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Mechatronics and Control System Design of a Hand Exoskeleton with a Sensorized Soft Glove

Ezekiel John Saldajeno[1], Perla Portillo[2], Mojtaba Sharifi[2], *Member, IEEE*,
Qiang Zhang[3], *Member, IEEE*, Sotoudeh Hamedi-Hagh[1], *Senior Member, IEEE*

***Abstract*— Post-stroke patients and individuals undergoing hand rehabilitation often grapple with prolonged and discomforting recovery processes. Hand exoskeleton products currently available in the market do not leverage precise input of therapist-assisted movements. Recognizing these challenges, technological solutions have emerged to assist and expedite rehabilitation, demanding practicality in lightweight design and user-centric features. Controlled with a sensorized soft glove (SSG), the designed hand exoskeleton focuses on user-centric attributes, including lightweight construction, durability, and comfort. The constructed hand exoskeleton leverages printable finger segment mechanisms and other lightweight components, enhancing replicability. The mechatronic system, featuring flex sensors and micro linear actuators, adopts a modular design, streamlining setup, storage, troubleshooting, and component replacement. A central microcontroller-driven main board ensures immediate communication between flex sensors on the soft glove and actuators on the hand exoskeleton, facilitating replication of individual finger flexion and extension movements. Experiments were performed to assess the hand exoskeleton's performance across various hand configurations using flex sensors placed where individual finger metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints are located on the printed segments, with RMSE between input rotational movements from the SSG and output rotational movements from the hand exoskeleton is less than 9.03°. Integrating printed finger segments promotes adaptability to diverse hand shapes and guarantees each user a personalized and comfortable fit. The flex sensor-based results show that the intended flexion or extension of the MCP or PIP joint on the SSG can be replicated by the hand exoskeleton.**

I. Introduction

Neurological impairments stemming from strokes significantly affect hand movement and control, presenting substantial challenges for survivors. In regions like the United States, Europe, and Australia, stroke emerges as a leading cause of adult-onset disability [1], with a concerning incidence rate of 400 individuals per 100,000 aged 45 and above experiencing a first stroke each year [2]. Recovery trajectories post-stroke require prolonged rehabilitation periods post-surgery [3] with outcomes hinging on factors such as the initial deficit's type and severity. Research indicates that by the six-month mark post-stroke, a notable 65% of patients struggle to integrate their impaired hand into daily tasks. Further complicating matters, specific indicators such as limited to no hand movement by four weeks significantly damage crucial neural pathways when examining hemispheric infarctions. To aid or hasten rehabilitation, wearable robotics or mechatronic systems, offering targeted assistance and facilitating repetitive movements, optimize neural retraining [4]–[6].

Hand exoskeleton designs have emerged as innovative devices to address manual labor-centered rehabilitation, offering both advantages and challenges in aiding hand control recovery through automation [7]. These exoskeletons provide targeted support, enabling users to engage in repetitive movements essential for neural retraining and increase the maximum range of motion [8], [9]. Customizable features allow for tailored rehabilitation programs, adapting to the specific needs and progression of each patient, with user interfaces such as Passive-assisted (PA), Active-assisted (AA), Active-unassisted (AU), Active-resisted (AR) and Bimanual-assisted (BA) [7]. Rehabilitation focused on regaining motor function and assessment, utilizing mechatronic systems, are verified clinically to have an enhanced path of recovery [10]. Hand exoskeleton designs for rehabilitation enable continuous flexion and extension of fingers, tracking repetitive hand movements, providing varying intensities and frequencies [11] as needed to recover hand functions [12]. With feedback sensors, user movements can be closely monitored for documentation and progress in rehabilitation planning. Feedback sensors can also provide data on a user's performance, increasing motivation to complete a rehabilitation session [13].

