Robot-Assisted Intervention for Subacute Stroke Patients with the Maestro Hand Exoskeleton

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***Abstract*— Stroke induced hand impairment is characterized by loss of independent joint control and patient-specific stiffening. Current hand therapies are not capable of precise control of multiple finger joints simultaneously. The Maestro hand exoskeleton is a device that allows for the precise control of the independent motion and forces of the hand at the joint level. Exploiting these features on the Maestro system, we are developing a robot-assisted intervention for the hand. Specifically, the Task Assistance (TA) intervention is a patient-specific, assist-as-needed, and adaptable controller aiming at training for healthy movement patterns on stroke survivors. We expect to test controller safety and feasibility on a subacute stroke survivor population.**

I. Introduction

With issues related to the access and cost of therapy as well as the limitations of current regimes to improve upper distal joint functions, hand robotic-assisted therapy has risen over the past decades to overcome these challenges. Such interventions aim to complement the therapist with adaptive tools that systematically assess and mediate progress on hand functionality [1], [2]. Controlling finger joint movements is challenging since the human hand has more than 20 degrees of freedom (DOF) densely located in a small space. There exist robots for hand rehabilitation that train for gross grasping and finger individuation. However, current hand exoskeletons are non-adaptable, as the prevalence of underactuated systems prevents assessment and coordination at the inter-joint and inter-finger levels [3]. Thus, these systems are unable to deliver training that ensures healthy movement patterns. Furthermore, the complexity of coupled underactuated systems renders it impractical to adjust the force distribution across joints on patients with different joint stiffnesses [1], [4]. This is an issue because stroke is characterized by reduced independent joint control, and early prediction of dexterity is paramount for determining the type, duration, and goals of effective hand rehabilitation. The Maestro hand exoskeleton represents a substantial innovation from current rehabilitation tools with a design capable of inter-finger motions, inter-joint coordination, high-intensity, and independent joint torque modulation. The objective of this research is to develop a novel controller exploiting these features in the Maestro system. Specifically, the Task assistance (TA) controller is a task-based training with real-time modulation of assistance and difficulty level to ensure patient participation and task saliency.

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II. Robot

The Maestro hand exoskeleton is a robotic tool with the ability to manipulate multiple digits of the human hand [5], [6]. The robot consists of three modules to actively assist the index and middle fingers and the thumb. Each finger module has two actuated DOF that induce bi-directional torque at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) finger joints. The thumb module contains four DOF with similar independent torque joint control capabilities.

III. Controls

With TA control, Maestro will apply assistive joint torques to help stroke subjects practice functional finger tasks. Unlike other robotic assistive interventions for stroke [4], the TA controller will support individual bi-directional joint actuation in the fingers to enable multiple gross and fine finger tasks used in activities of daily living (ADL). The proposed control method will take advantage of principles from adaptive assistive strategies [7] and assist-as-needed [8] control methods to provide assistance that decreases as the patient's finger function progresses. The TA intervention is summarized in Fig. 1.

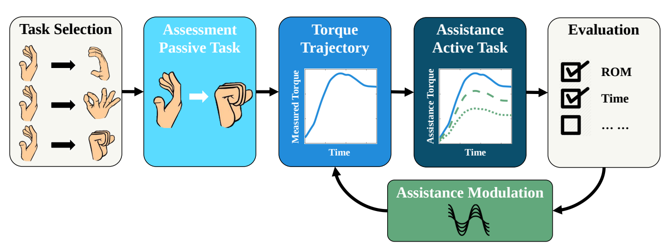

Fig. 1. An overview of the work flow for the task assistance (TA) intervention. After hand pose selection, the Maestro hand exoskeleton performs a passive task assessment and measures the robot joint torque trajectories necessary to reach the selected hand pose. Next, the user is asked to reach the hand pose during the active task, and the Maestro hand exoskeleton modulates the level of task assistance throughout the therapy session with the goal of encouraging increased user effort over time.

