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REGULAR PAPER

Design and Production of a Novel Cable Supported Hand and Wrist Rehabilitation Robot: Prototype Study

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Abstract
Rehabilitation robots are being used to assist limbs in performing basic functions. Most of the existing rehabilitation robots are not accessible for home environments, mainly due to lack of portability and high costs. In this study, a versatile rehabilitation robot is developed that can improve individuals' quality of life and can be used in clinical and in home environments, supporting treatment, and offering portability, wearability, and adaptability to individual needs. A novel four bar mechanism supported position controller is developed which is equipped with Bowden cable transmission on the fingers. Electrical actuators that facilitate hand movement have been selected based on their lightweight design and the ability to generate the necessary power. The robot is aimed to perform passive, isometric and active exercises regarding flexion/extension and radial/ulnar deviation movement experiments in order to illustrate performance of the proposed design. Experiments with a healthy subject are planned and followed through a human–machine interface software that is controlled by a microcontroller with an embedded program. Finally, the results of the experiments are presented separately for each finger owing to exercise type. The results of a healthy subject show that the developed rehabilitation robot sufficiently performed the planned tasks in the selected range. Moreover, it is proved that the designed and manufactured robot is feasible for clinical use to acquire the planned tasks after patient trials.

Keywords Rehabilitation robot · Hand and Wrist rehabilitation · Exoskeleton · Cable driven · Home rehabilitation

1 Introduction

Rehabilitation robots provide successful results compared to conventional approaches in terms of improving dexterity, quality of life, and hand functions [1]. After hand operations or after stroke, rehabilitation is needed to regain previous dexterity. Based on the treatment procedure, reproducible exercises should be done. Hand and wrist rehabilitation robots have gained significant attention in recent years due to their ability to provide controlled, repeatable, and adaptable therapies for patients with physical disabilities caused by stroke, cerebral palsy, or accident injuries [2]. These robots aim to enhance the effectiveness of rehabilitation by offering precision in movement, the ability to adapt to patient needs, and the capability to deliver therapy both in clinical and home environments. They have demonstrated a positive effect on patients'range of motion [3]. The World Health Organization recognizes medical devices as crucial components for ensuring the availability, accessibility, convenience, and affordability of healthcare services regionally and nationally within the framework of life sciences and healthcare [4–8].

Currently rehabilitation is usually performed manually by physiotherapists or by some medical devices which are extremely expensive. Difficulty reaching to a rehabilitation centre, not enough technical personnel and lack of motivation of patients to perform exercises at home are current problems in this context. Robot-assisted solutions in the field of rehabilitation allow patients to exercise at home that is becoming popular in recent years.

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Man makes his first communication with the objects around him by touching or grasping with his hand and wrist [9]. The human hand is one of the most crucial body parts due to its superior mobility, occupying more than one-third of the entire primary motor area of the brain, highlighting its significant physiological importance [9]. As a result of various accidents or stroke-like disorders, loss of function or joint restrictions occur, negatively affecting our lives [10, 11].

To improve the quality of life for patients such as turning knobs or holding a fork is essential. Therefore, there is a need for a robotic device capable of assisting not only in flexion/extension but also in abduction-extension movements. Another crucial requirement for such a device is to support thumb movements, which are critical for skilful object manipulation and resisting forces applied by the thumb. Additionally, palmar flexion/dorsiflexion of the wrist and pronation/supination of the forearm play integral roles in manipulation functions and fine movements [12]. There are different rehabilitation robots for the hand and wrist in recent years. The existing hand rehabilitation is generally conducted in medical centres under the supervision of physiotherapists, utilizing a limited array of costly medical devices. Commonly employed hand-wrist medical devices are often stationary or tethered to power sources, characterized by their bulkiness and lack of portability. The adjustment of rehabilitation devices'weight and dimensions are crucial, as non-ergonomic designs can detrimentally impact the rehabilitation process [13, 14]. Consequently, there is ongoing development of exoskeleton mechanisms aimed at facilitating correct exercises and enabling strong grips during rehabilitation, striving to mimic the natural structure of the hand [15–17]. Emphasis in the development of hand rehabilitation devices also focus on restoring mobility in the phalangeal regions of the hand [18–21], and several patent studies are dedicated to this specific area [18–25].

Device designs in the literature are categorized into three main groups in terms of power transmission: cable, pneumatic, and hydraulic transmission systems. In cable transmission systems, force input is utilized with end-effector admittance control [26]. In pneumatic systems, pressure is generated by compressing air sourced from an air generator, while hydraulic systems involve the movement of fluids to the end effectors. Pneumatic systems are increasingly being integrated with flexible systems today [27]. Newer systems utilizing flexible and artificial muscle systems for rehabilitation purposes [28] are also introduced. Advancements in smart materials over the past two decades have facilitated the integration of portable, soft, and flexible robots into our daily lives [13–16, 29–31]. However, they are far beyond making high power needed exercises.

Some of the hand exoskeleton devices are intended to perform virtual reality or remote manipulations with robot arms [16]. In the design of a device for physical therapy, a bidirectional motion is desired. Most of the designs in the literature are 2-degress of freedom (DOF) or 3-DOF limited systems where the human finger has four degrees of freedom [32]. The system supports three degrees of freedom for the index finger and four degrees of freedom for the thumb but controls only one degree of freedom at the same time through a pull cable. The multi degree of freedom system examples are the finger and hand system developed by Hasegawa, et al. with eleven DOF [33] and the hand exoskeleton developed at the Technical University (TU) of Berlin with twenty DOF [34].

Several upper extremity rehabilitation robots have been developed in different designs up to now. The study of Maciejasz et.al. contains an extensive survey on upper limb robots developed till 2014 [35].There, it is stated that there is still need to improve the design's functionality and reduce cost of home-based devices for therapy. Moreover, the therapy type depends on the user needs, so that a certain protocol is not valid for all patients. The first step of rehabilitation robots design starts with examination of human anatomy. The hand functioning covers a vast area of the motor cortex since it has a major role in daily life activities. The positioning of the hand is coordinated by the wrist so that the two limbs are studied together.

In a survey study in 2024, the key elements needed to develop human upper extremity rehabilitation robots are examined. The study presents the recent rehabilitation world by bridging between the anatomy, range of motion, anthropometric parameters, disability assessment techniques, and robot-assisted training methods [36]. They categorized designs into exoskeletons, end-effectors, and planar robots. The study identified key gaps, including limited portability, insufficient adaptability to diverse recovery stages, and challenges in integrating advanced control methods with user-friendly interfaces. These gaps underline the need for innovative designs that balance functionality, usability, and affordability.

The most common hand rehabilitation robots are Amadeo [37] and Hand of Hope [38]. Although their functioning is good, there is still need for hand and wrist training devices in commercially standards. As there are several factors considered before development of a new training device, degrees of freedom is regarded as the basic feature. The other parameters can be listed as kinematic design, actuation system, control algorithm, exercise types and use of extra sensing elements. MIT-MANUS is the first robotic rehabilitation device introducing controlled motion assistance [39]. Then the InMotion Wrist Robot demonstrated the repetitive functioning of the wrist [40]. Recent advancements in rehabilitation robots include both exoskeleton-based and end-effector-based designs. Exoskeleton designs, such as the MAHI Exo II and RiceWrist, focus on providing high degrees of freedom (DOF) to mimic natural hand and wrist movements. These devices often incorporate advanced control systems like impedance and adaptive control for human–robot interaction. On the other hand, simpler end-effector-based designs, such as POWROBOT by Kucuk and Mayetin [41], emphasize cost-efficiency and portability. These devices typically offer 3-DOF for wrist movements, including pronation/supination, radial/ulnar deviation, and flexion/extension, and are tailored for home-based rehabilitation. While these systems make rehabilitation accessible to a broader population, they lack the comprehensive motion capabilities required for complex rehabilitation scenarios. Despite significant progress, existing rehabilitation robots face some limitations such as limited degrees of freedom, portability and capability trade off and customizability. Most of the devices lack the ability to accommodate the wide range of disabilities and recovery stages for clinical use. The primary research gap lies in the need for a rehabilitation robot that combines high degrees of freedom with portability, affordability, and adaptability. This would enable comprehensive hand and wrist rehabilitation while addressing the practical challenges of usability in clinical and home environments. As highlighted by Hasan et al. [36], integration of biomechanical design principles with robust control strategies to enhance therapy effectiveness and patient outcomes is needed.

The robot under consideration in this study possesses several notable features when compared to existing systems. These features include portability on the hand-wrist, non-disruption of natural exercise, lightweight design, sufficient power generation, safety, high potential for faster recovery, and cost-effectiveness in comparison to immobile systems.

The hand-wrist rehabilitation system developed in this thesis incorporates an active actuator model in the control box, thus ensuring that it does not disrupt the natural movements of the hand and can perform stretching and strengthening stages. A novel four bar mechanism supported position controller is developed which is equipped with Bowden cable transmission. The electrical actuators that facilitate hand movement have been selected based on their lightweight and the ability to generate the necessary power. The upper exoskeleton system, equipped with Bowden cable transmission, has been engineered to ensure that it does not interfere with the anatomical structure of hand and wrist movements. The flexibility of the Bowden cables ensures that the motors can be placed away from the hand, reducing the weight on the exoskeleton and enhancing portability. This approach combines the lightweight design of Bowden cables with the mechanical efficiency of the four-bar linkage, providing an effective solution for finger movement control while maintaining user comfort and safety. Despite the challenges like limited force transmission and friction losses, Bowden cables still remain a popular choice for lightweight and flexible transmission systems, especially in portable and wearable devices like rehabilitation robots. A brief comparison between existing and the proposed design are given in Table 1.

The robot presented in this study is designed to overcome the limitations by providing 18-DOF, which supports a broader range of natural hand and wrist movements compared to conventional devices. The exoskeleton-based approach ensures compatibility with the human anatomy, enabling precise and comfortable motion assistance. Moreover, advanced control algorithms adjust the robot's support and resistance levels based on patient performance, facilitating personalized therapy. The design is optimized for both clinical and home use, ensuring portability without compromising functionality. Integrated safety mechanisms and a user-friendly interface prioritize patient comfort and ease of operation. The novelty lies in the design of newly proposed four-bar movement mechanism, and the potential benefits of this study include hand and wrist joint exercise simultaneously, portability, low-cost manufacturing and, high safety.

The paper continues with the kinematical design concepts and the mechanical construction. Section three gives theoretical concepts briefly. In the fourth section, experimental

Table 1 Differences of proposed design from the existing systems

Research	DOF	Movement Type	Exercise Type	Control Type	Power Transmission
A.Lince [2]	8 DOF	FLE/EX	Passive and active	Position control	Cable
D. Astarita et al. [3]	6 DOF	FLE/EX-AD/AB	Passive and active	Torque—position control	Link and spring
E. Peperoni et al. [7]	5 DOF	FLE/EX	Passive and active	Torque control	SEE
Y. Hasegawa et al. [33]	11 DOF	FLE/EX- AD/AB	Passive and active	Torque—position control	Link
C. Fleischer [34]	20 DOF	FLE/EX- AD/AB	Passive and active	EMG-Empedance and Position control	Cable + Link
U. Mayetin and S. Kucuk [41]	3 DOF	FLE/EX RA/UL	Passive and active	Empedance, torque and position control	Timing Belt + Bevel Gear
Proposed Robot	18 DOF	FLE/EX- AD/AB-RA/UL	Passive, izometric and active	Empedance, torque and position control	Cable

FLE/EX: Flexion/Extension, AD/AB:adduction/abduction, SEE, Series Elastic Element, RA/UL:Radial/Ulnar study is explained and the results are presented with discussions. Conclusion of the current work and the possible future improvements are described in the last section.

2 Design and Kinematics of Cable Driven Robot

The hand is situated at the distal end of the upper extremity and comprises three main components: the wrist, metacarpal bones, and fingers (digits) [9, 42]. The hand and forearm are interconnected and articulated through the wrist joint. The palm and fingers collectively constitute the hand structure. Within the hand, there are three distinct groups of bones: phalanges, metacarpal bones, and carpal bones. The bones of digits 2–5 (index finger, middle finger, ring finger, and little finger) consist of proximal, middle, and distal phalanges. Digit 1 (thumb) consists of a distal phalanx, a proximal phalanx, and a metacarpal bone. The palm area is formed by the convergence of the metacarpal and carpal bones. The hand and forearm maintain their functional connection through the wrist joint. Flexion and extension are possible in the metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint. Abduction and adduction in the MCP joint are another possible motion. The primary anatomical movements of the wrist and fingers that are considered in the design of exoskeleton systems are shown in Fig. 1. The movements of the proposed design presented in Fig. 2. For the wrist, the figure highlights flexion/extension and radial/ulnar deviation, which are essential for positioning the hand in daily tasks. For the fingers, it shows flexion/extension and abduction/adduction movements at the metacarpophalangeal (MCP) joints, which are critical for grip and manipulation functions. These movements form the basis for the rehabilitation exercises and kinematic modelling of the proposed robot, ensuring compatibility with the natural range of motion and functionality of the human hand.

