Design and Control of Soft Robotic Hand Rehabilitation Exoskeleton

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A Pilot Study on the Design and Validation of a Hybrid Exoskeleton Robotic Device for Hand Rehabilitation

Abstract

Background: The success of hand rehabilitation following either musculoskeletal or neurological impairments depends on the timing, intensity, repetition, and frequency, as well as task-specific training. Considering the continuing constraints placed upon therapist-led rehabilitation and need for better outcomes, robotic-assisted rehabilitation has been explored. Soft robotic approaches have shown to be promising for hand rehabilitation as they help reduce the complexity and size. These robotic exoskeletons are also have more tolerance for alignment with biological joints to those of the exoskeleton due to their intrinsic compliance.
Purpose: Design, develop and validate a soft robotic exoskeleton for hand rehabilitation.
Study Design: An iterative design process was employed to obtain design parameters which satisfy both kinematic and dynamic requirements for the hand exoskeleton. This design was validated through experimental studies.
Methods: Kinematics of the soft robotic digit was validated using a motion capture system with a fabricated soft robotic digit was attached on top of a human index finger. A pneumatic control system with associated control algorithms were developed to operate the exoskeleton based on three principal therapeutic modes: continuous passive motion, active assistive motion, and active resistive motion. Pilot studies were carried out using the full exoskeleton on one healthy participant and one post-stroke patient. Continuous passive motion and bilateral/bimanual therapy were applied to the hand by the soft robotic exoskeleton.
Results: Results showed that the soft robotic digits were able to produce required range of motion and accommodate for dorsal lengthening, with trajectories of center of rotation of the soft robotic joints in close agreement with center of rotation of the human finger joints. The results of the full exoskeleton showed the robust performance of the robot in applying continuous passive motion and bilateral/bimanual therapy.
Conclusions: This soft robotic exoskeleton is promising for assisting in the rehabilitation of the hand.

Keywords

Rehabilitation robotics, Hand therapy, Soft robotic exoskeletons, Continuous passive motion, Bilateral/Bimanual therapy, Neurological impairments

Introduction

Hands are our primary interface with the world, and any functional disabilities of the hand have a significant negative impact on individuals' physical, psychological, social, and economic well-being [1, 2, 3]. A wide array of physical and neurological conditions can cause functional impairments of the hand. Trauma such as burns, crush injuries, multiple fractures, and ligament damage are the most common hand injuries that lead to hand functional impairments. Stroke remains the main neurological cause of partial or full loss of sensory and motor function among adults, with the majority of stroke survivors failing to regain functional use of their paretic arm and/or hand [4, 5]. Cerebral Palsy (CP) is another example of a neurological condition where about 50% of children born with CP have functional limitations in their hand [6].

Impairments related to all the above scenarios require some form of rehabilitation for restoring hand functions. There are three main motion therapy methods that are applied in rehabilitation, namely, continuous passive motion (CPM), active assistive movement (AAM), and active resistive motion (ARM). In CPM, repetitive flexion and extension with a predefined trajectory is applied to the joint, in which patients remain relaxed with no active muscle contraction. CPM is typically used immediately after a trauma or a primary surgical procedure and meant to reduce edema and bleeding [7, 8]. CPM is also known to accelerate healing, improve tissue alignment, and create compliant tissues, aiding in greater restoration of the muscles, tendons, and ligaments. AAM works by having a patient try performing desired movements or activities to the best of their ability, while the therapist or robotic device assist their motion to complete the desired task. As the patient starts the motion in AAM, it involves both neurological and muscular components. Therefore, AAM is the preferred method in neurological rehabilitation to evoke neuroplasticity and mitigate common sequelae such as disrupted sensory pathways, spasticity, abnormal tone, and muscular weaknesses [5, 9, 10]. AAM in hand therapy involves functional task training; therefore, dexterous manipulation assistance is required. ARM applies external resistive force against a dynamic or static muscle contraction and the resistive motion is essential in both musculoskeletal and neurological rehabilitation. ARM has a profound effect on increasing muscle and bone mass, the tensile strength of connective tissue, as well as enrichment of neuromuscular excitation [11, 12].

Despite the many approaches and methods that are being used in both musculoskeletal and neurological rehabilitation, the outcome varies significantly, and the success depends on many aspects of rehabilitation. These factors include the timing, intensity, repetition, and frequency, as well as goal-oriented and task-specific training protocols [13]. Evidence suggests that constraints placed upon the total number of treatment hours and a shortage of available resources result in treatment being inadequate in its dosage requirement, thereby not optimizing functional return [14, 15]. In some cases, rehabilitation is a lifelong process where financial burdens, along with a lack of compliance to the program, can also have a significant effect on outcomes [16]. Considering the continuing constraints placed upon therapist-led rehabilitation and need for better outcomes, robotic-assisted rehabilitation has been explored to work as a complementary system to conventional therapy [17, 18].

In recent years, there has been significant progress in hand rehabilitation devices, however, their functionality is rather limited and not effective for a wide array of scenarios [19]. There are two types of hand rehabilitation robotic devices that are currently used: end-effector and exoskeleton-based systems. End-effector-based devices interface at the distal end of the finger, where motion is created through movements by the end-effector of the robot apply to the human fingers. Alternatively, exoskeleton-based devices are attached along the human hand where they match the anatomical structure of the hand with actuators placed directly or indirectly on the axis of corresponding finger joints [20]. Commercially available end-effector type hand rehabilitation devices include AMADEO® (Tyromotion GmbH) and InMotion HAND (Bionik Labs, Watertown, MA), which provide simple flexion and extension while rely on the user's hand biomechanics to determine the movements at the joint level. GLOREHA Sifonia (GLOREHA, Italy) is a hand robotic exoskeleton which provides an overall closing and opening motion for each individual finger. By considering the motion requirements for CPM, AAM, and ARM, devices with simple flexion and extension motions are mostly sufficient for CPM and ARM; however, AAM requires dexterous devices that can assist in practicing many daily living activities. Therefore, a robotic exoskeleton that has individual joint control, bidirectional motion, and is able to move freely in 3D space is required.

There are two robotic approaches currently utilized for making exoskeletons, i.e., hard robotics (conventional) and soft robotics. Hard exoskeletons are mostly made of rigid materials with complex mechanisms which are able to produce the required forces/torques and precise motion needed for the hand therapy; however, the mechanical complexity, weight, and size involved in these structures make it very challenging to create robotic exoskeletons for hands [21, 22, 23, 24, 19]. That difficulty is mainly due to size and close proximity of joints and inability to accommodate for hand deformities, as well as making a system that can fit to different hand sizes. Soft robotics, an emerging field in robotics, provides potential solutions to address the issues involved in conventional robotic systems by integrating soft and compliant components, such as fluidic elastomer actuators or tendon-driven mechanisms into robots' structure [25]. These approaches have shown to be a promising solution for hand exoskeletons as they help reduce the complexity, size, and cost associated with current rehabilitation and assistive devices, as well as provide more tolerance for alignment with biological joints to those of the exoskeleton due to their intrinsic compliance. Two recent systematic reviews [25, 26] have indicated that 45 soft robotic hand exoskeletons have been developed over the past 10 years, where a majority of them are capable of providing a continuous bending motion along their digit lengths. Although their simple actuation mechanism as well as their achievable range of motion (ROM) has made them a popular choice to use in hand exoskeletons, the continuous bending motion lacks controllability over the angle at any given joint [27, 28]. Examples of this are the McKibben pneumatic artificial muscle-based power-assist glove reported in [29] and the elastomeric fluidic actuator-based exoskeleton developed by the Harvard Wyss Institute [30]. A drawback of most of these systems is their low generated force/torque, which are significantly less than the required amount needed for stroke patient therapy. Tendon driven mechanisms have been adopted for developing soft robotic gloves which address the low force/torque issue of the pneumatic exoskeletons [31]. However, early versions of these systems only produced one-direction active actuation (flexion), while the other direction (extension) was provided passively using a spring. Some recent works have added active extension capabilities to these gloves [32, 33]; however, friction and backlash effect along tendons, as well as the requirements for holding the tendons always in tension, are some of the challenges for the control and operation of these systems [34].

