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An Adaptive Robotic Exoskeleton for Comprehensive Force-Controlled Hand Rehabilitation

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Abstract— **This study presents the development and validation of an innovative hand exoskeleton designed for the rehabilitation of patients with Complex Regional Pain Syndrome (CRPS), a condition frequently arising post-injury or surgeries. The prototype is tailored for the hand, a region commonly affected by CRPS, and is notable for its adaptability and a comprehensive sensor system for monitoring individual joint movements. Reliable sensor performance was defined through precise force measurements and stability over time, showing minimal drift. These features enable personalized rehabilitation and objective progress tracking, addressing limitations in traditional physiotherapy such as availability, cost, and time constraints. The contributions of this work lie in its innovative design and the potential for robotic systems to improve therapeutic outcomes in CRPS rehabilitation.**

I. INTRODUCTION

The integration of robotics in the field of rehabilitation, particularly for patients suffering from hand functionality impairments, has shown promising advancements in enhancing the effectiveness of therapy. Our previous research efforts have concentrated on developing an exoskeleton focused on the index finger, and subsequently, creating an application to augment this system's functionality for more comprehensive therapeutic applications [1, 2]. The necessity for such technological interventions arises from various conditions that lead to hand mobility limitations, such as neuromuscular diseases, injuries, stroke-induced restrictions, age-related declines, and complex regional pain syndrome (CRPS), which severely affect patients' daily living activities and quality of life [3–8]. CRPS is a chronic pain condition that most often affects one limb, usually after an injury, characterized by prolonged or excessive pain and changes in skin color, temperature, and swelling.

Conventional therapy methods often fall short due to their time-consuming nature, reliance on specialized therapists, high costs, and subjective interpretation of recovery [9, 10]. Robotic exoskeletons offer a more quantifiable, repeatable, and cost-effective alternative, supporting daily rehabilitation and leveraging the benefits of repetitive motion training in motor skill recovery [11–14]. However, their clinical adoption is hindered by complexity, usability issues, and challenges in accommodating hand biomechanics [7]. Recent advancements, such as 3D-printed soft exoskeletons for personalized therapy and adaptive systems responding to real-time muscle effort, are improving the effectiveness and accessibility of these technologies in rehabilitation [15, 16].

Building upon the foundational work by [17] and [18], which developed kinematically simple exoskeleton systems, our previous studies introduced enhancements in terms of sensing capabilities, actuation, and force feedback for the index finger [1]. These advancements paved the way for more effective rehabilitation by providing accurate data for therapy monitoring and facilitating user-friendly interaction through a dedicated mobile application, thus addressing some of the limitations that hinder the broader application of exoskeletons in clinical settings [19].

In this work, we expand our exoskeleton system to cover the entire hand, focusing on the long fingers for broader rehabilitation. The switch from linear to servo motors was crucial, enabling a more compact and adaptable design. A new rotary sensor for tracking abduction movements enhances the accuracy of monitoring diverse hand movements. These updates ensure compatibility with existing setups, maintaining ease of use across various environments. Additionally, the force sensor module was refined to be smaller, accommodating a wider range of hand sizes and improving the personalization of rehabilitation. The core contributions of this iteration are summarized as follows:

1) Expansion to include all the long fingers, widening the rehabilitation capabilities to the complete hand
2) Replacement of linear motors with servo motors for a more adaptable and compact system
3) Addition of a rotary position sensor for detailed abduction movement measurement, enhancing monitoring capabilities
4) Careful scaling of the system to maintain compatibility and user-friendliness.
5) Development of an interactive application to control the system.

II. MATERIAL AND METHODS

A. System Requirements

Building on the previous work by Dickmann et al. [1], this section revisits the essential requirements and design

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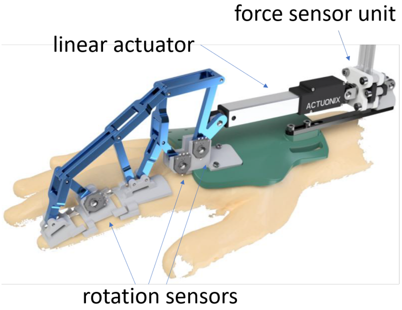

Fig. 1. The baseline exoskeleton by Dickmann et al. [1]. The system uses three rotation sensors to determine the positioning of the finger as well as a linear motor for actuation and the force sensor unit for control.

considerations for an effective hand rehabilitation exoskeleton. The initial system was developed with a focus on safety, biomechanical compatibility, and adaptability to various hand sizes and rehabilitation tasks. Key requirements included preventing hyperextension, enabling a large range of motion, recording diagnostic data, and supporting multiple rehabilitation modes [1]. Despite its innovations, the initial design, as displayed in Figure 1 (a) focusing solely on the index finger, lacked the ability to address the entire hand's rehabilitation needs. Specifically, the system did not measure abduction movements and its scalability was limited by the bulkiness of linear motors, restricting the ability to extend the system to all fingers effectively.