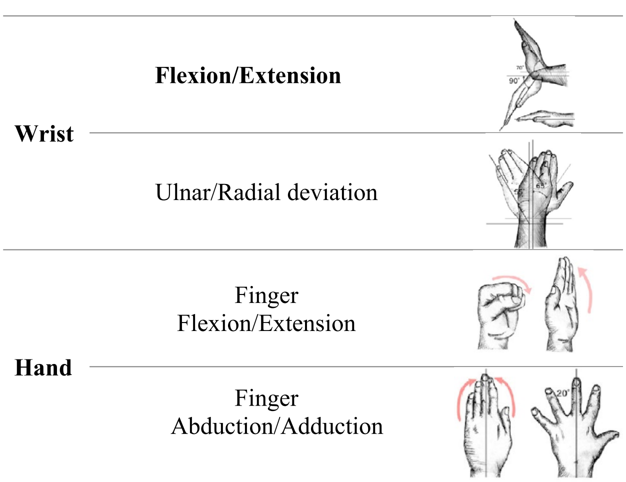

Fig. 1 Primary anatomical movements of the wrist and fingers [43, 44]

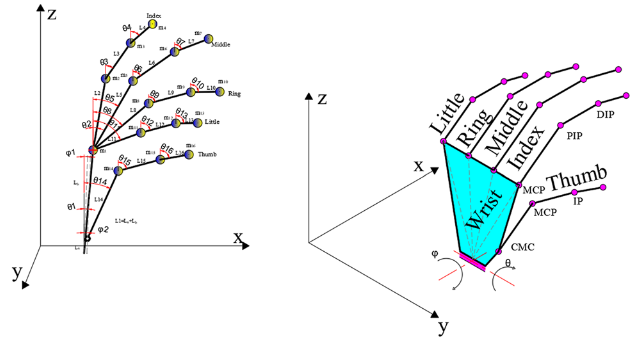

Fig. 2 18 DOF hand-wrist model, (teta: flexion/extansion, fi:ulnar/radial deviation)

The biomechanical model of the hand considers the structure of the limbs and their degrees of freedom. The interphalangeal (IP) and DIP joints have only one degree of freedom, allowing flexion and extension. The carpomatecarpal joint and MCP joints have two degrees of freedom, enabling both flexion/extension and abduction/adduction. Similarly, the wrist joint also possesses two degrees of freedom, allowing for flexion/extension and abduction/adduction [45]. The hand comprises the trapeziometacarpal (TM), metacarpophalangeal (MCP), and Metacarpal (MC) joints, each possessing 2 degrees of freedom for flexion/extension and adduction/abduction movements, while the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints exhibit 1 degree of freedom for flexion/extension movements [46]. It has been standardized that robot grippers are capable of executing sixteen fundamental grasping and holding manoeuvres [47, 48]. The wrist joint is situated between the radius and carpal bones. Therefore, this robot has 18 DOF including wrist's radial/ulnar deviation.

The kinematic design of the system is given in Fig. 3 which is an end-effector type mechanism. The parts of the system are numbered from 1 to 10 on the figure. Exoskeleton system enables each finger joint motion by using a four-bar mechanism on each segment to provide effective force transmission and smooth motion assistance while maintaining user comfort and system compactness. This mechanism is given in Fig. 4. The first three links of the mechanism are connected to each other. Fourth bar is the base of the finger itself. The actuation force is transmitted to the fingers via Bowden cable supports. The torque and force requirements at each joint are calculated to ensure adequate movement assistance. The torque generated by the motor is converted into linear force through the Bowden cable. The force applied to the inner cable moves the corresponding linkage in the four-bar mechanism. The mechanism linkage translates the linear force into angular

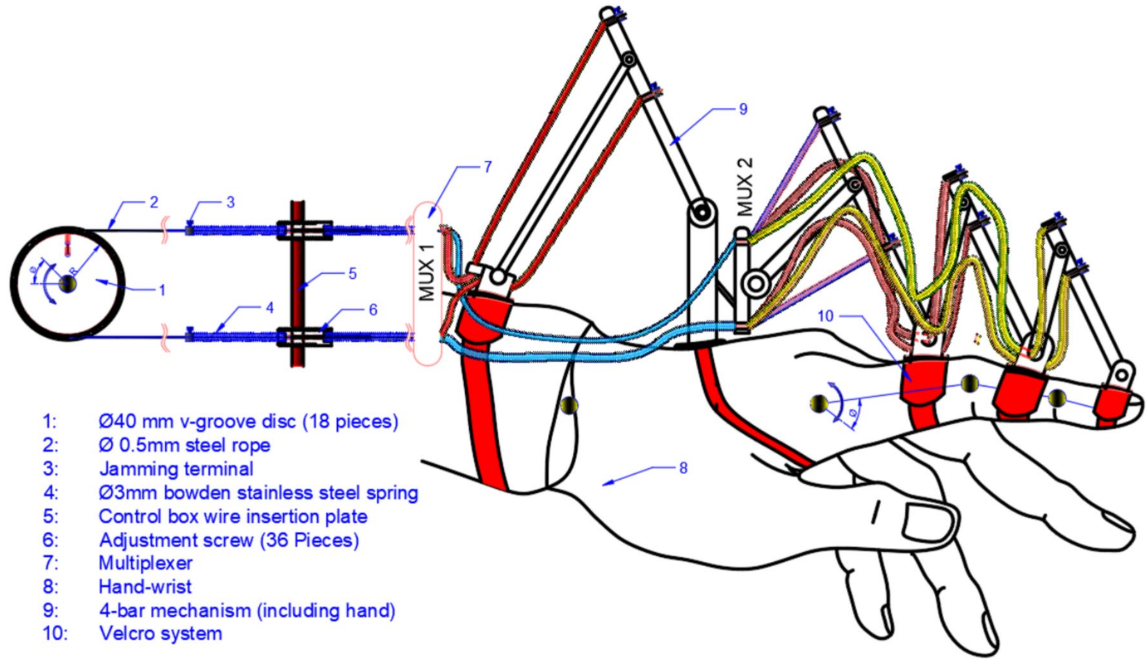

Fig. 3 Kinematic design of the proposed rehabilitation robot

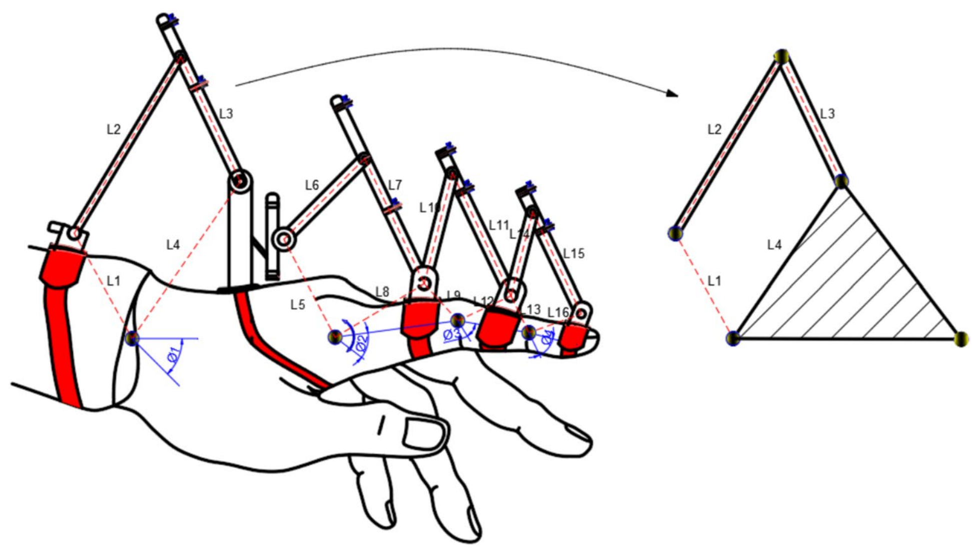

Fig. 4 Transmission system with four-bar mechanism on the hand

motion, enabling the desired flexion or extension of the finger joints. This setup ensures smooth and controlled motion across the finger's natural range of motion. For each five-digit, individual Bowden cables for each joint (e.g., MCP, PIP, DIP), are utilized. The placement of Bowden cables optimized manually to provide efficient force transmission with minimal resistance. The Bowden cable system in the proposed rehabilitation robot serves as a flexible and efficient transmission mechanism to control finger movements. The Bowden cable consists of an inner cable that slides within a flexible outer sheath. The inner cable transmits the actuation force from the motor located remotely in the control unit to the finger joints, allowing precise and controlled motion [49, 50].

2.1 Production of Prototype Robot

The system is manufactured and assembled by practical engineering tools at the universities' workshop. However, a more compact and precisely engineered robot can be manufactured for the final use. By focusing on portability, ease of use, and safety, the proposed system offers a reliable and effective platform for hand and wrist rehabilitation. The system is composed of several key components, as depicted in Fig. 5. These include the control unit, control panel, robot manipulator, and end-effector [42]. Each component is engineered to ensure reliability and compatibility with the overall system. The control unit houses the power supply, motor drivers, and electronic components required for precise actuation and control [31]. The unit is enclosed within a durable yet lightweight cover made of polymer materials to reduce overall weight while ensuring protection from environmental factors. DC motors with encoders are used to provide accurate position and torque feedback, enabling precise control of the rehabilitation exercises. The manipulator forms the core of the mechanical system and includes an upper arm support mechanism, a wrist movement transmission mechanism, and a hand support mechanism. The arm support mechanism is shown in Fig. 6. It consists of parts labelled digits 1 to 7. The assembly comprises the below arm support mechanism (1), adhesive tapes (2), upper arm upper support mechanism (3), wrist movement transmission mechanism (4), hand support mechanism (5), end effector slide mechanism (6), and adjustment screw (7). The upper arm support mechanisms are fabricated from genuine fibre glass material, while the remaining components are constructed from metallic iron to ensure rigidity. The manipulator's modular design ensures easy assembly and maintenance. The end-effector, shown in Fig. 7, is designed to accommodate the individual fingers and thumb. It consists of segmented parts for each digit, allowing independent movements. The integration of a four-bar mechanism further enhances the accuracy of the finger movements. The transmission system relies on Bowden cables for force delivery, minimizing the weight on the user's hand while maintaining flexibility. The Bowden cable transmits actuation forces from the control unit to the end-effector, ensuring smooth and precise motion. The cables are routed through strategically positioned guides to reduce friction and ensure efficient force transmission. Additionally, emergency stop buttons and safety mechanisms are incorporated to immediately halt operations in case of system faults, prioritizing user safety.

To optimize portability, the mechanical components are selected to be lightweight. The control box, made of transparent plexiglass and iron parts, ensures durability without compromising visibility and accessibility. The entire system can be easily transported and installed, making it suitable for home-based and clinical rehabilitation. Since the whole

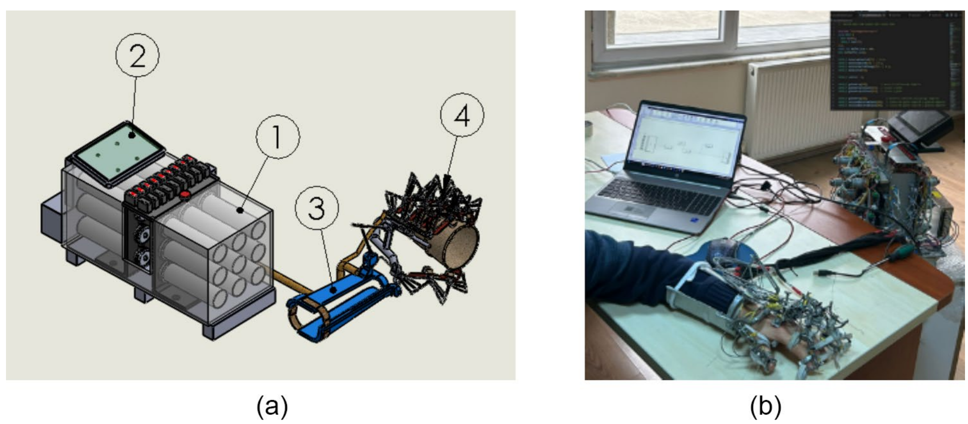

Fig. 5 (**a**) The CAD model (**b**) manufactured prototype of rehabilitation robot

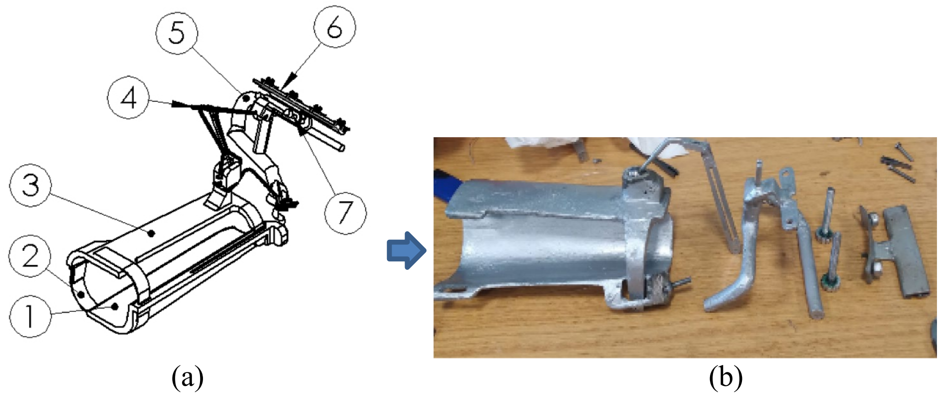

Fig. 6 Robot manipulator **a**) The CAD model **b**) Mechanism linkages

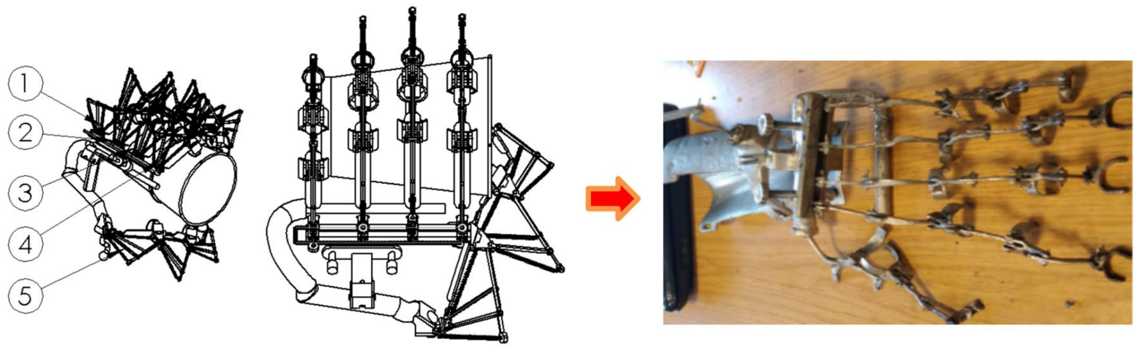

Fig. 7 End effector

components manufactured at the workshop, the appearances are not delicate. However, a more compact and precisely engineered robot can be manufactured for the final use.

2.2 Electronic Hardware

The control strategy is based on adaptive programming algorithms [51]. A single electronic board has been built for controlling each motor separately. This control structure is shown in Fig. 8. High technology instruments were used for the control architecture in the literature [52–57], Since the electronic products costs are increasing, we used an Arduino Mega 2560 Pro board with 16 MHz operating frequency for control and management of the whole system. A C code is developed for the main work. The management of the whole system consists of many sub-units as seen on block diagram in Fig. 8. The main control board works together with power management board and motor driver board. A DC gear motor with encoder is used to actuate the system via Pulse Width Modulation (PWM) signal. The technical specifications of this motor are given in Table 2. Proportional control is provided via the embedded software of the main control card with the position values obtained from the encoders. Finally, all data obtained during the training is saved on the memory card.