In this work, we present a soft robotic hand exoskeleton system designed for adults with hand impairments due to neurological conditions such as stroke. This robotic exoskeleton was designed to provide the required force/motion to the affected hand in order to restore the ROM and grip force by using a novel soft-and-rigid hybrid actuator [35]. This actuator architecture allows us to mechanically tune the design of the soft joint section that corresponds to the biomechanical requirements of each human finger joint, including ROM, center of rotation (COR), dorsal lengthening, and force/torque. The details in the manuscript include a system description, kinematic and dynamic considerations, control aspects, and initial testing of continuous passive motion with one post-stroke patient and bimanual therapy with a healthy participant.

Soft Robotic Exoskeleton System Description:

As seen in Fig. 1, the soft robotic hand exoskeleton system is comprised of three major components: 1) the sensorized soft robotic glove, 2) the control unit including hardware and software, and 3) the graphical user interface (GUI). The glove includes five soft-and-rigid robotic digits with discrete soft actuation sections over each joint. This approach combines the advantages of both soft and conventional robotic designs, i.e. actuators are made with flexible material and each joint corresponds to a designated actuator similar to the structure of conventional robotics. The pneumatic control unit, pressure sensors, valves, and microcontroller generate bending motion by applying pressure and vacuum to the soft actuator sections. The microcontroller receives finger trajectory data from inertial measurement units (IMU) at the tip of the robotic digit and pressure sensors in the controller. These data are used for controlling the angular position and velocity of flexion and extension through position control algorithms. The GUI allows for executing therapy protocols and data visualization. ***The wearable fixture includes a modified inner glove (the front part of the glove is cut that creates a large opening for easy wearing of the exoskeleton) through that the users can wear the exoskeleton. The soft robotic digits are attached on top of the inner glove through 3d printed posts at the semi-rigid sections. Elastic bands are added to the inner glove at the posts' location to avoid the relative motion between the human finger and soft robotic digits while it helps reducing the skin irritation.***

Design based on human hand's kinematics and dynamics compatibility

The hand is one of the most complex anatomical parts of the human body which includes multiple bones, joints and muscles that jointly generate dexterous manipulation with multiple degrees-of-freedom [19, 36]. Each finger is an articulated structure with four major bones (metacarpal, proximal phalanx, middle phalanx, and distal phalanx) and three joints (metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP)), except the thumb, which has only proximal and distal phalanges with two joints [40]. Developing a device for hand rehabilitation, such as robotic exoskeletons, requires consideration of a variety of design factors that assure safe and effective operation. From an engineering stand point, these factors can be categorized into two major groups of kinematic and dynamic requirements that will be discussed in detail in the following sections. The kinematics covers the requirements regarding the geometrical aspects of hand motion, which are described in terms of three factors: ROM at the joints, trajectory of COR of each joint, and the dorsal lengthening over the joints, as shown in Fig. 2. The dynamic requirements can be described as aspects of hand motion, which deal with factors in generating hand motion. These factors include the required external force/torque for moving an affected hand passively (overcoming the joint stiffness or spasticity in the case of neurologic conditions), physical interaction (contact forces) between the human and robotic exoskeleton, and providing the necessary grip forces for carrying out functional tasks. Additionally, it has been reported that light weight, less bulky structure, and wearability (ease of independent don and doff) are important design aspects to be considered [37, 38].

<u>Kinematic requirements:</u>

Range of motion (ROM): A variety of ranges of motion for the human finger joints have been reported in literature. Based on the overlap between these reported data, the overall ranges selected in our design were MCP: 0-60° and IP: 0-90° for the joints of the thumb and MCP: 0-90°, PIP: 0-100°, and DIP: 0-70° the joints of the rest of the fingers [39, 40, 41, 36]. To avoid hyperextension, the lower range was set to zero for stopping the motion during the extension of fingers. Since the reported functional ROM of the human fingers [41] is less than the active ROM, the design for the active range would satisfy the functional ROM as well.

Center of rotation (COR): One of the key factors in the mechanical design of exoskeletons is the coincident of the (remote) COR of the robotic mechanism with the finger joint axis of rotation [19]. This has been addressed in conventional robotic approaches by designing a series of mechanisms. Some examples include (1) a mechanism that directly attaches to the side of the finger to match the COR [42], (2) a complex linkage mechanism with remote COR that matches the finger joint axis of rotation [43], and (3) a redundant linkage structure where its extra degrees of freedom accommodate this requirement [44]. To eliminate the needs for matching the COR, a serial linkage that only attaches to the proximal and distal sections of each finger has been investigated [45]. This mechanism, however, can only apply an overall opening/closing motion without any individual joint control consideration. On the other hand, soft robotic approaches like continuous tube-shaped actuators [23] and tendon driven mechanisms [31] bypass this issue due to the fact that the human finger provides a skeletal structure for the motion of the exoskeleton; therefore, the COR matching would naturally happen without any extra design effort [19].

Dorsal lengthening over joint: One of the key kinematic factors that has been mainly neglected in hand exoskeletons' design is consideration of the skin lengthening that happens over each finger joint during movement. This lengthening for adults was measured as 12 mm in MCP, 16 mm in PIP, and 8 mm in DIP [27], which is significant in comparison to the overall length of the human fingers. Since the exoskeletons are mainly attached on top of the fingers, they must accommodate this kinematic requirement. In most hard robotic exoskeletons, this requirement was not necessary to address because of how they are attached to the fingers [19]. However, in soft robotic approaches, especially with tube-shaped soft actuators, this condition is not satisfied due to the use of an inextensible layer of material (e.g. paper) embedded at their base in order to create differential deformation characteristics required for the bending motion [23].

<u>Dynamic requirements:</u>

Force/torque for moving fingers (passive motion): Generally, patients who suffer from neurological injuries/disorders such as stroke or cerebral palsy have spasticity, which can be represented as a rotational (torsional) stiffness at the finger joints; however, only a few studies have been done for measuring this, and limited data are available on the spastic response at different angular velocities [46]. Spasticity leads to an abnormal increase in stiffness of the muscle, resulting in stiffer hand joints. Kamper et al. reported that the maximum extension torque generated by a stroke patient's MCP joint was 0.21 N.m, which is about 16% of the mean-generated torque by a healthy individual under the same condition, and the generated flexion torque was at least 0.75 N.m for the same patient [47]. Therefore, the torque deficit in stroke patients' impaired hands needs to be compensated by robotic exoskeletons in order to provide normal motion of the human hand. In addition, spastic responses at different angular velocities in the finger muscles following a stroke also need to be considered in the design as one of the most important factors. A study reported that the measured static stiffness at the MCP joint in a group of stroke patients at different angular velocities had a mean value of 1.6 N.mm/deg [46]. Therefore, the soft robotic digit must be designed with sufficient torque in order to overcome the stiffness during motion.

Force/torque for assisting with a functional task: For performing a functional task, the patient needs to actively move his/her fingers and provide sufficient grip force for grasping objects. The maximum grip force required for activities of daily living (ADL) has been reported to be about 68 N [38], but a majority of ADL related tasks require only less than 11 N [48]. Therefore, the exerted force/torque from the robotic exoskeleton to the human hand should be sufficient for providing enough grip forces for ADL while still helping to overcome the joint stiffness as necessary.

By considering all the above kinematic and dynamic requirements of hand motion, we have developed soft robotic hand exoskeletons using numerical simulations and experimental validation that satisfy the above requirements.