B. Kinematic and Dynamic Enhancements

The kinematic model of the previous iteration, which allowed for detailed tracking and control of finger movements through a series of linkages and joints, has been retained due to its effectiveness in simulating natural finger motion [1]. Figure 1 (b), referenced from our prior work, demonstrates the linkage structure that has been adapted and scaled in the current system to include the long fingers. Our approach remains focused on an underactuated system that provides a balance between simplicity and the capability to stimulate all three finger-flexion joints, aligning with the original design principles.

To address the initial system's limitations, we transitioned from linear to 9g servo motors of the make FS90R by FeeTech, achieving a marked reduction in the overall system size and enhancing its scalability for full-hand application. The smaller servo motors, now linked to the exoskeleton's kinematic structure via a tendon drive at the prior attachment site, exclusively manage finger extension. To enable finger flexion without the addition of a second servo motor, we integrated a mechanical spring as shown in Figure 2 (b). This strategic placement of the spring provides the necessary flexion momentum, thereby minimizing the system's complexity and resource requirements. Consequently, this modification leads to a more streamlined and effective design, ensuring the system can be expanded to include more fingers while maintaining user comfort and the device's practicality.

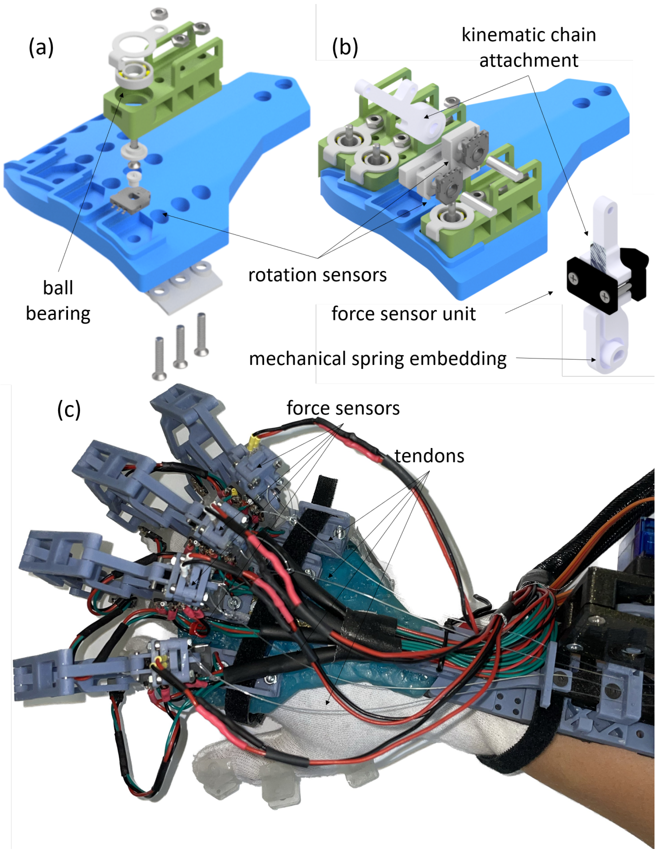

Fig. 2. Updated Mechanical System Design: (a) showcases the integration of abduction measurement, (b) provides a detailed view of the kinematic structure attachment and force sensor integration, and (c) presents a top view of the improved exoskeleton, illustrating the incorporation of the four long fingers, kinematic chains, motor attachments via tendons, and the comprehensive wiring setup for sensor data collection and connectivity.

Moreover, the integration of an additional rotary position sensor to measure abduction movements represents an enhancement over the previous system. This addition enriches our system's capabilities, allowing for a comprehensive assessment of hand movements by including measurements of abduction, which were previously unattainable. The integration of the new sensor is visualized in Figure 2 (a).

The dynamic model, essential for understanding the forces and motions within the system, continues to leverage the analytical framework established in the foundational work [1]. The adaptation of this model includes considerations for the new actuation methods and the additional rotary sensor data, ensuring accurate torque and force estimations across a broader range of hand movements.

