Empowering Healthcare with Robotics: Advancing Stroke Rehabilitation and Elderly Caregiving

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I. Introduction & Motivation

Healthcare plays a vital role in society, especially as the global aging population presents pressing challenges. By 2050, 22% of the world's population will be over 60 [28], leading to increased demand for healthcare services. Aging is associated with neurological conditions like stroke and social challenges such as caregiving. My research focuses on stroke rehabilitation and elderly caregiving, as both share two key challenges: (1) labor intensity and (2) service accessibility.

First, these services are labor-intensive. Stroke rehabilitation requires repetitive training, following the "power law of practice" in motor learning [11, 12], involving significant time and effort from healthcare providers. Similarly, caregiving demands continuous support, monitoring, and immediate emergency response. Robotics can help by delivering high-dosage, high-intensity robot assistance. Teleoperation further improves service efficiency, enabling healthcare providers to operate multiple robotic systems for different users, such as stroke patients and older adults [25].

Second, service accessibility remains a challenge. In geographically vast countries like the United States and Canada, many healthcare users with mobility limitations struggle to access healthcare facilities. Teleoperated robots [5], supported by advanced 5G/6G networks [4], offer a promising solution by bridging the gap between users and healthcare providers.

Driven by these challenges, my research aims to develop intuitive human-robot interfaces that allow healthcare providers to remotely operate robots assisting users in activities of daily living (ADLs), while addressing their physical, cognitive, and emotional needs. Previously, I focused on hardware interfaces, including developing upper-limb exoskeletons for stroke rehabilitation [17, 27, 15, 2, 26] and haptic devices [19] for bilateral teleoperation. Now, my work has shifted to software interfaces, specifically how robots can interpret human intent and engage intelligently using artificial intelligence (AI).

II. Prior Work

In this section, I will briefly introduce my previous work on developing upper-limb exoskeletons and haptic devices, along with the key research challenges and my contributions. My research is inherently interdisciplinary, as I believe meaningful collaboration across fields is essential for developing innovative technologies with real-world impact.

To address the challenges in stroke rehabilitation, I integrated robotics, biomechanics, physiotherapy, and neuroscience to develop exoskeletons with human-in-the-loop control for bimanual ADL training. Similarly, I combined mechatronics, solid mechanics, and soft robotics to design stiffness-rendering haptic devices for bilateral teleoperation. By drawing on multiple disciplines, my work bridges engineering and human-centered healthcare.

A. *Upper Limb Exoskeleton for Bimanual ADL Training*

Stroke rehabilitation requires bimanual ADL training. While conventional unimanual training, such as constraint-induced movement therapy (CIMT) [13], enhances motor function, it does not improve interlimb coordination because of the bilateral-specific neurons in the supplementary motor area and primary motor cortex [23]. Thus, bimanual training is essential for patients to relearn bimanual ADL tasks.

1) Bilateral Exoskeleton Design: Existing exoskeletons for bimanual training have limitations, including inadequate distal joint assistance [29], unnecessary restrictions on less-impaired joints [10], bulky design in bilateral configuration, and limited control frameworks for underactuated systems.

To address these challenges, I developed a 9-degree-of-freedom (DoF) Underactuated Upper Limb Exoskeleton—a lightweight (1.783kg), cable-driven system for bimanual ADL training [17, 27]. It features distal joint assistance from the elbow to wrist, while allowing passive scapula and shoulder movement, ensuring natural joint motion without restricting less-impaired joints. Its compact self-alignment mechanism with a passive ball joint enables bilateral configuration, avoiding interference between the two arms. The primary-secondary joint assistance strategy enables adaptive, patient-controlled movement without predefined task-space trajectories.

The exoskeleton's effectiveness was validated through experiments with ten healthy participants. It significantly reduced their muscle activity and motion differences in a symmetric bimanual ADL task. This exoskeleton presents a promising step toward effective, patient-driven bimanual stroke rehabilitation.

2) Exoskeleton Sensing for VR: Virtual reality (VR) offers a controlled, immersive environment for stroke rehabilitation, training patients in ADLs [1, 9]. However, its effectiveness is hindered by inaccuracies in robot motion sensing [24]. Conventional sensors, such as rotary encoders and inertial measurement units, have inherent issues like complex installation, signal drift, and magnetic interference.

To overcome these limitations, I proposed an innovative and reliable sensing system that combines rotary encoders with visual-inertial sensors for reliable joint angle measurements in upper limb exoskeletons used in VR training [18]. This system measures various joint types: encoders for hinge joints, visual-inertial sensors for ball and revolute joints along the limb's longitudinal axis. It provides real-time measurement to simulate virtual arms interacting with objects in VR.