The Hand of Hope (HoH) [14] is a commercially available hand exoskeleton. This device allows hand rehabilitation by utilizing actuators, featuring modularity, lightweight, torque, and electromyography (EMG) control. The JACE H440 Hand CPM (H440) [15] is another commercially available hand exoskeleton, highlighting a full composite motion, a programmable controller, and a fully adjustable splint. The HoH features an independent approach to rehabilitation and the H440 hand exoskeleton is extremely lightweight. For comfortable usage and mobility function, weight is considered greatly in hand exoskeleton designs [16]. The HoH by Rehab Robotics consists of a single joint control at the MCP joint, weighing 700 g for both small and medium sizes and 800 g for a large size. In contrast, the H440 weighs 298 g for the CPM and 213 g for the splint with the finger attachments on the distal phalanx. Soft hand exoskeleton designs such as the RElab tenoexo by Tobias Bützer et al. weigh as low as 148 g but require a separate 750 g backpack for user mobility that houses the motors

[1]Ezekiel John Saldajeno and Sotoudeh Hamedi-Hagh are with the Department of Electrical Engineering at San Jose State University, CA, USA. [2]Perla Portillo and Mojtaba Sharifi are with the Department of Mechanical Engineering at San Jose State University, CA, USA. [3]Qiang Zhang is with the Department of Mechanical Engineering and the Department of Chemical and Biological Engineering at the University of Alabama, AL, USA. (*Corresponding author: Mojtaba Sharifi, Email: mojtaba.sharifi@sjsu.edu*)

and other electrical components required to control the hand exoskeleton [17], [18]. For regular hand activities, a range of applied force recorded was from approximately 2 N to 35 N for healthy participants and approximately 2 N to 31 N for those with hand arthritis [19]. The JACE system can produce an adjustable force/tension of 1 N to 22 N. Similar to the H440, the actuators required must at least be able to produce the minimum to successfully move the finger joints.

To develop a functional prototype, careful consideration has been given to countless designs created by others. A mechanical design by Fuhai Zhang et al. [20] utilizes cables to enable actuation. This enables less weight and size on a user's hand and requires motors for tension control to be placed elsewhere like the arm, but risks an eventual decrease of cable tension. Rigid mechanical designs allow for maximum construction strength but create a considerably sized hand exoskeleton [21], [22], [23], [24]. For control ideas, the HoH features EMG controls, which need extensive noise filtering, the Flexotendon Glove-III features voice-controlled assistance [25], and the control design by Andreas Wege et al. uses Hall sensors [13]. Flex sensors can be utilized in the system for position recognition, as real-time processing of data is necessary [26].

In this study, a prototype hand exoskeleton controlled with an SSG was designed and constructed with a focus on lightweight and intuitive control. The utilization of 3D-printed segments allows for user tailoring and less weight with stable rigid mechanical construction without the eventual decrease of tension from cables. Micro linear actuators are utilized to create rotational movements that enable flexion and extension of the 5 finger segments on the hand exoskeleton independently. Ethylene-vinyl acetate (EVA) foam was used as a base that carries the 3D-printed segments and actuators for flexibility, strength, and comfort. The design consists of a single joint control at the MCP, where several bars then push the PIP segment, allowing the rotation for both joints simultaneously.

The communication module is separated from the hand exoskeleton for mobility and modularity, connected via wires. The module contains the main board where the signals from the SSG are received and translated to proper pulse-width modulation (PWM) signals to extend or retract the shafts of the actuators when prompted. It also contains the 5 motor drivers to control the 5 actuators independently. Flex sensors are employed atop the MCP and PIP joints of a soft glove that tracks the flexion and extension of an SSG user. Finger extension and flexion movements of the SSG are tracked in real-time and the constructed hand exoskeleton replicates these movements. This mechatronic and control system design of a hand exoskeleton has the potential to be helpful in user-tailored hand rehabilitation with the requirement of precise movements replicated from a sensorized soft glove.

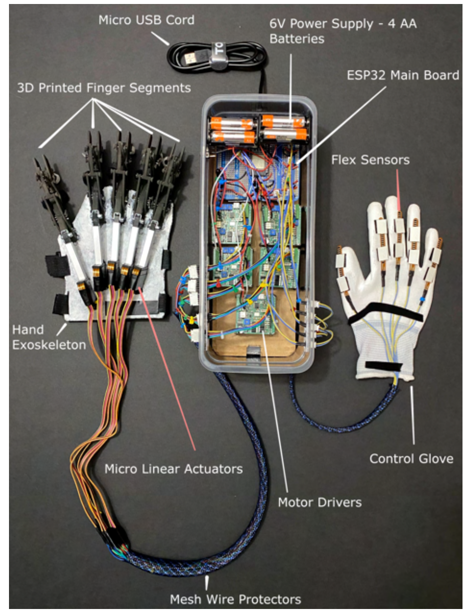


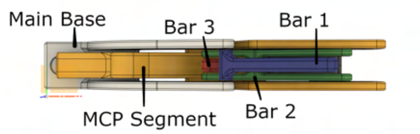
Fig. 1. Overview photo of the hand exoskeleton, communication box, and SSG. Parts labeled are the ESP32 microcontroller, 3D-printed segments, micro linear actuators, USB C power supply for the microcontroller, 6V power supply, motor drivers, and mesh wire protectors.

