Assisting Impaired Dexterity with User-Driven Robotic Hand Exoskeletons

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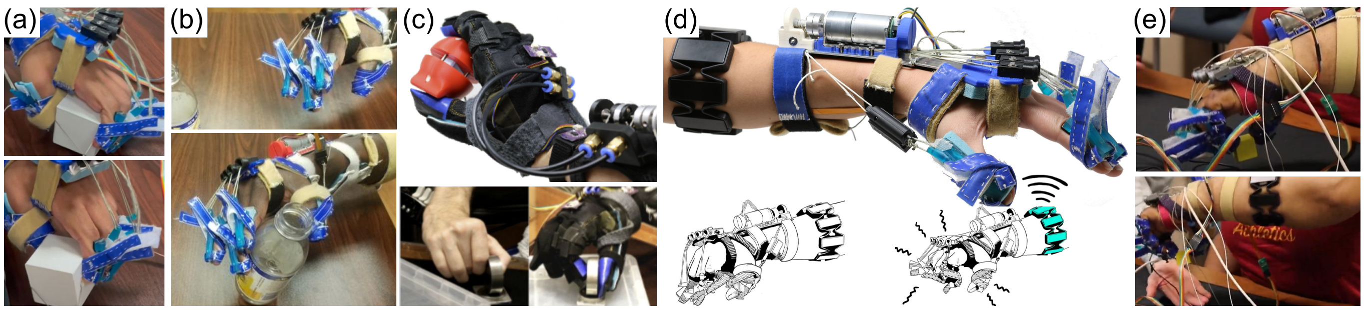

Fig. 1: My work builds wearable robots that make user-driven, functional exercise possible for people who cannot use their hands after neurological injury. (a) Maintaining hold on objects when pulling against resistance. (b) Enabling drinking motions with supination support. (c) Grasp force assistance and modulation. (d) Device control via forearm EMG activation. (e) Task-specific practice of whole arm movements.

Loss of manual dexterity due to diminished motor control and muscle weakness is a debilitating and chronic impairment for the majority of over 14 million individuals who experience a stroke or spinal cord injury each year [7, 8, 9, 10]. By motivating and enabling people to use the impaired arm in daily life, wearable robots can potentially counteract learned non-use and further deterioration of motor function [11, 12]. However, use of robotic devices for rehabilitation or assistance remains limited for these populations [13, 14]. This is in part because few devices are designed to accommodate the specific needs of, or seek input from, impaired users [15, 16, 17]. I build novel devices and interfaces in order to meet these needs.

My research builds devices that act on volitional effort from the impaired arm and leverage the user's residual movement capabilities. This work pursues two complimentary research directions. The first direction develops actuation methods to assist movements that the user cannot execute themselves, while preserving the user's ability to perform body-powered antagonistic movements [1, 2, 3, 4]. The second direction uses biosignals sensed by the robot to provide insights about impaired dexterity and motor learning, which we can uniquely observe in functional contexts by assisting movement [5]. I pursue both directions by building devices for, *while working alongside,* people with impairments and clinicians who work with them [6]. The result is robotics research that addresses problems with real impact for users' quality of life, and also has broader applications for general wearable systems. I aim to address the following fundamental research questions:

- How can we leverage a person's existing sensorimotor abilities to build robots that act in concert with human intent and augment the body without interfering with it?
- How can we use robotic intelligence to study human movement and planning during functional activities?
- What and whose design inputs are needed to build assistive technologies that are both useful and desired?

I. Research To Date

Wearable Robotic Devices for Restoring Functional Hand Movements After Neurological Injury. People are motivated to use assistive devices after neurological injury by a desire for independence and self-management [15], in particular to use their own hands in daily tasks. As a roboticist, I aim to build devices that restore functional dexterity without interfering with users' non-assisted capabilities. For stroke survivors, the mechanical challenge is managing the increased finger stiffness and involuntary flexion synergies as the hand is externally actuated. For individuals with hand paralysis after a spinal cord injury (SCI), the challenge is providing external grasp force without obstructing range of motion in the wrist.

One of our novel insights for assisting grasping after stroke is to leverage the stroke-specific stiffness reflex to actively self-assist in stabilizing the thumb in opposition. While assisting extension alone pulls the thumb away from the hand in a detrimental way for useful grasping, by coupling the involuntary thumb-flexion spastic reflex to the robot transmission we can provide "body-powered" active thumb stabilization with a single external actuator. In the first exoskeleton study to evaluate active and passive thumb assistance on an impaired population [1], we find that our approach helps users grasp and maintain a better hold on objects against resistance for longer durations (Fig. 1a: Top = active, Bottom = passive).

Assisting only grasping when a user lacks active forearm rotation severely limits the functional workspace of the hand [18]. Unlike prior works which constrain the upper arm's range of motion to anchor a device [19, 20], or envelop the entire forearm space preventing integration with a hand exoskeleton [21], we develop a novel spiral cable-based method to support the arm at varying wrist rotation angles that anchors on the forearm and preserves residual motion capability. In a case study with a stroke participant who could not reorient their arm, we demonstrate successful completion of functional tasks requiring neutral hand orientation [2] that could not be achieved with grasping assistance alone, such as reaching for and lifting a bottle to the face in a drinking motion (Fig. 1b).