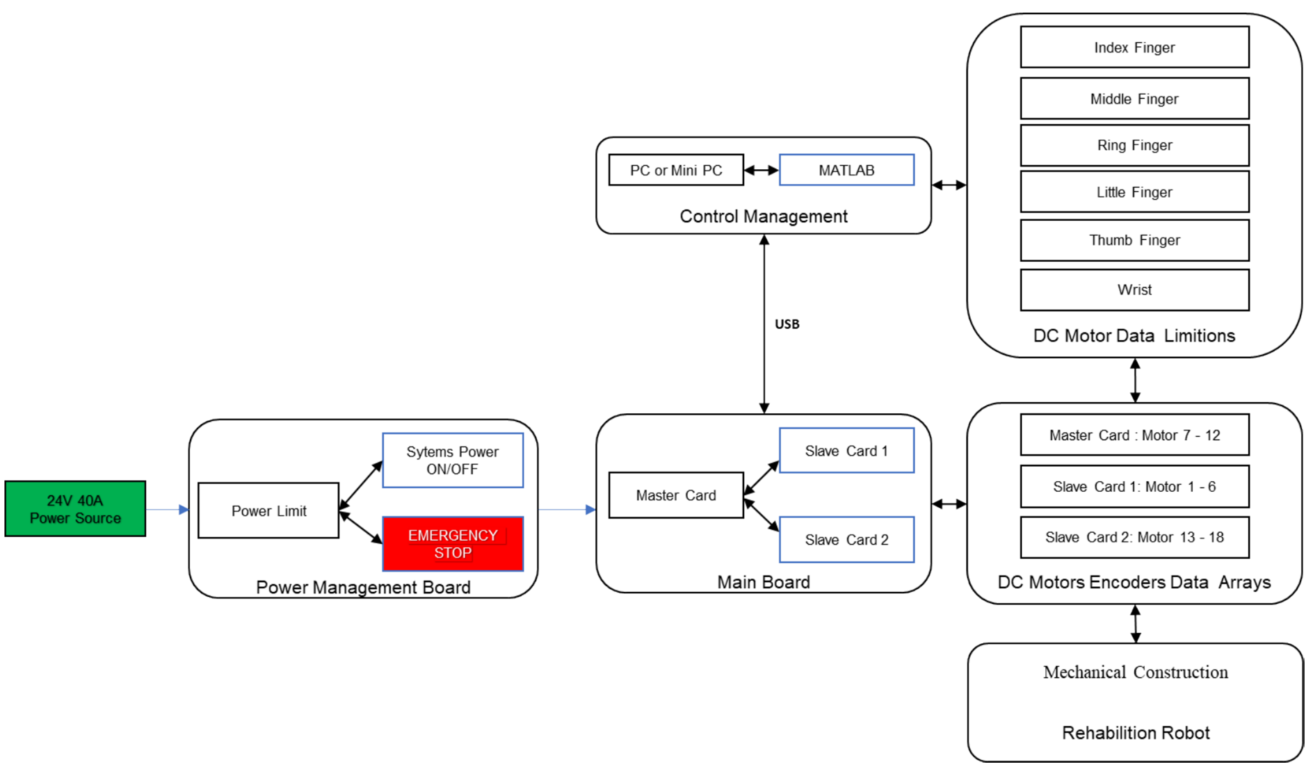

Fig. 8 The flowchart for electronic processing

Table 2 Technical specifications of the motor

Type	*Model*	*Ope.voltage*	*Gearration*	*Ratedtorque*	*Max.Loa.Cur.*	*Weight*
DFrobot	28*PA*51*G*	12*V*	56 : 1	10*kg.cm*	3.6*A*	270*g*

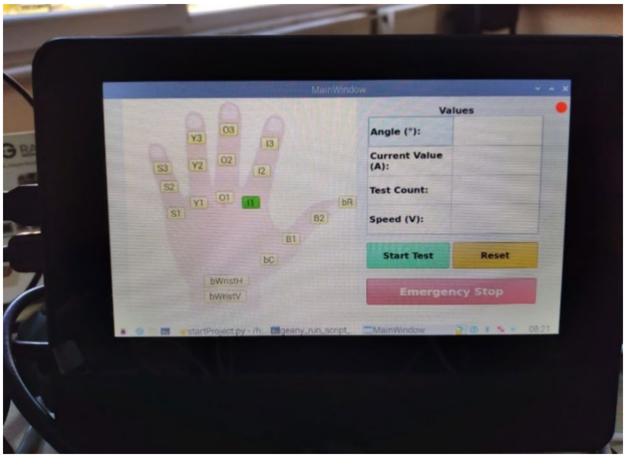

Fig. 9 The graphical user interface

These saved values can be examined by a physical therapist to evaluate the training. Experimental data were obtained from the encoders of DC motors compatible with the system designed for the hand-wrist in the MATLAB environment. A computer in Windows 11, with a 64-bit operating system and a 12th Gen Intel(R) Core(TM) i7-1255U processor is used with 1.70 GHz, 16.0 GB RAM. An HMI test software in C++is developed and the graphical user interface is designed as shown in Fig. 9 which runs on Raspberry PI single-board computer. The operation interface has multiple buttons including serial connection, motor reset, stop motion, passive, active and isometric rehabilitation training, MCP joint flexion/extension, PIP joint flexion/extension, DIP joint flexion/extension, and etc. The system has two computers, namely the motor controller and the Arduino Mega2560 microcontroller. Both computers use serial to communicate with the host computer. The computer is responsible for communicating with the Arduino Mega2560 and receiving the angular acceleration value of the encoders. After the main unit receives the information transmitted by Arduino Mega2560, it will send the data to the basic program, and the main computer will control the motion of the motor according to the data. The working steps is given in Algorithm 1.

Algorithm 1 Working steps

Step 1.	The power supply turns on. 220V energy is provided to the system
Step 2.	The gearbox cycle ratio is determined.
Step 3.	Angle value is received with the encoder on each motor. Initial reference position values are reset. Reference angle is entered.
Step 4.	IBT-2 H-bridge driver with 18 PWM inputs is used to drive the motors. These H-bridges come into play.
Step 5.	PWM signals are generated and converted to angle and velocity values.
Step 6.	Desired angle, frequency, number of repetitions and durations for the exercise are entered.
Step 7.	All data is recorded in MATLAB.
Step 8.	Stop the system if the values in step 7 are obtained.

2.3 Safety System

Failure to any desired rule may result with unwanted injuries. It is necessary to provide full confidence to the patients about the proposed rehabilitation robot that it is safe and the user alone can stop it immediately if something different rather than the ordinary protocol happens. Hence, a multistage safety protocol is preferred instead of providing security management by a single control unit. In traditional safety methods, movement limits were restricted to a certain extent by the limbs. In this study, besides limiting the movements, an emergency button has been added apart from the traditional designs. In this way, the energy input of the system can be interrupted and the operation can be stopped. On the other hand, the electronic software will automatically select the safe range when the speed, current, motor PWM frequency and repetitions exceed the minimum and maximum values. This range is predetermined for each motor. The work flow of this safety structure is given in Fig. 10.

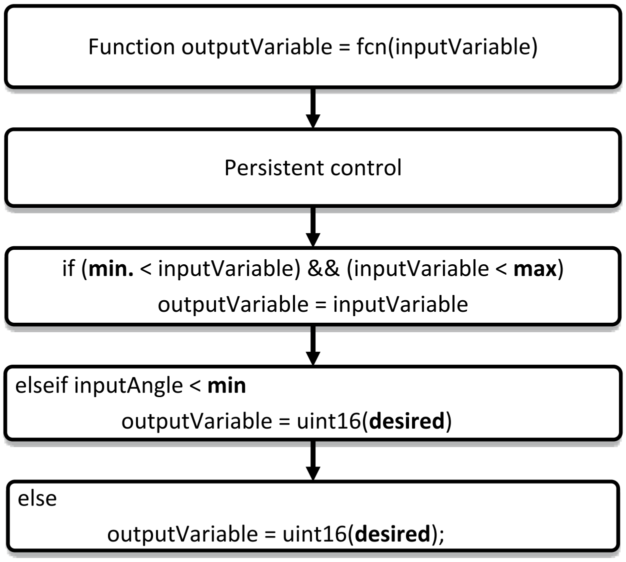

Fig. 10 The safety algorithm

In the system, the emergency button (DRN958, 16 mm) is utilized to promptly shut down the entire system for safety reasons, while the on–off button (DC118, 2 cm, 3P) serves for mechanical activation and deactivation of each motor. Additionally, a digitally adjustable 0-24 V, 40 A metal-case power supply, suitable for electronic circuits operating at 12 V, was employed as the power adapter.

3 Mathematical Model

A simplified mathematical model has been developed based on the principles of Lagrangian mechanics for solving the joint-limb model presented in this study [58]. Lagrange's method is based on the system's energy, independent of the forces applied to the system. The dynamics of the muscles and tendons, friction, and other disruptive effects have been neglected during deriving the general dynamic equations for simplicity.

The Lagrangian for a system of particles in the absence of an electromagnetic field is given as the difference of kinetic and potential energies. T is the kinetic energy and V is the potential energy, i serves for each joint that is regarded as DOF of fingers and j serves for wrist's DOF.

$$T_i = \frac{1}{2} m_i v_i^2 \ \rightarrow i = 1:16, \ \ V_i = m_i g h_i \ \rightarrow i = 1:16 \qquad L = T - V \tag{1}$$

m is the mass, v is the velocity and h is the height of the i th mass. Taking time derivative for each generalized coordinates, the final Lagrange equations due to the applied torque τ are obtained in Eq. (2) – Eq. (3).

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \tau_i \ \ i = 1:16 \tag{2}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}_j}\right) - \frac{\partial L}{\partial \varphi_j} = \tau_j \ \ j = 1:2 \ \begin{cases} j = 1 \rightarrow \tau_{17} \\ j = 2 \rightarrow \tau_{18} \end{cases} \tag{3}$$

The dynamic equation of a robotic system in a joint space is:

$$\tau = M(q)\ddot{q} + V(q, \dot{q}) + b(\dot{q}) + G(q) + \tau_{ext} \tag{4}$$

where τ is the 18×1 joint torque vector, M(q) is the manipulator inertia tensor, q, $\dot{q}$ and $\ddot{q}$ are the 18×1 joint position, velocity and acceleration vectors, $V(q,\dot{q})b(\dot{q})$ and $G(q)$ are 18×1 Coriolis and centrifugal, friction and gravity force vectors, respectively. τ_{ext} is the 18×1 torque vector that occurs due to unknown external effects [59]. The friction and gravity effects were neglected for simplification. The reference motion is tracked with a position controller. The admittance that maps the applied torque to the angular references for each joint is modelled by the formula:

$$\tau_a = M_d \ddot{q}_r + B_d \dot{q}_r + K_d q_r \tag{5}$$

where τ_a, M_d, B_d and K_d represent applied torque, desired inertia, viscosity and stiffness matrices, respectively. q_r, $\dot{q}$ and $\ddot{q}$ are reference joint angle, angular velocity and angular acceleration respectively. Each joint equation is modelled individually. The coupling effects are neglected. Therefore, the Eq. (5) can be represented in the frequency domain as:

$$\ddot{\varphi}_j = \frac{\tau_j + \frac{d}{dt}\left(\frac{\partial L_T}{\partial \dot{\varphi}_j}\right) - \frac{\partial L_T}{\partial \varphi_j}}{Mi} \tag{6}$$

The reference motion is generated by assigning the desired values to parameters in the Eq. (6), and the position controller follows for tracking the reference motion (Fig. 11). The equations containing the mathematical model of the system are large-scale and time-varying inputs, they were transferred to the Simulink environment as MATLAB-System-function. Forward kinematic solution was performed and simulations on position and position-torque control were obtained for passive, active and isometric exercises. The Simulink model for the control of the rehabilitation robot system is shown in Fig. 11.

The rehabilitation robot is designed according to the standardized anatomical hand measures which are given in Table 3 [2]. In the table, the first column shows the phalanges, the second column shows the flexion angle in radians, the third column shows the extension value as negative, the fourth column shows the motor's PWM frequency in Hertz, the fifth column