II. Development and Assembly of the Hand Exoskeleton and Sensorized Soft Glove

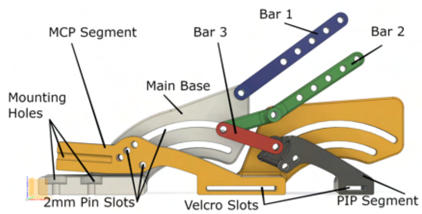
This section presents the design of the hand exoskeleton's structure, mechatronic system, and the SSG, with a focus on lightweight, high torque, and intuitive control. The prototype is depicted in Fig. 1, utilizing 5 separate actuators for individual finger control. The overview of the entire system consisted of the hand exoskeleton connected to micro linear actuators, the communication box that housed the motor drivers, the main board, and a 6-volt battery power source. The communication box is also connected to the SSG for input signals as the flex sensors were bent when a user flexed or extended their fingers.

A. Structural Design

Based on the HoH for its structural strength, the CAD design can be seen in Fig. 2. It is designed so that the MCP segment (yellow) is pushed by an actuator, bending the MCP joint of the user using the MCP joint itself as the virtual center. The MCP segment has 4 pins that slide through the curved slots of the main base (white), guiding the rotational movement. As the MCP segment moved through the curved slot, bar 2 (green) rotated about the axis of the 2 mm steel rod pin due to its connection via steel rod with bar 1 (blue) as it is pinned to the main base. As bar 2 rotated, bar 3 (red) is pushed onto the PIP segment (black), rotating the PIP joint, following the user's PIP joint as the virtual center. The position of the PIP segment depends on how far the MCP segment has been pushed out on the curved slots of the main base. In this design, the PIP joint's rotational movement depended on the MCP joint's rotational movement. This mechanism is placed on top of a 5 mm-shaped EVA foam on the dorsal side of the hand. The segments followed the metacarpal bones' direction, set for medium to large hands.



(a)



(b)

Fig. 2. Top (a) and cross-sectional (b) views of the finger exoskeleton. Parts depicted: Main Base (white), MCP Segment(yellow), PIP Segment (black), Bar 1 (blue), Bar 2 (green), Bar 3 (red), Mounting Holes, 2mm Pin Slots and Velcro Slots.

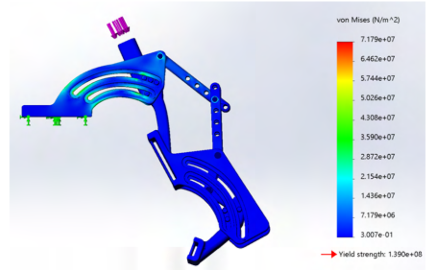
B. Stress and Strain Analysis of the Finger Segments for the Hand Exoskeleton

Stress and strain analysis was performed using the Solidworks simulation tool. It was observed using Nylon 12 as the material is sufficient for this design based on the forces it will bear. The FEA study simulated a finger segment used for the fingers based on the loads and motion it will carry. For the finger segments representative of the index, middle, ring, and pinky finger, as observed in Fig. 3, the pin is placed on the second slot from the top of the connecting bars to extend the fingers more due to its longer length and proportional rotational movement of the MCP and PIP joints.

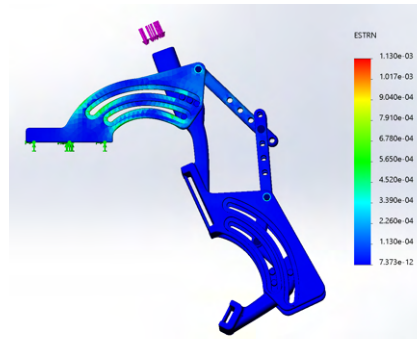
For the thumb, the pin was placed on the third pin slot from the top. This is due to the shorter length of the thumb thus requiring less of a displacement on the MCP joint, but more on the PIP joint, compared to the rest of the fingers. The external force was set to 45 N as that is the maximum force the linear actuator exerts. The pins and slots were represented as rollers/sliders. Figure 3 shows the system can take the stress of 7.179e07 MPa, and the strain of 1.130e-03, without breaking or getting damaged with a factor of safety of approximately 2. The results indicate that the printed segments are durable enough to handle forces from the actuator, causing a limit to the amount of rotational movement the structure has for safety precautions.

