

Establishment and Evaluation of a Robotic Wrist Exoskeleton for Rehabilitation

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ABSTRACT

Within the domain of neurorehabilitation, the scientific community has increasingly advocated for the employment of robotic apparatuses to facilitate prolonged and intensive motor therapy. Of particular importance is the frequently neglected hand and wrist rehabilitation, which is instrumental in regaining the fundamental abilities required for daily activities. A state-of-the-art hand-wrist exoskeleton has been devised, and the current research delves into the architectural intricacies of the wrist component, as well as the human factors that augment its effectiveness in conjunction with the hand segment during both virtual and assisted grasping tasks. Moreover, the design addresses pragmatic considerations, encompassing ergonomics, clinician usability, and adaptability for ambidextrous configurations. The functional workspace and dynamic properties of the wrist module have been appraised through methodical evaluations, showcasing its enhanced capabilities in comparison to preceding devices with regards to motion range, torque production, friction minimization, and closed-loop position bandwidth. These performance and operational attributes underscore the potential for the integration of the wrist module in future clinical investigations.

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1. Introduction

Disorders involving the neuromuscular system, which include cerebrovascular events (CVEs) and spinal cord injuries, have been found to benefit from robot-supported therapy, resulting in enhanced rehabilitation results [1]. As mortality rates decrease, around 795,000 people are affected by CVEs each year, with the costs expected to surpass the current \$320 billion forecast by 2020 [2]. Robotic rehabilitation devices enable high-intensity, extended-duration treatments crucial for motor function recovery and allow for the gathering of quantitative information to evaluate therapy outcomes [3, 4]. Nevertheless, specialized treatment for upper limbs, particularly the wrist and hand, is essential to regain the ability to perform daily life activities (ADLs). Several devices have been created for this purpose [4–11], but only a small number allow coordinated hand and wrist movement, thus overlooking the anatomical [12] and position-dependent passive characteristics [13]–[16] interconnections between the hand and wrist. The guidelines for developing integrated hand-wrist exoskeletons remain largely undefined due to the limited availability of such devices.

Functional recovery training after stroke has been shown to play a crucial role in supporting motor recovery after stroke. Essentially, this is a process of relearning, in which the brain's motor learning mechanisms interact with natural recovery or neuroplasticity to relearn motor skills that have been affected by stroke. There are many different approaches to restoring upper limb function, such as motor training, functional electrical stimulation, mirror therapy, and constraint-induced movement therapy. Positive outcomes of rehabilitation depend on factors such as the onset time, duration, intensity, and task orientation of the training session, as well as the patient's health status, attention, and effort.

Clinical research findings emphasize the importance of repeating functional motor exercises with a high number of repetitions to achieve neuroplasticity changes in the brain that lead to improved motor function. Additionally, exercises need to be meaningful and provide feedback to patients throughout the training process. Adhering to the principles of rehabilitation training can increase the effectiveness of

recovery exercises. However, it can also increase the workload and time demands on healthcare professionals, who are already overloaded. Training with assistive devices such as robots can be an important complementary option that helps ensure optimal training programs for patients, with high repetitions, practical exercises, accurate visual feedback, quantifiable and progressive exercises, and an engaging interface that promotes long-term patient engagement through attractive graphics. By using robots, patients can receive consistent and accurate feedback, allowing for precise and measurable training progress. Additionally, robots can be programmed to provide personalized training plans that are tailored to the specific needs and abilities of each patient. This not only improves the effectiveness of rehabilitation but also reduces the workload and time demands on healthcare professionals. Therefore, incorporating robotic-assisted training into rehabilitation programs can be an important step towards improving the quality of care for stroke patients.

Our methodology for designing hand-wrist exoskeletons identified several key factors that contribute to discoordination between redundant MCP and wrist modules. These include limitations in finger MCP range of motion, static friction and inertia in the wrist, and undesired interactions between the hand and wrist modules. To address these issues, upcoming exoskeletons should prioritize a cohesive interface between the hand and wrist modules, streamlined donning and doffing processes, ergonomic design for user comfort, and reduced discoordination effects caused by friction and inertia.

