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Design of a Flexible mechatronic system for mechanical impedance measurement of the wrist as one step towards robotic rehabilitation

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Abstract: Home rehabilitation is a great complement to inpatient rehabilitation, because it allows for more regular training, especially in rural areas, where the access to physiotherapists is limited. However, unsupervised training carries the risk of deviation from the prescribed protocol. An obvious solution is to introduce a technical means for rehabilitation and continuous monitoring of performance. This paper presents a robotic system for rehabilitation of three degrees of freedom of the wrist independently, implemented with only one actuator, optimizing the design and size of the system. The device provides measurements of joint torque-position dependence, allowing objective assessment of mechanical impedance and range of motion to evaluate the progress of rehabilitation. Derived from research on haptic devices, a measurement method was implemented to measure hand impedance in the high frequency range between 100 and 200 Hz using a combination of exciters and accelerometers in the handles. This allows continuous monitoring of gripping forces without the need for complex contact-based force sensors. In collaboration between the authors' technical and medical universities, a set of two-level passive and active safety measures was implemented to ensure the safety of the system's users. Therefore, the presented system shows the potential to evaluate the mechanical impedance of the wrist at both low and high frequencies and to monitor the progress during rehabilitation. In the next step, a baseline of wrist impedance will be measured in a target group of healthy volunteers in order to prepare for studies in motion-restricted subjects.

Keywords: wrist rehabilitation, mechanical impedance measurement, robotic system

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1 Introduction

Injuries can significantly disrupt patients' activities of daily living and rehabilitation interventions are critical to facilitate rapid recovery [6, 7]. However, traditional rehabilitation methods that require one-on-one sessions with a physical therapist, followed by unsupervised exercises, may not be effective. The unsupervised exercises can lead to a reversal of progress, as patients may ignore seemingly minor symptoms. In addition, prolonging the period of physiotherapist supervision is not feasible due to limited resources [5].

Home robotic rehabilitation has been shown to be useful in improving the quality of life and depression in people after stroke [11] especially since repetitive movement is a common rehabilitation approach employed to restore strength in rehabilitation [12]. A randomized controlled clinical trial was completed with 99 people who had limited access to formal therapy. Participants were randomized into one of two groups, (1) a home exercise program alone and (2) a home exercise program combined with a home-based robot-assisted rehabilitation [11]. The study found that the group with home-based robot-assisted rehabilitation had a significant improvement in quality of life compared to the group with a home exercise program alone [11]. Another study found that robotic therapy is gradually becoming popular for stroke rehabilitation to improve motor recovery, as robotic technology can assist, enhance, and further quantify rehabilitation training for stroke patients [3]. Furthermore, a pilot study found that home-based robotic therapy using the single-joint hybrid assistive limb robotic suit in the chronic phase of stroke was effective in improving upper limb activity [9].

Robotic therapy has been used for stroke rehabilitation and spinal cord injury, and it can provide high dosage and high intensity training, making it useful for patients with motor disorders [4]. The development of robotic devices for rehabilitation presents a number of challenges in sensing, actuation, robotic mechanism design, data processing algorithms, and control [1, 2]. The research presented suggests that robotic therapy is a promising technology for rehabilitation and has shown improvements in motor capacity and function in various patient populations.

This paper presents the design of a robotic system for wrist and forearm rehabilitation. The contributions of this work include the design of a mechatronic system that allows idependent control of three degrees of freedom (DOF) of the wrist with only one motor, two methods for measuring the mechanical impedance of the wrist, and initial results.

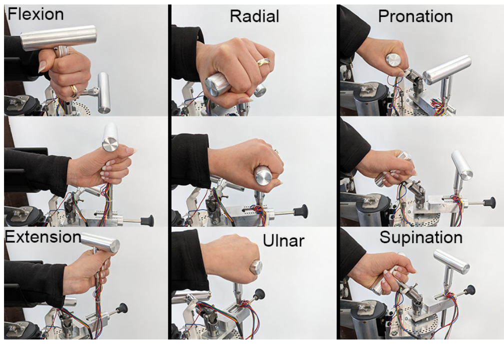

Fig. 2: Pictures of the different handles and their corresponding movements.