C. Addressing Scalability and Usability

The critical challenge of scaling the exoskeleton to the whole hand while maintaining a user-friendly interface has been addressed by carefully redesigning the system's components. The servo motors' smaller form factor and the addition of the rotary sensor enable a more versatile and less obtrusive design, facilitating ease of use in both clinical and home settings. This design iteration upholds the initial requirements of safety, simplicity, and efficacy, ensuring the system's relevance for a wide range of rehabilitation scenarios.

D. Optimization of Force Sensor Assembly

In the latest development cycle, we have advanced the force sensor assembly by transitioning from the A201 FlexiForce sensors, as utilized in the research by Dickmann et al. [1], to the more compact FlexiForce A101 model. The previous dual-sensor configuration, aimed at directional force measurement, did not align with our revised focus on pull forces exclusively. The A101 sensors, with their narrower profile of 7.6 mm and a force limit of 44 N, were chosen for their compatibility with the system's requirements across all four fingers, effectively addressing the constraints introduced by the 22mm wide sensors in Dickmann et al. [1]'s design. This allows the design to be slimmed down to a width of 16mm per force sensor unit from 23.5mm, which would have been too large to accommodate all the fingers.

To accommodate our system's exclusive emphasis on pull forces, we have streamlined the design to a single-sensor configuration. This adjustment reduces costs and simplifies the wiring architecture. An addition is a 3D-printed o-ring, printed out of flexible resin, positioned between the sensor and the pressure plate. The elasticity of the o-ring acts a very small spring that acts as a reset mechanism, ensuring the system's return to its neutral state after the load is removed, in case friction keeps the assembly from expanding. The presence of the o-ring does affect sensor readings; however, calibrated adjustments effectively nullify these impacts, preserving the accuracy of force measurements.

An update in our redesigned assembly is the addition of a centrally positioned force distribution disc within the sensor's active area. This ensures more even load application, improving measurement consistency and reducing potential inaccuracies from uneven force distribution, as recommended by the sensor manufacturer. The sensors are attached using double-sided scotch tape according to the manufacturer's instructions as well. The electrical circuitry design remains largely unchanged, still utilising a voltage divider to translate a change in voltage into a force read-out. This was done to ensure cost-effectiveness of the system while retaining adjustability and scalability.

As depicted in Figure 2 (b), the refined integration of our force sensor within the kinematic chain at the beginning of the kinematic structure enhances the system's performance by enabling precise force measurement. This direct incorporation into the kinematic chain, along with notable reductions in the system's overall size, underscores the advancements in our exoskeleton's design, optimizing both its functionality and compactness.

E. System Overview

The schematic presented in Figure 3 illustrates the architecture of our hand exoskeleton system, highlighting its core components: a Bluetooth Low Energy (BLE) module (I) for seamless wireless communication and control, sixteen rotatory position sensors (II) placed precisely for accurate joint angle monitoring, four servo motors (III) for the fine-tuned actuation of finger movements, and four force sensors (IV) to measure applied forces for dynamic feedback and adaptability. This integration of communication, sensing, and actuation technologies enables the system to emulate natural hand movements, emphasizing its adaptability across a range of applications.

