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Enhancing Wrist Telerehabilitation: Integrating Haptic Feedback and Remote Evaluation Models

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Abstract:
Stroke patients with hemiparesis often face significant challenges in accessing consistent and effective rehabilitation therapy due to limitations in mobility and the availability of specialized care. To address this, a new telerehabilitation system is introduced for stroke patients with hemiparesis. It consists of two internet-connected robots for remote wrist rehabilitation. A cloud-based website serves as a centralized interface for patients and doctors, allowing remote control of the system during therapy sessions. To enhance the haptic feedback and stability of the system, a torque/velocity control algorithm is implemented. These control algorithms incorporate damping and spring terms from an impedance control algorithm to synchronize and maintain the positions of both end effectors. Additionally, a wrist evaluation model has been introduced to calculate stiffness and damping coefficients, essential for monitoring patient progress and improving treatment efficacy. The wrist model is evaluated using multiple linear regression method. Experimental testing demonstrates the potential of the proposed approach in enhancing telerehabilitation system performance.

Keywords: Wrist Telerehabilitation System, Stroke Patients, Haptic Feedback, Remote Control, Regression Method.

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1 Introduction

Stroke aftermath often entails hemiparesis, weakening one side with altered wrist mechanics causing spasticity and movement resistance [1]. Traditional stroke rehabilitation relied on supervised repetitive exercises to enhance motor functions, but the introduction of robotic therapy offered a new avenue for precise repetition and comprehensive wrist rehabilitation [2]. Recognizing the crucial importance of training wrist extensions for daily activities, such as grasping and personal hygiene, emphasized the need for comprehensive rehabilitation strategies [3]. Recent advances in robotic rehabilitation systems have shown improvements in motor recovery and functional outcomes. However, these systems often require the presence of a clinician and regular visits to rehabilitation centers. Telerehabilitation, facilitated by haptic devices, enables remote evaluation and exercise options, often yielding outcomes comparable to traditional in-person therapy, and garnering high patient acceptance [4]. Current telerehabilitation systems offer remote therapy but still face challenges in providing precise feedback and comprehensive wrist evaluations. Research findings have underscored that the mechanics of the wrist are predominantly governed by stiffness rather than inertia [5]. Consequently, assessing the stiffness of a patient's wrist during their rehabilitation process holds significant value for treatment planning and exercise regimens. Moreover, it offers a means to gauge the patient's progress over the duration of therapy. Despite progress, there remains a gap in integrating precise haptic feedback and real-time stiffness assessment remotely. In this regard, a new wrist telerehabilitation system has been introduced, which allows for diverse wrist movements, particularly focusing on flexion and extension. The integration of haptic feedback into the system has enabled accurate assessment of wrist stiffness and motion capability by medical professionals, significantly boosting the ability for independent rehabilitation. To do this, a wrist evaluation model has been developed to measure wrist stiffness and damping independently. Additionally, web-based user-friendly interfaces have been implemented to facilitate ease of operation for both clinicians and patients, regardless of geographical distance. The proposed telerehabilitation system holds promise in revolutionizing stroke rehabilitation by providing a technology-driven solution that offers remote care options for patients.

2 Material and methods

2.1 Hardware Design

The mechanical structure of the wrist telerehabilitation system including two robots featuring a forearm rest and an end effector, has been depicted in Figure 1. The system integrates strain gauges to accurately measure external torque and employs Raspberry Pi single-board computers for interconnecting the robots and executing control codes predominantly scripted in Python. The sensor signal is boosted using the HX711 amplifier. For more detail about mechanical design refer to our previous publication [6].

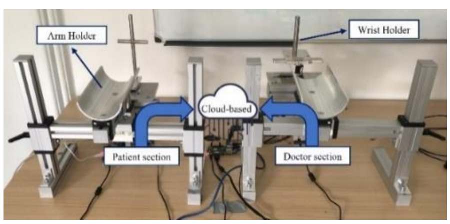

Figure 1: Wrist Telerehabilitation System with two rehabilitation robots being linked through a cloud-based server [6].

2.2 Controller algorithm

Impedance Control, frequently utilized in haptic teleoperation scenarios, offers a method to regulate a robot system's response to diverse environments [7]. The overarching objective of impedance control is to emulate the behaviour of the system akin to a spring-damper system [8]. The spring-damper model of a telerehabilitation system has been depicted in Figure 2. In order to reduce the inertial forces and damping effect, a control law is designed based on the force feedback method using Equation 1 [8].

$$\boldsymbol{T_a = K(\theta - \theta_d) + B(\dot{\theta} - \dot{\theta}_d) + k_f(T_e + K(\theta - \theta_d) + \cdots}$$
$$\boldsymbol{+B(\dot{\theta} - \dot{\theta}_d))} \qquad \textbf{(1)}$$

Where T_a and T_e are the actuation/ external torque, B is damping coefficient, K is the stiffness, $\dot{\theta}$ and θ are the angular velocity and position, $\dot{\theta}_d$ and θ_d are the desired angular velocity and desired position respectively.