C. Mechatronics System Design

For communicating between the flex sensors and actuators, the main control board must intake signals from the sensor, translate or remap analog values, and output them to the actuator. The microcontroller used, ESP32, was soldered onto two solderable breadboards for ease of prototype troubleshooting, powered via micro USB. A total of 5 Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC) pins were utilized for flex sensor signal inputs and



(a)



(b)

Fig. 3. Stress (a) and strain (b) results of finger segment for the pinky, ring, middle, and index fingers. The main base is a fixed geometry, an external load of 45N is applied to the MCP segment of a value of 45N. The max stress the finger segment will experience is 7.179e07 MPa, and the Max strain is 1.130e-03.

signal output to the motor drivers respectively, as well as the 3.3 V source it produces. The ESP32 reads voltage drops through the flex sensor, and translates the range onto specific PWM signals to output to the motor drivers. C++-based coding was used for faster integration due to its static form.

To actuate the hand exoskeleton, a micro linear actuator with a 50 mm stroke length and 50:1 gear ratio from Actuonix Motion Devices Inc. was employed. The actuator was chosen due to its maximum load capabilities of 35 N and weight of 32 grams, enabling sufficient torque for flexing and extending fingers as well as maintaining low weight. The linear actuator control board from the same company was utilized for communication. The control board takes 6V provided by 4 AA batteries to power the actuators, and a micro USB cord to power the EPS32. The varying output DAC signals from the ESP32 when a flex sensor is flexed or extended are taken in by the control board and outputted to an actuator.

D. Tracking Control System

To create a tracking control system with the sensorized soft glove, flex sensors, from Adafruit Industries, were slotted so that its center aligns directly atop the PIP joint, but with coding calibration, it can also be aligned with the MCP joint or both joints. The sensors have 25 kΩ to 100 kΩresistance with 77.57 mm by 6.41 mm dimensions. For real-time tracking, the system maps the maximum analog read to a 0 mm extension of the actuator shaft, the minimum analog read to a 50 mm extension, and analog values in between are mapped linearly within the extension range of the actuator shaft. The flex sensor can capture bending more effectively when the bending is in its center rather than closer to the endpoints. Several voltage divider calculations were performed to select the proper resistance value to create an output with the largest range of varying voltages, providing the ESP32 with the widest range of values to read and having the highest resolution.

E. Fabrication and Assembly

Fabrication of the finger segments utilizing 3D printers allows for user tailoring and fast replicability. The filament used for the 3D print is Nylon 12, a material applied in automotive systems due to its fatigue, impact, vibration, and low friction properties [27]. According to the simulated results, Nylon 12 material withstands the maximum force the actuator can produce. The 3D printing process using a Fuse 1 model took approximately 11 hours to print the five-finger mechanisms. After printing, the parts were cleaned and lightly sanded in the movement slots for less friction and smoother segment transitions.

The hand exoskeleton prototype, notably the 3D-printed finger mechanisms' main bases, were affixed to the upper portion of a 5 mm EVA foam structure. The use of EVA foam offered a dual advantage, combining flexibility to accommodate diverse hand shapes with the strength of a lightweight material. The attachment process involved securing velcro straps around the wrist area and the proximal and middle phalanxes of the fingers. This design ensured a secure fit and emphasized adaptability and comfort.