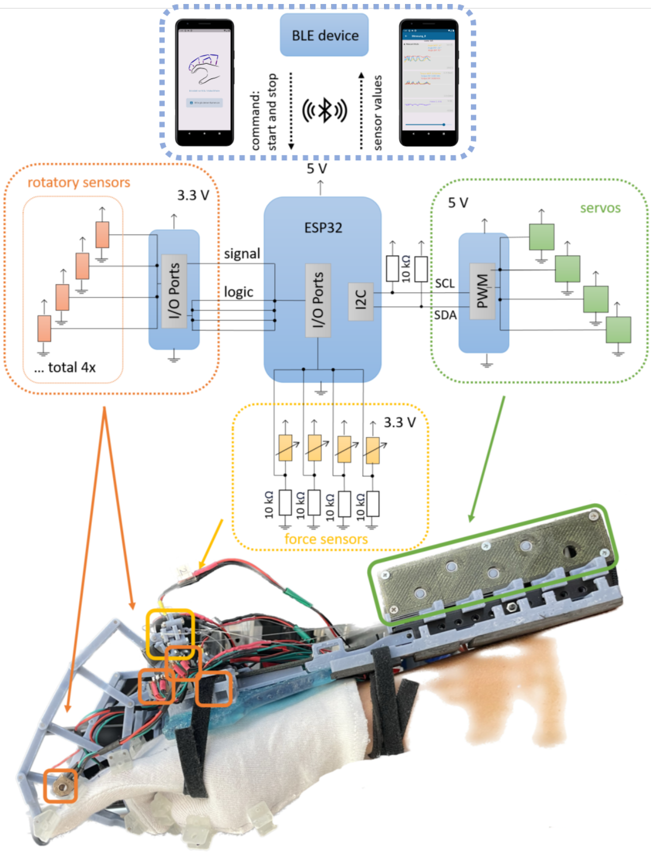

Fig. 3. Schematic Overview of the Hand Exoskeleton Hardware and Connections. The system features a Bluetooth Low Energy (BLE) module (I) for wireless communication and control, sixteen rotation sensors (II) for monitoring joint angles, four servo motors (III) for actuation, and four force sensors (IV) for measuring applied forces.

Further showcasing the system, the lower section of the figure in Figure 3 depicts the actually built exoskeleton, with the sensors integrated within color-coded for visual clarity. This part of the schematic reveals the kinematic structure developed for the index finger (shown on the left in gray) alongside the bracket for the servo motor assembly (depicted on the right in green). For enhanced usability, the exoskeleton employs black Velcro straps for secure attachment. The previous model's individual finger link attachments, used for the index finger, have been replaced with a glove in this design iteration. This improvement facilitates a much quicker and more straightforward fitting process for integrating the four long fingers, markedly improving the system's usability and efficiency in practical scenarios.

F. *Control Schemes*

The design and implementation of the control schemes are pivotal for enhancing the functionality and user interaction with the hand exoskeleton system. Two distinct control modes have been developed to meet the diverse user needs and application scenarios.

Free Movement Mode: The first control mode allows free movement, using precision rotation sensors to measure the long fingers' movements in detail. This mode captures the natural range of motion, enabling unassisted movements while monitoring and recording angular displacements. It is especially useful for tracking hand movements without interference, providing essential data for rehabilitation assessments and ergonomic studies.

Motor-Assisted Mode: The control system employs a feedback loop to dynamically adjust motor response based on real-time force feedback applied by the patient. The goal is to keep the force within a predefined optimal range. The motor switches between ”pul l” and ”push” modes depending on whether the force exceeds an upper threshold F_{upper} or falls below a lower threshold F_{lower}. The motor's response on PWM level M is calculated as:

$$M = \begin{cases} M_{\text{neutral}} + \left(\frac{F_{\text{upper}} - F}{F_{\text{upper}} - F_{\text{lower}}} \times (M_{\text{max}} - M_{\text{min}})\right) & \text{if pull} \\ M_{\text{neutral}} - \left(\frac{F - F_{\text{lower}}}{F_{\text{upper}} - F_{\text{lower}}} \times (M_{\text{max}} - M_{\text{min}})\right) & \text{if push} \end{cases} \tag{1}$$

with M_{neutral}, M_{max} and M_{min} representing the Motors neutral, maximal and minimal state. This approach allows the exoskeleton to adapt in real-time, ensuring safe and effective operation by actively assisting or resisting patient movements based on their specific needs.

III. EXPERIMENTS

The experimental phase of our study was designed to evaluate the performance and reliability of the newly developed exoskeleton system. With a keen focus on three critical aspects: sensor accuracy, sensor stability, and the efficacy of the force-control mechanism. These experiments were integral to validating the system's design and operational capabilities. Each experiment aimed to address specific questions:

- How accurate are the developed force sensor units in measuring forces applied by and to the user?
- Do the integrated rotation sensors maintain their accuracy over time, showing resilience to drift?
- How effectively does the exoskeleton's force-control interaction adhere to predefined thresholds, ensuring user safety and system responsiveness?

A. *Force Sensor Calibration and Performance*

The calibration of the force sensors was a critical step towards exploiting the exoskeleton's precise force measurement capabilities. By affixing the sensor housing to a 3D-printed fixture and applying known weights, we established a calibration range (0 to 12.9 N) that mirrors the system's operational requirements (Figure 4). This process enabled a detailed analysis of the sensor's response and led to the development of a quadratic polynomial model, which significantly enhanced measurement accuracy and reliability.

