Soft Robotic Glove Modulating Joint Torque Through Novel Passive Extensor Mechanisms

Hyungmin Choi, *Student Member, IEEE*, Kyu Bum Kim, *Student Member, IEEE*, Sangheui Cheon, *Student Member, IEEE*, Joon-Ho Shin, *Member, IEEE*, and Kyu-Jin Cho, *Member, IEEE*

***Abstract*—Soft robotic gloves have been widely researched to enhance the quality of life of people who cannot use their hands freely. Despite significant advancements in this field, most existing solutions have not adequately addressed adaptability to various individuals and tasks. Our robot overcomes these challenges through a novel passive extension mechanism, which enables adjustment of assistance torque for each finger joint adequately to various situations. To enable diverse assistance torque profiles without the need for extra actuators, two passive extensors with different moment arms for each finger joint have been implemented. A variable stiffness passive extensor adjuster (VSPE adjuster) is designed to change the stiffness and tension of each passive extensor easily. We've thoroughly verified the performance of each component through simulation and experiments. In the final demonstration of its feasibility, the robot was tested on three healthy participants and one participant with spinal cord injury, exhibiting its adaptability and promising potential for future real-world applications.**

***Index Terms*—Rehabilitation robotics, tendon/wire mechanism, wearable robotics.**

I. Introduction

THE hand serves a significant role in daily life; however, some individuals with disabilities have limited hand function, resulting in a diminished quality of life [1]. Soft robotic gloves have emerged as a possible solution for these individuals. By utilizing various soft actuation methods and components, these robotic devices can efficiently assist hand movement while adopting the complex shape of the hand and minimizing harm or injuries [2], [3], [4], [5], [6], [7], [8]. Furthermore, extensive research has been conducted on several elements of soft robotic gloves, including their structure, wearability, control mechanisms, and intent recognition [9], [10], [11].

Despite its advancements in numerous aspects, further development is still required to enhance its adaptability across various individuals and tasks. The biomechanical properties of each finger joint exhibit variability among individuals, particularly among those with disabilities [12], [13], [14], hence making it inadequate to apply for the same assistance across various people. Moreover, the divergence of muscle activation patterns among impaired individuals highlights the necessity of customized changes to joint assistive torque [15], [16]. Furthermore, it is crucial to carefully adjust the assistive torque to align with the training session, as the motions, assignments, and training type may differ depending on the tasks users need to perform [17]. For example, in some exercises like finger hook, the motion of the distal phalange requires to be prior to the proximal one, but in some other exercises like pinch grasping, the sequence or importance reverses [18]. Because of these factors, for a soft robotic glove to be utilized properly, the robot is required to be able to tailor assistive torque to each joint corresponding to the individual and tasks.

However, as many soft robotic gloves are designed as an under-actuated system for compact and efficient assistance, [9], it is hard to generate adequate assistance torque at each joint, considering each individual's distinct properties and requirements related to the target tasks [12]. To mitigate these variations, numerous researchers have conducted research for adjusting the assistance torque in response to diverse individuals and tasks. One straightforward solution is increasing the rank of the control input of the under-actuated system or making the system a fully-actuated system by adding additional actuators [5], [7], [19], [20], [21]. Although this strategy can control assistance torque magnitude and ratio at each joint, it requires a significant number of actuators and requires a complex system. An alternative method involves developing a modular glove capable of adjusting the torque at each finger joint by changing the actuator modules of the robot at each joint [2], but time-consuming for module replacement and limited adjustment torque range which depends on the number of modules are limitation of this method.

Although the previous approaches focused on actuators, the assistance provided by a soft robotic glove is not only composed of the torque generated by the actuator alone. Passive components (e.g. spring or rubber bands) have also been used to generate efficient assistance to the mild to moderately impaired disabled people while minimizing the number of actuators and improving the usability [5], [22], [23], [24]. These robotic systems usually provide users with the capability to modify the levels of assistance, allowing a certain degree of customization.

Manuscript received 11 September 2023; accepted 14 January 2024. Date of publication 6 February 2024; date of current version 23 February 2024. This letter was recommended for publication by Associate Editor M. Bianchi and Editor J.-H. Ryu upon evaluation of the reviewers' comments. This work was supported in part by the Translational Research Program for Rehabilitation Robots under Grant NRCTR-EX20007, in part by National Rehabilitation Center, Ministry of Health and Welfare, Korea, by the Ministry of Trade, Industry and Energy (MOTIE, Korea) under Project 20014480, and in part by the National Research Foundation of Korea (NRF) funded by the Korean Government (MSIT) under Grant RS-2023-00208052. *(Corresponding author: Kyu-Jin Cho.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Boards at Seoul National University under Application No. 2307/003-006.

Hyungmin Choi, Kyu Bum Kim, Sangheui Cheon, and Kyu-Jin Cho are with the Department of Mechanical Engineering, Seoul National University, Seoul 08826, South Korea (e-mail: kjcho@snu.ac.kr).

Joon-Ho Shin is with the Department of Rehabilitation Medicine, National Rehabilitation Center, Seoul 01022, South Korea (e-mail: asfreelyas@gmail.com).

This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2024.3362593, provided by the authors.

Digital Object Identifier 10.1109/LRA.2024.3362593

Fig. 1. Overall design of the proposed soft, cable-driven robotic glove with novel passive extensor mechanism.

Nevertheless, the existing passive components in soft robotic gloves solely possess the capability to modify the overall level of assistance, hence hard to regulate the assistance ratio between each joint. Some research groups suggested customization of the passive components by measuring the spasticity levels at each finger joint [25], but it is hard to tune in real-time depending on tasks.