<u>Soft-and-rigid hybrid actuator-based robotic hand exoskeleton</u>:

Inspired by the anatomy of the human finger (an articulated structure comprised of bones and joints), a novel architecture was considered for the design of each soft robotic digit of the robotic hand exoskeleton. Each soft robotic digit includes a combination of alternating three soft continuous joint sections designed as half-bellow shaped hollow structures and four semi-rigid blocks designed as connecting links between the soft joint sections, as shown in Fig. 3. The soft continuous sections act as joints corresponding to the finger joints, while semi-rigid blocks are corresponding to the bones of the finger.

The soft joint section architecture is comprised of corrugated hollow structures that are easily billowed and have a circle-rectangle compound shape. The semi-rigid section is similarly shaped, but mostly solid and non-corrugated. The asymmetric geometry between the top and bottom halves of the soft continuous joints causes the forward and backward bending motion when it is pressurized or vacuumed, respectively. Besides the required bending motion, as mentioned before, the soft continuous joints must provide the required lengthening (corresponding to dorsal lengthening of the finger joints) and match the COR of the joints to accommodate the overall movement of the human finger. A corrugated pattern was considered at the base of each soft continuous joint to accommodate for lengthening, as this helps to generate extension and contraction of the digit while the joints bend. Although inherent compliance of soft robotic actuators in general should eliminate the concern about matching the COR of the finger joint, emphasis was given to this key requirement to avoid stress on hand joints during operation.

A generic shape of a soft continuous joint with 6 ridges in-between two semi-rigid blocks is shown in Fig. 4. The design parameters are annotated on the figure and include the wall thickness (t_w), the groove depth at the base (h_3), the height of the upper part of each ridge (h_1) and the lower part of each ridge (h_2), the width of each interconnecting part between two adjacent ridges (i.e. interconnecting outside groove) (w_c), the pitch of each ridge (p), and the number of ridges (Ns). In this investigation, design consideration was given to achieve a desired ROM and torque for each unique joint, while the simultaneous actuation of all joints could be done at the same pressure. Each soft actuator section was designed with different geometrical and dimensional aspects, such as a varying number of ridges, wall thickness, and height ratio, in order to mechanically control the bending motion. This design enables each joint to bend and reach its full ROM at the same given pressure, which simplifies the actuation mechanism as well as the control system hardware and software.

Some of the robotic digits' dimensions, like the overall height, width of the base, overall thickness of the base, width of the actuator, and pitch of the soft actuator sections, are kept constant during the design process, as shown in Fig. 4. Generally, the overall dimensions were determined based on the standard size of the human hand. All other parameters, such as the number of the soft ridges (Ns), wall thickness of the soft actuator sections (t_w), depth of the groove in the base (h_3), height ratio of the soft ridge, the straight wall (h_1/h_2), and the width of the inter-connecting air channel (w_c), were examined with different values.

Elastomer, RTV silicone rubber (XIAMETER® RTV-4234-T4, Xiameter ®, Dow Corning), was used as the material for the fabrication of the soft robotic digits [20, 27]. All the described studies were performed using a robotic digit with a shared pneumatic line between all its actuators (Fig. 3). However, one key advantage of the hybrid actuated design, in comparison to other soft continuous bending actuators, is its capability for individual and selective joint actuation. This capability can be demonstrated where each soft actuator section of a robotic digit was separately actuated using their own dedicated pneumatic line [49]. This feature helps to accommodate custom control of selected joints which is necessary for particular grasping motions and can be done by adjusting the pressure of corresponding soft actuator sections. However, individual actuation requires more complicated control hardware and software in comparison to simultaneous actuation of joints.

<u>Experimental Validation</u>:

Single Soft Robotic Digit (kinematic validation with a non-impaired human finger): The design and performance of the soft robotic digits were validated through experimental testing, where a fabricated soft robotic digit was attached along with a human index finger, as shown in Fig. 5. Reflective markers were attached along with the human finger and the soft robotic digit in order to track the generated ROM, trajectories of the CORs, and lengthening over the knuckle. A motion capture system (Motion Analysis Corp, Santa Rosa, CA) with 12 cameras was used to track the motion of the markers. This system is capable of detecting the position of markers placed along with the digit to a resolution within 0.05 mm and angular position within 5°. Collected raw data were post-processed in the associated software for the human finger and in our own MATLAB code for the soft robotic digit to produce the required kinematic results (ROM, COR, and Dorsal Lengthening). For each test, the healthy participant was asked to be passive while the robotic digit moved her finger in a flexion and extension motion three times as the position data from this motion were collected. An IMU sensor was attached at the tip of the robotic digit to track its overall bending movement and provide feedback for the control algorithm.

Control and operation based on therapy need (bidirectional, assist as needed, CPM, active resistive motion)

<u>Overview of the control system</u>:

The control system is comprised of pneumatic (pump, solenoid valves, proportional valves) and electronic (microcontroller, sensors) components as shown in Fig. 6. The microcontroller receives feedback from the IMU sensor along with the pressure and vacuum sensors, while also operating the pump and the solenoid as well as proportional valves, all based on the control algorithm. The conjunction of this system generates the desired bending motion in the soft robotic digits. The pressure and vacuum solenoid valves are alternately activated to change the pathway of airflow into and from the robotic digit for forward and backward bending. The bleed valves are used for the case that we need to release the air from the system. A safety shutdown feature is provided for emergency cases where the therapist or patient can stop the operation and release the air from the system.

<u>Introduction to operation modes</u>:

The exoskeleton system is capable of providing the following operation modes.

Continuous Passive Motion (CPM): The soft robotic exoskeleton applies repetitive finger flexion and extension by actuating the robotic digits at a given angular position and velocity. The glove is designed to apply actuation pressure/vacuum to each finger individually. Given the differing stiffness in the finger, the sensorized glove applies an appropriate actuation algorithm to prevent hyper extension/flexion of some joints, while others are in the process of reaching desired ROM.

Patient Assisted Motion (PAM): The patient initiates the desired motion by attempting finger flexion or extension, which is detected by an IMU sensor at the tip of the robotic digit, triggering the proper algorithm to apply assistive force/motion to complete the task. This greatly helps the patient to carry out functional and task-oriented therapy, which is more important regarding the restoration of functions in the hand for independent living and better quality of life. The assist-as-needed feature adjusts the level of assistance based on the progress of the patients.

Active Resistive Motion (ARM): The glove applies resistance to the patient's finger motion by applying pressure or vacuum. The level of resistance is varied in response to the patient's current hand capabilities, detected by onboard sensors. This helps with the regaining of strength and grip power.

In all operation modes, onboard sensors continuously provide data that can be used for evaluating joint compliance, ROM, and strength. ***Although the exoskeleton is capable of providing these therapeutic modes only CPM was used in the pilot study. However, the feasibility of implementation of other two modes have been examined using a single soft robotic digit and we are currently planning to perform a pilot study on healthy individuals.***

<u>Control algorithms (position control)</u>:

In order to provide those aforementioned therapeutic modes, a feedback position control algorithm was developed in order to follow the desired trajectories. This algorithm receives the IMU sensor feedback (angular velocity and angular position) which compares them against the desired set values to create the errors. The control action (in this case the flow rate) will be determined based on a linear combination of the angular position error and angular velocity error. The command is sent to the proportional valve to open the valve accordingly in order to provide the required flow of pressurized air into/out of the soft robotic digit for generating forward and backward bending. The control parameters are selected using a trial-and-error process in order to generate desired dynamic and kinematic characteristics.

Even though our initial testing of the system was only limited to CPM in two forms, regular CPM and bilateral/bimanual CPM, this system could be applied to other applications such as virtual reality enabled therapy. In the bilateral/bimanual therapy mode, the patient uses both hands for carrying out the therapeutic schemes, where the soft robotic exoskeleton will be worn on the affected hand and a sensorized glove on the healthy hand. The healthy hand's motion guides the motion of the soft robotic to apply desired force/motion to the affected hand. Since the affected hand stays passive during the operation, this mode is similar to the regular CPM; however, the bilateral/bimanual motion therapy additionally provides active task-oriented functions for both hands, which stimulates both sensory and motor pathways to generate neuroplasticity. This stimulation not only provides cognitive feedback for the brain, due to the observation of movement of the affected hand (similar to the mirror therapy), but also provides actual physical motion to the hand that helps with reducing spasticity and improving muscle activities.