A. Subject-Specific Task Pose

For each task, the joint angle parameters are adjusted for the coupled human-robot system. These parameters include the initial and final joint positions of the DOF in the robot. To facilitate parameter adjustment, we implement a zero-torque (transparency) mode that allows for easy repositioning of the hand-robot system manually. Once the desired pose is adjusted, there is the option to lock joint positions as the therapist sees fit.

B. Joint Stiffness Assessment

In the assessment part of the intervention, we use a cubic Bézier curve to generate the angle trajectory ($\overrightarrow{\Theta}_{exo}(t)$) for the subject's fingers from the start pose to the end pose. The trajectories are imposed using position control at the joint level using the initial and final joint positions and a desired time of task execution, following a shape similar to a third order trajectory described in literature [9]. With this trajectory, we perform a passive task in which the subject is asked to relax. The robot joint torque values are recorded as a function of time for the relaxed state ($\overrightarrow{T}_{relaxed}(t)$). This is a reflection of subject's passive stiffness and their impairment. Next, the robot operates in transparency mode, and the subject will be asked to perform the task to the best of their ability. The measured kinematic data ($\Theta_{vol}(t)$) is then used to establish the initial assistance value for the assist-as-needed portion of the intervention.

C. Assist-As-Needed Intervention

The amount of torque assistance τ_i used throughout the training is related to the measured torque using the adaptive scaling function $\overrightarrow{\alpha}$ (Eq. 1). The i-th component of the scaling function α_{i_k} is computed after each trial (Eq. 2). The *forgetting factor* ($f < 1$) ensures that the patient applies increasing effort as the practice moves forward. The gain factor g adjusts the amount of assistive torque to the performance of the subject at the last trial using the performance index P_{i_k}. The performance index P_{i_k} is inversely related to the subject's range of motion and approaches zero when the subject is able to move through the whole movement. The assistive torque applied during the movement using the TA controller is calculated for each exoskeleton joint (i) as $\tau_i(t)$.

$$\tau_i(t) = \alpha_i \tau_{i_{relaxed}} \tag{1}$$

$$\overrightarrow{\alpha} : \alpha_{i_{k+1}} = f\alpha_{i_k} + gP_{i_k} \tag{2}$$

$$P_{i_k} = 1 - \frac{\theta_{i_{max,k}}}{\theta_{i_{max,des}}} \tag{3}$$

IV. Results

The TA intervention was tested with the index finger of a healthy user to validate its performance. The Maestro exoskeleton measured robot joint torque trajectories during a passive task. Based on the measured trajectories, the active task was implemented with varying levels of assistance, and results are shown in Fig. 2. During this task, a healthy user remained entirely passive while the robot assisted at either 50% or 100% of the desired torque trajectory. At the lower assistance level, joint positions only reached a fraction of the desired final joint positions. During a therapy session, user participation from the stroke patient will provide the remaining effort necessary to reach the final hand pose.

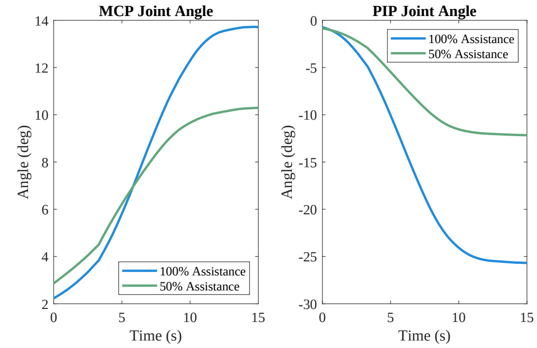

Fig. 2. Validation of assistance modulation during implementation of the TA intervention. The plots show the angular positions of the robots MCP and PIP joints during actuation at two different assistance levels.

V. Ongoing Work

Before the controller is ready for experiments with subacute stroke survivors, further development is needed to ensure ease-of-use. Improvements in the the physical-human robot interface will optimize the robot donning and doffing procedure. Also, the computer user interface will allow the therapist to seamlessly change pertinent parameters in the assistance controller providing more agency during experiments. Lastly the controller functionalities need to be integrated in the thumb module of the exoskeleton.

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