In this letter, we introduce a soft robotic glove featuring a unique passive extensor mechanism. This mechanism allows for tailoring the assistance torque at individual finger joints, making it adaptable to various task-specific needs and a wide range of people with mild to moderate hand disabilities. Our design deploys dual passive extensors for each finger, utilizing different moment arms at each joint, which contrasts with traditional designs that incorporate a single passive extensor. Also, Variable Stiffness Passive Extensor adjusters (VSPE adjusters) have been developed, which modify the stiffness and tension of each extensor by changing the length of the passive cable and locking the change automatically. Through this, the assistance torque applied at each joint can be easily adjusted without the need for supplementary actuators. The viability of the suggested methodologies has been validated through simulations and experiments. Finally, we applied our robot to four human subjects and showed its feasibility. The paper's structure is outlined as follows: Section II of the paper presents the design of the robot, with a particular focus on the dual passive extensor and VSPE adjuster. The simulation, experimental methodology, and results are presented in Sections III and IV, respectively, while the overall conclusion of the research is described in Section V.

II. Design

The overall design of the glove is illustrated in Fig. 1 and the various finger motions with different extensor states are presented in Fig. 2. The proposed robotic glove has been designed to target mild to moderate hand-impaired people (e.g. people with spinal cord injury (SCI) or stroke without high spasticity) considering the effectiveness of the passive components and preventing excessive tension. The key components of the glove are dual passive extensors and VSPE adjusters. Passive Extensor 1 (PE 1; red dashed line in Fig. 3) has a higher moment arm at the proximal interphalangeal (PIP) joint, whereas Passive Extensor 2 (PE 2; blue dashed line in Fig. 3) has a higher moment arm at the metacarpophalangeal (MCP) joint. Therefore, the torques generated by each extensor have different torque ratios at each joint, and depending on the various hand properties of users and target tasks, assistance torques can be tailored by adjusting the stiffness or tension of each passive extensor. The state of each passive extensor (stiffness and tension) is modulated by the VSPE adjuster which winds and unwinds the extensor on the spool to alter the length of the extensor. Through these mechanisms, the glove can generate various finger motions without increasing the number of actuators. The overall glove design and detailed mechanisms will be explained in this section.

A. Main Glove

The glove is designed as a modular glove divided into finger units and a body part to adapt to various sizes. The body part works as an anchoring part by holding the glove in its place and the finger part of the glove transmits force to the finger. An active flexor (Dyneema, Netherlands) and two passive extensors (TPU cord, Crystal Tec, Korea) are inserted into the thimble. The flexor passes through the volar side of the finger, mimicking the flexor digitorum profundus tendon of the human. The two passive extensors go through the extensor routers and are inserted into the VSPE adjusters. The extensor routers are attached on the dorsal side of the finger through velcro to adjust the location of the router depending on the user. The distal end of the VSPE adjuster and flexor sheath are inserted and attached to the slot located at the wrist, which performs as a tendon anchoring support [4]. The overall glove is manufactured using fabric and 3D printed parts (HP Jet Fusion 5200, HP, USA) to withstand the tension of the tendons with thin structures. The glove can be easily donned due to its modular design: around 2 minutes are required to put a finger unit and body part on an SCI participant with quadriplegia (50 seconds for a finger unit, less than 30 seconds for a body part, 45 seconds for connection). Following the previous study [3], the glove has been designed into four different sizes (S, M, L, XL) in both length and width, for covering various users.

B. Variable Stiffness Passive Extensor Adjuster

To modulate the assistance torque to each finger joint depending on the individual and task, both the magnitude of the overall joint torque and the torque ratio between each joint should be adjustable. To adjust them easily, two techniques are applied to the robot: variable stiffness passive extensor adjuster (VSPE adjuster) and dual passive extensor.

Firstly, the VSPE adjuster is designed to modify the magnitude of the assistance. Fig. 4 shows the detailed design of the proposed adjuster. Each extensor is affixed and wound around the adjuster's spool, with the extensor length being altered as the spool rotates. A torx-shaped moving key is located at the center of the VSPE. The moving key can slide up and down (Fig. 4(b)), and lock the angular position of the spool at 60-degree intervals (around 3.5 mm intervals of the extensor length). To rotate the spool, users should initially depress the moving key using the

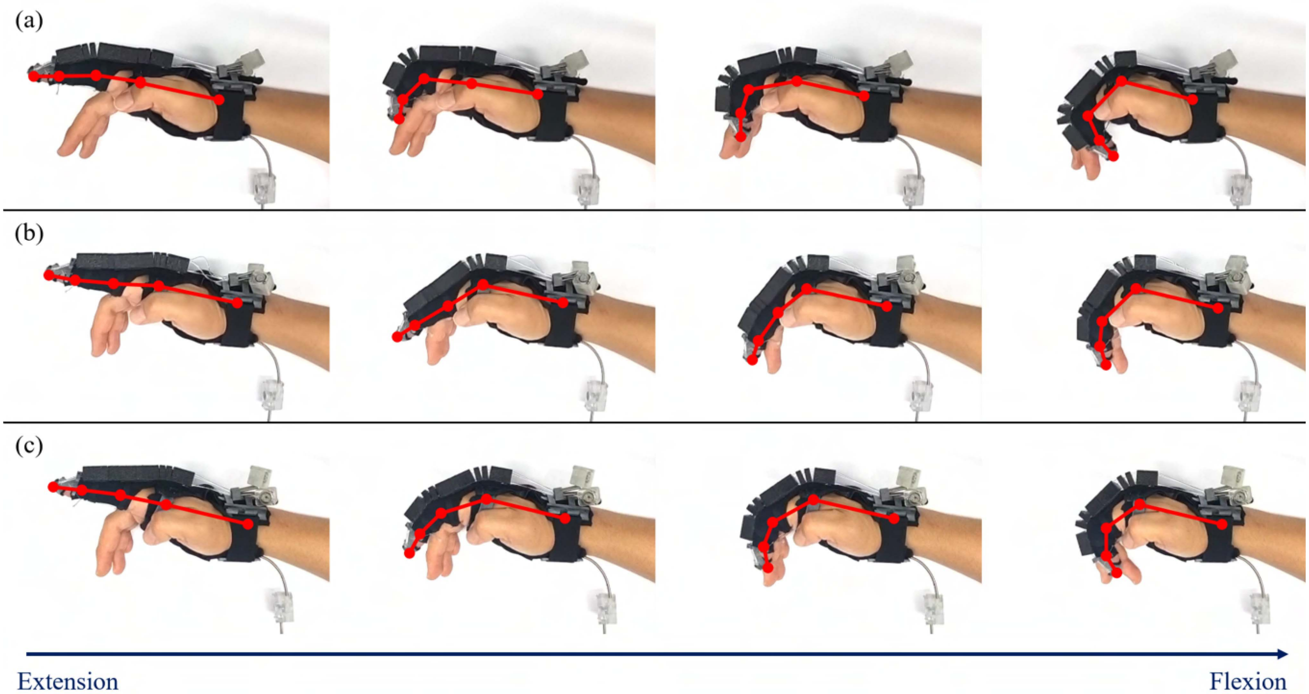

Fig. 2. Variation of the index finger motion occurred by the robot. The state of each passive extensor is different at (a), (b), and (c), and so does the finger move differently at each extensor state. The whole motion occurs without the voluntary movement of the wearer.