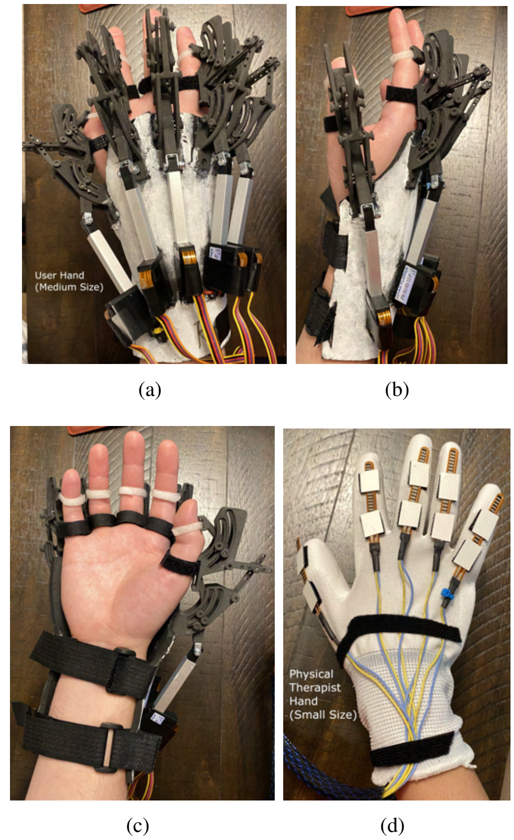


Fig. 4. Top (a), side (b), and under (c) views of the hand exoskeleton worn by a medium-sized hand. The top view of the SSG (d) shown is being used by a small-sized hand.

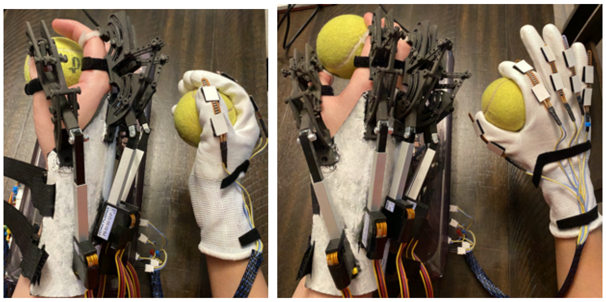
III. Results and Discussions

This section presents an overview of the outcomes derived from the implementation and testing of the prototype. Data is gathered to provide an understanding of the prototype's performance. Through the analyses of accuracy and delay data, the aim is to evaluate the system's current functionality to be improved for later iterations of the prototype. Figure 4 visually represents the hand exoskeleton and SSG, each worn by a medium and small-sized hand, respectively. Following the hand's primary curvature, the EVA foam enveloped the hand for optimal comfort. The 3D-printed mechanism was positioned on top of the fingers, serving as the primary base before the phalanxes. It further overlayed the MCP and PIP segments on the proximal and middle phalanxes, integrating ergonomic adaptability.

Analyzing the rotational movements of the constructed exoskeleton, the segment responsible for the MCP joint movement of the index to pinky fingers rotated from 0° to 70°, compared to the average actual measurement of 0° to anywhere between 80° and 90° in maximum flexion. The segment responsible for the PIP joint movement rotated from 0° to 115°, compared to the average measurement of 0° to 110° [28]. The designed MCP joint segment underperformed by 10° to 20°, while the PIP joint overperformed by 5°. For safety purposes, the testing completed with a test subject was done by grabbing objects at least 65 mm wide and without a test subject for maximum curvatures to prevent over-flexion of the PIP joint of the user. Flex sensors were placed at points where the MCP or PIP joints should be located. Elongating or shortening bars 1, 2, or 3 along with the proper pin placement on bars 1 and 2 can provide more accurate results, replicating the movements closer to a natural finger.

Through real-time tests, the exoskeleton was evaluated to grasp a standard-sized, 65 mm diameter tennis ball in Fig. 5. The SSG gripped the ball with only flexion in the thumb finger, shown in Fig. 5 (a). Having this grip including the abduction movement in the SSG's thumb finger, as shown in Fig. 5 (b), could not be replicated by the exoskeleton. The index finger flexes, while the thumb requires independent actuation or a dedicated motor for effective abduction and adduction movements. This analysis revealed potential refinement in the exoskeleton's design and functionality to include abduction and adduction movements.

The desired and actual trajectories of the linear actuator shaft's extension and retraction are shown in Fig. 6. The actuator was controlled using a flex sensor. The average RMSE of the trajectory was 3.88 mm, based on each data point taken every 5 ms in an 8-second interval of flexing and extending. The rotational movement tracking accuracy between the hand exoskeleton and the SSG is shown in Fig. 7. The rotational movement versus time was acquired by the flex sensors placed where the PIP and MCP joints of the



(a) (b)

Fig. 5. Hand exoskeleton tracking the SSG position in grabbing a standard-sized tennis ball: (a) with only flexion in the thumb finger, and (b) with flexion and abduction in the thumb finger

index finger are located, and at the PIP joint of the thumb finger. All data points were taken separately to maintain the proper timing of gathered data points.