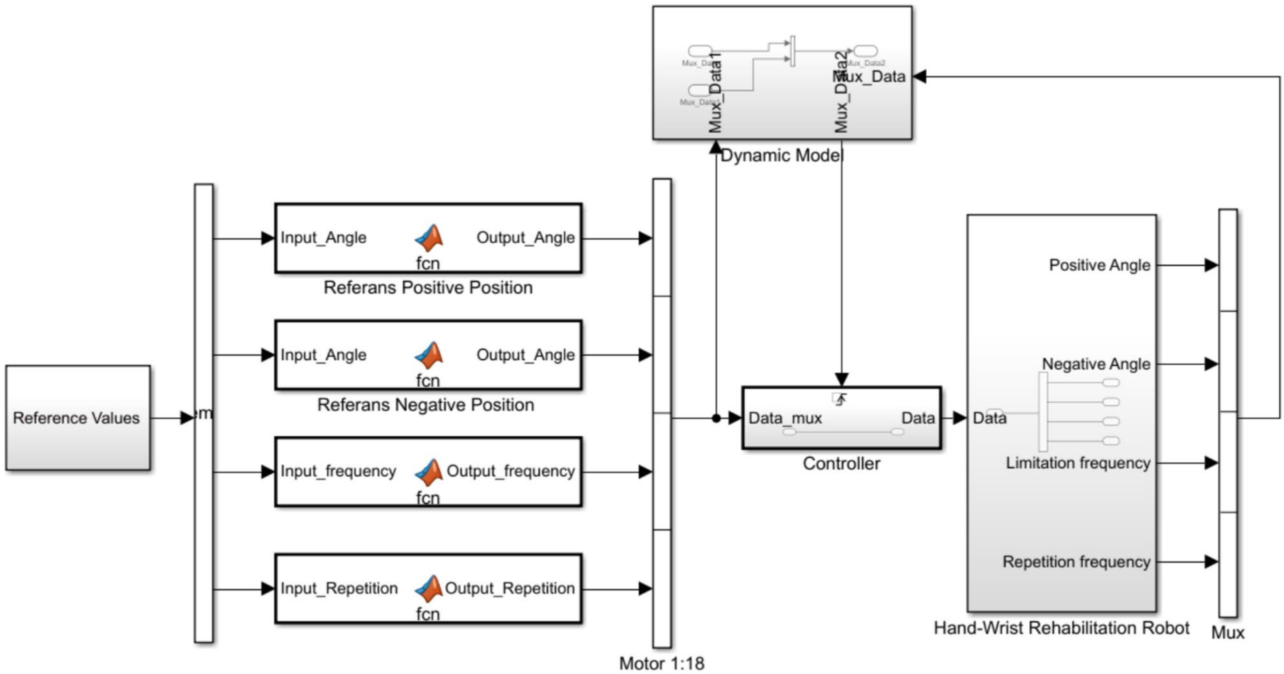

Fig. 11 Simulink model of the hand-wrist system

Table 3 Experimental protocol for exercises

Phalanx		Flexion (rad)		Extension (rad)		Motor PWM Frequency. (Hz)		Repetition		Time (s)	
		Pas-izo	Act	Pas-izo	Act	Pas-izo	Act	Pas-izo	Act	Pas-izo	Act
Index	MCP	0.87	0.87	0.26	0.26	32	22	3	3	20	20
	PIP	1.05	0.79	0	0	20	13	3	3	20	20
	DIP	0.79	0.52	0.05	0	20	12	5	3	20	20
Middle	MCP	0.87	0.87	0.26	0.26	35	25	3	3	20	20
	PIP	1.05	0.79	0	0	30	20	3	3	20	20
	DIP	0.79	0.52	0.05	0	20	12	5	3	20	20
Ring	MCP	0.87	0.87	0.26	0.26	32	22	3	3	20	20
	PIP	1.05	0.79	0	0	30	20	3	3	20	20
	DIP	0.79	0.52	0.05	0	20	12	5	3	20	20
Little	MCP	0.87	0.87	0.26	0.26	32	22	3	3	20	20
	PIP	1.05	0.79	0	0	30	20	3	3	20	20
	DIP	0.79	0.52	0.05	0	20	12	5	3	20	20
Thumb	TMC	0.52	0.52	0.14	0.14	30	22	3	3	20	20
	MCP	0.79	0.79	0	0	30	20	3	3	20	20
	IP	0.79	0.52	0.05	0	20	15	5	3	20	20
	Ab/Ad	0.44	0.44	0.44	0.44	25	20	3	3	20	20
Wrist	Fl-Ex	0.87	0.87	0.52	0.52	50	20	3	3	20	20
	Ra-Ul	0.17	0.17	0.34	0.34	25	15	3	3	20	20

shows the number of repetitions and finally the sixth column shows the duration of the exercise in seconds.

Torque of the motor is calculated due to the motor's angular velocity as,

$$\tau = \frac{VxI}{\omega}x0.02388, \ \omega = 2\pi f \tag{7}$$

V is the voltage in Volts and I is the current in Amps.

4 Experimental Study

The most common therapy exercises are given in [59] with detailed explanations. As this study is performed with healthy subject, the passive, isometric, and active exercises were selected. All procedures on human subjects were conducted in accordance with the ethical standards of the Declaration of Helsinki. A 34-year-old healthy male volunteer subject who has signed an informed consent form carried out experiments. For this pilot study, no ethical approval was required in accordance with ethical guidelines. He was wearing the exoskeleton on his left hand and wrist. After setting the relevant exercise and velocity, the rehabilitation started. The raw data is collected from the encoders connected to the Arduino Mega2560 microcontroller and sent to the main computer. After noise removal, the data is used for analysis. Passive range of motion (ROM) exercises are conducted to enhance joint flexibility in patients experiencing limited or no mobility in their hand or wrist. Passive rehabilitation is mostly used in the early stage of rehabilitation, which involve maintaining a passive position. The primary focus lies in ensuring completion of prescribed exercises rather than achieving time-critical rehabilitation objectives.

Trajectory control of the hand-wrist, and repetitive control experiments were performed. Several limitations were imposed in experimental exercises for safety reasons. To ensure the safety of the hand and wrist, exercises were conducted within a range of around 60% of the full range of motion. In passive and isometric exercises, MCP phalanx tension below 30 Hz were negative. Particularly in passive and isometric exercises involving the middle finger, MCP phalanx tension did not function effectively below 35 due to its inherent nature and power requirements. A total of 54 distinct trials were done for each phalanx, encompassing passive, isometric, and active conditions, with 3 to 5 repetitions of 20 seconds..

4.1 Passive ROM Exercise

This section presents passive exercises for the flexion–extension, radial-ulnar, and abduction–adduction movements of the hand and wrist robot. Passive exercises are applied in the early rehabilitation period after the onset of disability. In these exercises, patient involvement in the rehabilitation movement is minimal. Therefore, the rehabilitation robot is fully active. All exercise protocols adhered strictly to predefined limits specified within the works. Figure 12 (a-b-c-d) illustrate the passive exercise results for flexion–extension and radial-ulnar deviation of the wrist for 20 seconds. The desired position and measured actual position values are represented as red dashed line and blue straight line on the figures, respectively.

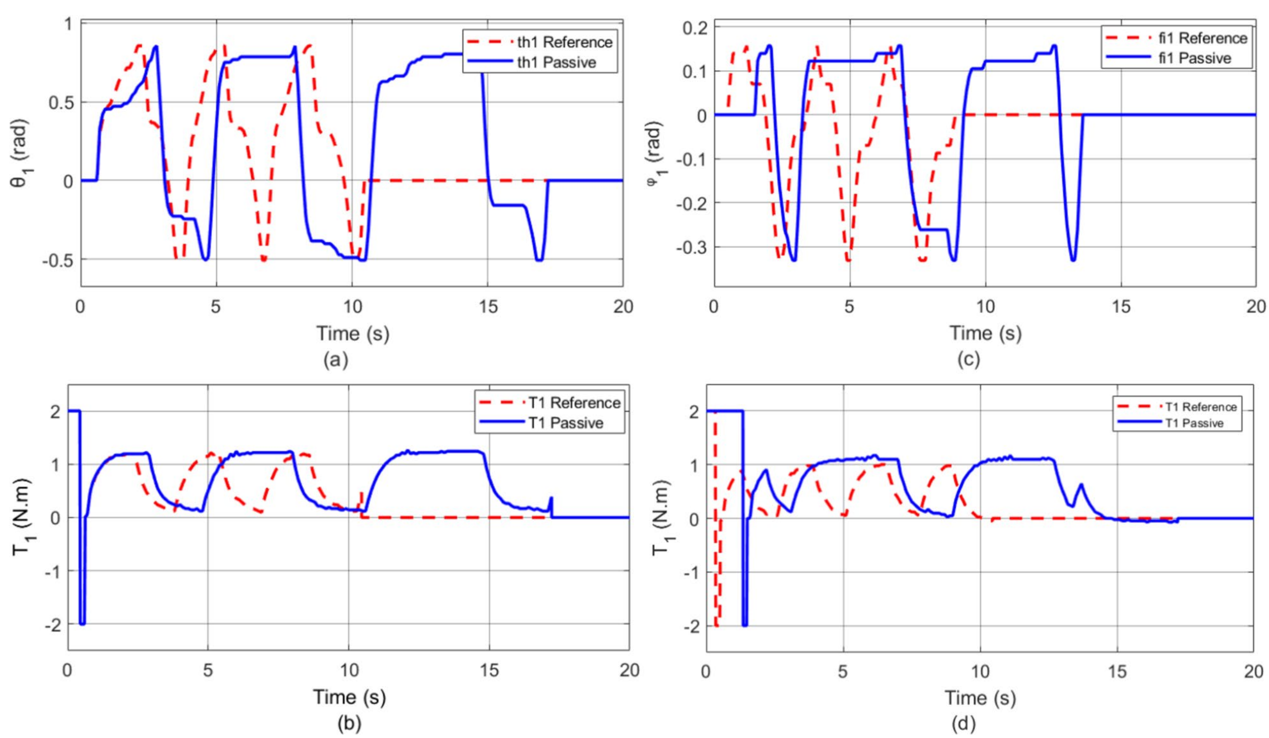

Fig. 12 The passive exercise of the wrist a-b) flexion–extension, and c) d) radial-ulnar angle and torque

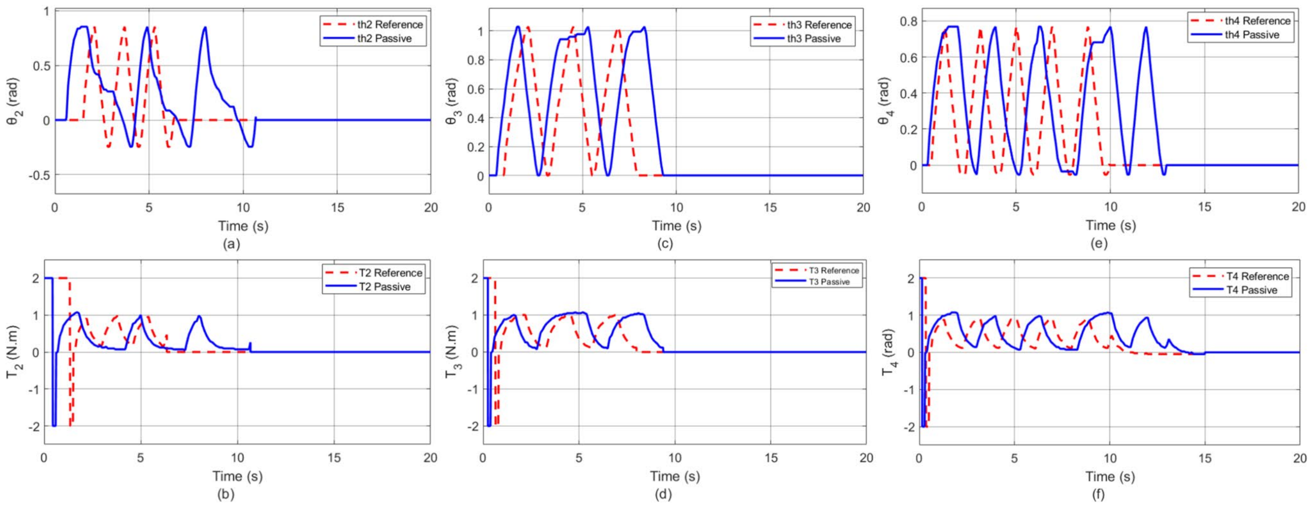

Fig. 13 The passive exercise of the index finger a- b) MCP, c-d) PIP, e–f) DIP angle and torque

Torque values denote the desired trajectory position and measured torques.

According to the wrist flexion–extension experiment, the maximum flexion angle can be obtained as 0.87 radians (49.8 degrees) and the extension angle is obtained as 0.52 radians (29.7 degrees). The maximum radial deviation can be obtained as 0.17 radians (9.7 degrees) and the ulnar deviation is obtained as 0.34 radians (19.4 degrees). As of the three trials, the maximum flexion and extension values and the radial and ulnar deviations were reached. However, the response is slower than the desired trajectory. The deflections may be due to friction and the Bowden cable. The torque values are 1.2 Nm for maximum flexion. According to the figures, the follow-up performance of the mechanism is good.

In Fig. 13, the passive exercise results for MCP, PIP and DIP joints of the index finger are presented.

From the figures, it can be seen that the maximum flexion and extension angles in Table 3 are reached for each MCP, PIP and DIP joints.

Figure 14 displays the passive exercise graphs for MCP, PIP, and DIP joints of the middle finger.

Figure 15 shows the passive exercise graphs for MCP, PIP, and DIP joints of the ring finger.

In Fig. 16, the passive exercise graphs for MCP, PIP, and DIP joints of the little finger are depicted.

Figure 17 and Fig. 18 depict the passive exercise graphs for TMC, MCP, IP and abduction–adduction movements of the thumb, respectively.

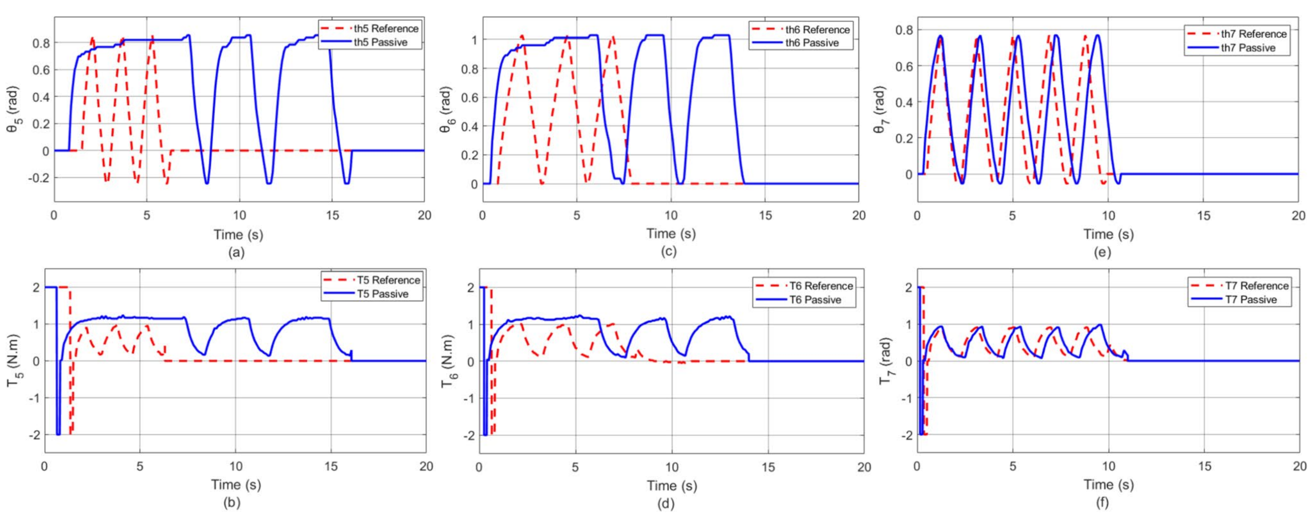

Fig. 14 The passive exercise of the middle finger a- b) MCP, c-d) PIP, e–f) DIP angle and torque

