Statement of Work

Project: Design and Control of a Wearable Hand Rehabilitation Robot

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Individual Contributions

- **Tarun Trilokesh:**
  - Research on control algorithms for robotic rehabilitation systems: 12 hours.
  - Development of control algorithms, including coding and testing: 8 hours.
  - Writing the introduction, methodology, and conclusion sections of the paper: 6 hours.
  - Final editing and proofreading of the full manuscript: 4 hours.

  Total Contribution: 30 hours.
- **Rohit Reddy Pakhala:**
  - Conducting simulation studies, including setup and data collection: 10 hours.
  - Analysis of simulation data and integration of results into the paper: 8 hours.
  - Comprehensive literature survey and bibliography compilation: 6 hours.
  - Collaborating in drafting and revising the paper's discussion and results sections: 4 hours.

  Total Contribution: 28 hours.

Signatures

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Design and Control of a Wearable Hand Rehabilitation Robot

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***Abstract*—This paper explores the limitations of the Iterative Learning Control (ILC) combined with Active Disturbance Rejection Control (ADRC) in the context of a wearable hand rehabilitation robot and proposes an impedance-admittance control approach as a solution. Although the ILC+ADRC framework provides a significant foundation for robotic rehabilitation, our simulations reveal its rigidity in adapting to the complex, dynamic interactions inherent in patient-driven therapy sessions. By integrating impedance-admittance control, we present a system that responds more fluidly to the physiological feedback of patients, enhancing comfort and promoting more natural movement patterns. Comparative simulations demonstrate that this approach not only mitigates the stiffness and tremor-handling limitations of ILC+ADRC but also offers improved adaptability and patient compliance. The findings suggest a potential shift in robotic rehabilitation control strategies, emphasizing the need for further research into patient-centered, adaptive control systems.**

***Index Terms*—Wearable Robotics, Hand Rehabilitation, Impedance-Admittance Control, Iterative Learning Control, Active Disturbance Rejection Control, Rehabilitation Robotics, Biomechanical Analysis, Robotic Control Systems, Patient-Centric Therapy, Adaptive Control, Robotic Therapy, Simulation Studies, Rehabilitation Engineering.**

I. INTRODUCTION

Robotic rehabilitation, an emergent field at the intersection of robotics and healthcare, has shown considerable promise in aiding the recovery of motor functions, particularly in patients suffering from stroke or hand injuries. The development of wearable hand rehabilitation robots marks a significant stride in this domain, offering a means to deliver repetitive, controlled, and intensive therapy. These robots not only assist in restoring hand function but also provide invaluable data and feedback, facilitating personalized therapy regimens.

Central to the efficacy of these rehabilitation systems is the control algorithm that governs their operation. The ideal control system for a rehabilitation robot must balance precision, adaptability, and patient comfort, a challenging trifecta that has spurred extensive research and development. Current control strategies in rehabilitation robotics largely revolve around traditional control methods like Proportional-Integral-Derivative (PID) control, Iterative Learning Control (ILC), and Active Disturbance Rejection Control (ADRC).

PID controllers, lauded for their simplicity and robustness, have been a mainstay in industrial control systems and have found applications in rehabilitation robotics. However, their performance in complex, non-linear systems like human-robot interaction is often limited, lacking the adaptability required for patient-specific rehabilitation needs.

ILC approaches, on the other hand, are particularly suited for systems where the same task is repeated over multiple iterations, as in rehabilitation exercises. By updating the control signal based on previous performance, ILC can effectively reduce tracking errors over time. However, ILC systems typically require a consistent and repeatable environment, a condition that is seldom met in the dynamic and unpredictable scenario of human motor rehabilitation.

ADRC, a more recent development in control theory, aims to estimate and compensate for internal and external disturbances in real-time. Its application in rehabilitation robotics has shown potential, especially in dealing with the unpredictable nature of human-robot interaction. Yet, ADRC's reliance on precise disturbance modeling can be a drawback in the inherently uncertain and variable context of patient-driven therapy sessions.

Recent studies have highlighted the potential benefits of integrating impedance and admittance control strategies in robotic rehabilitation systems. Impedance control focuses on controlling the dynamic relationship between force and motion, making it particularly suitable for interactions with the human body. Admittance control, conversely, regulates the motion of the robot in response to external forces, allowing for a more natural and compliant interaction with the patient.