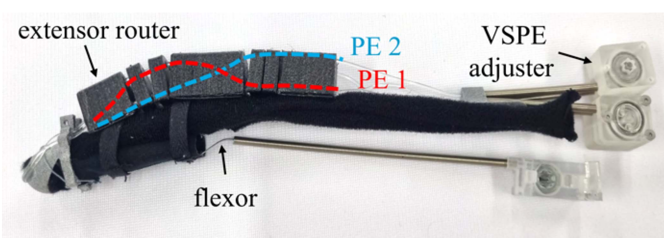

Fig. 3. Detailed explanation of the finger part. Two passive extensors are inserted into the design. In Passive Extensor 1 (PE 1, red dashed line), the moment arm at the PIP joint is higher compared to the MCP joint. In passive extensor 2 (PE 2, blue dashed line), the moment arm at the MCP joint is higher compared to the PIP joint.

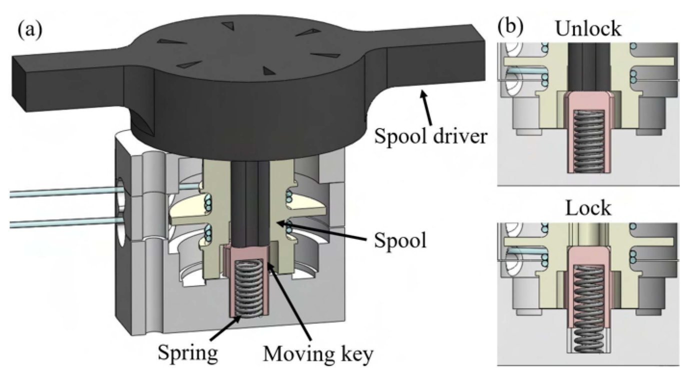

Fig. 4. (a) Overview of the VSPE adjuster mechanism. (b) Two different states of the moving key. When the key moves up, the keyhole on the spool, the moving key, and the keyhole on the bottom surface are connected to each other, and the rotation of the spool locks. When the key moves down, the moving key does not contact with the keyhole on the spool, so the spool can rotate with the spool driver.

spool driver before turning the driver. Once the spool driver is withdrawn from the spool, the moving key moves upward, inserted into the keyhole of the spool, automatically locking the spool's rotation and securing the extensor at the desired length. This mechanism supports the comfortable adjustment of each extensor's stiffness as well as the initial pre-stretched length.

The principle of how the extensor's pretension and stiffness are modified can be explained through mathematical modeling. At first, the tension of the passive extensors can be represented as:

$$F_p = f(E, \varepsilon) \tag{1}$$

where E represents Young‘s modulus of the extensor cable, and ε represents the strain of the extensor. As Young‘s modulus is determined by the material of the extensor, the force applied by the passive extensor is mostly determined by the strain of the extensor. In previous soft robotic gloves, the tension on the passive extensor is often modulated by pre-stretching the cables. This method can be modeled as:

$$F_p = f(E, \varepsilon) = f(E, (s + \tilde{s})/L_0) \tag{2}$$

where s denotes the stretched length of the extensor by finger movements, $\tilde{s}$ denotes the pre-stretched length, and L_0 denotes the initial length of the extensor when tension is zero.

On the other hand, since the VSPE adjuster winds and unwinds the cable around the spool, it can be perceived as changing the initial length of the extensor. When the tension is applied, the portion of the extensor wound around the spool will not be elongated due to the friction between the extensor and the spool. This non-participant portion can be assumed to be fixed to the spool and has the same effect of decreasing the length of the spring (extensor). Therefore, although the tendon stretched from L_0 to $L_0 + \tilde{s}$, this non-participant portion of the extensor decreases the initial length of the extensor from L_0 to $l_0(\tilde{s})$, making the force on the passive extensor as

$$F_p = f(E, \varepsilon) = f(E, (l_w(\tilde{s}) - l_0(\tilde{s}) + s)/l_0(\tilde{s})) \quad (3)$$

where $l_w(\tilde{s})$ is the stretched length of the extensor due to winding. As can be seen in (3), the proposed mechanism changes not only the length of the spring but also the stiffness of the extensor, which is different from the previous research and amplifies the assistance force change.

C. Dual Passive Extensor Tendon Routing

The assistance torque applied to the finger through the robot is the summation of the torque generated by both the extensor (τ_e) and flexor (τ_f)

$$\tau_{assist} = \tau_e + \tau_f \quad (4)$$

Thus, modifying the direction of either τ_e or τ_f can change the ratio of the assistance torque applied at each joint.

