Synergy-based Controller for Upper-body Training and its Effects on Motor Behavior

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I. BACKGROUND AND MOTIVATION

Stroke is a leading cause of disability in the US. More than 80% of stroke patients suffer upper extremity dysfunction. Most patients have limited ability to perform daily activities with upper-extremities due to several impairments such as weakness, spasticity, hypertonia, and abnormal synergies [1–4]. Rehabilitation robots are promising because these systems can deliver training at high dosage and intensity. Clinical studies show that robot-mediated upper-body training after stroke results in recovery comparable to high-intensity conventional therapy in both sub-acute and chronic phases. However, these systems are unable to deliver training that significantly affects the recovery process. The challenge stems from the limitations of robot's hardware design and software control in delivering training that targets motor impairments and maintains movement quality. Algorithms have been developed to support a patient's arm weight, for passively moving the patient's upper-body in the direction of task completion, for modulating this task assistance to match patient needs and abilities (assist-as-needed), or for introducing disturbances and constraints to knock the patient off-the-course (error-augmentation). Weight-support and task assistance are helpful for patients with weakness to train functional tasks, and passive assistance can help prevent increased muscle stiffness [5], potentially improving range-of-motion in patients with spasticity and hypertonia [6].

Currently, abnormal synergies are not targeted directly with robotic training, and they remain dominant in and deleterious to the recovery process. Animal and human studies show that directly training against synergy by ensuring movement quality during task completion, especially in the early stages of recovery, improves recovery outcomes when compared to allowing for compensatory movement patterns. In the long-term, a robotic system capable of targeting impairment and recovery process, will open the possibility of a systematic investigation of effects of interventions type (e.g., movement-quality-focused and task- completion-focused), timing (e.g., acute, sub-acute, chronic stages), dosage, and intensity on the recovery process.

II. RESEARCH IDEA

Although several hypotheses have been discussed in the literature, there is still no consensus on what neurophysiological mechanisms are underlying abnormal synergies, and it is also still unclear whether and how the stereotypical synergies of stroke patients change with training. Ellis and colleagues [7] investigated the effect of progressively increasing load in shoulder abductors by gradually reducing weight support

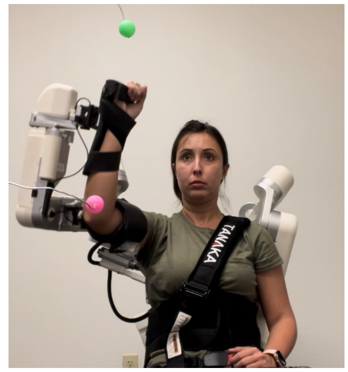

Fig. 1: The Harmony Exoskeleton and experimental setup in a representation of one of the tasks executed in the study.

throughout a training program. They have demonstrated that patients training with progressively higher loads exhibited greater improvements in motor coordination compared to patients that only trained with full weight support. The work of Ellis and colleagues considers a stereotypical abnormal pattern exhibited by stroke patients called flexor synergy, which represents a coupling between elbow flexion and shoulder abduction. To attenuate the flexor synergy, the progressively higher load gradually increases the effort required from the subject's motor inputs in a selective way, i.e., only in shoulder abductors. In both Ellis's work and also in a subsequent study that applied similar procedures [8], progressively higher loads have been only investigated in the horizontal plane. The horizontal orientation simplifies the method to gradually and selectively increase the effort required from the shoulder abductors because it can rely only on the gravity pull. However, this is not generalizable to other planes. Therefore, this work aims to design and test a synergy-based controller to selectively and gradually increase the load required in joint directions conducive to unwanted synergy patterns. The goal is to achieve training modalities focused on movement quality without depending on gravity to provide pulling forces, with the aim of accommodating training of functional movements in different planes. The synergy-based controller, combined with weight support and movement assistance implemented on our highly capable robotic exoskeleton, Harmony [9] (Fig.1), compose a tool for systematic investigation of stroke rehabilitation interventions. This investigation could help unearth key ingredients for maximizing the effectiveness of robot-mediated training for upper-body stroke recovery.

