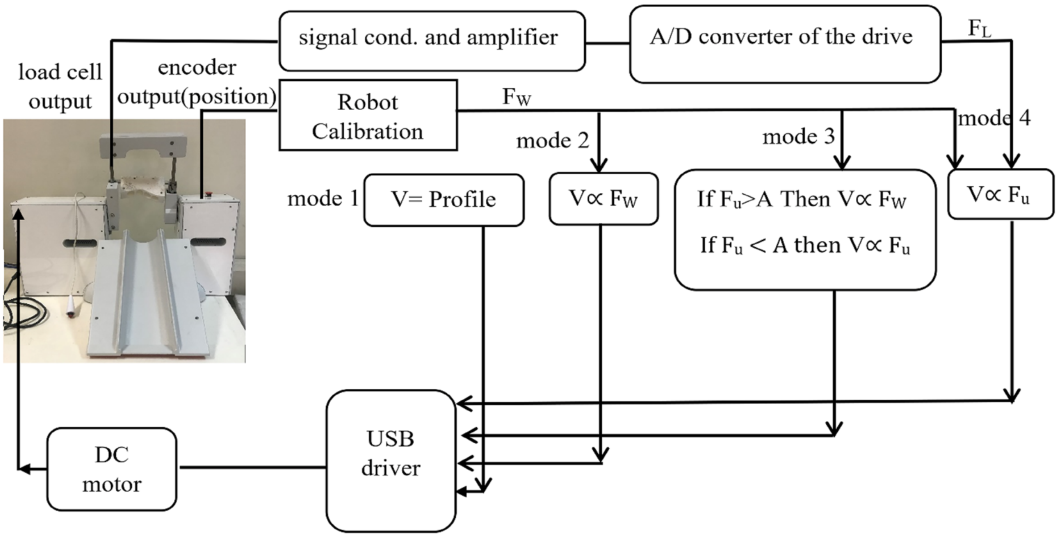

Figure 9. The control diagram of the robot, mode 1; passive, mode 2; active, mode 3; active-assisted and mode 4; active-resisted.

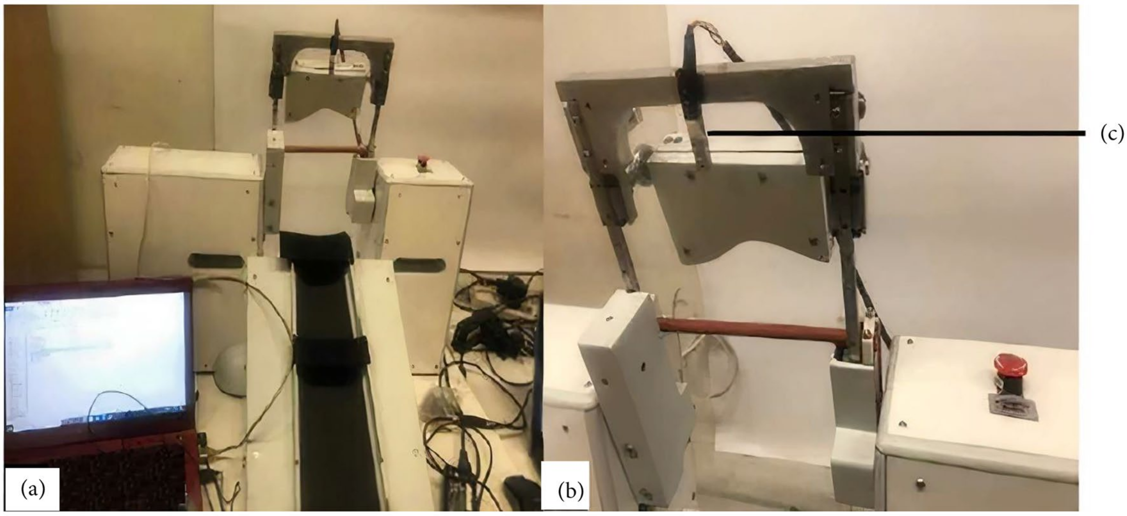

Figure 10. (a) the whole setup for the active technical test, (b) the closed view of the new sensor attachment, (c) the external sensor.

robot in passive mode and the wrist range of motion is calculated. The angle of the robot changes from 0 to 110 degrees, set in the GUI, with an increment of 5 degree. At each angle, the real angle of the wrist is measured. Table 1 shows the results of the passive mode test.