Results and Discussion

Experimental validation for kinematic requirements:

The ranges of motion at the MCP, PIP, and DIP joints of the soft robotic digit were obtained during three cycles of flexion-extension testing while interacting with the healthy participant's index finger, as shown in Fig. 7(a). It should be noted that due to difficulties in tracking the attached reflective markers on the soft robotic digit and participant's index finger for the full flexion configuration, the robotic digit maximum rotational angle at the tip with respect to the wrist (tracked by the IMU sensor) was set to 200°, therefore, the participant's finger was not able to bend enough to reach its full ROM during this testing. Even with a 200° flexion setting (less than full range of flexion), the achieved ranges of motion were MCP: 0-83˚, PIP: 0-79˚, and DIP: 0-30˚, with total rotation of 192°, which are consistent with the functional ROM of the human finger that is required to do ADL [38].

The trajectories of COR within the MCP, PIP, and DIP joints in the participant's index finger and the remote COR of the corresponding robotic digit during flexion and extension are shown in Fig. 7(b). The location of each joint on the participant's index finger was determined directly by tracking the markers attached to MCP, PIP, and DIP (see in Fig. 5) and using the software associated with the motion capture system. For the soft robotic digit, the coordinates of the markers obtained from the motion capture were fed into our own MATLAB code to determine the trajectory of the remote COR for each soft joint section. The results shown in Fig. 7(b) indicate a very good agreement between the trajectories of COR for both the robotic digit and the human finger; therefore, this kinematic requirement was satisfied using the soft-and-rigid hybrid actuator. It should be noted that the slight deviation between the trajectories could be due to the error in the motion tracking of the markers attached to the soft robotic digit and the human finger joints.

Figure 7(c) shows that the soft sections of the robotic digit can generate approximately 10 mm, 12 mm, and 6 mm of lengthening at the MCP (with six ridges), PIP (with four ridges), and DIP (with two ridges) joints, respectively, during three cycles of flexion and extension motion. These values are slightly less than the full lengthening of soft robotic digits reported in [27, 28] due to non-full flexion testing on the participant. The lengthening was measured starting from the non-inflated state of the soft joint sections, which had corresponding lengths of 30 mm, 20 mm, and 10 mm. Although the comparison of the DIP lengthening results between the three cycles indicates good consistency, the lengthening results for the other two joints show a slight deviation which corresponds with the similar variation trend in the ROM, as seen in Fig. 7(a). This could be related to errors in tracking the markers and involuntary human motion that interferes with the motion provided by the soft robotic digit.

Pilot study with one stroke patient using CPM:

In a study [28], the soft robotic exoskeleton was tested with five healthy individuals in order to evaluate its operational performance, ease of use, and level of comfort based on the exoskeleton's operation and participants' feedback. In this work, after experimental validation of the design of the soft robotic digits, the operation of the soft robotic exoskeleton was tested with one stroke patient (Female, 78 years-old, right hand) to assess similar factors, as we did with healthy volunteers. ***The original hand posture of the subject that sustained the stroke was a mildly clenched fist with a low level of spasticity that allowed opening of the hand through passive stretching***. The patient wore the exoskeleton for a total of 64 minutes including the time for donning (about 7 minutes) and doffing (one and half minute). There were few pressure points and redness on the dorsal middle and ring fingers and radial side of the wrist after wearing the device. Patient comments were that the device was hard to use but it did not cause any pain. We applied CPM flexion and extension with total range of rotation at the tip between 0-100° to her hand for 40 minutes during multiple short trials. Examples of these collected IMU sensor data are shown in Fig. 8(a) and (b). The soft robotic digit associated with the thumb was deactivated to avoid interference with the motion of the other digits. The soft robotic exoskeleton applied motion to the patient's fingers to reach the targeted range of 100° or reach the maximum-allowed actuation pressure of 105 kPa which is set for safety of the patient. As shown in Fig. 8(a) and (b), the ranges of motion for the middle and ring fingers were improving over the time of the operation to reach the targeted flexion angle (100°), while the other two fingers (index and little) were almost steady around 80° in both trials. The reason that the fingers would not be able to reach the target value in the first place was the spasticity of the patient's hand which in some cases, like middle and ring fingers, the soft robotic exoskeleton was able to overcome the joint stiffness and improve the ROM. It should be noted that the soft robotic exoskeleton was able to bring all of the fingers back to 0° extension very consistently. ***Although consistency between the results of CPM operation in two trials (shown in Fig. 8(a) and (b)) was expected, the variation in the results of two***

trials are due to following reasons. First, the involuntary hand motion of the human subjects which creates variation in the results. Second, the measurement errors introduced by 6 DoF IMU sensors. Third, the limitation of the control algorithm used for the CPM which is based on the kinematics and cannot compensate for the uncertainties and nonlinearities involved in the soft robotic exoskeleton's dynamics.

Pilot study with a healthy participant using Bilateral/Bimanual therapy:

The capability of the soft robotic exoskeleton to eventually be used in bilateral/bimanual operation was tested on a non-impaired individual. The participant worn the data glove (commanding glove) on the right hand and the soft robotic exoskeleton on the left hand. During the testing, the participant was asked to keep the left hand (with the soft robotic exoskeleton) relaxed with no voluntary muscle contraction while moving the right hand (with the data glove) in a closing and opening motion. The thumb finger was deactivated on the soft robotic exoskeleton to avoid interfering with the motion of the other fingers. The motion of the fingers was tracked by the data glove and the position data were sent to the pneumatic controller in real-time as reference inputs (desired trajectories). The controller also received the position feedback from IMU sensors on the soft robotic exoskeleton where they were compared against the reference inputs in order to determine the required control action for following the desired trajectories. Figure 9 shows the collected data from both data glove and the soft robotic exoskeleton for index, middle, ring, and little fingers. The soft robotic exoskeleton was able to follow the input trajectories received form the data glove with a very good agreement (mean error: 12.4° in Index, 7.7° in Middle, 5.3° in Ring, and 5.6° in Little). Some variations were observed especially for the index finger, which can be attributed to fitting of the robotic exoskeleton user hand, delay in the pneumatic system, and potentially the user's involuntary muscle action during the test. The performance of the robotic exoskeleton in view of applying bilateral/bimanual therapy will be further evaluated with post-stroke participants in future studies.

Conclusion

In this work, the design and development of a soft robotic hand exoskeleton, with five sensorized soft robotic digits and a wearable fixture, for rehabilitation in adults with stroke was presented. We demonstrated a novel soft-and-rigid actuator architecture that combines advantages from soft and conventional robotic approaches to produce the desired kinematic features of the human finger including, ROM at the joints, the coincident of COR of the robotic mechanism with the human finger joint, as well as the dorsal lengthening over the joint. An iterative design process was used to obtain the desired design parameters which satisfy both kinematic and dynamic requirements, while other key factors like having a light weight, less bulky structure, and easy wearability were also considered. Experimental validation was carried out using a motion capture system where a single soft robotic digit was attached on top of a human index finger. The flexion and extension motion of the finger, produced by the robot, was recorded through the tracking coordinates of the attached reflective markers. A pneumatic control system with the associated feedback position control algorithms was developed to operate the robotic exoskeleton based on three principal therapeutic modes: continuous passive motion, active assistive motion, and active resistive motion. The obtained results showed that the soft robotic digit was able to produce the required ROM and dorsal lengthening. In addition, the trajectories of the remote COR of the soft robotic mechanism was in close agreement with COR of the human finger. A pilot study was carried out on one stroke patient where continuous passive motion with a range of rotation of 0-100° was applied to the hand by the soft robotic exoskeleton during multiple trials. The results showed the robust performance of the robot in applying CPM therapy while improvement in flexion and extension motion of the middle and ring fingers was observed during the operation.