We propose to address unwanted synergies in robot-aided training through a controller that implements movement coaching based on the concept of operant conditioning, where a motor behavior is either rewarded or penalized to reinforce or discourage certain synergies. Here, we define synergy as joint-coordination, or a profile of joint-velocities. Exoskeleton robots are uniquely suited to the implementation of this training method due to their simultaneous sensing and control abilities in the joint level. A similar method has been introduced in the context of rehabilitation by Crocher [10]. Their proposed controller modulates joint-coordination with a viscous-field while letting the subject's hand free to move. The viscous-field penalizes joint-coordinations that do not match a specific profile by dissipating energy from the human subject's motor inputs. A subsequent study [11] investigated the effects of this controller in healthy individuals, and results indicated adaptation and generalization in the presence of the controller, but no long-lasting effects. In addition, there was a decrease in movement peak-speed suggesting that subjects adopted a strategy to overpower the viscous-field instead of adapting to the desired profile. We speculate that this could be caused by the overly-restrictive nature of Crocher's controller, allowing for only one profile of joint coordination.

Our idea is to penalize only the unwanted joint-coordinations by dissipating energy from the human subject's motor inputs, requiring higher effort to maintain certain motor behaviors. Conversely, the controller does not interfere with a subject's movements in all other movement patterns. To achieve this desired effect, a set of n velocity constraints in joint-space must be chosen to define a region in the n-dimensional joint-velocity space. These constraints can be defined as directional ratios between joints (e.g., simultaneous elbow flexion and shoulder flexion). The controller outputs a torque inversely proportional to the joint-velocities, which emulates a viscous-field that corrects a subject's movement towards the closest boundary within the region defined by the selected constraints.

III. ONGOING EXPERIMENTS

We are investigating the feasibility of the synergy-based controller in 15 healthy participants in an ongoing experimental protocol approved by Internal Review Board of The University of Texas at Austin. In the proposed experiment, the participants perform voluntary point-to-point reaching movements. Our goals are 1) to examine if a subject's effort in fact increases when executing an undesired joint-coordination and 2) to investigate if the synergy-based controller can be used to selectively increase effort requirement in specific joints to explore the concept of training with progressively higher loads as subjects improve control in joint directions conducive to unwanted synergy patterns. To investigate the first point, the synergy-based controller will target all movement patterns that include simultaneous shoulder flexion and elbow extension while subjects execute two voluntary point-to-point reaching movements, one enforcing simultaneous shoulder and elbow flexion, and one enforcing simultaneous shoulder flexion and elbow extension. To investigate the second point, the synergy-based controller will target all movement patterns that include simultaneous shoulder extension and elbow movements while subjects execute a voluntary point-to-point reaching movements maintaining the shoulder 90 degrees flexed. In both tasks, the participants repeat each the movement with different gains, which modulate the magnitude of the damping force. In addition, the controller gains are set such that the effort increase is present only in the shoulder joint. We record joint angles from Harmony's encoders, interaction forces from ATI six-axis force/torque sensors attached to the physical connection points, and muscle activity from surface electromyography (sEMG) sensors. Robot data is recorded with a sampling rate of 100Hz and sEMG data is recorded in 2KHz. We rectify, filter, and normalize muscle activity data for each participant using Maximal Voluntary Contraction.

Currently, 14 participants have completed the experimental protocol. We expect to provide evidence supporting the hypothesis that effort inputs in the shoulder joint will be greater when executing the movement that requires the undesired joint-coordination, but not for the movement that requires a joint-coordination not-targeted by the synergy-based controller. We also expect to provide evidence supporting the hypothesis that the synergy-based controller can gradually increase the effort requirement in a selective way whereas reduced weight support can only increase the overall effort requirement.

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