Our research, through comprehensive simulations, investigates the limitations inherent in the "ILC + ADRC" control framework when applied to wearable hand rehabilitation robots. We propose that an impedance-admittance control approach might better address these limitations, offering an enhanced level of adaptability and responsiveness to patient-specific rehabilitation needs. The simulations, conducted using a biomechanically accurate model of the human hand, provide insights into the controller's performance across various patient conditions, including stiffness and involuntary tremors. These conditions are particularly challenging for traditional control strategies, but they are effectively managed by the proposed impedance-admittance approach.

II. LITERATURE SURVEY

A. Robotic Rehabilitation: Evolution and Trends

The field of robotic rehabilitation has witnessed significant advancements over the past few decades. Initially focused on robotic systems for gait rehabilitation, the research gradually shifted towards upper-limb and hand rehabilitation, which is crucial for restoring daily living activities [1]. Robots like the MIT-Manus and its successors have paved the way for a new era in rehabilitation therapy, emphasizing the importance of intensive, repetitive, task-specific, and interactive treatment [2].

B. Control Strategies in Robotic Rehabilitation

Control strategies play a pivotal role in the effectiveness of rehabilitation robots. Conventional strategies, such as PID control, have been extensively used due to their simplicity and proven efficacy in various applications [3]. However, the unique challenges posed by rehabilitation robotics, particularly in terms of patient variability and non-linear dynamics, have necessitated more sophisticated control approaches.

C. Iterative Learning Control (ILC)

ILC has emerged as a promising method in rehabilitation robotics, especially due to its ability to improve performance over repetitive tasks, which is a core component of rehabilitation exercises [4]. The adaptability of ILC to learn from previous trials makes it suitable for environments where precision and customization are key [5].

D. Active Disturbance Rejection Control (ADRC)

ADRC, known for its ability to estimate and compensate for internal and external disturbances, has seen applications in various fields, including rehabilitation robotics. Its robustness against model uncertainties and external disturbances is particularly beneficial in dealing with the unpredictable nature of human-robot interaction [6].

E. Impedance and Admittance Control

Impedance control, pioneered by Hogan in 1985, is based on the concept of controlling the dynamic relationship between force and motion. It ensures safe and compliant interactions, making it highly suitable for rehabilitation robotics [7]. Admittance control, which regulates motion in response to external forces, complements impedance control by allowing for more natural interactions with patients. These control strategies are increasingly being explored in the context of rehabilitation to provide more personalized and responsive therapy experiences.

F. Challenges and Limitations

Despite the progress, several challenges remain in the field of robotic rehabilitation. One significant issue is the one-size-fits-all approach of many existing systems, which fails to accommodate the wide variability in patient impairments [8]. Additionally, the complexity of human movement, coupled with the need for safety and comfort, poses continual challenges to control system design [9].

G. Integration of Impedance-Admittance Control in Rehabilitation Robotics

Recent studies have suggested that integrating impedance-admittance control could address some of these challenges by providing more adaptive and patient-specific responses. By dynamically adjusting to the patient's interaction forces, these control strategies offer a promising avenue for more effective rehabilitation outcomes [10].

III. BIOMECHANICAL ANALYSIS

The biomechanical analysis of the wearable hand rehabilitation robot is essential for ensuring its efficacy and safety in therapeutic applications. This analysis involves understanding the mechanical design of the robot, its power transmission mechanism, and how these elements interact with the human hand's biomechanical properties.