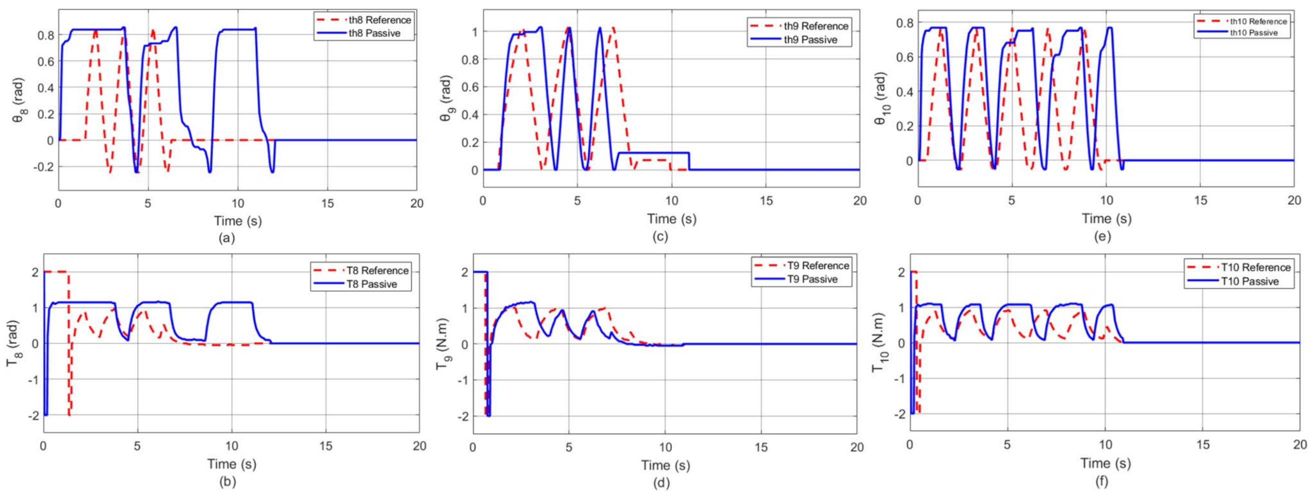

Fig. 15 The passive exercise of the ring finger a-b) MCP, c-d) PIP, e–f) DIP angle and torque

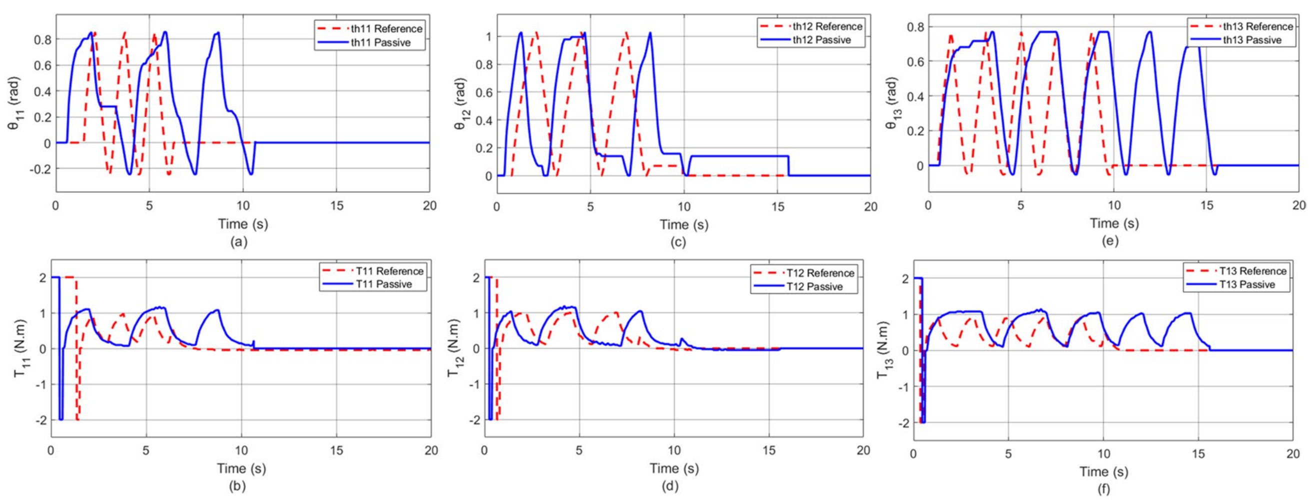

Fig. 16 The passive exercise of the little finger a-b) MCP, c-d) PIP, e–f) DIP angle and torque

The passive exercise results are in good accordance with the proposed flexion–extension and abduction -adduction values. There seems a delay in time, that can be because of friction of the Bowden cable and the performance of each motor.

4.2 Isometric ROM Exercise

In isometric exercise, the patient resists the force at certain intervals for the rehabilitation movement. This resistance was applied in each repetition according to the conditions during each application. The exercises were carried out within the limits specified. In the experimental study, the trajectory of the rehabilitation robot in passive exercise was taken as a reference. Isometric exercise limits are specified in Table 3. The isometric exercise flexion–extension graph of the wrist is given in Fig. 19 a-b, and the radial-ulnar graph is provided in Fig. 19 c-d. The isometric exercise MCP, PIP, and DIP results of the index finger is given in Fig. 20.

The isometric exercise of the middle finger of MCP, PIP, and DIP is given in Fig. 21. The isometric exercise of the ring finger for MCP, PIP, and DIP is given in Fig. 22. The isometric exercise of the little finger for MCP, PIP, and DIP is given in Fig. 23. Finally, the isometric exercise of the thumb TMC, MCP, IP, and abduction–adduction are given in Fig. 24 and in Fig. 25.

4.3 Active ROM Exercise

Active exercises are the treatments in which the patient completes the movements by applying force as part of the

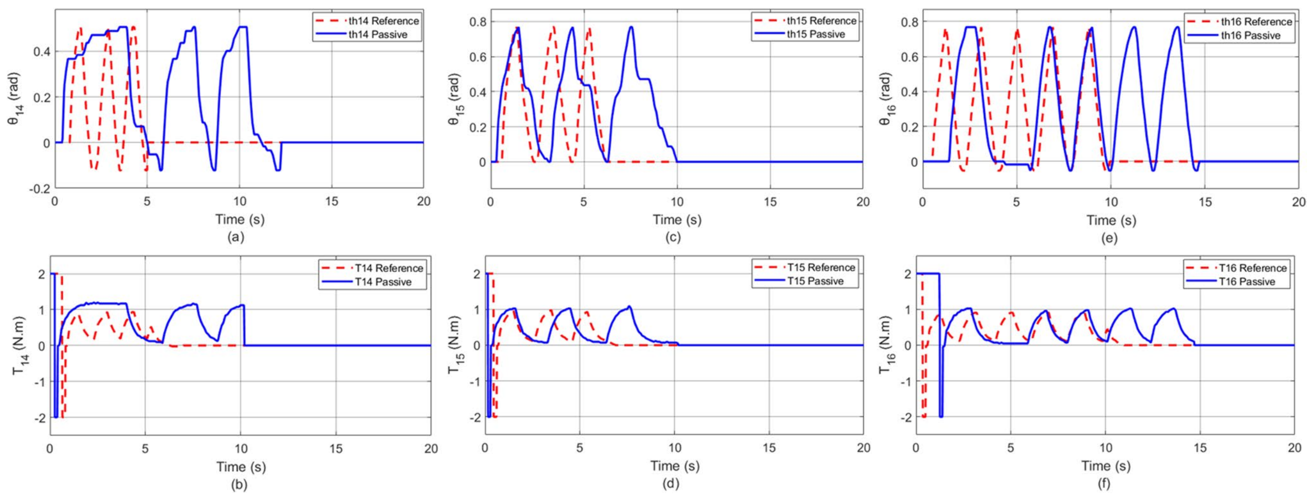

Fig. 17 The passive exercise of the thumb a- b) TMC, c- d) MCP, e- f) IP angle and torque

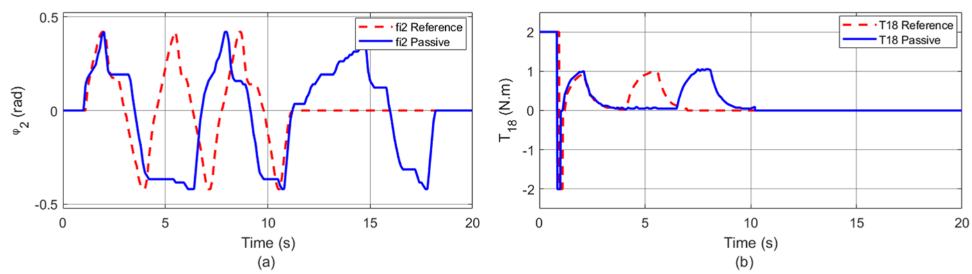

Fig. 18 The passive exercise of thumb abduction–adduction angle and torque

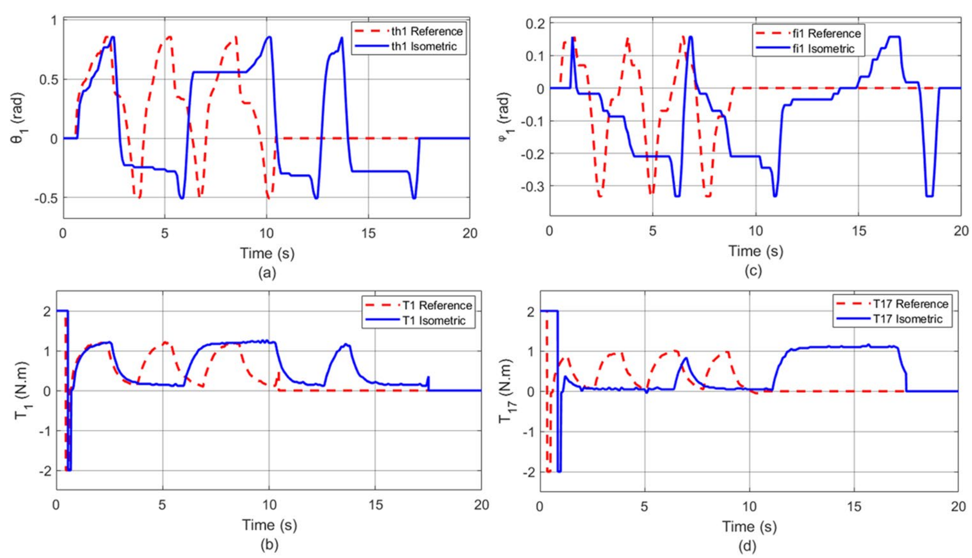

Fig. 19 The isometric exercise for wrist a- b) flexion–extension, c- d) radial-ulnar angle and torque

rehabilitation process. These exercises were performed in each repetition according to the specific conditions that arose during each practice session. The exercise protocols were conducted within the limits specified in the thesis. In the experimental study, the trajectory of the rehabilitation robot during passive exercise was used as a reference. For safety purposes, the natural range of motion of the hand and wrist was limited to 50–60% of its full capacity. Active exercises of the hand and wrist were performed under the conditions detailed in Table 3. During active exercises involving DIP

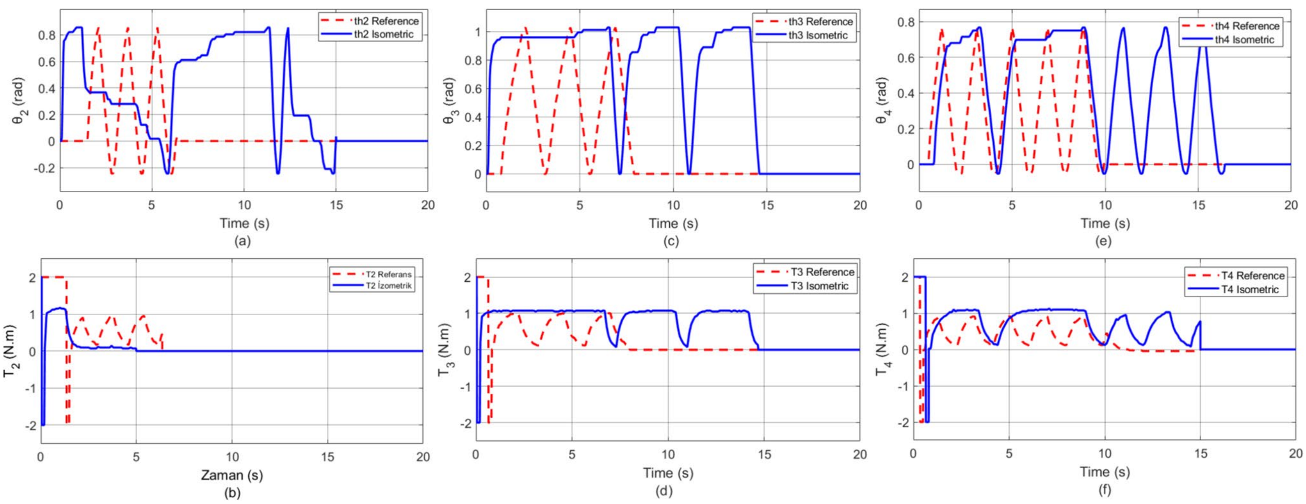

Fig. 20 The isometric exercise for index finger a- b) MCP, c- d) PIP, e- f) DIP angle and torque

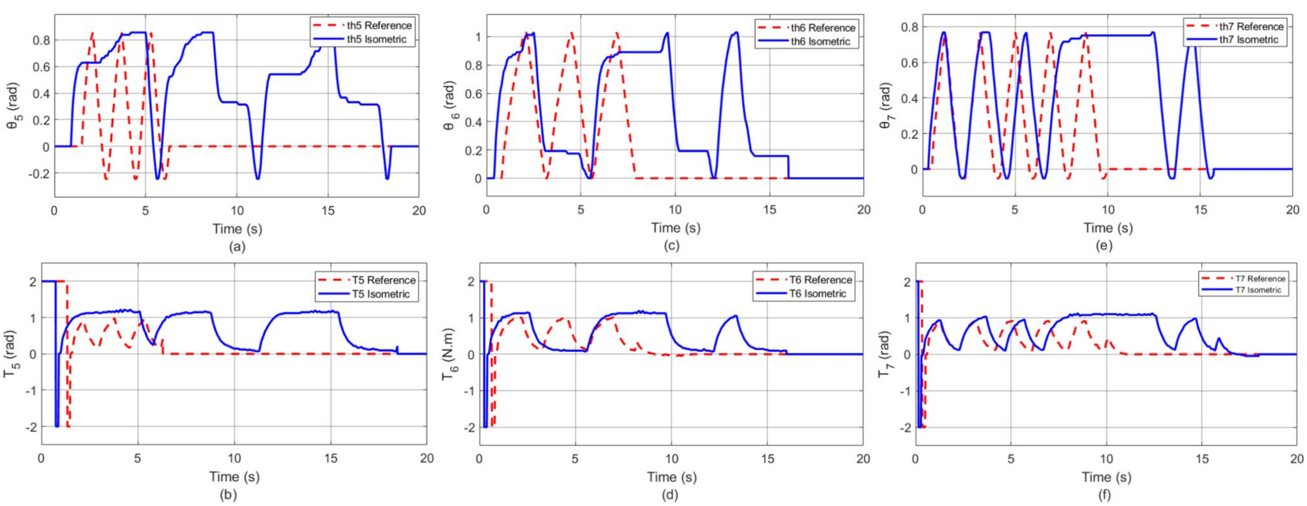

Fig. 21 The isometric exercise of the middle finger a- b) MCP, c- d) PIP, e- f) DIP angle and torque

and PIP phalanxes, the range of motion and repetitions were reduced, with the robot trajectory serving as a reference. This adjustment is specific to active exercises because independent movement of the DIP and PIP phalanxes to the reference orbit posed safety risks. The tension force on the fingers increases sequentially from DIP, PIP to MCP, providing concrete evidence of the human's natural physiology. TMC, MCP, and wrist tension values were naturally high, indicating compatibility with the natural hand functioning. The active exercise flexion–extension plots of the wrist and the radial-ulnar exercise are provided in Fig. 26. The active exercise of the index finger for MCP, PIP, and DIP are shown in Fig. 27. The active exercise of the middle finger for MCP, PIP, and DIP are given in Fig. 28. The active exercises of the ring finger for MCP, PIP, and DIP are shown in Fig. 29. The active exercises of the little finger for MCP, PIP, and DIP are provided in Fig. 30. The active exercise of the thumb for TMC, MCP, IP, and abduction–adduction are shown in Fig. 31 and in Fig. 32.