Our team also emphasized the importance of enhancing dynamic performance and ensuring compatibility with surface electromyography and passive marker motion capture systems. To accomplish these goals, we developed a wrist rehabilitation robot that represents an upgraded version of earlier hand-wrist exoskeletons. The robot features significant upgrades to each degree of freedom, including a primary rotational joint for pronation/supination of the forearm and two rotational joints for the wrist's flexion/extension.

2. Design And Implementation

The robot also includes a fourth passive linear DOF to manage minor misalignments between the user's and robot's joints. Each actuated DOF is powered by a brushed DC motor, and capstan-cable drives ensure backlash-free operation. To ensure accessibility for users with sensitive skin, we utilized an open design that allows for swift donning and doffing.

Our assessment of the device's capabilities focused on the wrist's range of motion and torque output. Table 1 outlines the specifications of the device, and Figures 1 and 2 illustrate the hand-wrist exoskeletons in use. Overall, our new device represents a significant improvement in hand-wrist exoskeleton design, with superior performance, adaptability, and seamless integration with the hand exoskeleton.

Table 1. Comparison of Device Features with ADL Requirements and Additional Wrist Devices

Joint	Range of Motion [deg]						Max Continuous Torque [Nm]							
	ADL	MIT	IIT	WG	ME-II	RW-S	OpenWrist	ADL	MIT	IIT	WG	ME-II	RW-S	OpenWrist
PS	150	140	160	180	180	180	170 (85 P, 85 S)	0.06	1.85	2.77	2.87	2.75	1.69	3.50
FE	115	120	144	180	65	130	135 (70 F, 65 E)	0.35	1.43	1.53	1.77	1.45	3.37	3.60

The design of robotic exoskeletons presents a significant challenge, particularly in regard to the donning and doffing process. Previous models of exoskeletons required users to slide their hand through a ring encircling the pronation/supination (PS) joint, which could be difficult for individuals with restricted motor control and spasticity. Additionally, the closed design of the exoskeleton necessitated uncomfortable wear and required the user to don the device after positioning their arm in the wrist exoskeleton. To address these issues, a new open curvilinear rail and slider system has been developed to replace the traditional closed radial bearing.

The rail system consists of four rail sections with a 50mm radius connected to a central hub, with a single 90mm radius rail section linking them to provide 200mm of rail space. Two slider mechanisms attached to a stationary frame and elbow support section manage the anticipated moment loads, with the rails and hub moving while the sliders remain stationary. The PS joint permits a total of 160 degrees of motion due to the spacing between the sliders, and the rail hub rotates and serves as a capstan arc in the

transmission system. This capstan-cable transmission results in over double the torque output, increasing from 0.5 Nm to 3.0 Nm, owing to the improvements.

Significant modifications to the distal joints were necessary to counterbalance the increased inertia of the PS joint. The FE actuator was relocated from the dorsal side of the hand to the palmar side, enhancing hand ergonomics, and excess material and weight were eliminated. The incorporation of foam-padded elbow support addresses previous devices' ergonomic limitations by providing a more comfortable fit. Additionally, the support reinforces the integrated assumption of exoskeletons by restricting user movement around the exoskeleton.

The device's functionality has been further refined with several new features, including in-line cable tensioning mechanisms for each joint, which maintain cable tautness and can be rapidly re-wrapped and tensioned with a 1/4" wrench and pre-made cable sections. The cable has also been upgraded to a pre-stretched, flexible 7x19 strand core stainless steel, further reducing friction and preventing cable slack during regular operation. Other enhancements include the transition from 6061-T6 aluminum alloys to 7075-T6 aluminum alloys, the integration of hybrid-ceramic ball bearings with Si3N4 balls in the FE and RU joints, and the organization of electrical cables through joint axes to eliminate wire dangling and drag. The application of a white polymer-ceramic coating is particularly relevant, as it facilitates passive marker motion capture research and is compatible with surface electromyography due to its low infrared signature and high dielectric strength.