Future work:

Future work will continue to refine and improve the hardware and software of the device. The future control algorithms will be dynamic model-based which addresses this aspect while we will use 9 DoF IMU sensors with better accuracy to reduce the angular rotation measurement errors. Future work will also investigate the ability of the hand to grasp and perform functional activities and assess the potential clinical benefit to each of the control modes, CPM, PAM, ARM.

Acknowledgments

This paper is based upon work supported partially by National Science Foundation grant no. 1605635 and the Texas Medical Research Collaborative (TexasMRC) fund. Authors would like to thank the University of Texas at Arlington Research Institute (UTARI) and the University of North Texas Health Science Center (UNTHSC) for supporting this project. Special thanks to Ms. Alexandra Lindsay and Dr. Haleh Aghajani for her valuable inputs to this paper and Ms. Aida Nasirian for helping with the tests.

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Figure 1: Soft robotic exoskeleton system worn on a user's hand showing its three main components

Figure 2: Definition of the kinematic parameters, range of motion (θ), location of center of rotation C (xc,yc), and lengthening (L) for a single soft joint section

Figure 3: Fabricated soft-and-rigid hybrid architecture soft robotic digits

Figure 4: Cross section of a generic shape of a soft joint section in between two semi-rigid with associated design parameters

Figure 5: Experimental validation setup using a single soft robotic digit attached to a human index finger, with reflective markers attached along both robot and the human finger, for tracking the motion using the motion capture system

Figure 6: Schematic of the control system with pneumatic and electronic components for a soft robotic digit

Figure 7: Experimental data obtained for (a) range of motion of each soft joint section, (b) the location of the center of rotation of both robotic digit and the human finger, and (c) lengthening of the soft joint sections

Figure 8: Collected data from CPM testing on a stroke patient

Figure 9: Angular motion of (a) the index, (b) middle, (c) ring, and (d) little finger obtained during bilateral/bimanual testing on a healthy participant