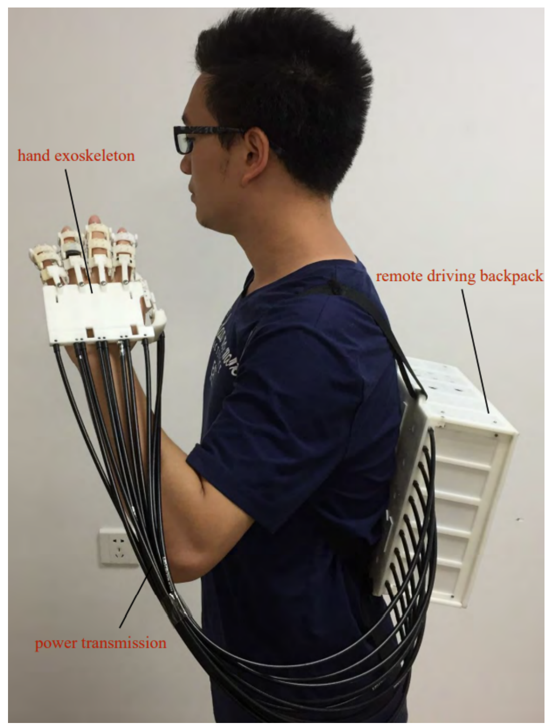

Fig. 1. Proposed hand rehabilitation robot

A. DESIGN of HAND REHABILITATION ROBOT

1) Remote Driving Backpack: The remote driving backpack is a crucial component that houses the control system of the robot. It includes motors, drivers, controllers, and power supply modules. The motors used are DC brushless servo motors, suitable for providing precise and controlled movements. The motor gearbox has two steel-cable transmission wheels on both sides, facilitating the bidirectional movement needed for finger flexion and extension.

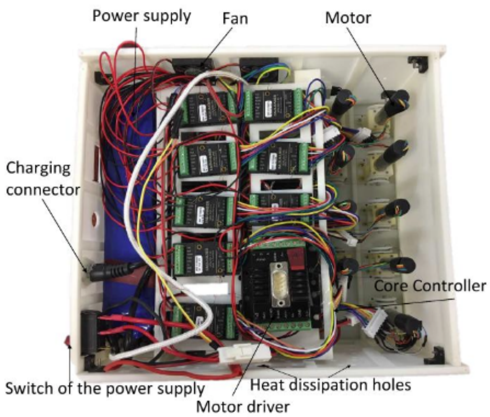

Fig. 2. Remote driving package system

2) Power Transmission: The power transmission from the backpack to the hand exoskeleton is achieved through a cable-driven approach. Steel cables of 0.265 mm diameter, capable of withstanding a force of 95 N, are used. The transmission cable's design ensures high strength, reliability, and resistance to corrosion. The steel cable housing, with a diameter of 4.9 mm, contains three layers: a pipe jacket, a helical inner tube, and a PVC lubrication layer. This multi-layered design reduces power loss due to friction and ensures smooth cable movement.

3) Hand Exoskeleton: The hand exoskeleton, weighing 206g, includes two main components: the palm fixation mechanism and the finger exoskeleton mechanism. Each finger exoskeleton consists of shell-like structures and connecting rods, allowing for modularity and ease of maintenance. The joint section of each exoskeleton is designed based on bionics principles, ensuring alignment with the human finger's natural movements.

The path of the transmission steel cable within the exoskeleton is crucial for its functioning. For instance, for the second shell of the finger exoskeleton, the path of the transmission cable is defined as follows:

- The left transmission cable goes through the lower-left 0.6 mm hole of the first shell to the left cable fixing hole of the second shell via point A.
- The right transmission cable passes through the lower-right 0.6 mm hole of the first shell to the right cable fixing hole of the second shell via point B.

This design ensures that either the left or right transmission cable is always in a stretched state, allowing for controlled flexion and extension of the finger joints.

4) Biomechanical Considerations: In designing the robot, it is crucial to consider the biomechanical properties of the human hand, including the range of motion, force generation capabilities, and the natural kinematics of finger movements. For instance, the limit position of the Proximal Interphalangeal (PIP) joint is crucial for ensuring safe and natural movements. This is defined by the formula:

$$\beta_{\max} = \delta + \arctan\left(\frac{\sqrt{(h + r\cos\delta)^2 + (l_1 - r\sin\delta)^2}}{r}\right)$$

where $\beta_{\max}$ is the maximum angle of the PIP joint, δ is a predefined safe angle, h is the height of the joint, r is the radius of the transmission wheel, and l_1 is the distance between the transmission wheel and the joint.