Examining the index, middle, ring, and pinky finger's exoskeleton provided insights into the accuracy based on the RMSE when flexing and extending. All examinations for safety were done with movement limits to the SSG at 70° for the MCP joint and 115° for the PIP joint of the index finger, 90° for the PIP joint and 10° for the MCP joint of the thumb. In Fig. 7 (a), the segment exhibited an average RMSE of 7.09° for the index PIP joint. The thumb segment, depicted in Fig. 7 (b), showed an average RMSE of 9.03° for the PIP joint. The index finger's MCP joint exhibited an average RMSE of 6.62°, as seen in Fig. 7 (c). This trajectory tracking had about a 0.2-sec delay. This analysis confirms the common delay existing between tests caused by the communication module to be improved.

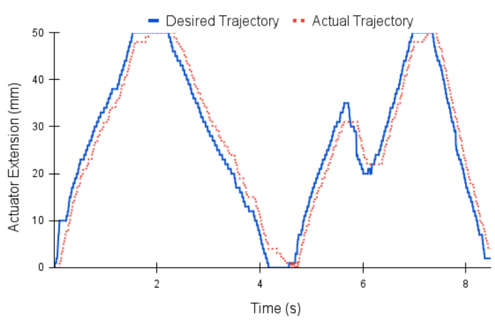
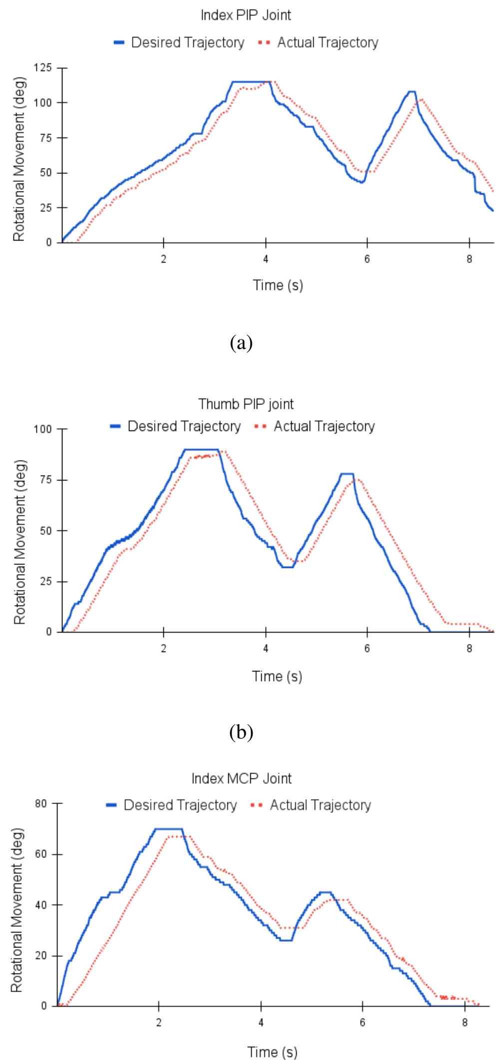


Fig. 6. Desired and actual trajectories of the actuator shaft for an extension up to 50 mm. The desired trajectory is generated by a flex sensor.

Through analyses of various movement parameters, several insights can be addressed. Examining data that illustrated delays in communication, one plausible explanation is the sequential execution of actions by the main board, initiating and completing one action before initiating another. Additionally, the $\pm 30\%$ resistance tolerance of the flex sensors was taken into account, but the sensor's instability can contribute to this delay and inaccuracy. Using potentiometers can provide more stable analog values to be read by the communication module. The speed of the hand exoskeleton movements depends on the maximum actuator speed. If the



(c)

Fig. 7. Rotational movements of (a) index PIP joint, (b) thumb PIP joint, and (c) index MCP joint: of the desired trajectory from the SSG and actual from the hand exoskeleton. The average RMSE for the rotational movements are 7.09°, 9.03°, and 6.62°, respectively

SSG user moves faster than the no-load maximum speed of 30 mm per second by the actuator, the RMSE increases. Motors with faster speed, despite lower torque can enhance this tracking performance.