The torque generated by the two passive extensors can be represented as [26]:

$$\tau_e = -J_e^T(q)F_e = \begin{bmatrix} J_{e_1}^T(q) & J_{e_2}^T(q) \end{bmatrix} \begin{bmatrix} F_{e_1} \\ F_{e_2} \end{bmatrix} \quad (5)$$

where $J_{e_i}(q), F_{e_i}$ denote the Jacobian and tension of the i^{th} extensor, respectively. To generate various extensor assistance torque, $J_{e_1}(q)$ and $J_{e_2}(q)$ should not be parallel. Given that each component of $J_{e_i}(q)$ is the moment arm of the tendon at each joint, cable height at each joint is designed differently at PE1 and PE2. We have designed the extensors primarily focusing on the modulating torque ratio between PIP and MCP joints (τ_{MCP}/τ_{PIP}). PE 1 has been designed to have a greater moment arm at the PIP joint compared to the MCP ($h_{1_{DIP}} = 3$ mm, $h_{1_{PIP}} = 10$ mm, $h_{1_{MCP}} = 0.5$ mm), so increasing tension on PE1 will decrease τ_{MCP}/τ_{PIP}. In contrast, PE 2 has a greater moment arm at the MCP joint ($h_{2_{DIP}} = 1$ mm, $h_{2_{PIP}} = 0.5$ mm, $h_{2_{MCP}} = 10$ mm) and increasing tension of PE2 will increase τ_{MCP}/τ_{PIP}. Therefore, the robot can generate either higher PIP extension assistance by increasing PE1 engagement (e.g. stroke patients with high PIP joint stiffness) or higher MCP extension assistance by tensioning PE2 more (e.g. individuals with flexed MCP joint). The height of each extensor is designed to minimize the overall height of the glove while covering the joint stiffness variation of the PIP and MCP joint ($0.75 \leq k_{MCP}/k_{PIP} \leq 2$ in [5]). By designing the tendon path of PE1 and PE2 as above, changing the tension of each passive extensor can alter not only the magnitude but also the direction of τ_e, and consequently, the ratio of assistance torque by the robot without increasing the number of actuators.

III. Experiments

A. Variable Stiffness Passive Extensor Adjuster

The performance of the VSPE adjuster has been verified by demonstrating how the tension-elongation curve of the extensor varies depending on the number of windings around the spool. Tensile tests have been obtained using a linear stepper motor (FSL40, FUYU, China). The initial length of the passive extensor was set as 200 mm, and the passive extensor connected to the adjuster was pulled 100 mm. Six different winding states were tested (0, 1, 2, 3, 4, 5 times), and each trial was repeated five times. Before each trial, the initial length of the tensile machine was set as the tension generated by the extensor was under 0.05 N.

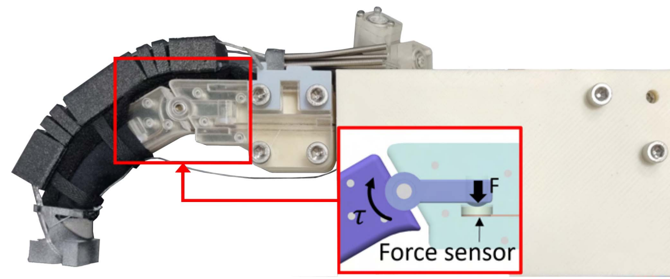

Fig. 5. Experiment setup for measuring assistance torque modulation. A finger mockup with force sensors embedded in each phalange is covered with a finger glove.

B. Dual Passive Extensor

We investigated whether the proposed dual passive extensor tendon routing is able to deliver various torque ratios to each finger joint. Both simulation and experiment have been conducted to show how the torque applied to each joint changes according to the state of the passive extensor, especially at the PIP and MCP joints. The indexes of the performance of the dual passive extensors were set as the torque proportion applied to the PIP and MCP joints ($\tau_{PIP}^{prop}, \tau_{MCP}^{prop}$), and the torque ratio between the PIP and MCP joints (τ_{MCP}/τ_{PIP}). The proportion of the assistance torque at each joint is defined as the ratio of the assistance torque at the target joint to the magnitude of the torque vector torque at the whole finger joints ($\tau_{target}/|\tau_{\mathbf{whole}}|$).

Experiments have been conducted using a finger mockup (Fig. 5) to show the torque modulation performance of the dual passive extensor. The joint radii of the mockup were set as 8 mm, 10 mm, and 12.5 mm at the DIP, PIP, and MCP joints, and the length of each phalange is 23 mm, 28 mm, and 43 mm respectively (from distal to proximal). The joints were designed using steel pins and ball bearings. A bar is attached at the proximal side of each phalange and protrudes along the proximal direction. As the torque is applied, the bar pushes the force sensor (Singletact, U.K.) located at the next phalange, changing the applied torque to the linear compression force. Given that the length of each bar is identical at all phalanges, the torque ratio at each joint can be assumed to be the same as the ratio between measured force at each force sensor. Three different configurations have been selected for experiments: one ordinary configuration ($q = (q_{DIP}, q_{PIP}, q_{MCP}) = (\pi/6, \pi/6, \pi/6)$), and two extreme configurations ($q = (0, \pi/2, 0), (0, 0, \pi/2)$). To demonstrate the glove's ability to change the torque ratio, each VSPE adjuster winds the extensor 0–5 times. Six trials have been conducted for each extensor combination. Each passive extensor was stretched over 10 times beyond 100 % of its initial length before starting the experiment considering the cyclic softening of the TPU cord, and the data was recorded after the force reached a saturated state.

TABLE I
NUMBER OF WINDINGS OF EACH PASSIVE EXTENSOR

Trial No.	Initial	Trial 1	Trial 2	Trial 3
PE1	0	4	2	0
PE2	0	0	2	4

The simulation used a 2D quasi-static kinematic model of the finger-glove system. The geometry of the simulated finger and glove are the same as the one used in the mockup experiments. The elongation-tension relationship is derived from the measurements. The routing paths of extensor cables were set to be identical to those of the proposed extensors in the robot. The initial length of each passive extensor was set as 200 mm. The simulation was conducted using Matlab software (MathWorks, USA).

C. Glove Performance

The robotic glove has been applied to three healthy participants with no known impairments and one SCI participant with quadriplegia who cannot move fingers voluntarily to verify its performance. The experimental protocol obtained approval from the institutional review boards at Seoul National University (IRB No.2307/003-006), and each participant provided written informed consent before participating. The experiment was designed to be immediately stopped if participants complained about severe discomfort or pain.