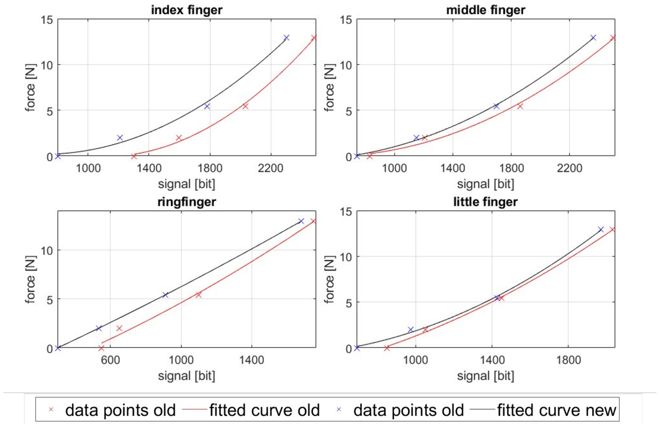

Fig. 4. Calibration Curves for the Force Sensor Across All Long Fingers Over a Three-Week Period, Indicating Initial (Black) and Updated (Red) Readings. A slight drift in sensor readings is observed, underscoring the need for regular recalibration to maintain precision.

Evaluations conducted three weeks after initial calibration were designed to test the long-term stability of the sensors. While minor drifts were noted, such as those documented for the index finger's force sensor (Figure 4), necessitating periodic recalibration, the sensors demonstrated consistent performance in static conditions. These results emphasize the need for regular calibration to ensure ongoing measurement accuracy and suggest avenues for improving sensor stability, including technological enhancements and algorithmic refinements.

B. *Rotatory Position Sensor Calibration and Performance Evaluation*

To ensure the high precision of the exoskeleton's rotary position sensors, a calibration process was implemented to establish reference positions corresponding to 0° angles. This crucial step, as illustrated in Figure 5, enables the accurate correction of any offset from the measured angles, enhancing the fidelity of angular measurements. The calibration involves deducting the identified offset from the potentiometer's reading, resulting in an adjusted angle output accurately reflecting the actual joint position.

To assess the long-term stability of these sensors, particularly their resistance to drift, a systematic analysis was carried out, as summarized in Table I. This study specifically evaluated whether the sensors would exhibit temporal drift affecting their accuracy over time. The conclusive results, detailed in the table, demonstrate that the rotation sensors exhibit remarkable stability, showing no significant drift in readings over both short and prolonged durations. This stability confirms the sensors' reliability and their aptitude for integration into applications where precision is paramount.

C. *Force-Control Interaction Evaluation*

Following approval by the local research ethics committee (501/21 S-KH), we conducted tests on a subject to assess the

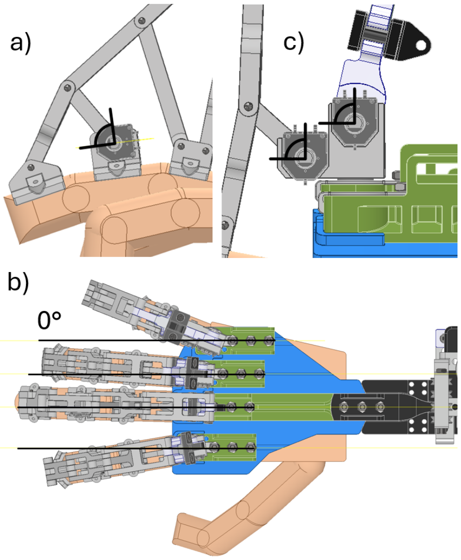

Fig. 5. Calibration methodology for determining joint positions corresponding to 0° angles, utilizing color coding for sensor identification: blue for the first rotation sensor and the abduction/adduction sensor (sections a and b), yellow for the second (section a), and green for the third rotation sensor (section c).

TABLE I
TWO-WEEK DRIFT ANALYSIS FOR RING FINGER SENSORS.

Sensor	**Initial (°)**		**Three-Week (°)**	
ID	**Measure**	**Deviation**	**Measure**	**Deviation**
1	0.10	±0.05	0.10	±0.06
2	0.05	±0.03	0.04	±0.03
3	0.07	±0.03	0.08	±0.04
4	0.02	±0.02	0.05	±0.03

exoskeleton's force control capabilities and its adaptability for full-hand application. The exoskeleton's ability to capture motion and force data across all fingers is depicted in Figure 6, highlighting its proficiency in recording angular movements (top row) and force trajectories (bottom row) at a 40 Hz sampling rate, with the established force thresholds prominently marked.