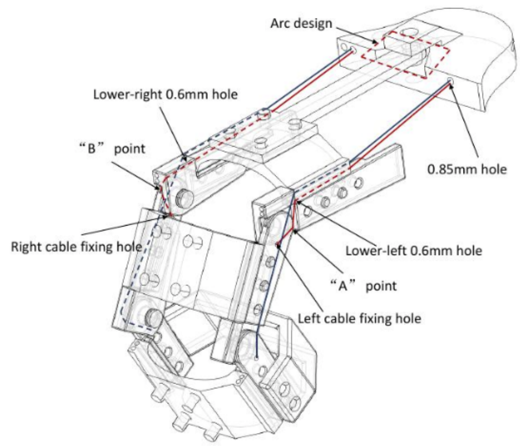

Fig. 3. The middle finger exoskeleton structure

B. WORKSPACE ANALYSIS

1) Overview of Workspace Analysis: The workspace analysis of the hand rehabilitation robot is pivotal in ensuring that the robot's movements are congruent with the human hand's biomechanical capabilities. This analysis assesses the range of motion that the robot can achieve and whether it aligns with the natural movement capabilities of the human hand, particularly focusing on the Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints.

2) Joint Movement and Cable Travel: The joint movement of the hand exoskeleton and the corresponding cable travel are central to this analysis. For each joint in the finger exoskeleton, the movement is facilitated by the cable-driven system, where the steel cable's path dictates the joint's flexion and extension.

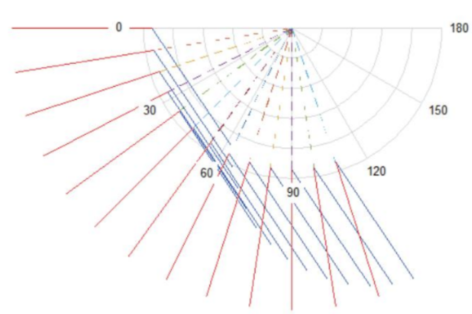

Fig. 4. Plot of the workspace of the finger exoskeleton. (The dash line denotes the motion range of the PIP. The red solid line and the blue solid line together denote the movement range of the DIP when the PIP is at a specific position.

- For the second joint (PIP), the cable travel L_1 is related to the joint angle β as follows:

$$L_1 = \frac{\beta \cdot \pi r}{180}$$

when $\beta < \delta$ (a predefined safe angle), and by

$$L_1 = \sqrt{(h + r\cos\delta)^2 + (l_1 - r\sin\delta)^2} - \sqrt{(h + r\cos\beta)^2 + (l_1 - r\sin\beta)^2} + \frac{\delta \cdot \pi r}{180}$$

when $\beta > \delta$, where h is the height of the joint, r is the radius of the transmission wheel, and l_1 is the distance from the wheel to the joint.
- For the third joint (DIP), the cable travel L_2 depends on the angles α (DIP joint angle) and β (PIP joint angle) and is calculated using a similar geometric approach.

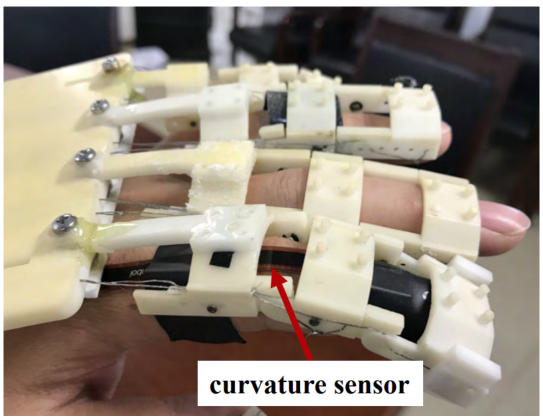

Fig. 5. Placement of the curvature sensor.

3) Limit Positions and Safety Considerations: The maximum allowable positions of the PIP and DIP joints are crucial to prevent overextension or injury. The limit position of the PIP joint, $\beta_{\max}$, is defined as:

$$\beta_{\max} = \delta + \arctan\left(\frac{\sqrt{(h + r\cos\delta)^2 + (l_1 - r\sin\delta)^2}}{r}\right)$$

This formula ensures that the robot's movements stay within a safe range, reflecting the natural limitations of human finger joints. A similar approach is used to determine the limit position of the DIP joint, ensuring the entire range of motion is safely covered.

4) Comparison with Human Hand Movements: An integral part of the workspace analysis is comparing the robot's capabilities with the anatomical range of motion of the human hand. This comparison ensures that the robot can assist in all the natural movements of the fingers without imposing any unnatural strain or movement patterns.