In summary, the new open curvilinear rail and slider system addresses previous ergonomic limitations and allows for more comfortable and accessible donning and doffing of the exoskeleton. The incorporation of new features and materials also enhances the device's functionality and compatibility with research and clinical applications.

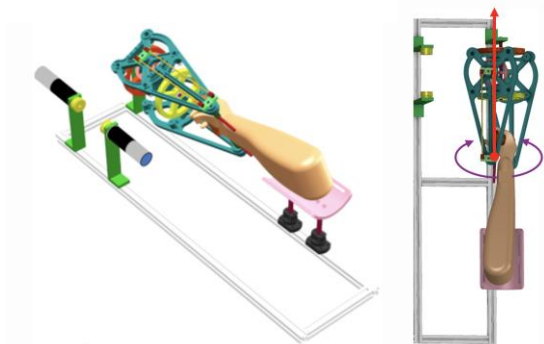


Figure 1. *The Integrated Wrist Exoskeleton for Synchronized Hand-Wrist Rehabilitation in Robotics*

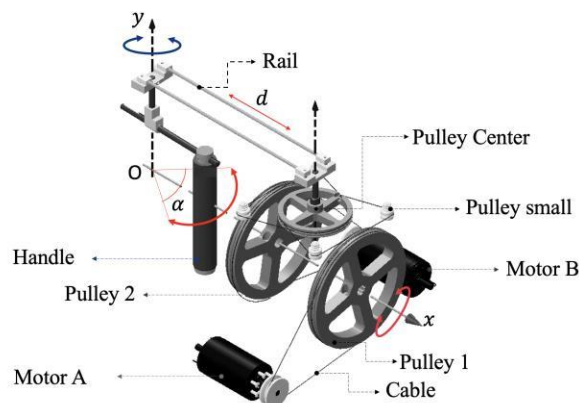


Figure 2. *The configuration of the rehabilitation wrist robot*

The wrist rehabilitation robot has been designed to operate alongside the hand exoskeleton, but it also has an independent handgrip available for wrist-only studies. One significant concern during the design process was the misalignment between the robot's neutral position and the user's neutral position caused by the vertically aligned grips commonly used in wrist exoskeletons. To address this, various

grip angles were evaluated by measuring the neutral grip angle of different individuals and examining the flexion/extension-pronation/supination (FE-PS) workspace to ensure user comfort. The final grip design, with a modified shape at its attachment point and angled at 30 degrees, was chosen based on user feedback and expands the FE-PS workspace area by approximately 51% compared to the initial vertical grip.

3. Characterization

In the characterization section, the experimental evaluation of the wrist rehabilitation robot is explored, focusing on position bandwidth, static and kinetic friction, viscous damping coefficients, and inertia-related factors. To minimize gravitational disturbances, the device was aligned, and two other joints were restrained using a high proportional gain PD controller, and the passive degrees of freedom associated with the grip were securely fastened. The specific characterization experiments performed were identical to those conducted for the research team's other devices, except for the bandwidth test. The dynamic properties of the device were analyzed using the model and logarithmic decrement techniques outlined in [21], and the step response of the underdamped system allowed for the differentiation of inertial, viscous, and dry friction contributions to exponential decay. The physical system required the use of a proportional controller due to zero stiffness, allowing the actuator to function as a relatively soft spring. Spring constants of 15 Nm/rad and 5 Nm/rad were implemented for the PS and FE components, respectively, to ensure efficient and precise control of the wrist rehabilitation robot during the experimental assessment as shown in Fig. 3 below.