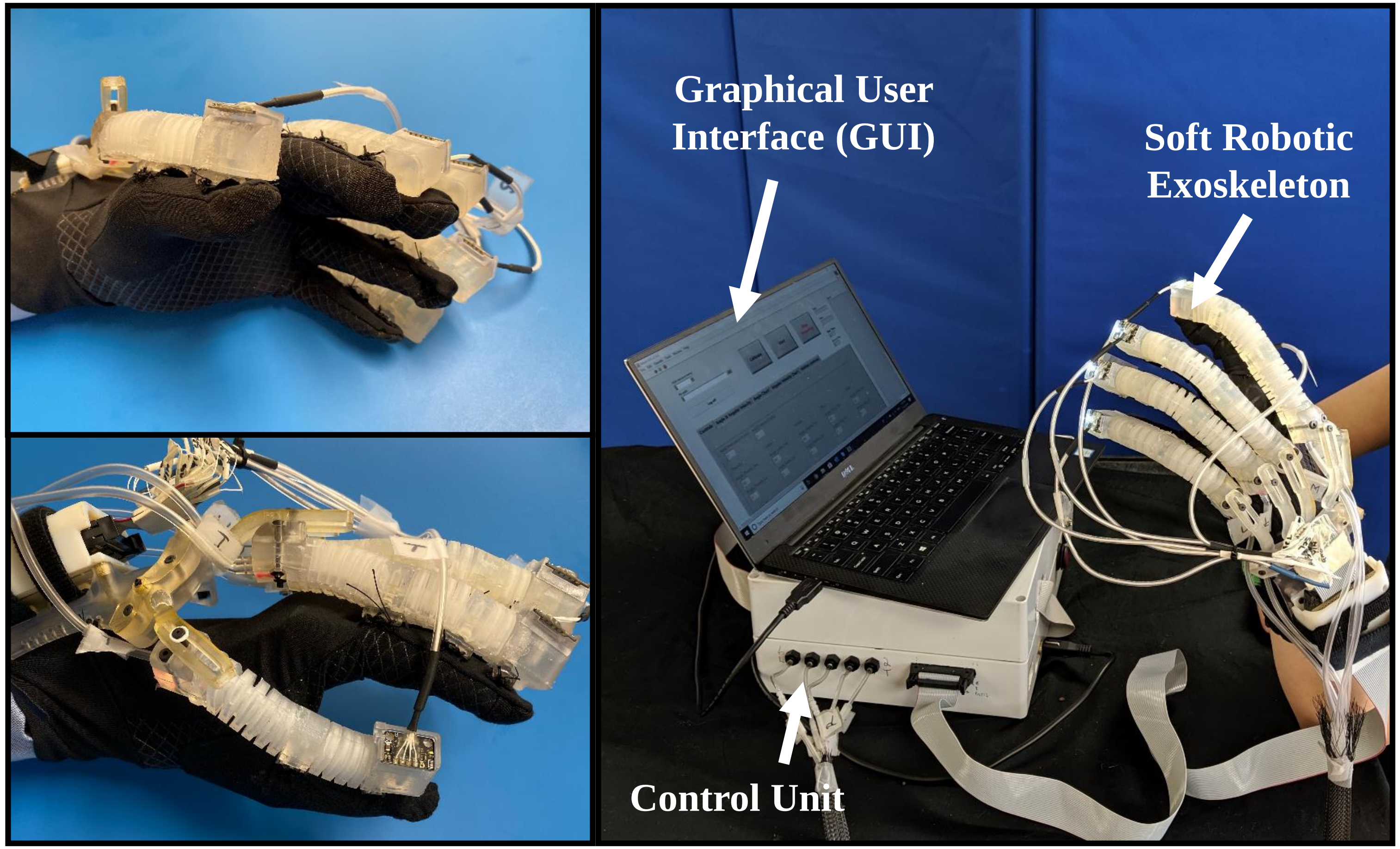

Graphical User
Interface (GUI)
Soft Robotic
Exoskeleton
Control Unit

Figure 1

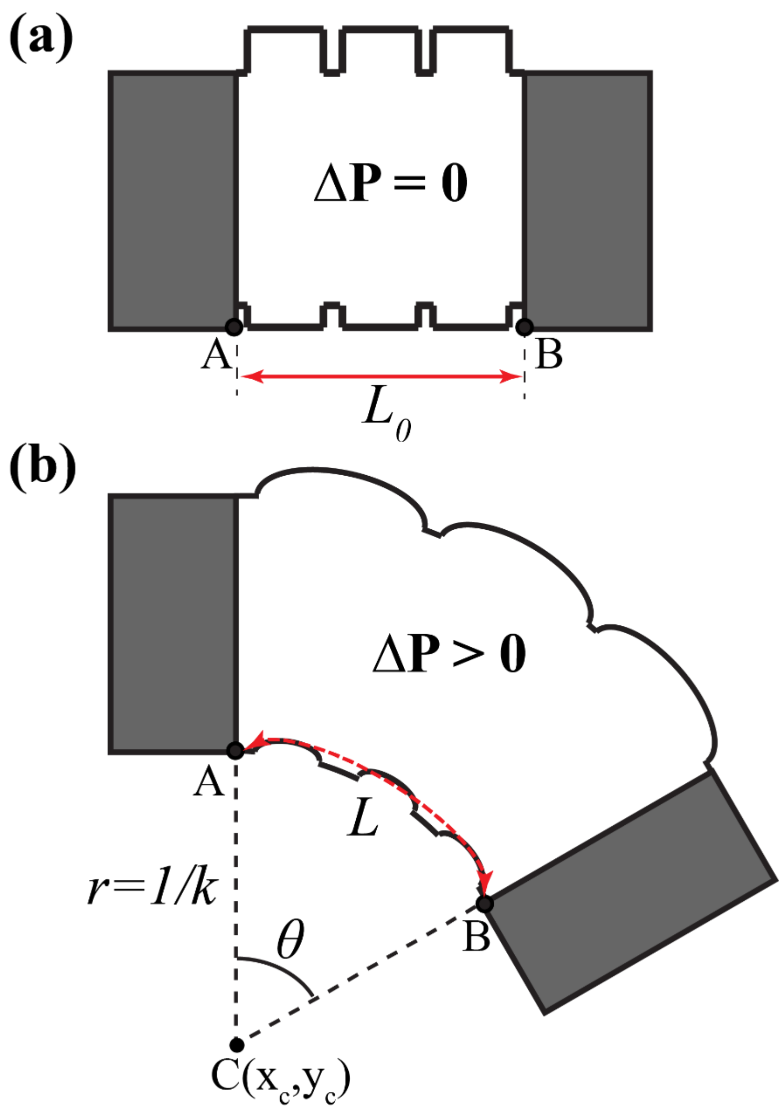


Figure 2

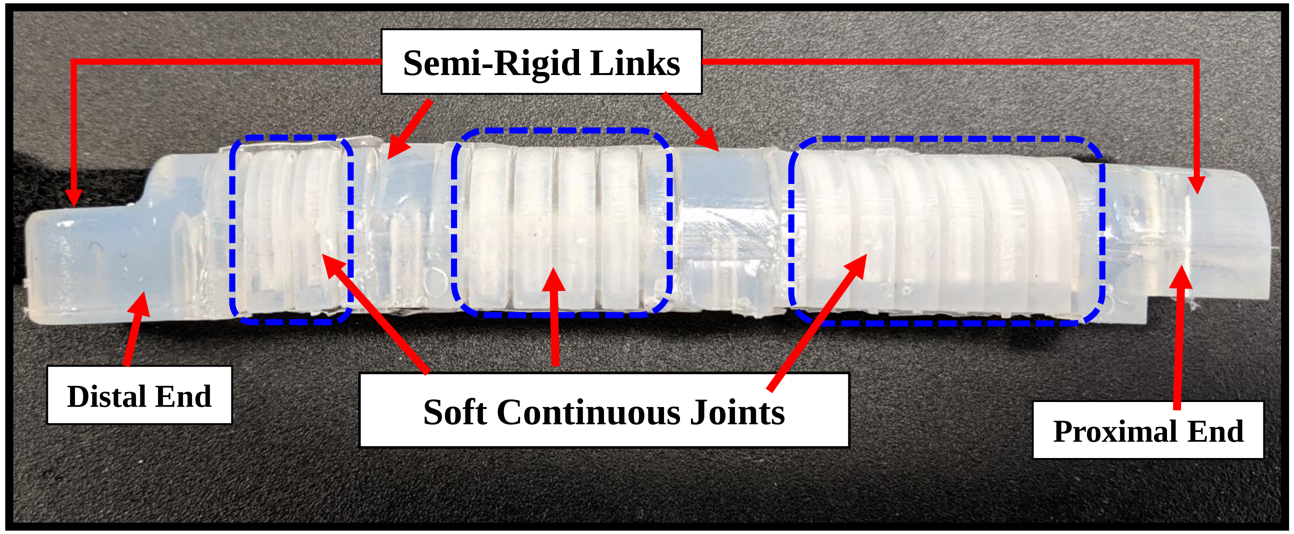

Semi-Rigid Links
Distal End
Soft Continuous Joints
Proximal End

Figure 3