IV. Conclusion

A hand exoskeleton, controlled using a sensorized soft glove, was designed, fabricated, assembled, and tested to address the challenges faced by post-stroke patients and individuals undergoing hand rehabilitation. The objective of this development was to leverage a user's precise movement with real-time input and control a hand exoskeleton worn by a second user. The exoskeleton's construction featured a 272 g lightweight design optimal for comfort. By incorporating printable finger segment mechanisms and other lightweight components, the exoskeleton ensures ease of replication, and user-centric design, making it a practical solution for a broader user base.

The adopted mechatronic system enhanced the ease of maintenance for the exoskeleton, addressing concerns associated with rehabilitation devices. Examinations that encompassed various hand configurations and movements, validated the exoskeleton's performance across individual finger movements, with rotational movement RMSE less than 9.03°. Considering the future trajectory of the project, enhancements to the entire system are imperative, including wireless communication. Utilizing potentiometers, an EMG system, or Hall effect sensors holds the potential to enhance accuracy beyond that achievable with flex sensors. With further developments, this mechatronic system design of a hand exoskeleton has the potential to be employed in user-tailored hand rehabilitation with the requirement of precise movements replicated from a sensorized soft glove.

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REFERENCES

[1] A. Cisnal, J. Pérez-Turiel, J. C. Fraile, D. Sierra, and E. de la Fuente, "Robhand: A hand exoskeleton with real-time emg-driven embedded control. quantifying hand gesture recognition delays for bilateral rehabilitation," *IEEE Access*, vol. 9, pp. 137 809–137 823, 2021.

[2] B. H. Dobkin, "Rehabilitation after stroke," *New England Journal of Medicine*, vol. 352, no. 16, pp. 1677–1684, 2005, pMID: 15843670.

[3] K. Xia, X. Chen, X. Chang, C. Liu, L. Guo, X. Xu, F. Lv, Y. Wang, H. Sun, and J. Zhou, "Hand exoskeleton design and humanndash;machine interaction strategies for rehabilitation," *Bioengineering*, vol. 9, no. 11, 2022.

[4] M. Oghogho, M. Sharifi, M. Vukadin, C. Chin, V. K. Mushahwar, and M. Tavakoli, "Deep reinforcement learning for emg-based control of assistance level in upper-limb exoskeletons," in *International Symposium on Medical Robotics (ISMR)*, 2022, pp. 1–7.

[5] L. B, P. E. Pinter D, S. W. Pichler G, M. G. Weiss E, F. F. Gattringer T, and E. C, "An exploratory intervention study suggests clinical benefits of training in chronic stroke to be paralleled by changes in brain activity using repeated fmri." *Clinical Interventsions in Aging*, vol. 11, pp. 97–103, 2016.

[6] N. Lacuata, B. O'Dell, A. John, C. Pelletier, D. Jefferson, R. Lineberger, and M. Sharifi, "Design and fabrication of a modular, lightweight, and portable upper limb exoskeleton for shoulder and elbow," *Proceedings of the ASME 2023 International Mechanical Engineering Congress and Exposition. Volume 5: Biomedical and Biotechnology*, p. V005T06A063 (9 pages), 2023.

[7] P. Tran, S. Jeong, K. R. Herrin, and J. P. Desai, "Review: Hand exoskeleton systems, clinical rehabilitation practices, and future prospects," *IEEE Transactions on Medical Robotics and Bionics*, vol. 3, no. 3, pp. 606–622, 2021.

[8] R. Casas, M. Sandison, T. Chen, and P. S. Lum, "Clinical test of a wearable, high dof, spring powered hand exoskeleton (handsome ii)," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 29, pp. 1877–1885, 2021.

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

[10] M. Dragusanu, M. Z. Iqbal, T. L. Baldi, D. Prattichizzo, and M. Malvezzi, "Design, development, and control of a hand/wrist exoskeleton for rehabilitation and training," *IEEE Transactions on Robotics*, vol. 38, no. 3, pp. 1472–1488, 2022.

[11] J. C. Castiblanco, I. F. Mondragon, C. Alvarado-Rojas, and J. D. Colorado, "Assist-as-needed exoskeleton for hand joint rehabilitation based on muscle effort detection," *Sensors*, vol. 21, no. 13, 2021.