4.1.2. Active mode test

Another technical test is performed to check the capability of the robot in compensating its weight while performing in the active mode. To perform this test, another load cell (1-B-S-50Kg.0.2B, Zemic, Netherlands) is attached to the connector piece. This new setup is shown in Figure 10.

By applying a finger force on this loadcell and moving the robot arm, periodically, two series of data are collected: the force monitored by the external loadcell and the torque measured by the internal loadcell. The force which is sensed by the internal sensor would be calculated by dividing the internal load cell output by the torque arm. Figure 11 shows these two forces.

4.2. Clinical tests

To find any possible problem that may occur during the rehabilitation, the device is tested on five healthy subjects. None of them were reported to encounter a serious problem

Table 1. The results of the passive mode technical test.

Robot angle (degrees)	Real angle measured by SolidWorks(degrees)
0- degree (home position)	99.24
0-5	106
5-10	110.01
10-15	113.14
15-20	115.23
20-25	119.51
25-30	124.97
30-35	129.33
35-40	132.39
40-45	135
45-50	140
50-55	145
55-60	149
60-65	154.57
65-70	159.93
70-75	165.80
75-80	169.20
80-85	174.13
85-90	178.90
90-95	185.90
95-100	190.67
100-105	196.20
105-110	202.80

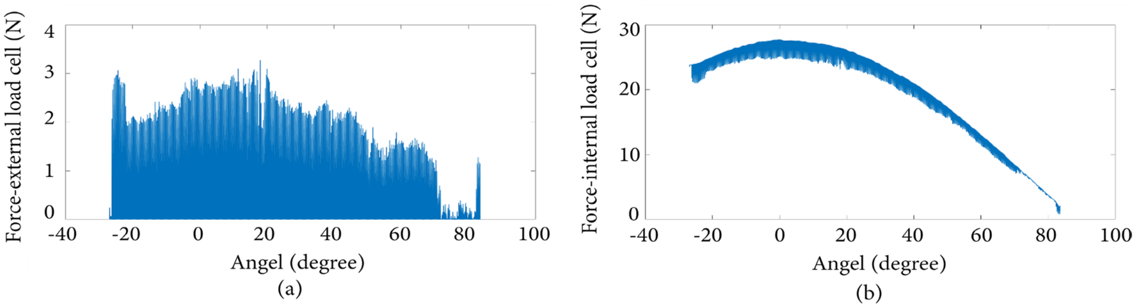

Figure 11. The results of the active test. (a) The output of the external load cell and (b) The force corresponding to the internal load cell output.