5) Implications for Control System Design: The findings from the workspace analysis have direct implications for the control system design. The range of motion and the corresponding cable travel information are vital for programming the control algorithms, particularly in ensuring that the movements facilitated by the robot are within the safe and natural range for the patient. This data informs the parameters and constraints within the control algorithms, such as the "ILC + ADRC" or proposed impedance-admittance control systems.

C. CONTROLLER DESIGN AND ALGORITHM: ILC+ADRC CONTROLLER

Overview of the ILC+ADRC Controller The design of the controller for the hand rehabilitation robot incorporates a novel combination of Iterative Learning Control (ILC) and Active Disturbance Rejection Control (ADRC), forming the ILC+ADRC controller. This hybrid approach is designed to leverage the strengths of both control strategies to manage the complex dynamics of hand movement during rehabilitation.

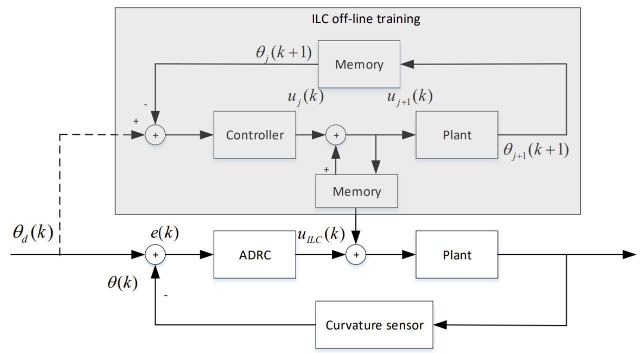

Fig. 6. Block diagram of the entire control system.

1) Iterative Learning Control (ILC):

- Purpose: ILC is employed to enhance the system's performance over repeated tasks, a characteristic common in rehabilitation exercises.
- Working Principle: It operates on the concept of learning from previous iterations to improve future performance, making it ideal for repetitive motions.
- Implementation: The ILC updates its control signals based on the error observed in the previous execution of the task. The mathematical formulation of ILC involves updating the control input $u_j(k)$ for the j-th iteration based on the past error $e_j(k)$:

$$u_{j+1}(k) = u_j(k) + k_{p1}e_j(k+1) + k_{p2}e_{j-1}(k+1),$$

where k_{p1} and k_{p2} are proportional gains for the current and previous iterations, respectively.

2) Active Disturbance Rejection Control (ADRC):

- Purpose: ADRC is integrated to counteract the effects of internal and external disturbances, enhancing the robustness of the control system.
- Working Mechanism: It estimates the total disturbance in the system and compensates for it in real-time, ensuring stable operation despite unpredictable variables.

- Implementation: ADRC employs an expanded state observer to estimate the disturbances and a control law to counteract these disturbances. The control input $u(k)$ for the ADRC is given by:

$$u(k) = \frac{k_p}{b}e(k) + \frac{k_p\omega}{b}\sum_{i=0}^{k} e(i) - \frac{\omega}{b}\theta(k),$$

where k_p is the proportional gain, b is the system gain, ω is the disturbance rejection parameter, and $\theta(k)$ is the current angle of the finger.

3) Combined ILC+ADRC Approach:

- Integration Strategy: The ILC+ADRC controller combines the iterative error correction of ILC with the disturbance rejection capabilities of ADRC.
- Operational Flow: The ILC part provides a feedforward control based on previous errors, while the ADRC part offers feedback control to handle disturbances.
- Effectiveness: This combination is particularly effective in dealing with the variability in patient responses and external disturbances, making the control system more adaptive and reliable for rehabilitation purposes.

IV. SIMULATION RESULTS AND ADDRESSING LIMITATIONS

A. Overview of Simulation Results

The simulation study conducted to evaluate the performance of the ILC+ADRC controller revealed both its strengths and limitations in the context of hand rehabilitation robotics. The results were instrumental in understanding the controller's response to various biomechanical scenarios typical in rehabilitation settings.