Two scenarios have been devised considering the situation where the glove could be used. The first scenario simulated the execution of Continuous Passive Motion (CPM) exercises by the robotic glove (CPM scenario). The glove passively flexed and extended the index finger of each user using both passive extensors and an active flexor. Before starting the experiments, the excursion length of the flexor was set for each individual. During the experiments, the closed-loop position control was applied to move the flexor from the initial position to the determined length.The second scenario was designed to simulate active finger rehabilitation for people with spasticity or dystonia in finger flexors (Active finger rehabilitation scenario). Such individuals often struggle to perform finger extension or desired hand movement due to the higher tone on the flexor. Thus, providing adequate assistance on the extension could enhance the hand function. Therefore, to see whether the glove could generate various hand motions while cooperating with the subjects, only passive extensors exerted assistance onto the finger, and the flexor was kept slack during the scenario. The second scenario was conducted by only the healthy participants as an SCI participant cannot move the finger voluntarily.

Prior to the experiment, each participant was equipped with a well-fitted glove for their right hand. For healthy participants, two EMG sensors (Trigno, Delsys, USA) have been applied on the forearm to monitor the activities of the participants. They were then instructed about the correct upper limb posture to maintain during the experiments, consisting of a neutral wrist and forearm position.

The first experiment, aiming to replicate a CPM exercise, required participants to remain relaxed for the duration and the activation of the finger muscles has been monitored through EMG sensors. A unique combination of passive extensors, as listed in Table I, was chosen and assigned to the glove differently for each iteration. The active flexor then operated to pull and release the flexor tendon five times, generating a full flexion range for the index finger using a Slider-Tendon Linear Actuator [27] with a DC motor (2224B006S, Faulhaber, Swiss). This process was repeated for all combinations of passive extensors listed in Table I, where the orders were randomized. After the first experiment, three healthy participants were asked to perform the second scenario after a short break. The process of the experiment is similar to the first one, but participants were instructed to perform a series of finger flexion movements with their index finger on their own without considering the configuration of their fingers.

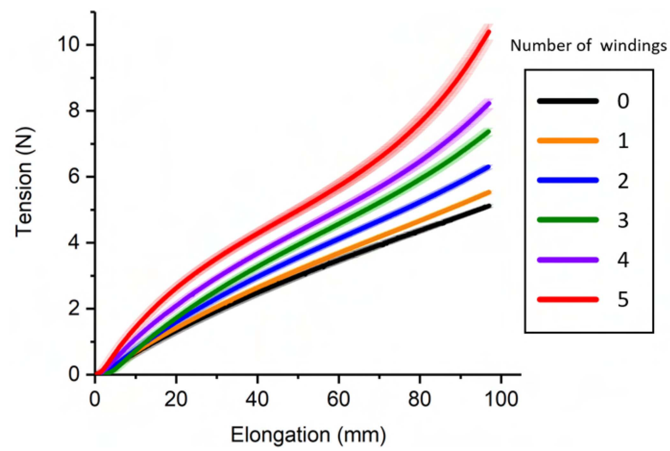

Fig. 6. Elongation and tension relationship at six different winding states of the passive extensor. The solid line represents the average value of the tension measured in the same elongation at each winding, and the standard deviation of each data point is represented as shaded areas around the solid line.

The performance index is derived from measuring the joint angle trajectories of the index finger under various passive extensor combinations, as enumerated in Table I. Joint angles of the index finger were recorded during the experiments using the motion capture system (PrimeX 13 W, Optitrack, NaturalPoint, Inc., USA). Three reflective markers were positioned on each finger phalange, each set forming the local coordinates for each phalange. The coordinate of each phalange is defined as follows: Z axis is aligned with the flexion-extension axis of each joint, X axis is aligned with the longitudinal axis of the phalange. Each joint angle was determined using ZYX Euler angles between the proximal and distal local coordinate systems.

IV. RESULTS

A. Variable Stiffness Passive Extensor Adjuster

Fig. 6 illustrates the tension-elongation relationship of the passive extensor fixed to the VSPE adjuster. As can be seen in the graph, the stiffness of the extensor changes depending on the number of windings of the extensor around the spool. As the number of windings on the adjuster increases, the tension applied on the extensor at the same elongation increases, which means that the stiffness of the extensor increases. Furthermore, the absence of abrupt tension changes around the graph indicates that the moving key mechanism effectively maintains the winding state of the adjuster stably. Consequently, the VSPE adjuster allows the users to modify the assistance level and stiffness of the structures easily.

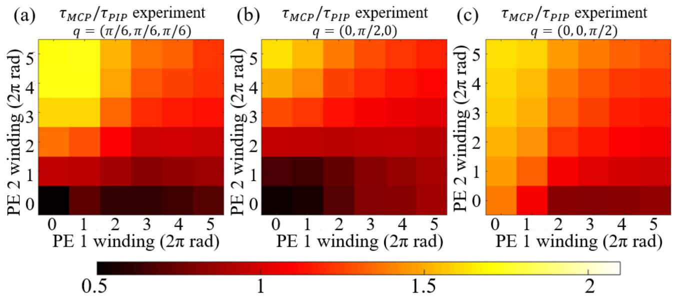

Fig. 7. Heatmap of the torque ratio from experiments in different configurations. (a) $q = (\pi/6, \pi/6, \pi/6)$ (b) $q = (0, \pi/2, 0)$ (c) $q = (0, 0, \pi/2)$.

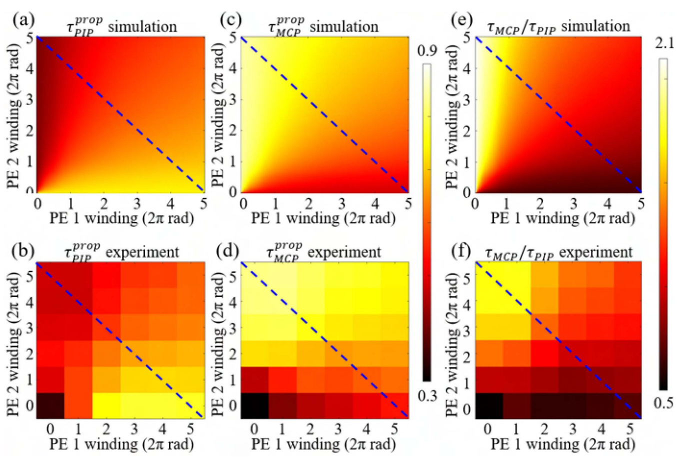

Fig. 8. Heatmap of the torque proportion and ratio. (a) Simulation results of the τ_{PIP}^{prop}. (b) Experiment results of the τ_{PIP}^{prop}. (c) Simulation results of the τ_{MCP}^{prop}. (d) Experiment results of the τ_{MCP}^{prop}. (e) Simulation results of the τ_{MCP}/τ_{PIP}. (f) Experiment results of the τ_{MCP}/τ_{PIP}.