Individuals with hand paralysis caused by C6-C7 level SCI often have preserved wrist mobility. They can bend the wrist backwards to passively shorten the finger tendons, which enables them to generate low-force grasps [22]. However, maintaining this wrist hyperextension limits the arm workspace during reaching since wrist and elbow movements are coupled [23]. We built an exoskeleton (Fig. 1c) for an SCI participant that implements a novel throttle-based wrist control that enables the user to grasp an object with a desired amount of force using only a minimal degree of wrist extension, then maintains that grasping force on an object while allowing the user to relax their wrist when reaching forward [3].

Volitional Control of Robot-Assisted Hand Movement. We use forearm surface electromyography (EMG) to infer intended motions from muscle activation patterns when the user exerts effort to move the hand (Fig. 1d). Individuals who lack the muscle strength after stroke to open their hands themselves also often lack proprioceptive feedback needed to produce consistent EMG patterns, which instead drift over time [24]. In the first use of semi-supervised learning for an orthosis with a stroke population, we developed a disagreement-based classification method [4] to adapt to this biosignal drift. Unlike semi-supervised methods designed for amputees or other individuals with neuronormative muscle signalling [25, 26, 27, 28], our method is applicable for individuals with abnormal muscle coactivations. Our method can be trained using less data and achieve a higher offline classification accuracy compared to supervised methods, and is usable for online robotic control by impaired users.

Actively exerting effort to move the impaired arm, as the user does when performing functional tasks with robotic assistance, can provoke involuntary abnormal synergies and amplify stiffness effects of muscle tone [29, 30]. Such complications add difficulty for user-controlled devices to effectively assist hand movement during functional tasks. In experiments with three stroke participants, we studied how volitional effort, exerted in an attempt to open or close the hand, affects resistance to robot-assisted movement at the finger level, modeled as stiffness [5]. State-of-the-art stiffness estimation methods either passively stretch the fingers [31, 32, 33, 34] or evaluate volitional effort while the fingers do not move [29, 35]. We measured changes in stiffness when the user is actively exerting effort to activate robot-assisted hand movements (Fig. 1e), compared with when the fingers are passively stretched, as well as overall effects from sustained active engagement and use. We found volitionally-controlled hand movement to increase muscle tone in the finger to a much greater degree than from passive-stretch or sustained exertion over time. These are the first known observations of stiffness effects from robot-assisted active movement in this population. Importantly, our findings suggest that developers should anticipate higher stiffness effects when relying on user-driven, effort-based control for robotic devices.

Engaging Clinicians and Impaired Users in Early-Stage Device Design. Many promising devices are ultimately abandoned because they fail to meet users' actual needs [36, 37]. Inspired by our discussions with clinicians and by other focus group studies [13] that explored community perceptions of robotic devices, we conducted a national online survey of therapy practitioners to gather insights on the main barriers and opportunities for our device, uniquely early on in the design cycle when major device changes can still be made. Results from our cross-sectional mixed methods study [6] identified responsivity and compatibility with real-world tasks, ease of setup, and ability for the impaired user to independently operate the device as the main barriers to clinical translation. We are currently pursuing follow-up studies that analyze our interviews with survivors of stroke and spinal cord injury.

II. Future Directions

My prior work gives impaired users the opportunity to move their hands with robotic assistance. In future work, I plan to study how the human-robot system should work together to improve overall motor coordination. How can we leverage human adaptation to build more responsive robots? How can we take advantage of impairment synergies to not just stabilize, but produce functional movements? The following research avenues contribute critical next steps towards realizing devices that can be taken anywhere for fully-independent use.

Bidirectional Human-Robot Intent Inferral and Co-Training. Our prior work [4, 5] treats the human user as a static generator of intents, and attributes distribution shifts of biosignals solely to complications of impairment. But humans themselves are adaptive agents who change behavior from perceptual feedback of whether the robot moves as-expected. I propose using biofeedback of inferred intents, which embed an estimation of which muscles are involved in opening and closing efforts, to train the user to move the arm in ways that minimally provoke abnormal muscle synergies. Prior works have demonstrated therapeutic potential from biofeedback [38, 39], but not with participants who require movement assistance. Biofeedback can also potentially be a tool for teaching users to train better intent inferral algorithms, by recurrently updating classification models during practice sessions as the human learns to generate more separable muscle activation patterns. Co-training human biosignal generation and robotic inferral would improve overall performance and task generalization.

Grasp Pre-Shaping via Body-Powered Reflex. Pre-shaping the hand when reaching for objects (keeping fingers straight for planar objects like books, curling fingertips inwards for smaller objects like pens, etc.) is an important component of human grasp planning [40, 41, 42] that is lost during robot-assisted grasping. To enable our device to produce these types of poses, I propose adapting our lightweight cable transmissions to also strategically leverage the stroke reflex flexion motions that we observed during active opening [5]. This novel method would enable users to shape the pre-grasp hand pose more closely to objects of interest, improving grasp performance, without needing to use additional actuators.

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