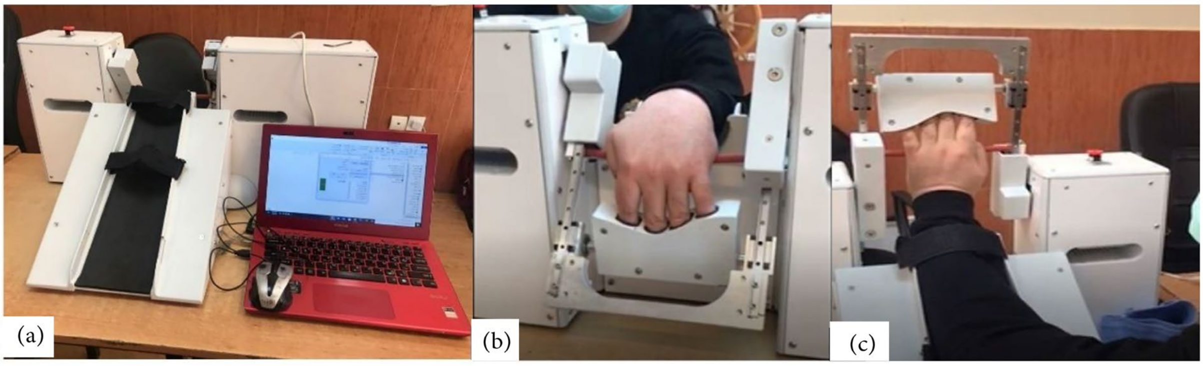

Figure 12. (a) The hardware setup for the clinical test. (b) the patient's hand in the home position. and (c) the hand in the stretching position.

while exercising with the device. Afterward, the test is conducted on 10 post-stroke patients, within the age range of 21-70, and with left-side affected. Figure 12 shows the setup and the patient exercising with the device.

The purpose of this test is to evaluate the effectiveness and usability of the device for the patients and therapists. In Table 2, the specifications of the recruited patients in this experiment have been shown. All participants were informed consent to the experiment that was approved by the Research Ethics Board of Tehran University of Medical Science (IR.TUMS.REC.1394.1505).

Testing the device on the patients shows that the most used movement mode is the passive mode. Only one patient could do the exercise in active-assisted mode. 7 of 10 patients could do the exercises well without any problem. The duration of training was adjusted with respect to the strength and ability of patients. One of the three patients, who could not practice with the device, had wrist pain in the home position due to wrist stiffness. Therefore, a higher starting position was set for him. In the other two patients, the finger cover structure and the hand were not connected well and the hand came out of the cover while moving. It was concluded from the clinical test that Hand-Robo-Hab can increase the motivation of patients in the treatment process because some of them were passionate to work with the device more than once.

5. Discussion

Neurological diseases such as CVA, can diminish the hand's performance. In this regard, various types of devices have been developed to restore hand functions [11,31,32]. In this article, we presented the design and fabrication of Hand-Robo-Hab, a therapeutic device, to exert physiotherapy movements on the wrist and fingers. The design is based on clinical observations, through which the needs of therapists and patients are extracted. Accordingly, the most important need for therapists is eliminating repetitive and tedious movements, and for the patient's pivotal movements to reduce spasticity. In this regard, according to the information in [33,34], the average length and thickness of fingers are obtained and the Hand-Robo-Hab is designed, fabricated, and evaluated by conducting some technical and clinical tests.

One of the most important features of this robot is its simple structure where only one actuator is employed for 4 DOF provided by the robot, which is rarely seen among similar models. Compared to the [35,36] that use Pneumatic Artificial Muscle (PAM), the components of this robot are designed to be very simple and efficient.

Besides, the robot's light weight makes it portable. The device is composed of a hand cover that can hold four fingers of different sizes and thicknesses. Another prominent feature of the proposed robot is its usability for both right and left hands, which is accomplished for the first time. Consequently, this device can be used for a wide range of patients regardless of the damaged side of the brain. Additionally, by using a force-constant spring, different spasticity among the four fingers and also among the different subjects can be compensated.

A wide range of therapeutic robots have been designed solely for finger physiotherapy [20–22] and some of them can be used just for the wrist [29,37,38]. Since simultaneous functions of the wrist and fingers along with restoring appropriate their range of motion is important for achieving hand dexterity and satisfied healing, both wrist and fingers are considered as the target for the proposed robot.

Another option that distinguishes this device from the other models is its software and control strategy. Most of the devices are Continuous Passive Motion (CPM), such as [39,40], and can exert only passive motions. In the presented prototype, four mechano-therapy movements would be created. Consequently, the Hand-Robo-Hab can be used not only for post-stroke patients but also for any neurological deficit.

Table 2. The specifications of the participants (patients).