B. Dual Passive Extensors

The results of the torque ratio experiment are depicted in Fig. 7. For more understanding of the torque transmission ratio changes in dual passive extensors, further analysis of the results and comparison with the simulation have been conducted on the ordinary configuration $q = (\pi/6, \pi/6, \pi/6)$, and the results are plotted in the Fig. 8. To show the tendency more intuitively, several data points are plotted as a 2D graph (Fig. 9). These data points correspond to the blue diagonal line in Fig. 8, where the sum of the winding angle of two spools of the VSPE adjusters is the same.

Examining the results, we can confirm that the torque ratio applied to each joint changes according to the state of the extensors. As we move from left to right in the heatmaps, the torque corresponding to the PIP joint gradually brightens, while the torque corresponding to the MCP joint gradually darkens. This means that as PE 1 (higher moment arm at the PIP) is wound more and the tension on PE1 becomes stronger, more torque would be applied on the PIP joint compared to the MCP. Conversely, as we move from bottom to top, the torque corresponding to the MCP joint gradually brightens, while the torque corresponding to the PIP joint gradually darkens. This means that if PE 2 (higher moment arm at the MCP) is wound more on the adjuster and the tension applied on PE2 becomes stronger, the proportion of the MCP torque increases. This

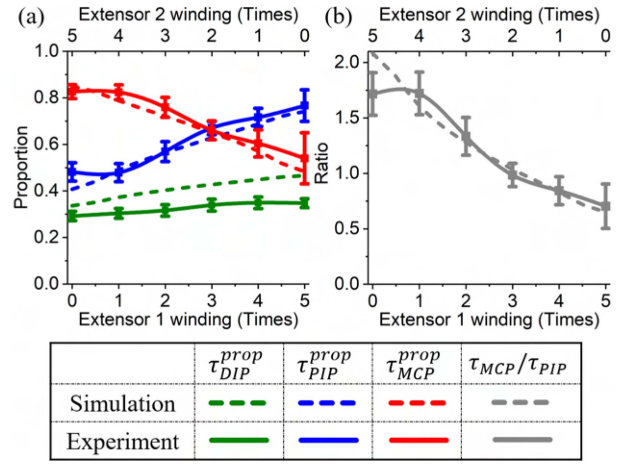

Fig. 9. (a) 2D plot of the torque proportion at each joint. (b) 2D plot of the torque ratio between PIP joint torque and MCP joint torque when the sum of total winding times of two extensors is 5 times (blue dotted line in Fig. 8).

tendency can be observed regardless of the joint configuration (Fig. 7) and is consistent in both experiments and simulations (Fig. 8). These results show that dual passive tendon routing can effectively change the torque ratio applied to each joint without additional actuators. Furthermore, this phenomenon follows the height (moment arm) differences of the extensors at each joint, which means that the tendency of change can be predicted based on the height of the extensor at each joint, allowing therapists or users to use this system more intuitively.

Some differences exist between the results of the simulation and the experiment. One of the factors is the friction between the routers and the extensors. The tension of the extensor decreases from proximal to distal due to friction on the cable path, which explains why the DIP torque ratio is somewhat lower in the experimental value than in the simulation. Additionally, the stiffness of the glove's fabric itself might have influenced the torque applied to each joint in the actual experiment, which was not considered in the simulation. This factor explains the difference between the experiments and the simulation results where the extensor tension is low (in the case of fewer windings at both extensors). However, the overall trends of the experimental results and the simulation are similar, and the trend of the experimental results for the PIP and MCP joint torques follows the tendency of the simulation results.

C. Glove Performance

The results of the index finger movements of the participants with the robotic glove are depicted in Fig. 10 (CPM scenario) and Fig. 11 (Active finger rehabiltation scenario). The movement of the index finger in the CPM scenario is a movement generated solely by the robot, without any voluntary movements from the participants. As can be seen in Fig. 10, the robot can generate both flexion and extension movements of the finger, even when applied to diverse individuals. Throughout the experiment, the discomfort or pain that participants felt was checked periodically, and none of them complained about it.

A key observation is that finger movements can be modified by altering the number of windings of each passive extensor on the adjuster. As VSPE winds PE 1 more (e.g. trial 1), the graph shifts

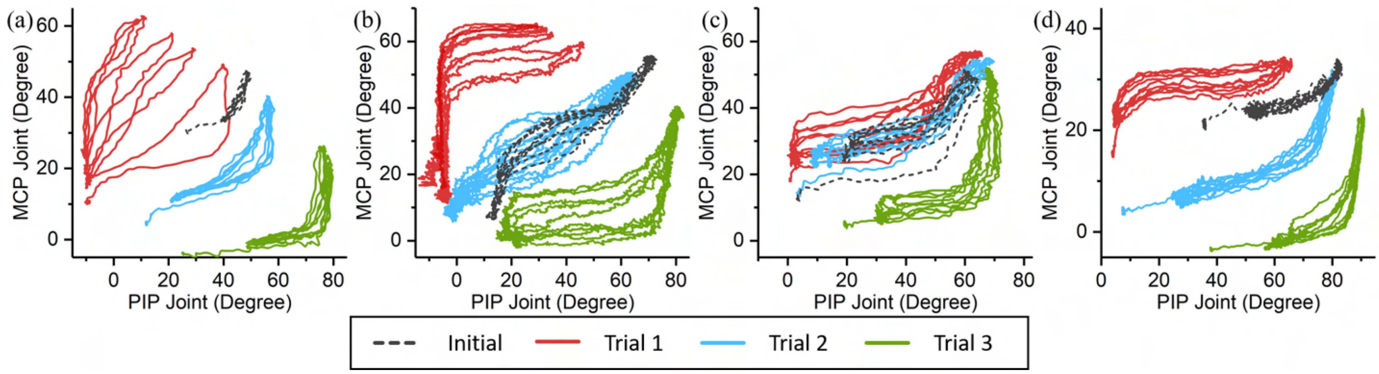

Fig. 10. Movement of PIP-MCP joints of index finger during CPM scenario. (a) Finger joints movement of participant 1. (b) Finger joints movement of participant 2. (c) Finger joints movement of participant 3. (d) Finger joint movements of the participants with SCI.