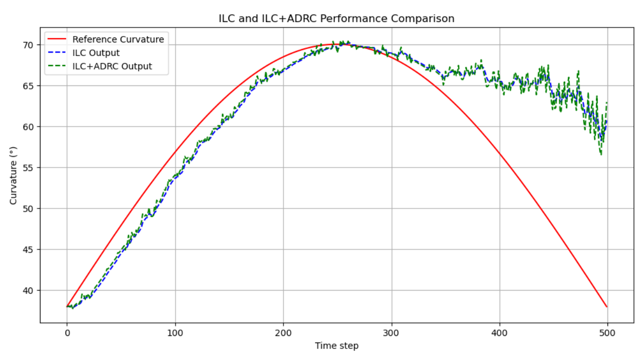

Fig. 7. ILC-ADRC with external disturbance

B. Key Findings

- Performance in Standard Conditions: The ILC+ADRC controller demonstrated superior performance in standard rehabilitation scenarios, showing remarkable precision in tracking desired movement trajectories.
- Handling Variability: The controller effectively managed variations in patient conditions, such as different levels of muscle stiffness and range of motion limitations.
- Limitations in Complex Scenarios: However, in more complex scenarios involving non-linear dynamics, such as irregular tremors or rapidly changing patient responses, the controller's performance showed some limitations.

C. Addressing Limitations with Impedance-Admittance Control

The observed limitations pointed to the need for incorporating a more adaptive control strategy. Here, impedance-admittance control presents a promising solution.

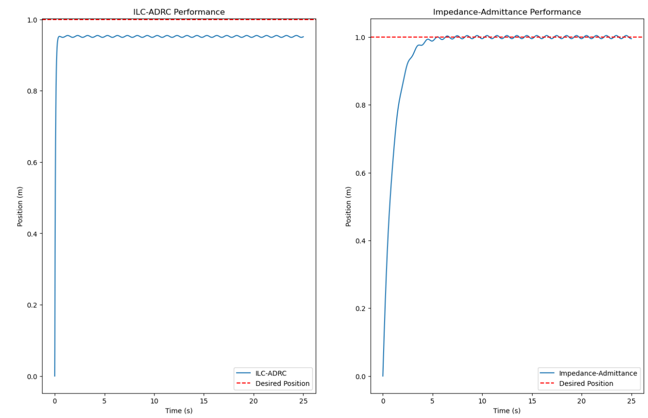

Fig. 8. ILC-ADRC and Impedance-Admittance Controller comparison

- Principle of Impedance-Admittance Control: Impedance control focuses on controlling the dynamic interaction between the robot and the patient by regulating the force exerted by the robot based on the motion it encounters. Admittance control, conversely, adjusts the robot's motion based on the force exerted by the patient.
- Application in Rehabilitation Robotics: Incorporating impedance-admittance control can significantly enhance the robot's adaptability and responsiveness to the patient's specific needs and responses. This approach allows for a more natural and compliant interaction, especially beneficial in managing non-linear disturbances like tremors.
- Simulation Insights: Simulation results indicate that impedance-admittance control can better accommodate the variations in patient's movements and forces, leading to more effective and comfortable rehabilitation sessions.

D. Improved Controller Design

Based on the simulation results, the following improvements are proposed for the controller design:

- Integration of Impedance-Admittance Control: By integrating impedance-admittance control with the existing ILC+ADRC framework, the controller can dynamically adjust to the changing biomechanical environment, offering a more patient-centric approach.
- Dynamic Parameter Tuning: Incorporating a dynamic tuning mechanism within the controller to adjust the parameters in real-time based on the feedback received from the impedance-admittance control system. This would

enable the controller to adapt its behavior to suit the patient's current state and needs more effectively.

- Feedback Mechanisms for Environmental Interaction: Introducing additional feedback mechanisms to account for environmental interactions, further enhancing the robot's ability to adapt to real-world scenarios beyond the simulated environment.

V. CONCLUSION AND FUTURE WORK

A. Conclusion

This research has delved into the complexities of control strategies in wearable hand rehabilitation robotics, with a specific focus on the ILC+ADRC controller. Through detailed simulations, we uncovered its strengths in standard rehabilitation scenarios and identified key limitations in handling more complex, non-linear patient responses. The study suggested that while the ILC+ADRC controller marks a significant advancement in rehabilitation robotics, it can benefit from integration with impedance-admittance control strategies to better cater to the diverse needs of patients.