2 Mechatronic design

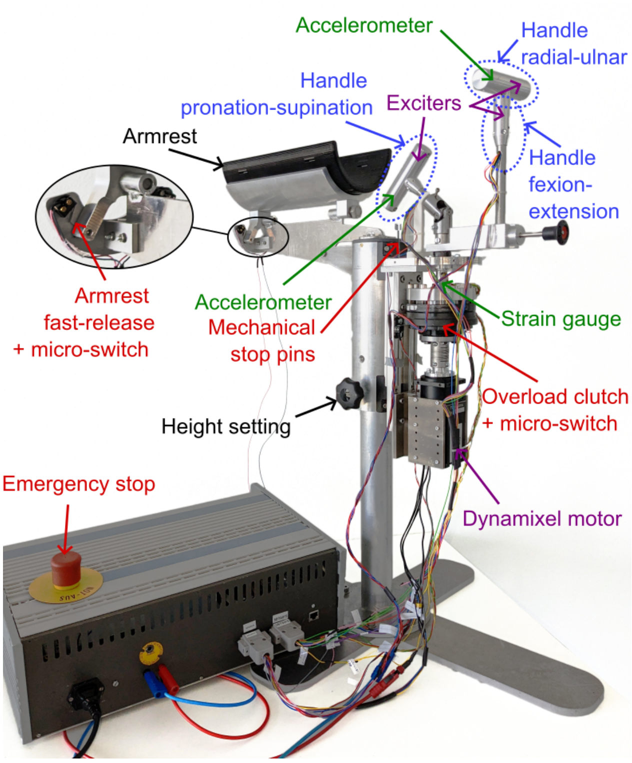

Fig. 1: Picture of the system showing the main components. The colors meaning are as follows: blue for the different handles, green for the sensors, purple for the actuators, red for the safety features and black for the other functionalities.

2.1 Control of 3 DOF with one motor

The main limitations of robots for home rehabilitation are price and limited size and weight for easy transportation. To minimize these, this system was designed to work with only one motor. Figure 1 shows an overview of the system and its various components. The motor, a Dynamixel PH54-200-S500-R, is mounted vertically at the base of the system. It is connected to two handles (figure 2. The handle for pronation-supination is positioned at an angle of 45° to the axis of the motor thanks to a universal joint and a guide part. A special armrest, also oriented at 45°, aligns the arm with the handle. The second handle can be positioned in two positions: high for flexion-extension, and low for radial-ulnar, as shown in the figure 2. Alignment and friction reduction between the motor and the handles is provided by a beam coupling and two ball bearings. The pronation-supination handle can be easily moved sideways out of its guide to clear the way for the user to grasp the other handle. Therefore, depending on which handle the user is holding, the three DOF of the wrist can be controlled with the same motor. The system is height adjustable to suit the user's position.

2.2 Safety features

In the context of robots interacting with humans, the safety of the system is paramount. This is even more true in a medical context. Therefore, this system is equipped with several safety features at the mechanical, hardware, and software levels. These are highlighted with the red markers in figure 1.

At the mechanical level, there is an overload clutch (SIKUMAT® ST 45.1 4479-040 001) between the motor and the handles shaft. Its limit torque has been calibrated on a special test bench and set at 14 Nm. When the preset limit torque is reached, the clutch disengages, thus eliminating the transmission of motion between the motor and the handle. The clutch automatically re-engages when the load drops below the limit torque again. In addition, a microswitch is located near the clutch to detect clutch movement caused by overload. This allows the drive to be shut down immediately. If the user feels the need to release the handle because he is uncomfortable, he can press either side of the armrest to rotate it sideways, making it easier to release the hand. This rotation also triggers a microswitch that stops the system. To limit the robot's range of motion, two mechanical stop pins can be placed at the minimum and maximum desired positions.

In addition to these mechanical safety features, a maximum torque and position limits are defined in the motor control software. These limits can be set by the user or therapist at the beginning of each exercise.

Finally, at the hardware level, an emergency stop button is integrated to easily shut down the entire system in the event of a hazard. This button, located on the top of the electronics housing, can be easily pressed by the user's free hand, foot (if the system is on the floor), or another person.

2.3 Means of measurement of the mechanical impedance

Traditionally, exercise machines are controlled by force $\underline{F}$, position $\underline{x}$ or velocity $\underline{v}$. However, when it comes to muscles and joints, monitoring should focus on the dynamic properties of the body. Mechanical impedance $\underline{Z}(\omega) = \frac{\underline{F}(\omega)}{\underline{v}(\omega)}$ accounts for the dependence of force on the dynamics of a movement and has been shown to be a relevant parameter for rehabilitation monitoring [13]. $\underline{Z}$ can be considered as a damping, $p\underline{Z}$ as mass, and $p^{-1}\underline{Z}$ as a spring. By definition, impedance is frequency dependent. In any mechanical contact situation, different frequency ranges represent different properties of the human arm. While in the range of < 20 Hz mainly kinesthetic and muscular properties influence the mechanical impedance, the range > 100 Hz clearly corresponds only to tactile properties, i.e. the mechanics of the skin [8, 10]. With a system design capable of operating and measuring in these frequency ranges, the assessment of muscle tension and skeletal mechanics can be clearly distinguished from the compression state of skin contacts. This allows for comprehensive monitoring of the rehabilitation task and correction of kinesthetic data collection from the influence of mechanical contact stiffness.