5 Results and Discussions

The preliminary experimental results of the rehabilitation robot underscore its effectiveness in performing passive, isometric, and active exercises. The collected datasets,

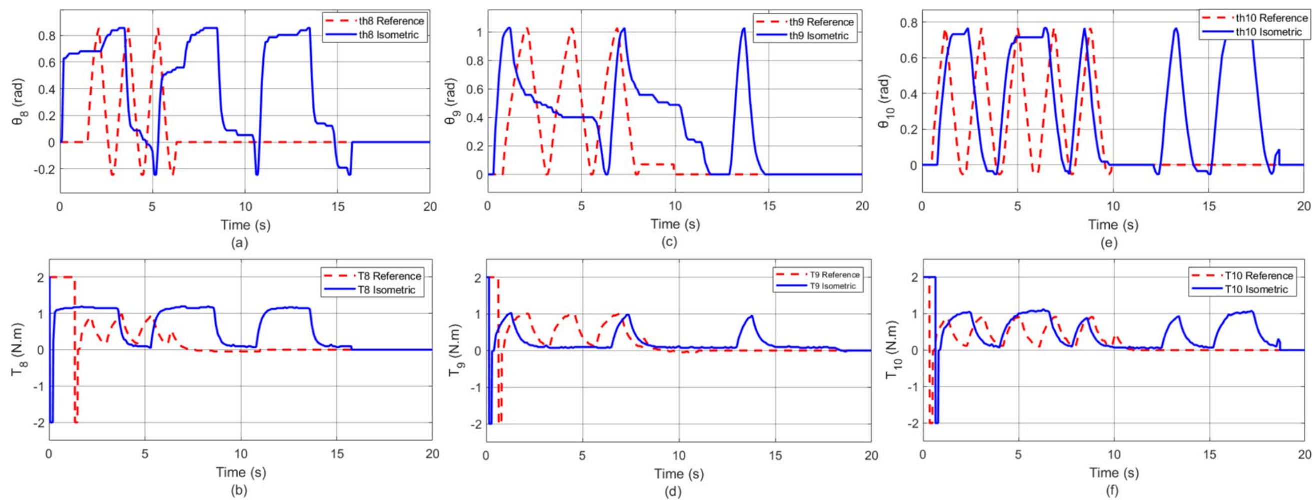

Fig. 22 The isometric exercise of the ring finger a-b) MCP, c- d) PIP, e- f) DIP angle and torque

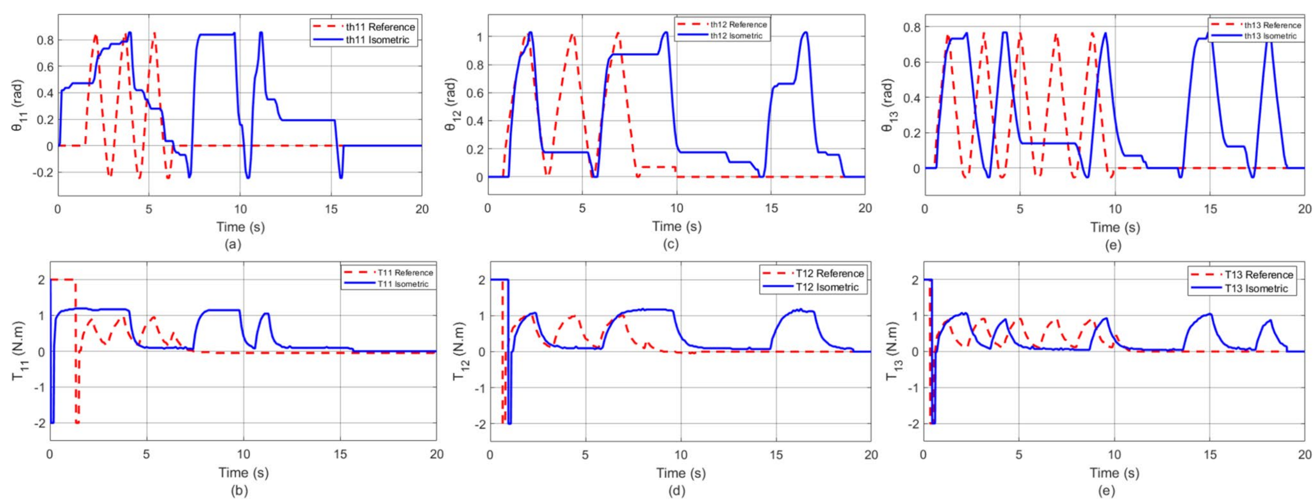

Fig. 23 The isometric exercise of the little finger a-b) MCP, c-d) PIP, e- f) DIP angle and torque

consisting of angular and torque measurements, align well with the natural physiological ranges of the human hand and wrist. This consistency demonstrates the feasibility of the proposed design for use in clinical and home-based rehabilitation settings. Compared to existing devices such as the Amadeo and Hand of Hope, which focus primarily on limited degrees of freedom and specific rehabilitation exercises, the proposed robot’s 18 degrees of freedom offer a broader range of motion and functional capabilities. Unlike systems such as the MAHI Exo II and Rice-Wrist, which rely heavily on rigid and stationary designs, the lightweight and portable nature of the proposed robot makes it more suitable for home-based applications. This aligns with the findings of S.K. Hasan et al. [36], who emphasized the need for portable and adaptable rehabilitation systems to enhance accessibility and patient compliance.

One notable observation is the robot's ability to complete the predefined motion trajectories in most test scenarios. However, challenges were observed in specific exercises, such as thumb abduction–adduction and MCP joint movements during passive exercises. These issues likely stem from the complexities of thumb biomechanics and the required torque to overcome joint resistance. Similar difficulties have been reported in other studies, such as those involving cable-driven systems by Sanjuan et al. [44], highlighting the inherent limitations of force transmission in such mechanisms. Addressing these challenges may involve refining the

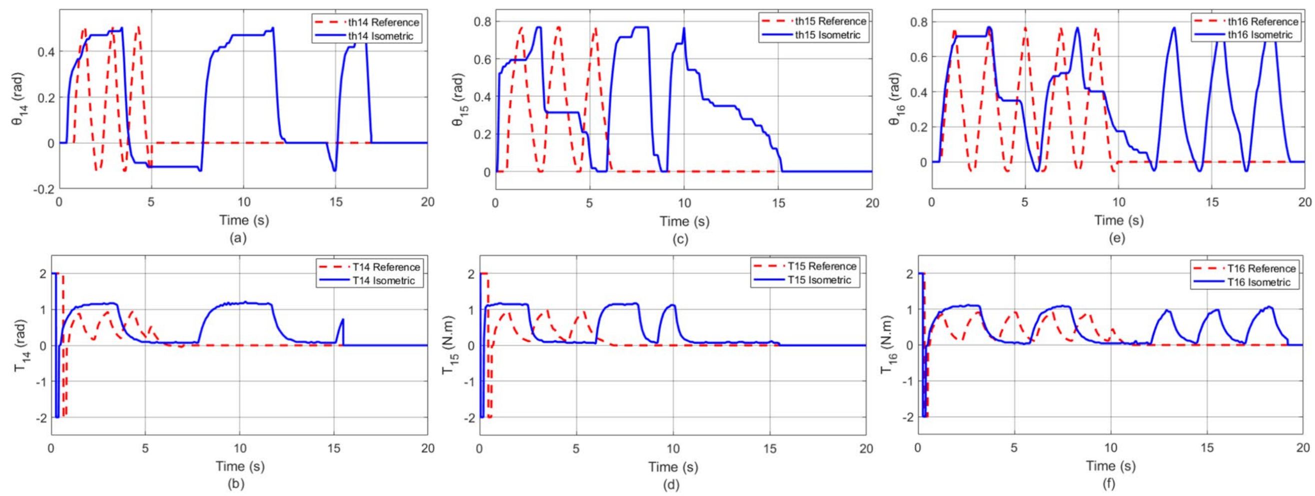

Fig. 24 The isometric exercise of the thumb a- b) TMC, c- d) MCP, e- f) IP angle and torque

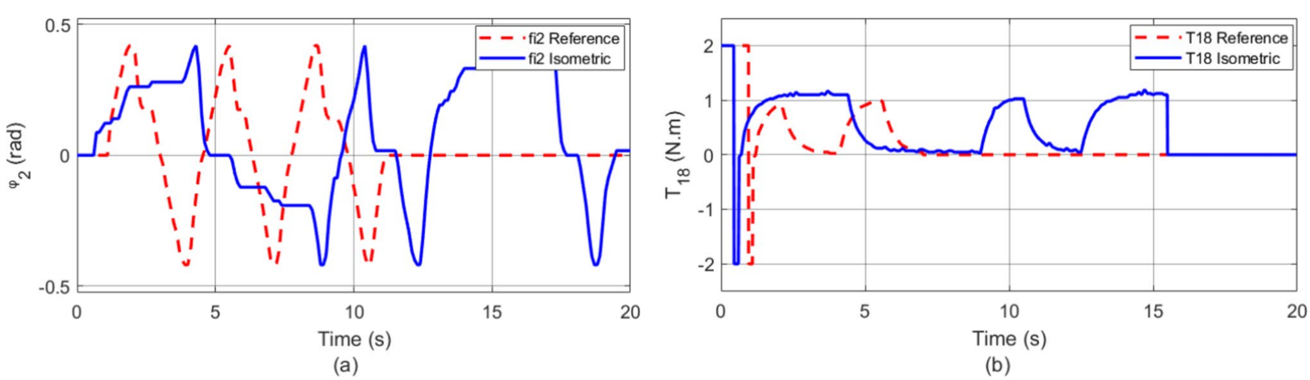

Fig. 25 The isometric exercise of the thumb abduction–adduction angle and torque

Bowden cable transmission system or optimizing the control algorithms to account for biomechanical variability. Moreover, the simplified mathematical model may have limitations in some test cases.

Isometric exercises revealed limitations in the robot's ability to resist forces effectively, particularly at the DIP joints during flexion movements. This could be attributed to the inherent constraints of the cable-driven system in transmitting high forces. Studies like those by Mayetin and Kucuk [50] have also noted similar issues in cable-driven rehabilitation systems, suggesting the potential for hybrid actuation systems or augmented designs incorporating force sensors to improve performance.

The passive and active exercise results indicate that the robot achieves sufficient angular positions and torque outputs to facilitate effective rehabilitation. The emphasis on maintaining safety protocols, such as limiting the range of motion to 50–60% of full capacity, ensures user safety while achieving therapeutic goals. The multistage safety protocols, including emergency stop buttons and predefined operational limits, further reinforce the system's reliability and patient-centric design. Comparatively, traditional systems like MIT-MANUS [39] and InMotion Wrist Robot [40] lack the advanced safety measures integrated into the proposed design, underscoring its novelty in prioritizing user safety.

In comparison to existing systems, the proposed robot's lightweight and compact nature, combined with its basic control algorithms, represents a significant advancement in rehabilitation robotics. Existing literature, such as the work by Maciejasz et al. [35], has highlighted the need for systems that balance functionality, usability, and affordability. The proposed robot directly addresses these gaps by incorporating personalized rehabilitation protocols, and portability, making it more adaptable to diverse patient needs and recovery stages.