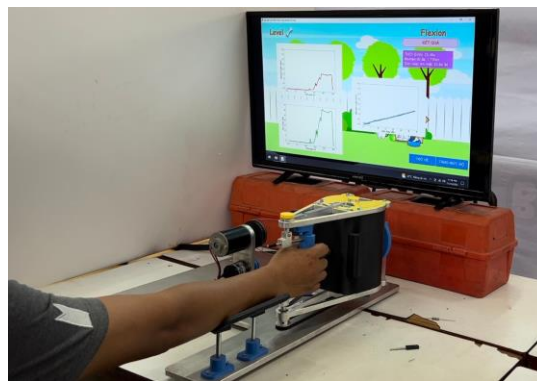


Figure 3. *The real model of the rehabilitation wrist robot*

To conduct the evaluation, a command was issued to record three complete cycles of a square wave position input with an amplitude of 20 between each step. The assessment covered most of the joint workspace with initial joint angles of -50, 0, and 50 degrees for pronation/supination (PS) and -30, 0, and 30 degrees for flexion/extension (FE). The underdamped response was analyzed by extracting peaks and troughs for both the upper and lower responses and comparing them to determine the joint inertia, viscous damping coefficient, and kinetic friction properties of the joint. The average parameters and proportional gain constant were used to reproduce the model presented in [21], demonstrating the model's accuracy. A simulated sample response is depicted in Figure 4. Mechanical impedance refers to the relationship between velocity and forces applied to a mechanical system. In the context of the frequency domain, the impedance can be defined using the following expression:

$$Z(j\omega) = F(j\omega) / V(j\omega)$$

where $Z(j\omega)$ is the equivalent impedance rendered at the end-effector will be the contribution of the inertial, viscosity and elastic terms; $V(j\omega) = j\omega X e^{j\omega t}$ is the velocity of the end-effector and $F(j\omega)$ represents the applied force, all as functions of the angular frequency ω . And, $F(j\omega)$ is defined as: $F_K = KXe^{j\omega t}$ for the elastic force; $F_B = j\omega BX e^{j\omega t}$ for damping field; $F_M = -\omega^2 MX e^{j\omega t}$ for inertial field.

This approach provides a comprehensive understanding of the wrist rehabilitation robot's dynamic behavior at different joint angles and frequencies. The impedance analysis enables researchers to optimize the control system and refine the overall performance of the robot, ensuring efficient and precise movement during rehabilitation exercises. The agonist-antagonist actuator is represented as a second-order system (mass-spring-damping), as shown in Fig. 4. In this model, F_d symbolizes the

desired force applied to the end-effector; T_{Rd} and T_{Ld} stand for the desired tension on each cable; K signifies the desired stiffness, B represents the desired damping, and M denotes the desired mass coefficient. The equivalent impedance of the end-effector is defined as:

$$Z = Z_M + Z_B + Z_K = \frac{F_M}{V} + \frac{F_B}{V} + \frac{F_K}{V} = j\omega M + B + \frac{K}{j\omega}$$

Hence, the desired force is computed as:

$$F_d(s) = T_{Rd}(s) - T_{Ld}(s) = \left(Ms + B + \frac{K}{s} \right) \dot{X}(s) = Z(s)\dot{X}(s)$$

In this initial study, we aim to investigate a controller that can produce a desired damping-elastic behavior of the end-effector or establish a desired force equivalent to:

$$F_d(s) = K(x_d - x) + B\dot{x} = \left(B + \frac{K}{s} \right) \dot{X}(s) = Z_d(s)\dot{X}(s)$$

The diagram of the applied controller is illustrated in Fig. 4. When the end-effector interacts with its surroundings, its movements (both position and velocity) are calculated from the encoder measurements, and the controller receives feedback accordingly. It is crucial to emphasize that there are two actuation cables, with each cable specifically designed to execute a pulling action exclusively. This configuration allows for precise control of the end-effector's motion, ensuring smooth and accurate interaction with the environment. By carefully monitoring the position and velocity of the end-effector, the controller can make adjustments in real-time to optimize the performance of the rehabilitation robot. This level of control is essential for providing a safe and effective rehabilitation experience, as it enables the robot to adapt to the patient's needs and the specific constraints of the environment. Furthermore, the use of two actuating cables, each dedicated to performing a pulling action, contributes to the robot's overall stability and reliability during operation.