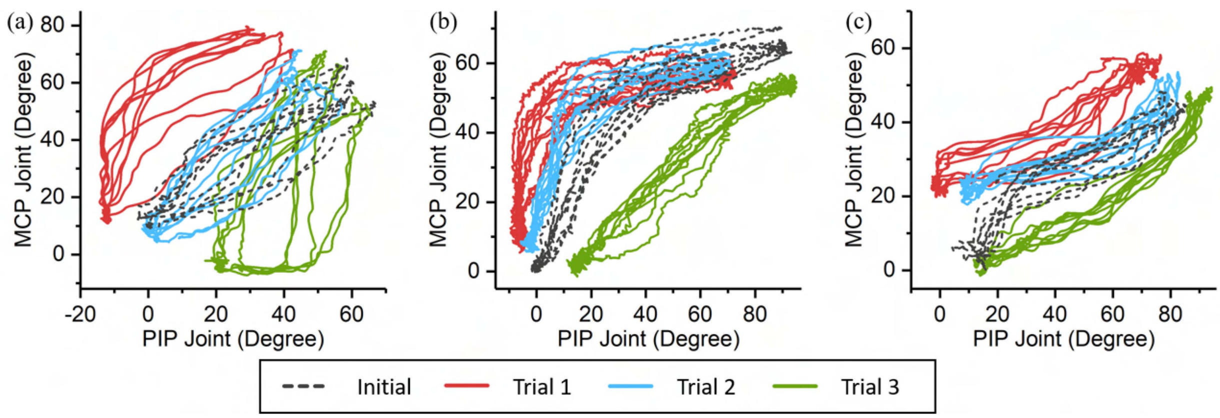

Fig. 11. Movement of PIP-MCP joints of index finger during active grasping rehabilitation scenario. (a) Finger joints movement of participant 1. (b) Finger joints movement of participant 2. (c) Finger joints movement of participant 3.

towards the upper-left side. This suggests that as the stiffness and tension of PE 1 increase, the PIP joint is relatively more extended than the MCP joint during finger flexion and extension. Conversely, when PE 2 is wound more on the adjuster (e.g. trial 3), the finger movement tends to be located on the lower-right side of the graph, which means that the MCP joint is more extended than the PIP joint during operation. These phenomena correspond with the moment arm ratios of each extensor and are consistent with both simulation results and mock-up experiment results in the previous section.

Another interesting point is that the trends of the movement are consistent, even if the robot was applied to different participants (even with hand disabilities), adjacent fingers interfere with movements of the index finger (especially at the SCI participant), or the scenario changes. While hand movements vary due to individual hand characteristics, the tendency of each joint movement is similar across the subject. Increasing assistance through PE1 resulted in a more pronounced extension movement in PIP while increasing tension on the PE2 led to a more pronounced extension movement in MCP. Furthermore, the finger joint movement trend does not stand out only in the CPM scenario where the robot exclusively drives the finger movement. It is also prominent in the active finger rehabilitation scenario where participants actively bend their fingers. This suggests that the introduced dual passive extensor can provide necessary assistance in a variety of situations predictably. Therefore, in real applications, the clinicians or users can customize the assistance only changing the VSPE of each PE considering the hand biomechanical properties or residual functions. For example, if someone needs more assistance in PIP extension, winding the VSPE adjuster of PE1 more would be an appropriate approach. Or if someone has higher flexor tone or rigidity on the MCP joint compared to other joints and thus requires additional extension assistance on the MCP, making PE2 stiffer by winding the VSPE spool connected to PE2 more would be a solution.

V. Conclusion

This letter introduces a customizable, soft, cable-driven robotic glove that is designed for people with mild to moderate hand disabilities. For the robot to adapt to the user's needs in various situations, the robot implements a dual passive extensor mechanism and VSPE adjuster to tune the assistance torque at each joint. By allocating different moment arm ratios between joints for each extensor, the assistance torque profile can be altered by modifying the stiffness and tension of each passive extensor. Simulations and experiments have confirmed that the proposed dual passive extensor mechanism can adeptly modulate the assistance torque profile without the need for additional actuators. The robot's feasibility was demonstrated by applying it to individuals across two potential scenarios. The robot successfully assisted hand movements and the configuration of the finger has been adjusted in response to changes in the assistance torque profile through the extensors. Moreover, as most of the glove is designed with soft and flexible materials, participants can get assistance through the robot without experiencing discomfort or pain.

Several areas remain to be addressed in the future. Firstly, while our current research proposes a method to adjust the assistance torque profile depending on the situation, a methodology to determine optimized parameters for a specific situation is not fully developed. In future studies, it will be necessary to develop a customization algorithm capable of identifying these parameters based on given circumstances. Additionally, although the participants did not show any discomfort, the tensioned extensor continuously compressed the finger joint, so the long-term effects of this compression should be analyzed. Moreover, the proposed mechanism would be hard to apply to severely impaired patients, so further research is needed to apply the robot to more diverse people. Lastly, the robot was tested on a small number of individuals to show its feasibility, so it should be applied to a larger and more diverse number of people for clinical validation.

References

[1] D. G. Kamper, "Restoration of hand function in stroke and spinal cord injury," Neurorehabilitation Technology. Berlin, Germany: Springer, 2016, pp. 311–331.

[2] S.-S. Yun, B. B. Kang, and K.-J. Cho, "Exo-glove PM: An easily customizable modularized pneumatic assistive glove," *IEEE Robot. Automat. Lett.*, vol. 2, no. 3, pp. 1725–1732, Jul. 2017.