Despite its promising results, the study has certain limitations. The preliminary tests were conducted on a single

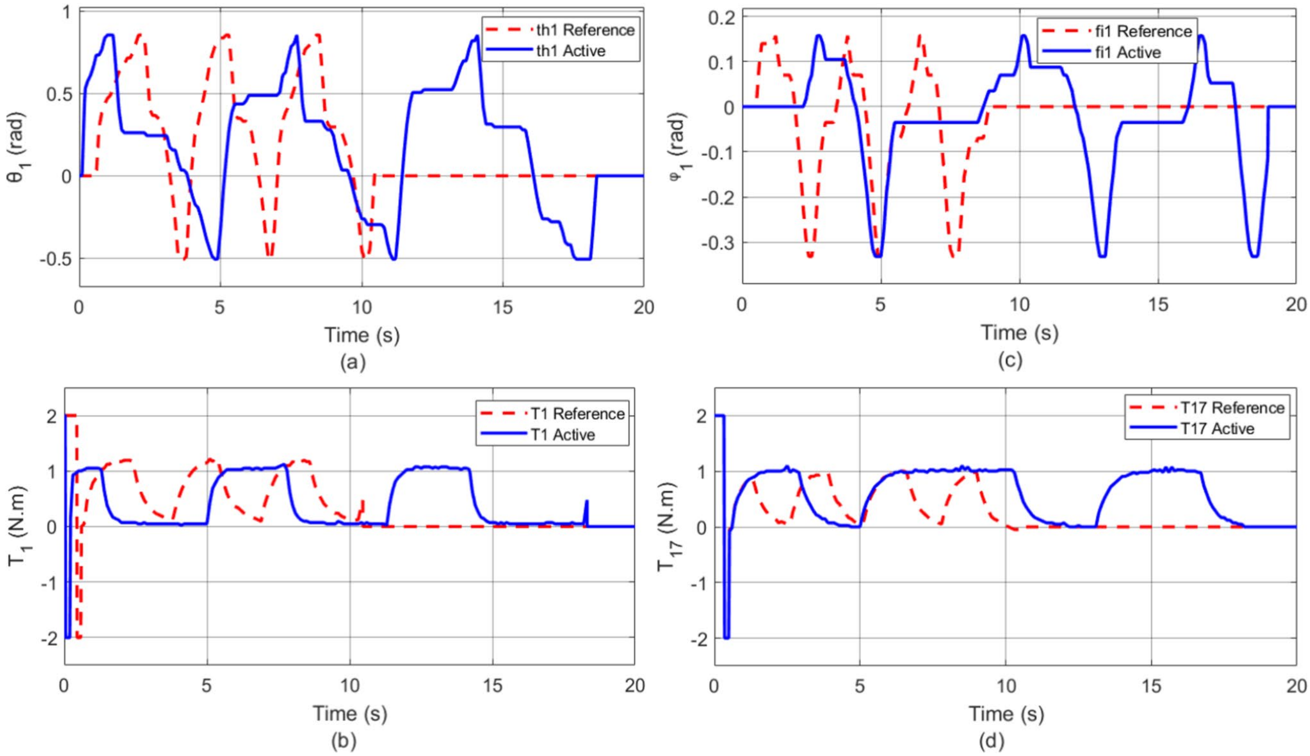

Fig. 26 The wrist active exercise a- b) flexion–extension, c- d) radial-ulnar angle and torque

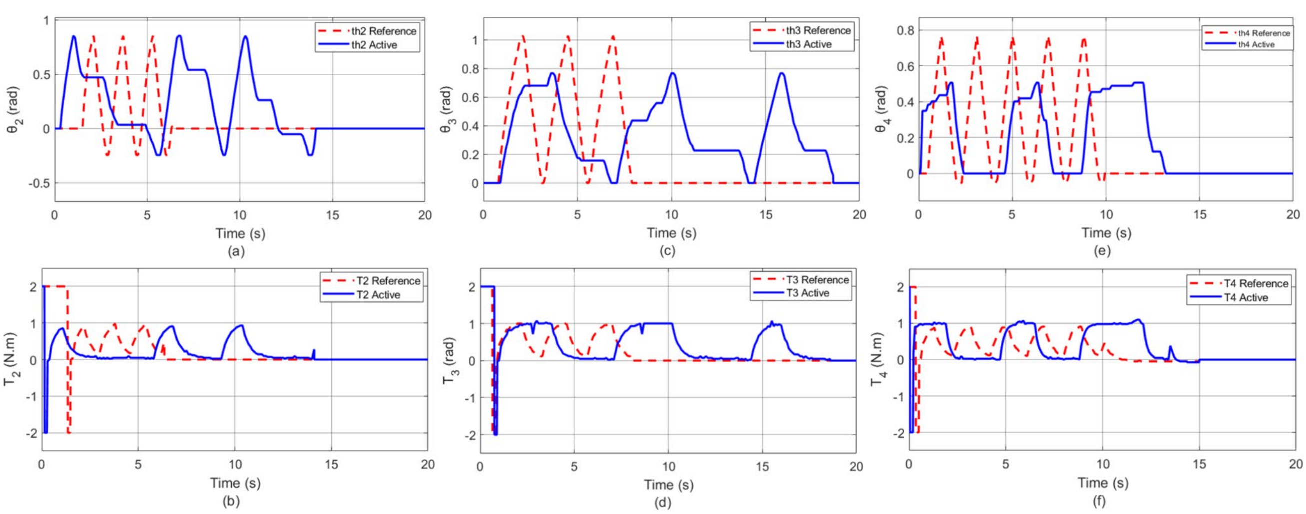

Fig. 27 The index finger active exercise a- b) MCP, c- d) PIP, e- f) DIP angle and torque

healthy subject, which limits the generalizability of the findings. Future studies should involve a larger, more diverse participant pool, including individuals with varying levels of disability. Furthermore, the study's focus on angular positions and torque measurements could be broadened to include metrics such as patient comfort, usability, and long-term therapeutic outcomes. Integrating feedback from physiotherapists and patients will be critical in refining the design and ensuring its clinical efficacy. Additionally, exploring the integration of gamification elements and haptic feedback could enhance user engagement and motivation, as suggested by Chu and Patterson [13].

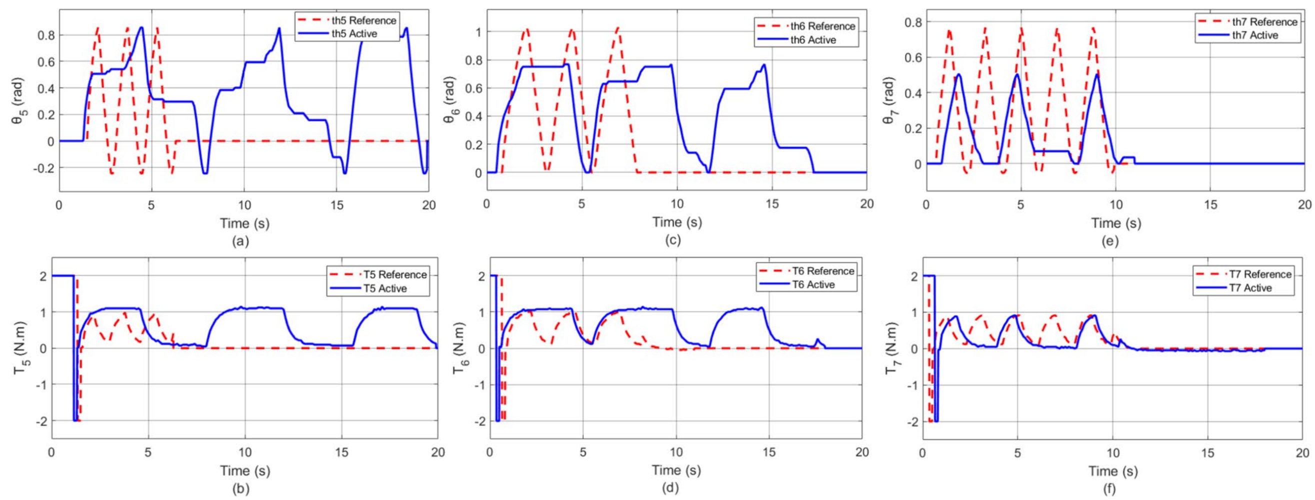

Fig. 28 The middle finger active exercise a- b) MCP, c- d) PIP, e- f) DIP angle and torque

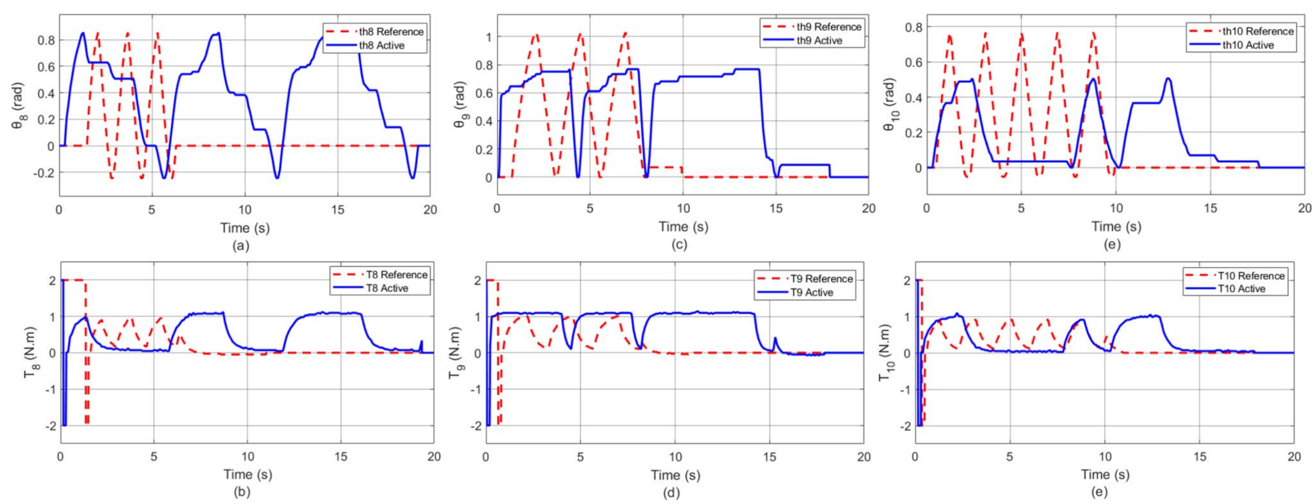

Fig. 29 The ring finger active exercise a-b) MCP, c-d) PIP, e- f) DIP angle and torque

6 Conclusion

This study presents the design, development, and experimental evaluation of a novel cable-driven hand and wrist rehabilitation robot. The 18 DOF robot, combined with its lightweight and portable design, address critical gaps in existing rehabilitation technologies. The preliminary experimental results demonstrate the robot's capability to perform passive, isometric, and active exercises effectively, with torque and angular position outputs that align with the physiological characteristics of the human hand and wrist. Key contributions of this study include the development of a Bowden cable-based transmission system, a novel four-bar linkage mechanism, and advanced safety protocols. These innovations enhance the robot's functionality, adaptability, and user safety. The study highlights the potential of the proposed system to support rehabilitation in both clinical and home environments, offering a cost-effective and versatile solution for patients with hand and wrist disabilities.

Future work will focus on optimizing the robot's design and control algorithms to address observed limitations, such as performance challenges in specific joints and force transmission constraints. Expanding the scope of experimental studies to include diverse patient populations and long-term evaluations will provide valuable insights into the robot's therapeutic efficacy. Additionally, integrating features such as

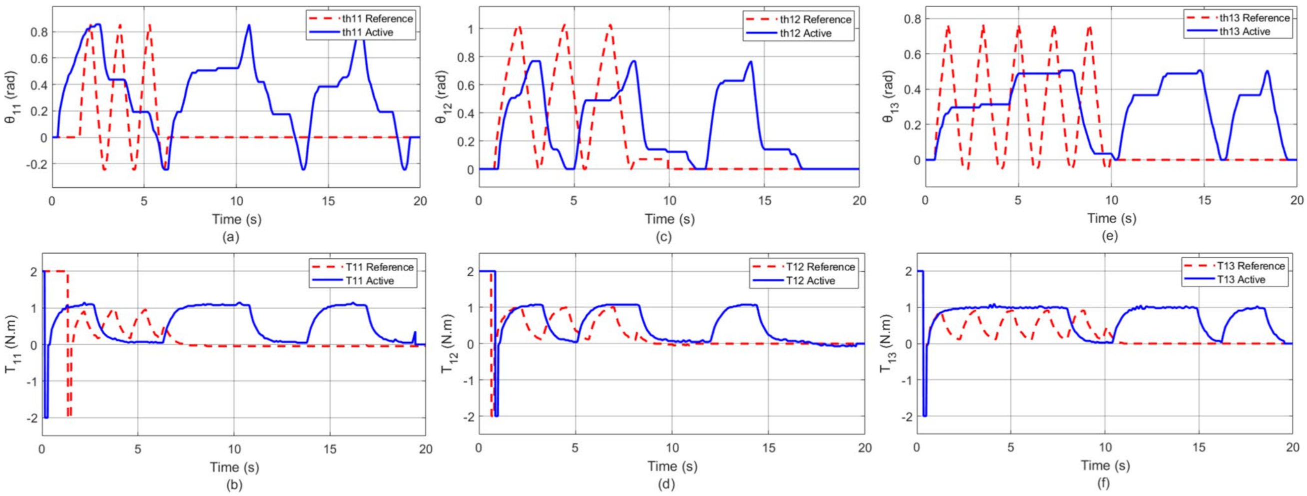

Fig. 30 The little finger active exercise a-b) MCP, c- d) PIP, e–f) DIP angle and torque

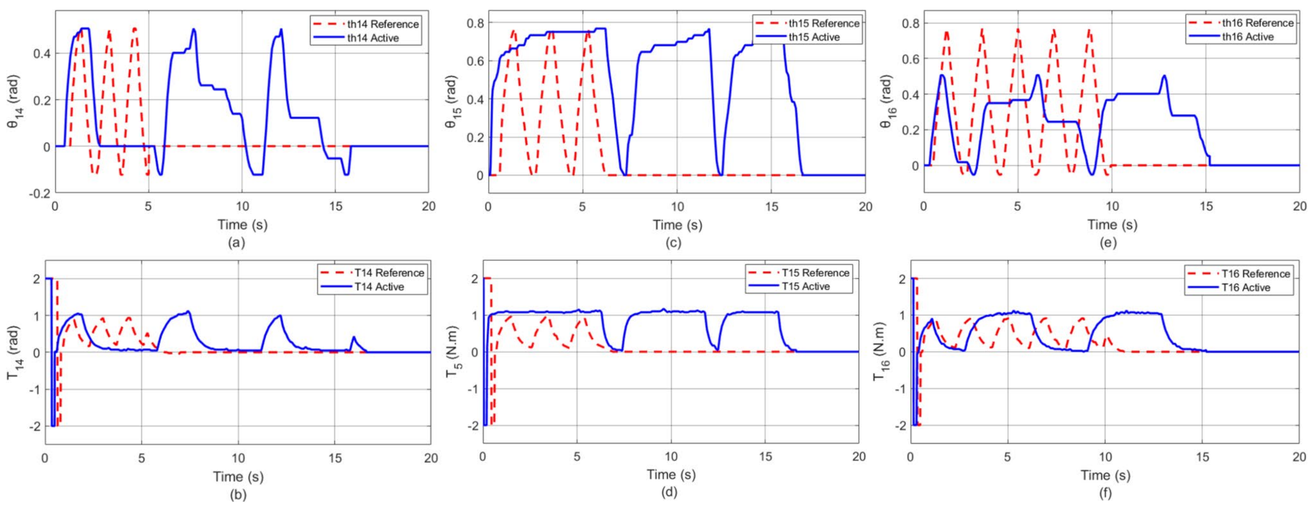

Fig. 31 The thumb finger active exercise a- b) TMC, c- d) MCP, e- f) IP angle and torque

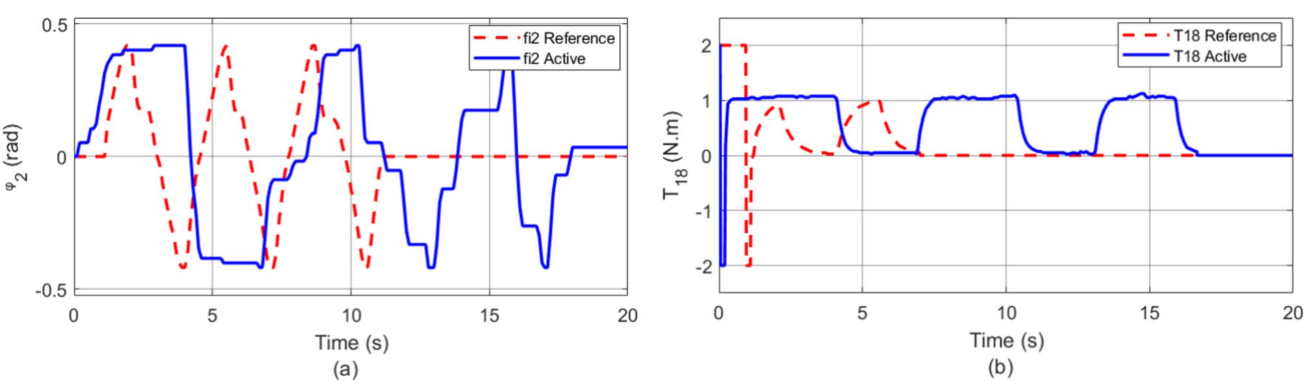

Fig. 32 The thumb active exercise abduction–adduction angle and torque

haptic feedback, gamification, and wireless connectivity could further enhance user engagement and rehabilitation outcomes.