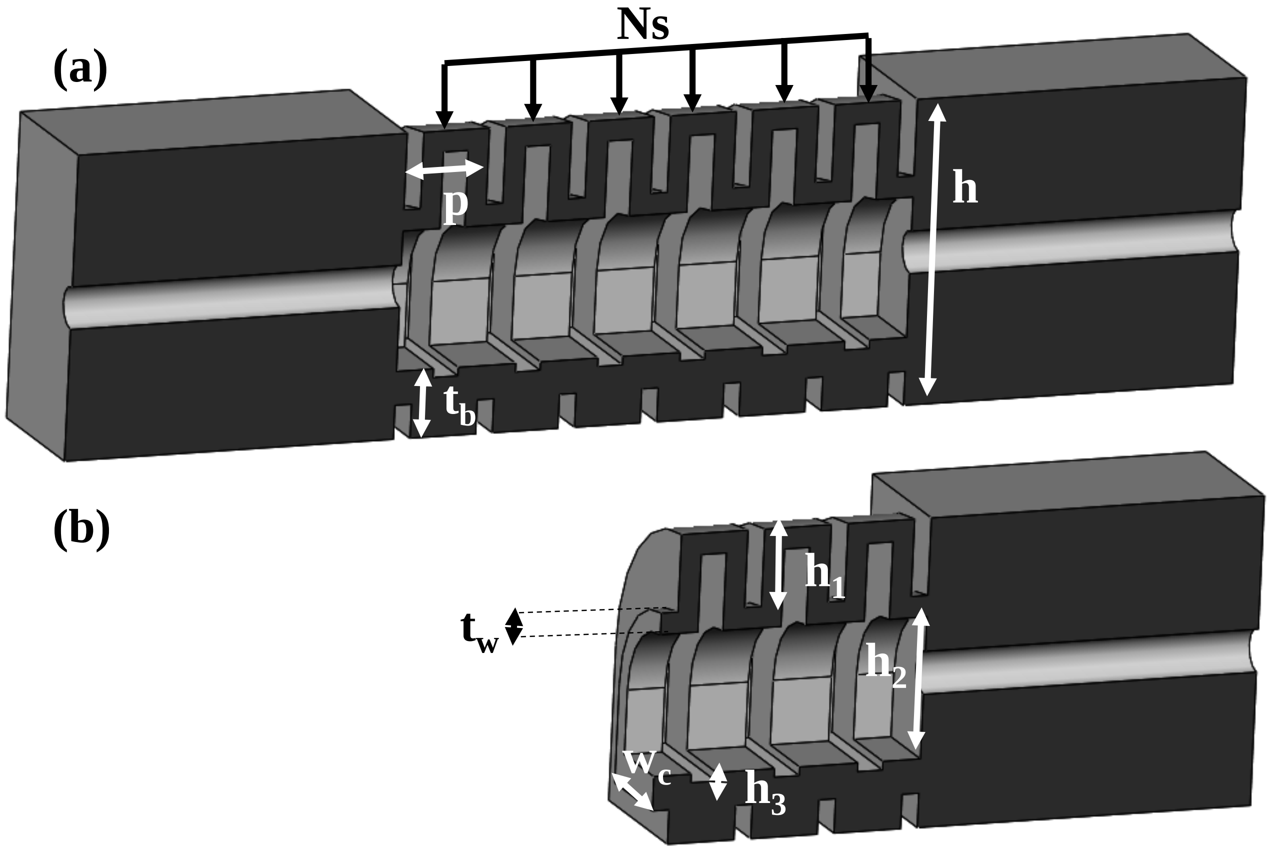


Figure 4

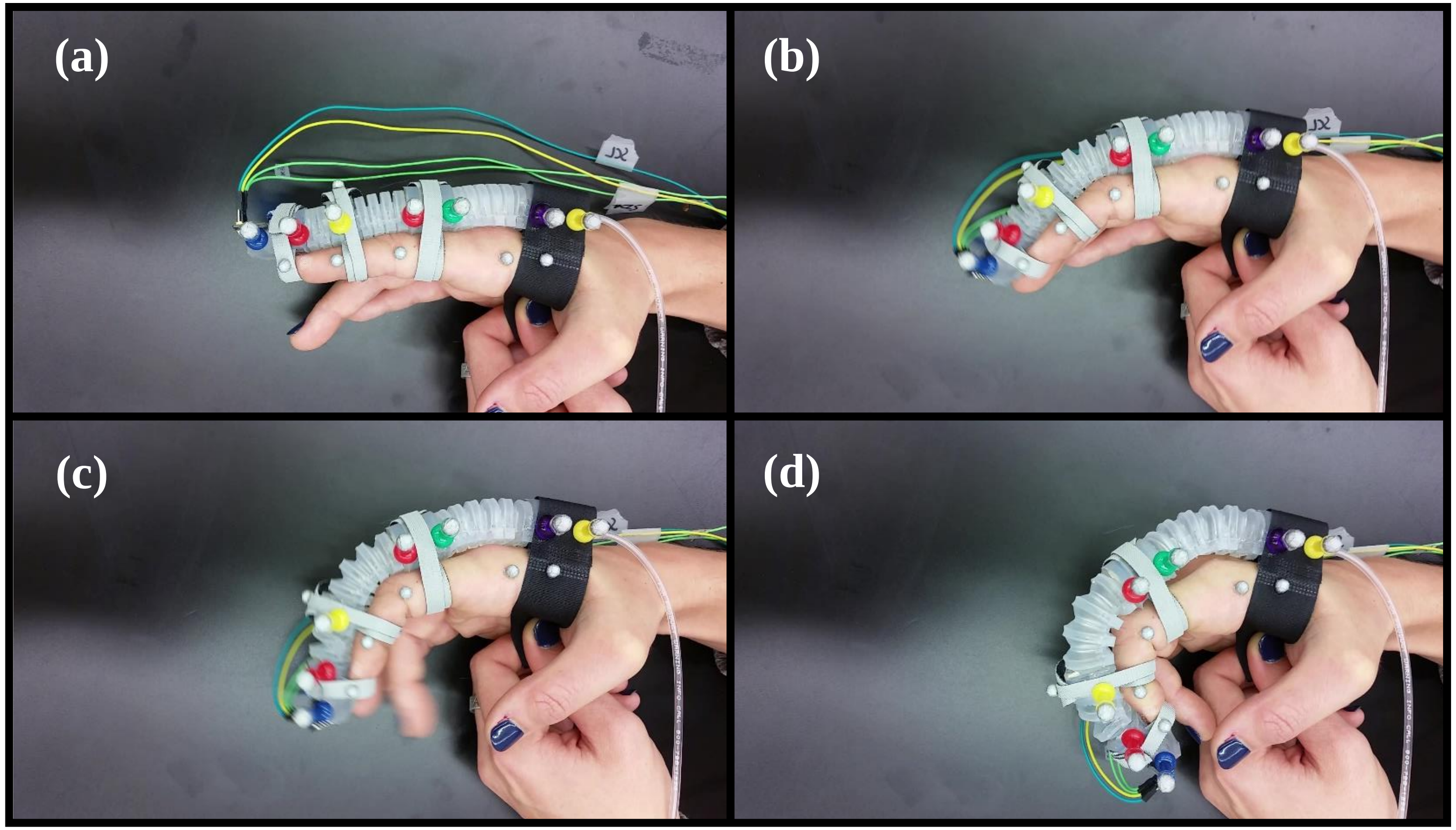


Figure 5

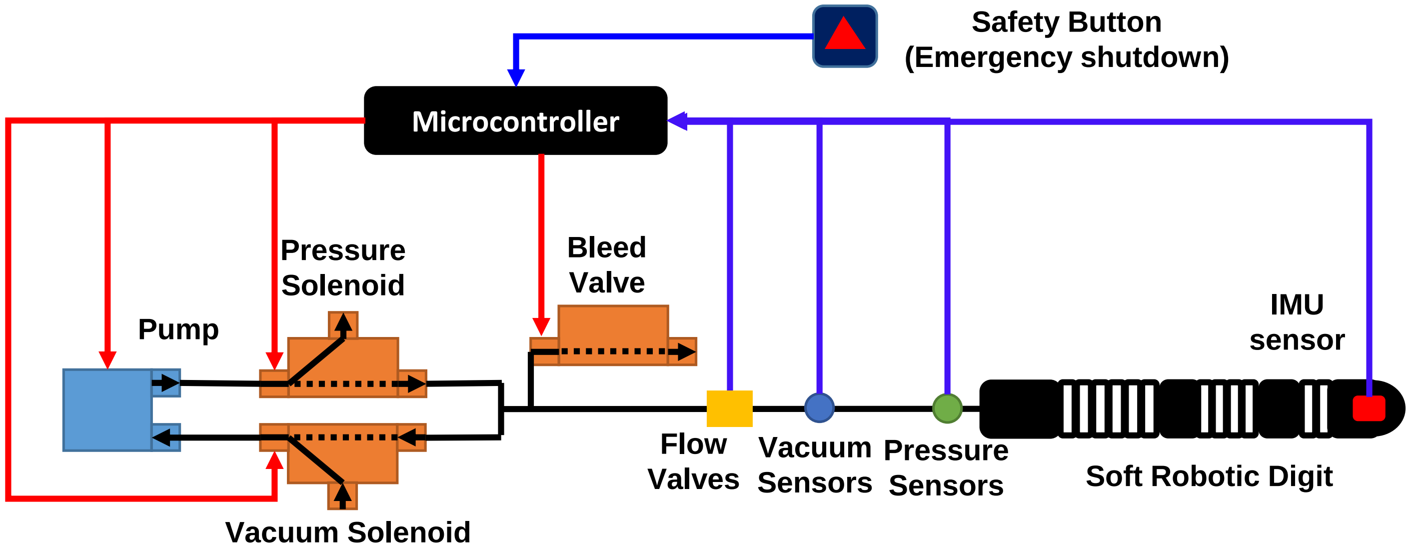

Safety Button
(Emergency shutdown)
Microcontroller
Pressure
Solenoid
Bleed
Valve
Pump
IMU
sensor
Flow
Valves
Vacuum
Sensors
Pressure
Sensors
Soft Robotic Digit
Vacuum Solenoid