This analysis involved defining operational force boundaries at 0.6 N and 2.6 N, within which the system reliably modulated force outputs, occasionally exceeding these parameters by a marginal 0.4 N. Detailed evaluation demonstrated a direct relationship between servo motor actuations and force modulation—extensions induced force increments, whereas flexions, facilitated by the torsion spring mechanism, led to decrements. This dynamic illustrates the control the system maintains over force application, validating the integrated force control approach and the utility of servo motors for refined actuation in a wearable exoskeleton context.

IV. DISCUSSION

This study presents an initial evaluation of a new hand rehabilitation exoskeleton, focusing on notable design improvements, scalability, and control mechanisms. Building on the work of Dickmann et al. [1], our research seeks to advance the field by addressing some limitations of earlier models, particularly aiming to support full-hand rehabilitation and adapt to hands sized between 7.5 to 10.5. Innovations introduced, such as updated kinematic configurations and the transition from linear to servo motors, suggest potential enhancements in the system's adaptability and efficiency over prior designs.

In comparison to existing models, our exoskeleton aims to offer improvements by supporting all of the long fingers, beyond the index finger. The integration of rotary sensors for tracking abduction movements and the use of servo motors contribute to the system's potential for greater compactness and functionality. These changes are designed to better mimic natural hand movements and broaden the scope of possible rehabilitation scenarios, although the evaluation of these enhancements remains preliminary.

The theoretical and practical implications of our findings are intended to contribute to the understanding of hand rehabilitation, proposing that more refined exoskeleton designs might more closely support complex hand functions. However, given the limited scope of our experimental evaluations, these conclusions should be considered as initial insights rather than definitive outcomes. Further research and more comprehensive testing will be critical to fully assess the system's capabilities and its impact on patient rehabilitation.

A. Comparison with Prior Work

In comparing our findings to previous studies, particularly the work by Dickmann et al. [1] and Wilhelm et al. [19], it becomes evident that the developed exoskeleton improves upon the previous studies. Dickmann et al. [1] laid the groundwork by demonstrating the feasibility of using an exoskeleton for index finger rehabilitation, focusing on essential design considerations like safety and biomechanical compatibility. However, their model, while innovative, was limited by its focus on a single finger and the use of linear motors, which constrained the system's adaptability and scalability. Our research builds on this foundation, addressing these limitations through comprehensive design and functionality enhancements.

An enhancement in our exoskeleton is its scalability and comprehensive adaptability to encompass the entire hand. Moving beyond the original design focused on the index finger by Dickmann et al. [1], our system broadens its functionality to include all long fingers, measuring previously untrackable abduction and adduction movements. This expanded capability offers a more holistic rehabilitation experience, closely replicating the natural movements of the hand, which is anticipated to enhance recovery outcomes. The effectiveness of these improvements in facilitating comprehensive hand rehabilitation will be further investigated in a dedicated study.

Moreover, the transition from linear to servo motors marks an advancement in our exoskeleton design. This shift not only reduces the system's overall bulkiness—addressing one of the primary concerns highlighted in the work of Dickmann et al. [1] —but also enhances the system's scalability.