[3] L. Cappello et al., "Assisting hand function after spinal cord injury with a fabric-based soft robotic glove," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–10, 2018.

[4] B. B. Kang, H. Choi, H. Lee, and K.-J. Cho, "Exo-glove poly II: A polymer-based soft wearable robot for the hand with a tendon-driven actuation system," *Soft Robot.*, vol. 6, no. 2, pp. 214–227, 2019.

[5] D. H. Kim, Y. Lee, and H.-S. Park, "Bioinspired high-degrees of freedom soft robotic glove for restoring versatile and comfortable manipulation," *Soft Robot.*, vol. 9, no. 4, pp. 734–744, 2022.

[6] T. Bützer, O. Lambercy, J. Arata, and R. Gassert, "Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities," *Soft Robot.*, vol. 8, no. 2, pp. 128–143, 2021.

[7] P. Tran et al., "FLEXotendon Glove-III: Voice-controlled soft robotic hand exoskeleton with novel fabrication method and admittance grasping control," *IEEE/ASME Trans. Mechatron.*, vol. 27, no. 5, pp. 3920–3931, Oct. 2022.

[8] T. Bagneschi, D. Chiaradia, G. Righi, G. D. Popolo, A. Frisoli, and D. Leonardis, "A soft hand exoskeleton with a novel tendon layout to improve stable wearing in grasping assistance," *IEEE Trans. Haptics*, vol. 16, no. 2, pp. 311–321, Apr.–Jun. 2023.

[9] B. Noronha and D. Accoto, "Exoskeletal devices for hand assistance and rehabilitation: A comprehensive analysis of state-of-the-art technologies," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 2, pp. 525–538, May 2021.

[10] C.-Y. Chu and R. M. Patterson, "Soft robotic devices for hand rehabilitation and assistance: A narrative review," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–14, 2018.

[11] M. Zhu, S. Biswas, S. I. Dinulescu, N. Kastor, E. W. Hawkes, and Y. Visell, "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications," *Proc. IEEE Proc.*, vol. 110, no. 2, pp. 246–272, Feb. 2022.

[12] D. H. Kim, S. W. Lee, and H. S. Park, "Development of a biomimetic extensor mechanism for restoring normal kinematics of finger movements post-stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 10, pp. 2107–2117, Oct. 2019.

[13] S. Park, L. Bishop, T. Post, Y. Xiao, J. Stein, and M. Ciocarlie, "On the feasibility of wearable exotendon networks for whole-hand movement patterns in stroke patients," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2016, pp. 3729–3735.

[14] C. J. Nycz, T. B. Meier, P. Carvalho, G. Meier, and G. S. Fischer, "Design criteria for hand exoskeletons: Measurement of forces needed to assist finger extension in traumatic brain injury patients," *IEEE Robot. Automat. Lett.*, vol. 3, no. 4, pp. 3285–3292, Oct. 2018.

[15] F. Scotto di Luzio et al., "Modification of hand muscular synergies in stroke patients after robot-aided rehabilitation," *Appl. Sci.*, vol. 12, no. 6, 2022, Art. no. 3146.

[16] S. W. Lee, K. Triandafilou, B. A. Lock, and D. G. Kamper, "Impairment in task-specific modulation of muscle coordination correlates with the severity of hand impairment following stroke," *PLoS One*, vol. 8, no. 7, 2013, Art. no. e68745.

[17] B. Sheng, J. Zhao, Y. Zhang, S. Xie, and J. Tao, "Commercial device-based hand rehabilitation systems for stroke patients: State of the art and future prospects," *Heliyon*, vol. 9, 2023, Art. no. e13588.

[18] H. Hoffman, "25 hand exercises for stroke recovery," Saebo, Accessed: Aug. 31, 2023. https://www.saebo.com/blog/reclaim-your-dexterity-with-hand-exercises-for-stroke-recovery/

[19] S. W. Lee, K. A. Landers, and H.-S. Park, "Development of a biomimetic hand exotendon device (biomHED) for restoration of functional hand movement post-stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 4, pp. 886–898, Jul. 2014.

[20] P. Agarwal, J. Fox, Y. Yun, M. K. O'Malley, and A. D. Deshpande, "An index finger exoskeleton with series elastic actuation for rehabilitation: Design, control and performance characterization," *Int. J. Robot. Res.*, vol. 34, no. 14, pp. 1747–1772, 2015.

[21] B. C. Vermillion, A. W. Dromerick, and S. W. Lee, "Toward restoration of normal mechanics of functional hand tasks post-stroke: Subject-specific approach to reinforce impaired muscle function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 8, pp. 1606–1616, Aug. 2019.

[22] K. H. Heung, R. K. Tong, A. T. Lau, and Z. Li, "Robotic glove with soft-elastic composite actuators for assisting activities of daily living," *Soft Robot.*, vol. 6, no. 2, pp. 289–304, 2019.

[23] P. Tran, S. Jeong, S. L. Wolf, and J. P. Desai, "Patient-specific, voice-controlled, robotic flexotendon glove-ii system for spinal cord injury," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 898–905, Apr. 2020.

[24] R. Alicea, M. Xiloyannis, D. Chiaradia, M. Barsotti, A. Frisoli, and L. Masia, "A soft, synergy-based robotic glove for grasping assistance," *Wearable Technol.*, vol. 2, p. e4, 2021.

[25] C. B. Park and H.-S. Park, "Portable 3D-printed hand orthosis with spatial stiffness distribution personalized for assisting grasping in daily living," *Front. Bioeng. Biotechnol.*, vol. 11, 2023, Art. no. 895745.

[26] R. Ozawa, H. Kobayashi, and K. Hashirii, "Analysis, classification, and design of tendon-driven mechanisms," *IEEE Trans. Robot.*, vol. 30, no. 2, pp. 396–410, Apr. 2014.

[27] B. Kim, U. Jeong, B. B. Kang, and K.-J. Cho, "Slider-tendon linear actuator with under-actuation and fast-connection for soft wearable robots," *IEEE/ASME Trans. Mechatron.*, vol. 26, no. 6, pp. 2932–2943, Dec. 2021.