Figure 6

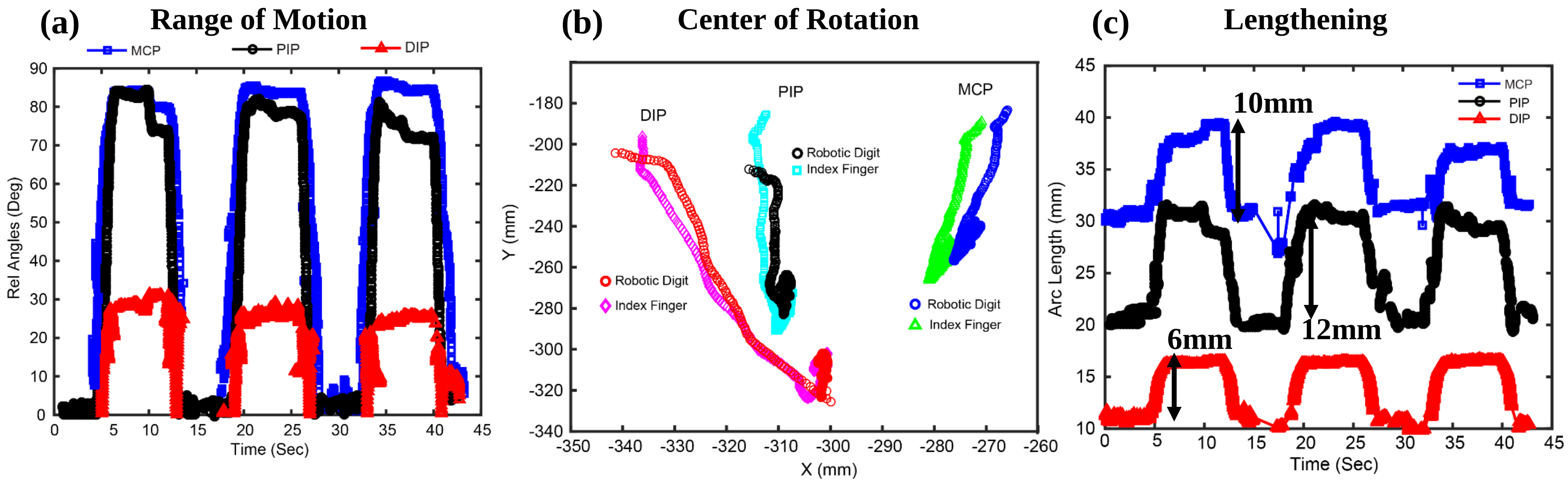
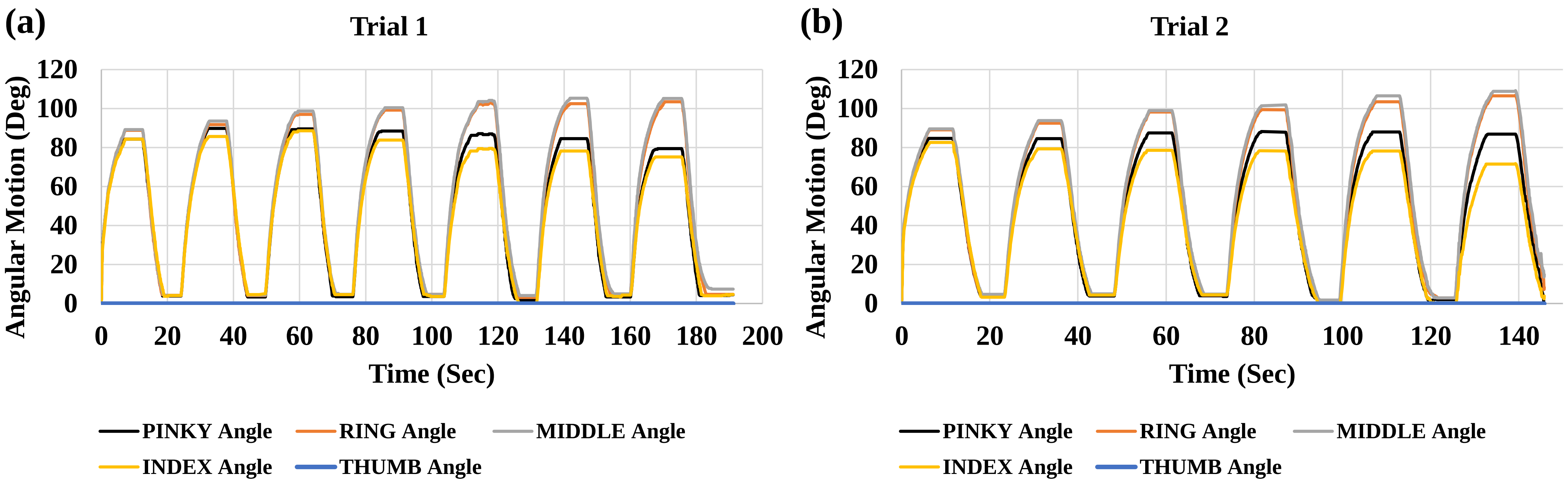

(a)
Range of Motion
MCP
PIP
DIP
Rel Angles (Deg)
Time (Sec)
(b)
Center of Rotation
DIP
PIP
MCP
Robotic Digit
Index Finger
Y (mm)
X (mm)
(c)
Lengthening
MCP
PIP
DIP
10mm
12mm
6mm
Arc Length (mm)
Time (Sec)

Figure 7



(a)
Trial 1
Angular Motion (Deg)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
Time (Sec)
PINKY Angle
RING Angle
MIDDLE Angle
INDEX Angle
THUMB Angle
(b)
Trial 2
Angular Motion (Deg)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Time (Sec)
PINKY Angle
RING Angle
MIDDLE Angle
INDEX Angle
THUMB Angle

Figure 8

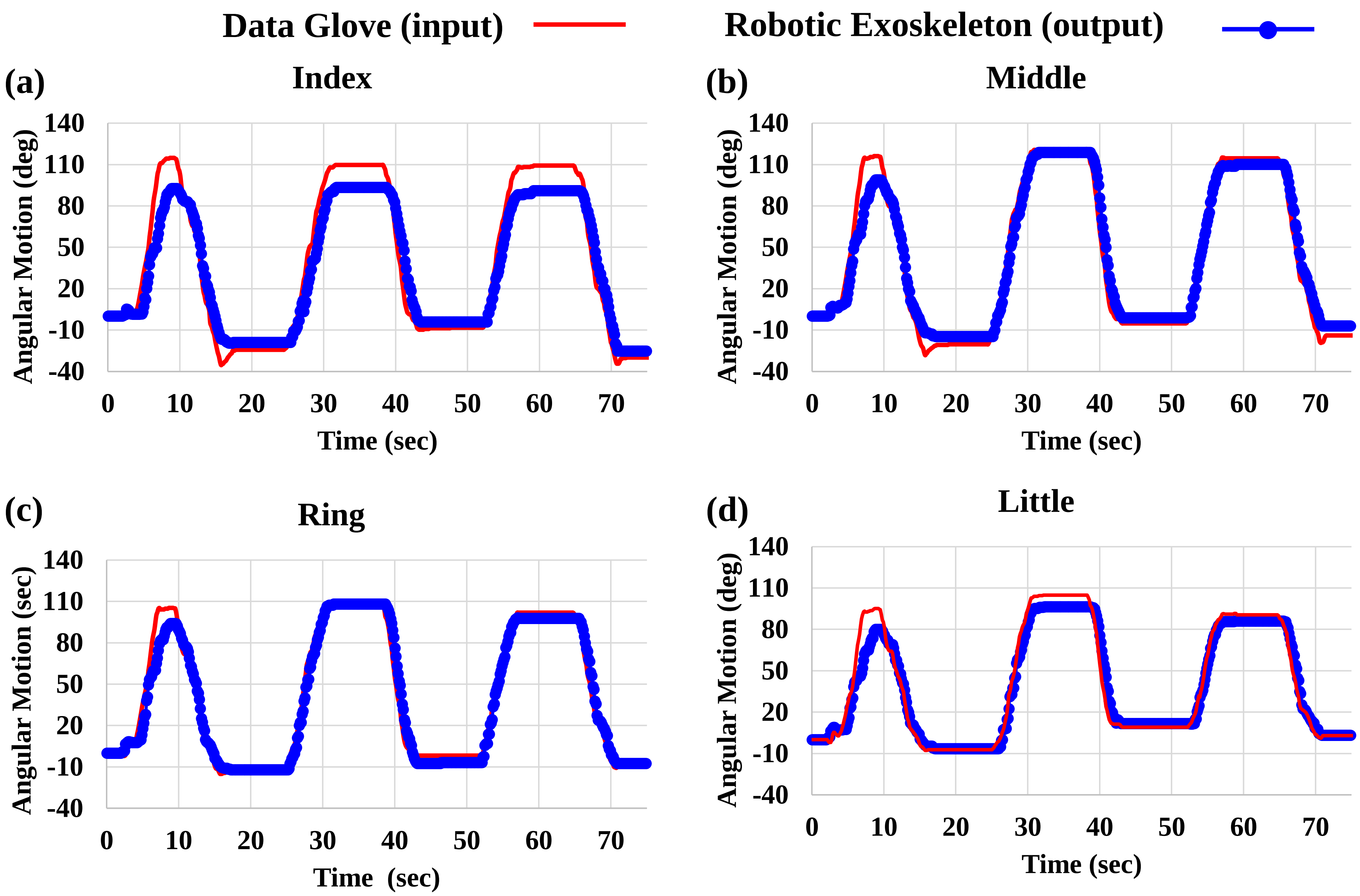

Data Glove (input)
Robotic Exoskeleton (output)
(a)
Index
Angular Motion (deg)
140
110
80
50
20
-10
-40
0
10
20
30
40
50
60
70
Time (sec)
(b)
Middle
Angular Motion (deg)
Time (sec)
(c)
Ring
Angular Motion (sec)
Time (sec)
(d)
Little
Angular Motion (deg)
Time (sec)

Figure 9