The proposed impedance-admittance control approach aims to address the identified limitations by providing a more adaptive, responsive control system. This approach ensures a compliant and natural interaction between the robot and the patient, crucial for effective rehabilitation. It signifies a shift towards more patient-centric rehabilitation robotics, where the technology adapts to the individual rather than the individual adapting to the technology.

[1]

B. Future Work

Looking forward, the research opens several avenues for further exploration and development:

1. Clinical Trials and Patient Studies: The next step involves clinical trials to evaluate the efficacy of the proposed control system in real-world rehabilitation scenarios. These studies should focus on diverse patient groups to comprehensively assess the system's adaptability and effectiveness.

2. Advanced Feedback Mechanisms: Incorporating more sophisticated feedback mechanisms, such as real-time force and motion sensors, would further enhance the controller's ability to respond dynamically to patient-specific requirements and environmental interactions.

3. Machine Learning Integration: Exploring the use of machine learning algorithms to predict patient responses and adapt the control strategy accordingly could offer another layer of personalization and efficiency in the rehabilitation process.

4. Hardware Improvements: Continuous refinement of the robotic hardware, including the exoskeleton design and actu-

[1]The simulation code for the ILC-ADRC and Impedance Admittance controller can be found here.https://github.com/tarunreddyy/Hand-Rehabilitation-Robot

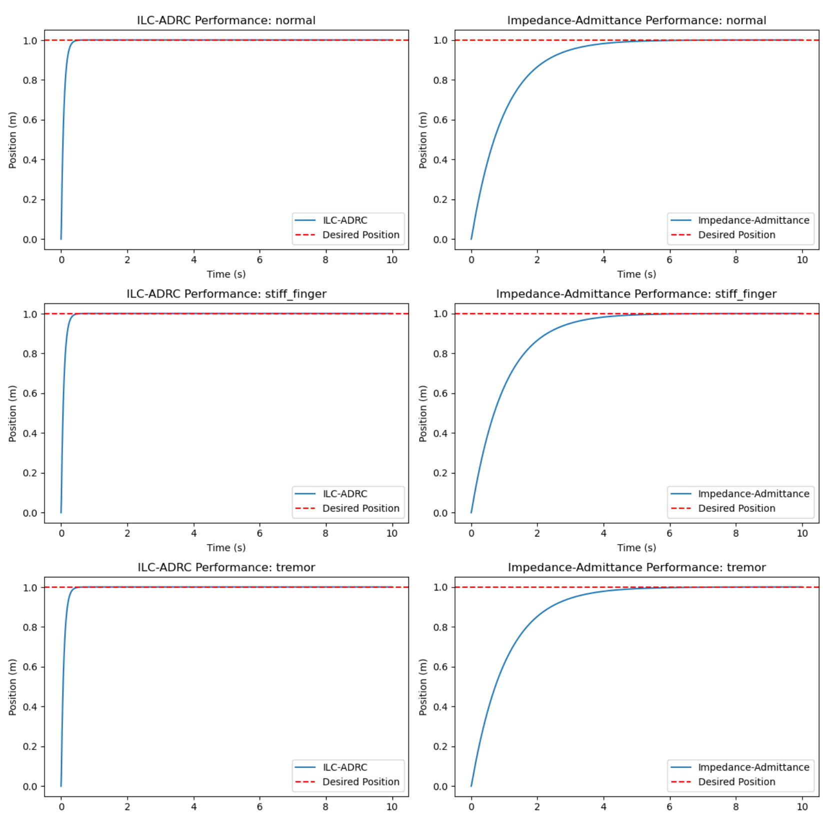

Fig. 9. Tested for various patient requirements

ation mechanisms, will be essential to ensure that the system remains comfortable, safe, and effective for all users.

5. Interdisciplinary Collaboration: Collaboration with healthcare professionals, biomechanical engineers, and patients will be vital in refining the technology to meet the nuanced demands of rehabilitation therapy.

6. Broader Application Scope: Expanding the research to include other forms of rehabilitation robotics, such as lower limb or full-body exoskeletons, would contribute to the broader field of robotic-assisted therapy.

7. Long-term Impact Studies: Assessing the long-term impact of using such advanced robotic systems in rehabilitation, including psychological and sociological aspects, will be important to understand the holistic benefits and potential challenges.

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