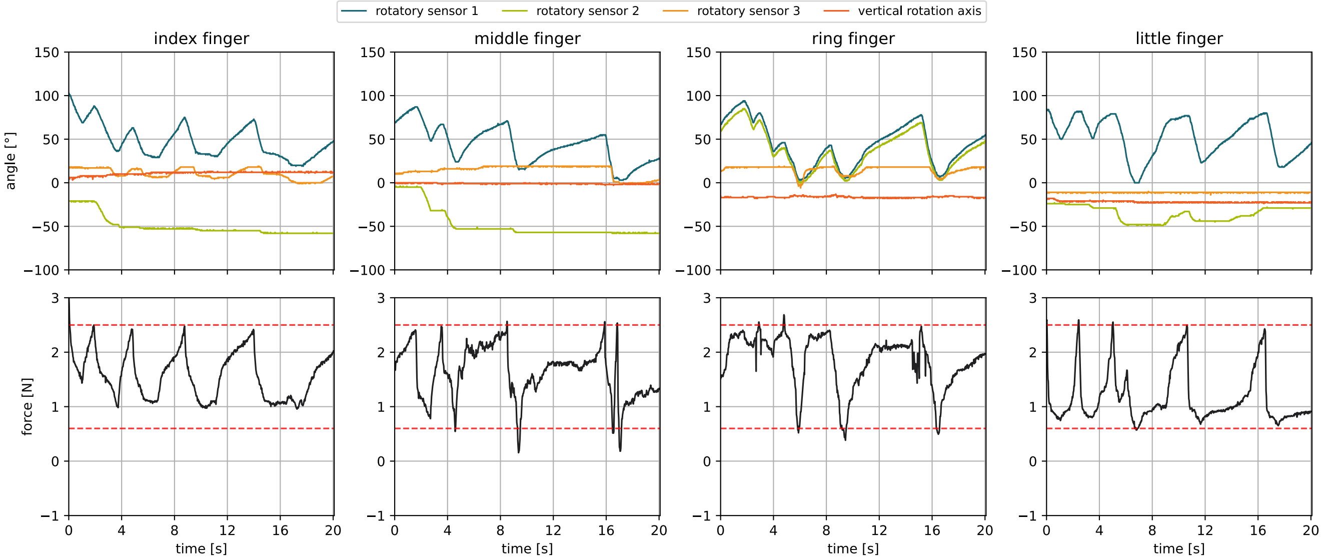

Fig. 6. Visualization of Sensor Readings and Servo Motor Control for Exoskeleton Functionality Verification, showcasing angular measurements (upper row) and force dynamics (lower row) for the subject test. The figure illustrates the system's adeptness at interpreting sensory feedback and executing servo motor commands within the defined force limits, affirming the operational accuracy of the force control strategy.

By utilizing servo motors, our design achieves a marked improvement in system size and weight, making it more user-friendly and less intrusive for the wearer. This is a critical factor for ensuring patient comfort and compliance, especially in long-term rehabilitation scenarios.

Wilhelm et al.'s research [19] contributes to the discourse on rehabilitation robotics by emphasizing the importance of user-centric designs and adaptive control systems. Our work aligns with these principles, offering a refined control scheme that supports multiple rehabilitation modalities. The incorporation of a motor-assisted mode, alongside the traditional free movement mode, allows for personalized rehabilitation experiences. This adaptability is further enhanced by our system's ability to accurately monitor and adjust forces applied by and to the user, ensuring a safe and effective rehabilitation process.

However, compared to soft exoskeletons like those reviewed by Saldarriaga et al. [15], our rigid system may lack in comfort and wearability, which are crucial for long-term use. As Bardi et al. [20] suggest, integrating intelligent control systems like EMG or EEG could further enhance our device's responsiveness and address remaining ergonomic challenges.

B. *Limitations and Future Research*

Despite the advancements our exoskeleton demonstrates in hand rehabilitation, it presents limitations that necessitate further investigation. Notably, the observed drift in force sensors, although minor, underscores the need for enhanced sensor stability to maintain measurement accuracy essential for precise rehabilitation exercises. Additionally, the current design's residual bulkiness and the still remaining weight associated with servo motors mounted on the forearm compromise wearability and user comfort, potentially impacting long-term usage and compliance ([1]; [19]). While moving the servo motors away from their wrist mount could help alleviate the perceived weight, the corresponding Bowden tubes for the chosen tendon diameter proved inadequate for the applied force and would crumple in on themselves when the tendon was loaded. Additionally Bowden tubes would cause an increase in friction that would necessitate bigger servos.

Future research will focus on addressing these challenges to refine the exoskeleton's design and functionality. The development of an autonomous recalibration feature through a mobile application is proposed to counteract sensor drift, ensuring sustained system accuracy. Efforts will also explore material and actuation mechanism advancements to reduce the system's overall weight and bulk, enhancing ergonomic wearability. Moreover, conducting a targeted rehabilitation study with CRPS patients will provide valuable insights into the exoskeleton's therapeutic efficacy and inform design optimizations for personalized rehabilitation solutions. These endeavors aim to further the exoskeleton's practical application in diverse rehabilitation settings.

V. CONCLUSIONS

This research developed and tested a hand rehabilitation exoskeleton for CRPS patients, demonstrating its potential to improve therapy outcomes. Incorporating all long fingers, servo motors, and rotary sensors, the exoskeleton provides personalized rehabilitation that simulates natural hand movements, addressing the limitations of traditional physiotherapy. While challenges like sensor drift and system complexity remain, the prototype's accurate sensor performance and motor control show promise for enhancing CRPS therapy.

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