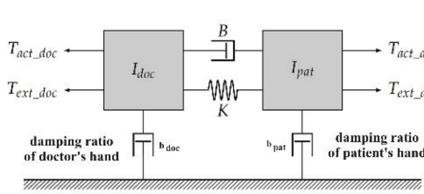

Figure 2: Impedance Control Algorithm Schematic.

2.2.1 Haptic Feedback Control

While the previously implemented impedance controller does offer some semblance of haptic feedback, it suffers from significant latency due to the spring modelled between the two end effectors. Ideally, to achieve flawless haptic feedback devoid of any delay, a rigid rod should replace the spring model between the two end effectors. To simulate a rigid rod between the patient and doctor end effectors for optimal haptic feedback, the remote torque exerted by the user should equal the external torque. In its simplest form, the actuation torque Ta for each motor can be expressed as $T_a = T_e + T_r$. However, while this straightforward controller equation may provide a sense of haptic feedback, it fails to ensure that the two end effectors synchronize. Additionally, given that this system operates over the internet, one must also consider the inherent internet delay that persists. To maintain synchronization between both end effectors, one can reconsider employing the spring and damping coefficients from the previous impedance control algorithm. In this setup, haptic feedback is modelled using a rigid rod while virtual springs and dampers handle the tracking of position and velocity for both robots. The resulting control algorithm is represented by Equation 2:

$$\boldsymbol{T_a = T_e + T_r + K(\theta_r - \theta) + B(\dot{\theta}_r - \dot{\theta})} \qquad \textbf{(2)}$$

Here, K denotes stiffness, B represents the damping coefficient, θ_r signifies the remote position, and $\dot{\theta}_r$ denotes the remote angular velocity. Thus, $\theta_r - \theta$ signifies the position error between the two end effectors, and $\dot{\theta}_r - \dot{\theta}$ indicates the error in angular velocity between them. With this control algorithm, the end effectors can maintain synchronization as they did in the previous impedance controller. However, by summing both torques, the haptic feedback becomes more realistic. Moreover, the latency resulting from compressing the spring before moving the end effector is eliminated, as the sum of both torques models a rigid rod between the end effectors. Consequently, the time delay of the system improves, with the only remaining delay stemming from the inherent internet delay.

In another scenario, velocity is also considered as a control parameter. To establish a velocity-based control algorithm, the torque-based controller described earlier serves as a suitable starting point, offering adequate haptic feedback with minimal error or delay. The actuation velocity could be derived from $\dot{\theta}_a = Ta/B$, leading to a velocity control law presented in Equation 3.

$$\boldsymbol{\dot{\theta}_a = \frac{1}{B}(T_e + T_r)\frac{K}{B}(\theta_r - \theta) + (\dot{\theta}_r - \dot{\theta})} \qquad \textbf{(3)}$$

2.2.2 Remote Control

The wrist telerehabilitation system utilized Google Cloud Platform, including Google Compute Engine for robust communication between doctor and patient robots. A web server facilitated seamless data exchange among system components. The doctor/patient users created virtual machines via Compute Engine instances for hosting cloud servers, ensuring uninterrupted availability of the website. Requests from clients triggered communication with Raspberry Pi units via the cloud server. Secure communication channels with Raspberry Pi units were established via Secure Shell (SSH). Hypertext Transfer Protocol (HTTP) enabled effective client-server interactions.

3 Result and Discussion

3.1 Control algorithm performance

Several experiments evaluated a control algorithm's effectiveness with single-side and double-side movements. Single-side tests involved moving one end effector while the other mirrored it. Torque control errors were acceptable, about 0.267 rad for position and 0.300 rad/s for velocity as reported in table 1. However, velocity control was more accurate, with max errors of 0.167 rad for position and 0.231 rad/s for velocity, as expected. In double-sided movement, the doctor robot shifted 90° left, then the patient robot returned. Results, in Table 1, indicate acceptable errors for telerehabilitation: max 0.109 rad and 0.127 rad/s for position and velocity, respectively.

Table 1: Empirical assessment of control algorithms.

Algorithm/Parameter (Unit)		Average Error value		
		Single-sided movement		Dual-sided movement
Torque Based Control	Position (rad)	Doctor	0.267	0.063
		Patient	0.087	
	Velocity (rad/s)	Doctor	0.300	0.082
		Patient	0.083	
Velocity Based Control	Position (rad)	Doctor	0.167	0.109
		Patient	0.085	
	Velocity (rad/s)	Doctor	0.231	0.127
		Patient	0.070	