The system proposed in this work allows to measure the impedance both at low frequencies (< 20 Hz) and at high frequencies (> 100 Hz). In the former case, the motor controls the wrist in a periodic motion at a given frequency, while the speed of the motor is detected by its internal sensors. The torque is measured by two T-Rosette (-45°, +45°) strain gauges set in a full Wheatstone bridge on the shaft between the motor and the handle (Figure1). For the latter, small exciters (EXS 241408WA - Grewus) are integrated into the handles (Figure 1) and their vibrations are measured with accelerometers (SEN-13963 - SparkFun Electronics). In the absence of a dedicated way to measure the force exerted by the exciter on the hand in this system, the impedance is determined by the model of the handle under a given excitation while it is free (not touched by the user) as a reference measurement. Then the acceleration is measured while the handle is gripped and compared to the acceleration of the free handle. The difference is used to determine the impedance of the hand at high frequencies.

3 Results

Some results were obtained while validating the functionality of the mechanical impedance measurement at low and high frequencies. The experiment was performed on a healthy volunteer (female, 30 years old, 1.64 m, 60 kg).

In a first step, the torque is measured while the motor controls the wrist movement at different speeds between the minimum (-62°) and maximum angle (105°) of the wrist. Figure 3 shows the torque versus wrist angle curves during the flexion and extension motion for one repetition of each of these speeds. We see a clear separation between the two directions of motion, with the upper curves corresponding to the direction of maximum angle (flexion) and the lower curves corresponding to the direction of minimum angle (extension). The torque is approximately linear in the middle of the range of motion while increasing rapidly near the extremities. We also note two outliers that can be easily filtered out in the software. This shows the feasibility of measuring at low frequencies and further calculating the mechanical impedance with this setup.

Next, the high frequency measurement is performed as described in section 2. The exciter in the flexion-extension handle is driven at a frequency of 170 Hz (close to its resonant frequency). The acceleration is measured in four different configurations: without touching the handle, with a hand lightly touching the handle, with a hand gripping the handle with maximum force (tight-touch), and with an intermediate

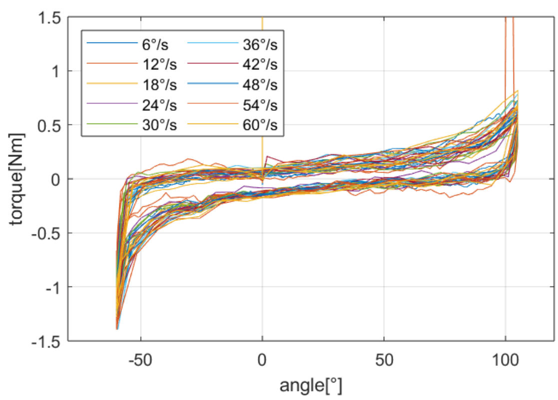

Fig. 3: Example of a group of torque-displacement curves plotted at different speeds of motion.

Tab. 1: Amplitude of the measured acceleration depending on the level of gripping force on the handle.

Gripping level	Acceleration amplitude (m/s^2)
no-touch	6.38
slight-touch	5.73
middle-touch	5.68
tight-touch	5.62

degree of gripping the handle. The acceleration is sampled at a frequency of about 700 Hz. Table 1 shows the distribution of the measured acceleration for each of these configurations. We can clearly see that the higher the gripping force, the lower the acceleration. This shows that it is possible to measure mechanical impedance at high frequencies with this setup, as described in section 2.

4 Conclusion

In this paper, the realization of a system for hand-wrist rehabilitation in three independent degrees of freedom with a single actuator is proposed and demonstrated. The system has been developed with the goal of home rehabilitation and a possible extension towards tele-rehabilitation. Based on previous work within and outside the team, the requirements for the mechanics, actuators, and sensors were defined, aiming at multiple functions such as continuous velocity and force measurement, and low and high frequency impedance measurements. With clinical trials in mind, several safety features were included to provide both passive mechanical and active electronic safety. All features have been tested and verified to the point that the system is now ready for extended data collection. The system can therefore be considered both ready for our planned human wrist impedance studies and an example of a simple, portable and user-friendly device with the option for further product-oriented development.

Author Statement

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