In conclusion, the proposed hand and wrist rehabilitation robot represents a significant step forward in assistive robotics, offering a promising platform for advancing the field of robotic rehabilitation and improving patient quality of life.

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Authors'Contributions **MM:** Contributed to conceptualization and methodology. Performed the data analysis, graphics. Writing original draft.

NGÖ: Contributed to conceptualization, writing, reviewing and editing. Supervision and project administration.

All authors read and approved the final manuscript.

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Data Availability The datasets generated and analysed during the current study are not publicly available as additional human experiments are required to complete the dataset. Data will be made available upon completion of the study and can be requested from the corresponding author.

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval Not applicable.

Consent to Participate All procedures on human subjects were conducted in accordance with the ethical standards of the Declaration of Helsinki. An informed consent form was signed by the subject.

Consent for Publication An informed consent form was signed by the subject.

References

1. Adar, S., et al.: Effect of robotic rehabilitation on hand functions and quality of life in children with cerebral palsy: a prospective randomized controlled study. Am. J. Phys. Med. Rehabil. (2024). https://doi.org/10.1097/PHM.0000000000002430
2. Lince, A.: ReHand-a portable assistive rehabilitation hand exoskeleton, Doctor of Philosophy Thesis, Mechanical, Politecnico di Torino (2016)
3. Astarita, D., et al.: MITEx: A Portable Hand Exoskeleton for Assessment and Treatment in Neurological Rehabilitation, (in eng). IEEE Int Conf Rehabil Robot **2023**, 1–6 (2023)
4. WHO, Medical devices managing the mismatch : an outcome of the priority medical devices project. Geneva, Switzerland: World Health Organization (2010)
5. Yue, Z., Zhang, X., Wang, J.: Hand rehabilitation robotics on post-stroke motor recovery. Behav. Neurol. **2017**, 3908135 (2017)
6. Kabir, R., Sunny, M.S.H., Ahmed, H.U., Rahman, M.H.: Hand Rehabilitation Devices: A Comprehensive Systematic Review (in eng). Micromachines (Basel) **13**, 7 (2022)
7. Peperoni, E., et al.: Self-Aligning Finger Exoskeleton for the Mobilization of the Metacarpophalangeal Joint, (in eng), IEEE Trans Neural Syst Rehabil Eng (2023)
8. McConnell, A.C., et al.: Robotic devices and brain-machine interfaces for hand rehabilitation post-stroke, (in eng). J Rehabil Med **49**(6), 449–460 (2017)
9. Güdemez, E., Ataker, Y., Ece, S.C., Çerezci Ö., Ataker Y., Canbulat N., Güdemez E., Eds. *El Rehabilitasyonu*. Amerikan Hastanesi Yayınları: Vehbi koç Vakfı Amerikan Hastanesi (2013)
10. Bandara, D.S.V., Gopura, R.A.R.C., Hemapala, K.T.M.U., Kiguchi, K.: Development of a multi-DoF transhumeral robotic arm prosthesis. Med Eng Phys **48**, 131–141 (2017)
11. Du Plessis, T., Djouani, K., Oosthuizen, C.: A review of active hand exoskeletons for rehabilitation and assistance. Robotics **10**(1), 40 (2021)
12. Ueki, S., et al.: Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy. IEEE/ASME Trans. Mechatron. **17**(1), 136–146 (2012)
13. Chu, C.Y., Patterson, R.M.: Soft robotic devices for hand rehabilitation and assistance: a narrative review, (in eng). J Neuroeng Rehabil **15**(1), 9 (2018)
14. Noronha, B., et al.: Soft, Lightweight Wearable Robots to Support the Upper Limb in Activities of Daily Living: A Feasibility Study on Chronic Stroke Patients, (in eng). IEEE Trans. Neural Syst. Rehabil. Eng. **30**, 1401–1411 (2022)
15. Fontana, M., Dettori, A., Salsedo, F., Bergamasco, M.: Mechanical design of a novel Hand Exoskeleton for accurate force displaying, in 2009 IEEE International Conference on Robotics and Automation, pp. 1704–1709 (2009)
16. Ozkul, F., Barkana, D.E.: Upper-extremity rehabilitation robot RehabRoby: methodology, design, usability and validation. Int. J. Adv. Robot. Syst. **10**(12), 401 (2013). https://doi.org/10.5772/57261
17. Wolbrecht, E.T., Morse, K.J., Perry, J.C., Reinkensmeyer, D.J.: Design of a thumb module for the FINGER rehabilitation robot, in 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 582–585 (2016)
18. Becchi, F., Sale, P., Sieklicki, W., Stellin, G.: Aid device for the movement and / or rehabilition of one or more finger of a hand, United States Patent US 2017 / 0266075 A1 (2017)
19. Beenken, G.M.: Finger rehabilition / exercise device, United States (1994)
20. Deshpande, A., Agarwal, P.: Robot finger exoskeleton, United States Patent US 2016/0296345 A1 (2016)
21. Fausti, D., Seneci, C.: Hand Rehabilition Device, United States Patent US 2013/0072829 A1 (2011)
22. Akdoğan, E.: Upper limb therapeutic exercise robot, Patent WO 2015/041618 A3, (2015)
23. Kelly, R.: Veriable tension glove, US (2016)
24. Tsui, M.K.F., Tong, K.Y.: Wearable power assistive device for hand rehabilitation, U.S. (2017)

25. Tong, K.Y., Pang, P.M., Chen, M., Ho, S.K., Hongfu, Z.H., Chan, D.T.: Wearable power assistive device for helpinhauser to move their hand, US (2013)
26. Dimapasoc, B.: Design of a Dexterous Three-Fingered Hand Exoskeleton for Stroke Patient Rehabilitation. Mechanical Engineering, University of California, ProQuest LLC, Master of Science (2017)
27. Mata Amritanandamayi, D., Udupa, G., Sreedharan, P.: A novel underactuated multi-fingered soft robotic hand for prosthetic application. Robot Auton Syst **100**, 267–277 (2018)
28. Wang, Y., Xu, Q.: Design and testing of a soft parallel robot based on pneumatic artificial muscles for wrist rehabilitation, (in eng). Sci Rep **11**(1), 1273 (2021)
29. Alain, F.: Glove Exoskeleton for Extra-Vehicular Activities: Analysis of Requirements and Prototype Design, PhD thesis, Politecnico di Torino (2014)
30. Hinchet, R., Vechev, V., Shea, H.R., Hilliges, O.: DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake, Proceedings of the 31st Annual ACM Symposium on User Interface Software Technology, pp. 901–912 (2018)
31. Yap, H.K., Jeong Hoon, L., Nasrallah, F., Goh, J.C.H., Yeow, R.C.H.: A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness, in 2015 IEEE International Conference on Robotics and Automation (ICRA*)*, pp. 4967–4972 (2015)
32. Stergiopoulos, P., Fuchs, P., Laurgeau, C.: Design of a 2-finger hand skeleton for VR grasping simulation, Proceedings of the Eurohaptics Dublin, 2003 (2003)
33. Hasegawa, Y., Mikami, Y., Watanabe, K., Sankai, Y.: Five-fingered assistive hand with mechanical compliance of human finger, pp. 718–724 (2008)
34. Fleischer, C., Kondak, K., Wege, A., Kossyk, I.: Research on Exoskeletons at the TU Berlin, pp. 335–346 (2009)
35. Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy, A., Leonhardt, S.: A survey on robotic devices for upper limb rehabilitation. J. Neuroeng. Rehabil. (2014). https://doi.org/10.1186/1743-0003-11-3
36. Hasan, S.K., Bhujel, S.B., Niemiec, G.S.: Emerging trends in human upper extremity rehabilitation robot. Cogn Robot **4**, 174–190 (2024)
37. Tyromotion.: Amadeo Finger-Hand-Rehabilitation. Available: https://tyromotion.com/en/products/amadeo/ . Accessed 08 Jan 2025
38. Rehab-Robotics.: Hand of Hope Basics. Available: https://www.rehab-robotics.com.hk/hoh/hoh_basic.html . Accessed 08 Jan 2025
39. Hidler, J., Nichols, D., Pelliccio, M., Brady, K.: Advances in the understanding and treatment of stroke impairment using robotic devices, (in eng). Top Stroke Rehabil **12**(2), 22–35 (2005). (**Spring**)
40. Hsieh, Y.W., Lin, K.C., Wu, C.Y., Shih, T.Y., Li, M.W., Chen, C.L.: Comparison of proximal versus distal upper-limb robotic rehabilitation on motor performance after stroke: a cluster controlled trial, (in eng). Sci Rep **8**(1), 2091 (2018)
41. Mayetin, U., Kucuk, S.: Design and Experimental Evaluation of a Low Cost, Portable, 3-DOF Wrist Rehabilitation Robot with High Physical Human-Robot Interaction. J Intell Robot Syst **106**(3), 65 (2022)
42. Bazira, P.J.: Surgical anatomy of the hand. Surg (Oxford) **40**(3), 155–162 (2022)
43. Gopura, R.A.R.C., Bandara, D.S.V., Kiguchi, K., Mann, G.K.I.J.R.A.S.: Developments in hardware systems of active upper-limb exoskeleton robots: a review. Robotics Auton. Syst. **75**, 203–220 (2016)
44. Sanjuan, J.D., et al.: Cable driven exoskeleton for upper-limb rehabilitation: A design review. Robot Auton Syst **126**, 103445 (2020)
45. Serbest, K.: El Kaslarının Rehabilitasyonu İçin Aktif Dinamik El – El Bileği Ortezi Tasarımı. Doktora Tezi, Sakarya Üniversitesi Fen Bilimleri Enstitüsü (2017)
46. Drake, R.L., Vogl, A.W., Mitchell, A.W.M.: Gray's Anatomy for Students. Churchill Livingstone Elsevier, pp. 1–1150 (2010)
47. Cutkosky, M.R., Howe, R.D.: Human Grasp Choice and Robotic Grasp Analysis. Dextrous Robot Hands **1**, 5–31 (1990)
48. Bullock, L.M., Zheng, J.Z., Rosa, S.D.L., Guertler, C., Dollar, A.M.: Grasp Frequency and Usage in Daily Household and Machine Shop Tasks, IEEE Transactions on Haptics, vol. 6 (2013)
49. Gates, D.H., Walters, L.S., Cowley, J., Wilken, J.M., Resnik, L.: Range of motion requirements for upper-limb activities of daily living. Am. J. Occup. Ther. **70**(1), 7001350010p1-7001350010p10 (2016)
50. Mayetin, U., Kucuk, S.J.M.: A low cost 3-DOF force sensing unit design for wrist rehabilitation robots. Mechatronics **78**, 102623 (2021)
51. Loskutova, A., Roozbahani, D., Alizadeh, M., Handroos, H.: Design and Development of a Robust Control Platform for a 3-Finger Robotic Gripper Using EMG-Derived Hand Muscle Signals in NI LabVIEW. J Intell Robot Syst **110**(3), 133 (2024)
52. Tagliamonte, N.L., Formica, D., Scorcia, M., Campolo, D., Guglielmelli, E.: Force control of a robot for wrist rehabilitation: Towards coping with human intrinsic constraints, pp. 4384–4389 (2010)
53. Pehlivan, A.U., Sergi, F., Erwin, A., Yozbatiran, N., Francisco, G.E., O'Malley, M.K.J.R.: Design and validation of the RiceWrist-S exoskeleton for robotic rehabilitation after incomplete spinal cord injury. Robotica **32**, 1415–1431 (2014)
54. Squeri, V., Masia, L., Giannoni, P., Sandini, G., Morasso, P., Engineering, R.: Wrist Rehabilitation in Chronic Stroke Patients by Means of Adaptive. Progressive Robot-Aided Therapy **22**, 312–325 (2014)
55. Erdogan, A., Satici, A.C., Patoglu, V.: Passive velocity field control of a forearm-wrist rehabilitation robot, (in eng). IEEE Int Conf Rehabil Robot **2011**, 5975433 (2011)
56. Martinez, J.A., Ng, P., Lu, S., Campagna, M.S., Celik, O.: Design of Wrist Gimbal: A forearm and wrist exoskeleton for stroke rehabilitation, in 2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR), pp. 1–6 (2013)
57. Atlihan, M., Akdoğan, E., Arslan, M.S.: Automation, and Robotics, Development of a therapeutic exercise robot for wrist and forearm rehabilitation, pp. 52–57 (2014)
58. Winter, D.A.: Biomechanics and Motor Control of Human Movement. John Wiley & Sons New Jersey Published simultaneously in Canada, pp. 1–296 (1990)
59. Basteris, A., Nijenhuis, S.M., Stienen, A.H., Buurke, J.H., Prange, G.B., Amirabdollahian, F.: Training modalities in robot-mediated upper limb rehabilitation in stroke: a framework for classification based on a systematic review, (in eng). J Neuroeng Rehabil **11**, 111 (2014)

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