Subjects	Sex	Modes of movement therapy	Duration and number of uses	Result
Subject 1	Female	Passive	2 minutes- 1 time	Done
Subject 2	Female	Passive	3 minutes- 1 time	Done
Subject 3	Female	Passive	6 minutes- 2 times	Done
Subject 4	Male	Passive-active assisted	5 minutes- 2 times	Done
Subject 5	Male	Passive	5 minutes- 2 times	Done
Subject 6	Female	Passive	5 minutes- 2 times	Done
Subject 7	Male	Passive	5 minutes	Done
Subject 8	Male	Passive	Less than 1 minute	Not completed, due to the wrist stiffness and pain
Subject 9	Male	Passive	Less than 1 minute	Not completed
Subject 10	Female	Passive	Less than 1 minute	Not completed

To investigate the device's ability to cover an acceptable wrist range of motion, the passive mode test, is done as explained in the section. It can be seen from Table 2 that the device can rehabilitate the wrist in the range of 99 to 203 degrees. In the active mode test, the robot weight compensation ability is approved. By comparing the two graphs shown in Figure 11, it can be observed that the force corresponding to the internal load cell output follows the force calibration diagram. The finger forces shown in Figure 11(a) add the disturbance-shaped signals to the force resulting from the weight signal, Figure 11(b). Since the main load cell measures both the user force and robot weight at each angle, it can be inferred that the weight is not borne by the user and is compensated by the motor.

For the clinical test, the device is tested on both healthy and post-stroke patients. The results show the usability and effectiveness of the device for both patients and therapists.

6. Conclusion

In this paper, a desktop robotic system is introduced with 4-DOFs, which are actuated by only one actuator, with the aim of rehabilitation of the wrist and four fingers. The system design satisfies the requirements of all physiotherapy movements: passive, active-assisted, active, and active resisted. This device is designed and fabricated based on patients' and therapists' needs. Besides, some important items such as velocity, time, and force are precisely controlled. All of these specifications bring great potential for its further clinical applications.

The tests on healthy subjects and patients show that this device can be a good alternative to conventional therapies and is widely used in rehabilitation centers, due to the satisfaction of patients and physiotherapists. The patients show great motivation in utilizing this device and physiotherapists are satisfied when working with the device.

To show the effects of the robot on the disease process and the rate of improvement in patients, more extensive clinical tests will be performed and the results of exercises with this robot can be seen in stroke patients.

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Conflicts of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
The author is an Editorial Board Member/Editor-inChief/Associate Editor/Guest Editor for Scientia Iranica and was not involved in the editorial review or the decision to publish this article.

Authors contribution statement
Fatemeh Mohandesi: Conceived of the presented idea, developed the theory, performed clinical observations, sketching different models by software, prototyped the device, carried out the clinical and technical test, interpreted the clinical and technical results. wrote the initial draft of article, doing the revision of the article especially the literature review and introduction.

Alireza Mirbagheri: Developed the theory, sketched and evaluated different designed models, developed the control algorithm, prototyped the device and support the writing the whole manuscript.

Hamid Khabiri: Performed clinical observations, prototyped the device, carried out the technical test, correct the initial draft of the manuscript, contributed in revising the article.

Mohammad Mehdi Mirbagheri: Providing consultation on both clinical and technical aspects of the manuscript.

Noureddin Nakhostin Ansari: Conceived of the clinical and medical issues of the project, supporting additional information about post-stroke patients, provided post-stroke patients for the clinical observations, contributed in interpretations of the clinical results.

Maryam Norouzi: Finalized the software model, contribute in prototyping the device and writing the manuscript.

Rouzbeh Kazemi: Provided post-stroke patients in Tabasom clinic for the clinical test.

Mehrnaz Aghanouri: Developed the control algorithm, performed the computations, contributed in the technical test, correct the initial draft of the manuscript, contributed in revising the manuscript.

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