3.2 Wrist Evaluation Model

Joints in the human body, including the wrist, can be effectively modelled using a spring-damper system [9]. Employing the mass-spring-damper model allows for the deduction of the equation of motion for a second-order linear system, as shown in Equation 4. Assuming negligible inertia of the wrist [5] and substituting the constant values, the equation is simplified as follows:

$$\boldsymbol{I_w\ddot{\theta} + B_w(\dot{\theta} - \dot{\theta}_r) + k_w(\theta - \theta_r) = T_e} \quad \textit{(4)}$$

$$\boldsymbol{B_w(\dot{\theta}) + k_w(\theta - 3.14) = T_e} \quad \textit{(5)}$$

Here, k_w represents the wrist stiffness, B_w is the wrist damping coefficient, I_w is the wrist inertia, and T_e denotes the external torque. It should be noted that this model only considers wrist movements in flexion and extension. To implement the wrist evaluation model, calibration is essential to determine wrist stiffness. This involves gathering position, velocity, and torque data to accurately establish stiffness and damping coefficients. Each calibration step is executed with a consistent motor torque to maintain consistency, allowing only external torque variation. Establishing the motor's position with this torque is crucial due to varying wrist ranges of motion, requiring a devised method. Prior research [5] indicates nonlinearity in the torque-angular position relationship beyond a threshold during wrist flexion/extension, deviating from spring-damper system linearity. Safety considerations for the patients also had to be prioritized, as excessive movement of the robot end effector could risk wrist injury. Hence, the initial step of calibration involved gently moving the user's wrist with a small motor torque of 0.1 *Nm* until the external torque measured by the sensor reached -0.2 *Nm* during flexion. This calibrated position, denoted as $\theta_{calibration}$, was recorded and utilized throughout the calibration process. Subsequently, the calibration proceeded by incrementally moving the end effector using varying constant torques towards the $\theta_{calibration}$ position. Five constant motor torque levels were applied: 0.1 *Nm*, 0.2 Nm, 0.3 *Nm*, 0.4 *Nm*, and 0.5 *Nm*. Each torque level started from the initial position of 3.14 rad and moved towards $\theta_{calibration}$ using a constant motor torque. Upon reaching $\theta_{calibration}$, the motor halted and returned to the starting position, repeating this sequence for each torque level. Throughout the calibration, the patient remained passive, solely holding onto the end effector without exerting additional force. The external force acting on the end effector was limited to the natural stiffness and damping forces of the wrist. Data on position, velocity, and torque was collected for each calibration sequence. Figure 3a depicted the calibration data obtained for a specific user, which would be utilized to determine the wrist stiffness and damping coefficients.

After collecting the data, the system's unknowns, B_w and k_w, were determined using multiple linear regression with Python's sklearn library. The regression yielded a stiffness coefficient of -0.139 $N.m^{-1}$ and a damping coefficient of -0.080 $N.s.m^{-1}$. The regression plane showed a relatively good fit to the dataset (R-squared value of 78.8%), as illustrated in Figure 3b.

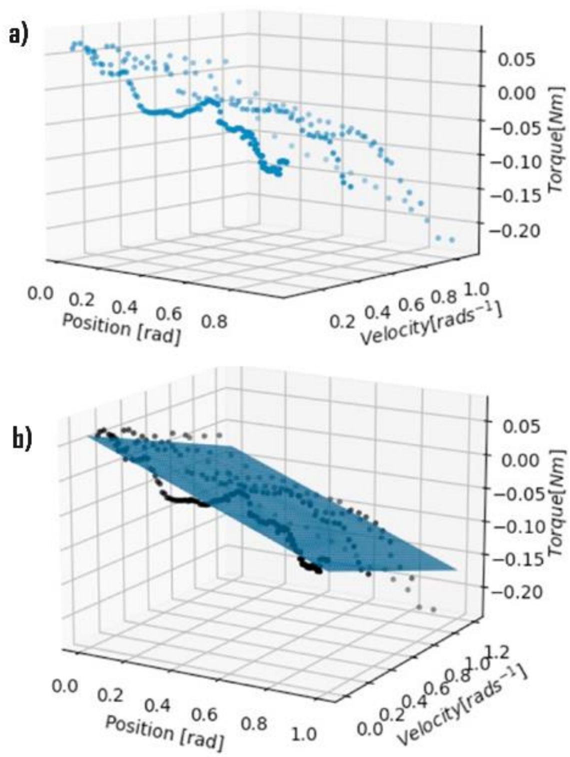

Figure 3: a) Calibration Data for a Single User, b) Multiple Linear Regression fit of Calibration Data.

4 Conclusion

In this study, a new wrist telerehabilitation system with the aim of haptic feedback for Wrist treatment was introduced. In order to assess the performance, different control strategies were used, including torque and velocity-based control. A wrist evaluation model was developed, utilizing a spring and damper system to determine individual stiffness and damping coefficients, aiding in patient progress tracking and clinical decision-making. The wrist telerehabilitation system employed Google Cloud Platform's infrastructure, specifically Google Compute Engine - VM Instances, to establish robust communication between doctor and patient robots. Experimental tests showed that the maximum error for both position and velocity was less than 0.267 rad and 0.300 rad/s, respectively, which was acceptable for Telerehabilitation application. After calibration, the wrist stiffness and wrist damping coefficient were determined using the multiple linear regression method with proper fitting conditions. Tracking alterations in the patient's wrist stiffness could improve the doctor's assessment of their response to treatment, which is promising for telerehabilitation applications.

Author Statement

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