[12] M. Norouzi, M. Karimpour, and M. Mahjoob, "A finger rehabilitation exoskeleton: Design, control, and performance evaluation," in *2021 9th RSI International Conference on Robotics and Mechatronics (ICRoM)*, 2021, pp. 301–308.

[13] M. Sandison, K. Phan, R. Casas, L. Nguyen, M. Lum, M. Pergami-Peries, and P. S. Lum, "Handmate: Wearable robotic hand exoskeleton and integrated android app for at home stroke rehabilitation," in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine Biology Society (EMBC)*, 2020, pp. 4867–4872.

[14] Rehab-robotics: Hand of hope. [Online]. Available: https://www.rehab-robotics.com.hk/hoh/index.html

[15] Jace systems: Jace h44 hand cpm. [Online]. Available: https://www.jacesystems.com/products/hand/jace_hand.htm

[16] I. Priadythama, W. L. Yeoh, P. Y. Loh, and S. Muraki, "The effect of the degree of freedom and weight of the hand exoskeleton on joint mobility function," *Robotics*, vol. 11, no. 2, 2022.

[17] T. Bützer, O. Lambercy, J. Arata, and R. Gassert, "Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities," *Soft Robotics*, vol. 8, no. 2, pp. 128–143, 2021, pMID: 32552422.

[18] Relab tenoexo: a robotic hand orthosis for therapy and assistance in activities of daily living. [Online]. Available: https://relab.ethz.ch/research/current-research-projects/Robotic%20Hand%20Orthosis%20.html

[19] M. Riddle, J. MacDermid, S. Robinson, M. Szekeres, L. Ferreira, and E. Lalone, "Evaluation of individual finger forces during activities of daily living in healthy individuals and those with hand arthritis," *Journal of Hand Therapy*, vol. 33, no. 2, pp. 188–197, 2020.

[20] F. Zhang, L. Hua, Y. Fu, H. Chen, and S. Wang, "Design and development of a hand exoskeleton for rehabilitation of hand injuries," *Mechanism and Machine Theory*, vol. 73, pp. 103–116, 2014.

[21] D. Leonardis, M. Barsotti, C. Loconsole, M. Solazzi, M. Troncossi, C. Mazzotti, V. P. Castelli, C. Procopio, G. Lamola, C. Chisari, M. Bergamasco, and A. Frisoli, "An emg-controlled robotic hand exoskeleton for bilateral rehabilitation," *IEEE Transactions on Haptics*, vol. 8, no. 2, pp. 140–151, 2015.

[22] I. Jo and J. Bae, "Design and control of a wearable hand exoskeleton with force-controllable and compact actuator modules," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 5596–5601.

[23] D. Esposito, J. Centracchio, E. Andreozzi, S. Savino, G. D. Gargiulo, G. R. Naik, and P. Bifulco, "Design of a 3d-printed hand exoskeleton based on force-myography control for assistance and rehabilitation," *Machines*, vol. 10, no. 1, 2022.

[24] C. Hernández-Santos, Y. A. Davizón, A. R. Said, R. Soto, L. Félix-Herrán, and A. Vargas-Martínez, "Development of a wearable finger exoskeleton for rehabilitation," *Applied Sciences*, vol. 11, no. 9, 2021.

[25] P. Tran, S. Jeong, F. Lyu, K. Herrin, S. Bhatia, D. Elliott, S. Kozin, and J. P. Desai, "Flexotendon glove-iii: Voice-controlled soft robotic hand exoskeleton with novel fabrication method and admittance grasping control," *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 5, pp. 3920–3931, 2022.

[26] G. Saggio and G. Orengo, "Flex sensor characterization against shape and curvature changes," *Sensors and Actuators A: Physical*, vol. 273, pp. 221–231, 2018.

[27] K. G. Mostafa, C. Montemagno, and A. J. Qureshi, "Strength to cost ratio analysis of fdm nylon 12 3d printed parts," *Procedia Manufacturing*, vol. 26, pp. 753–762, 2018, 46th SME North American Manufacturing Research Conference, NAMRC 46, Texas, USA.

[28] A. Wege, K. Kondak, and G. Hommel, "Mechanical design and motion control of a hand exoskeleton for rehabilitation," in *IEEE International Conference Mechatronics and Automation, 2005*, vol. 1, 2005, pp. 155–159 Vol. 1.