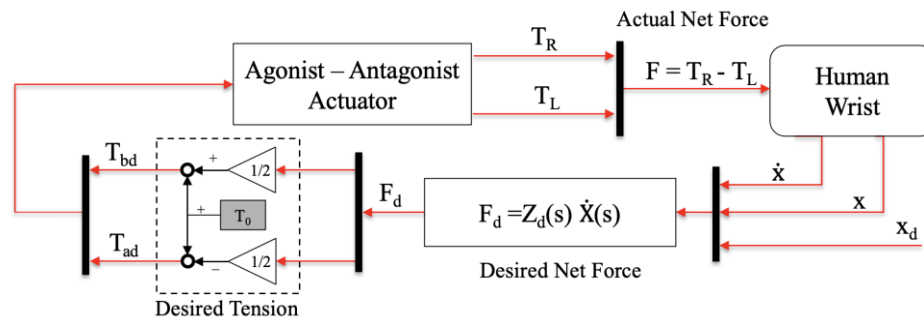


Figure 4. Schematic representation of the impedance control algorithm implemented in the wrist rehabilitation robot

$$\begin{cases} T_{Rd} = \frac{F_d}{2} + T_0 \\ T_{Ld} = -\frac{F_d}{2} + T_0 \end{cases}$$

In the given system, T_0 represents the pre-tension exerted on the cable, ensuring that the system maintains a constant positive tension. The impedance control algorithm employs an NI-DAQ board as the controller, capable of real-time control with a 1 ms sampling time. The desired tensions are subsequently converted into desired motor torques and, eventually, desired motor currents.

4. Conclusion and Discussion

In order to improve the efficacy of hand-wrist exoskeletons as rehabilitation instruments, various design aspects need to be addressed. The model presented in [21] accurately represents the dynamic properties of the device. However, during testing of the flexion/extension (FE) module, gravitational influences were observed at static friction values between 40-60 degrees. Attempts to mitigate this effect were unsuccessful, possibly due to the asymmetrical design of the module. While the use of curved rails increases inertia and static friction at the pronation/supination (PS) joint, the open design takes precedence for performance. Periodic peaks in the PS joint suggest that minor rail misalignments may

result in elevated static friction values. Continuous adjustments and break-ins are expected to address this issue. Enhanced torque output on the PS joint helps offset any negative consequences of increased inertia and friction during control implementation. Dynamic friction values for hand-wrist exoskeletons contribute no more than 6% to the total continuous torque output in any specific joint. Closed-loop position bandwidth either exceeds or approaches the 5 Hz attainable by humans in uncontrolled movements, marking an improvement compared to other hand-wrist exoskeletons.

Two separate studies involving participants and wrist pointing tasks further evaluated and validated the wrist rehabilitation robot, although not discussed in detail here. Research in [22] suggested that the dynamic properties of the hand-wrist exoskeleton impact movement smoothness in wrist pointing tasks, while [23] demonstrated similar wrist pointing trajectories recorded by robot encoders and passive marker motion capture systems. The wrist module of the hand-wrist exoskeleton meets the predefined design objectives for integrated hand-wrist exoskeletons. The open PS design simplifies donning and doffing the device for individuals with disabilities and enables pre-dressing of the hand-wrist exoskeletons. The equipment meets or exceeds the criteria for activities of daily living (ADL) concerning torque and range of motion across all joints. Ergonomic factors are addressed through adjustable foam-padded elbow support and a 30-degree angled grip for standalone use. Practical enhancements, such as streamlined maintenance and ambidextrous configuration, boost the device's effectiveness in clinical settings.

The research team has developed a new physical therapy device using robotics technology that is specifically designed to assist in the functional recovery of wrist movement for patients who have suffered a stroke or have nerve system injuries. The device enables patients to repeat movements and receive feedback that is sent back to the brain, allowing them to perform more movements than with traditional therapy methods. This opens up the potential for the device to become a labor-saving tool. Through the device, attractive and highly effective functional recovery games can be designed with a 3D multi-functional program that is tailored to the adaptive abilities of each patient, helping to increase the patient's range of motion during training. This enables patients to actively engage in training through enjoyable and easy-to-use games.

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