Experimental results, compared to Vicon as the reference standard, showed that the visual-inertial sensors achieved root-mean-square errors (RMSE) below 2.3491° and demonstrated a strong correlation ($r \geq 0.9640$, $p < 0.001$). Furthermore, experiments with seven healthy participants revealed that the muscle activations, joint range of motion, and joint trajectories in the VR task closely mirrored those in real-world tasks. This sensing system is easy to implement, magnetometer-free, and can be adapted to other robotic systems, offering a promising solution to enhance the accuracy and reliability of VR-based rehabilitation.

3) Exoskeleton Control for Asymmetric Bimanual ADLs: Existing upper limb exoskeletons face major challenges in training asymmetric bimanual ADLs. Traditional task-space control methods [22, 21, 3] often struggle to provide individualized joint motions necessary for training compensatory techniques in occupational therapy [20]. They also lack the flexibility to customize joint error tolerances for motor learning [11] and patient safety. Moreover, these methods are unsuitable for underactuated exoskeletons.

To overcome these challenges, I proposed a novel exoskeleton control framework that integrates independent impedance joint control and visual guidance in VR to facilitate asymmetric bimanual ADL training [14]. This framework enables the robot to provide personalized assistance for each joint based on the patient's impairments while incorporating therapist-demonstrated joint trajectories for compensatory techniques. The VR visual guidance helps patients coordinate their movements by allowing them to anticipate robot assistance and match it with their unassisted joint motions.

I validated the framework with 15 healthy participants, who demonstrated significant reductions in joint angle errors and muscle activation, indicating the effective robot assistance. VR-guided motion also showed a strong correlation with therapist-demonstrated motions. This approach enables personalized impaired-joint support, promotes coordinated movement, and ensures user safety by training in VR. The results highlight the framework's potential to enhance asymmetric bimanual ADL training and advance stroke rehabilitation.

B. Pneumatic Haptic Device for Bilateral Teleoperation

While robots can improve service efficiency, accessibility remains a significant challenge in countries with large geographical landscapes. Due to limited telepresence [6], healthcare providers face difficulties in assisting users in ADLs.

A key challenge in robot teleoperation is providing kinesthetic feedback that helps operators gauge appropriate robot grip force, especially when grabbing daily objects with varying stiffness. Existing systems struggle with issues such as system instability [7], sensation distortion [7], and joint misalignment in kinesthetic devices like exoskeletons [8].

To address these limitations, we proposed a novel wearable haptic device [19], using a honeycomb jamming mechanism to provide real-time, adjustable stiffness feedback during teleoperated object-grasping tasks. The device, weighing only 20 grams, can vary its stiffness from 1.15N/mm to 2.64N/mm using 30kPa vacuum pressure, offering operators kinesthetic feedback similar to direct object grasping. This device is integrated into a bilateral teleoperation framework, allowing operators to control grip force with accurate haptic feedback on object stiffness. The key advantages of the device include its lightweight and compact design, ensuring finger mobility, and its ability to provide reliable feedback.

Experimental results demonstrated the device's effectiveness, showing a small RMSE and strong correlations in motion, stiffness rendering, and force feedback during object-grasping tasks. The device provided stable, real-time kinesthetic feedback, enabling strong potential for telerehabilitation and VR, where precise, responsive haptic feedback is essential.

III. Future Work

As noted, my research aims to develop intuitive human-robot interfaces that enable healthcare providers to remotely assist users in ADLs, while ensuring robotic support addresses users' physical, cognitive, and emotional needs.

To date, my work has primarily focused on robot hardware interfaces, particularly developing exoskeletons to assist users in ADLs and haptic devices to improve telepresence by providing healthcare providers with haptic feedback. However, achieving my broader research goal remains a challenge, as it involves not only the interaction between healthcare providers and the robot, but also between the robot and users at remote locations. This leads to the central research question: How can a robot simultaneously interact with both the healthcare provider and the user, ensuring that the provider can control the robot intuitively while guaranteeing user safety and delivering meaningful assistance in the remote location?

This question drives my future research toward developing an intuitive teleoperation framework with shared autonomy for older-adult caregiving. Building on my human-centered robotics experience, I aim to integrate robotics, biomechanics, psychological theories, and machine learning to enhance teleoperation by understanding caregivers' intentions and helping them monitor older adults' physical, emotional, and cognitive states, reducing caregivers' cognitive and physical load.

This research includes two main components: (1) an intelligent teleoperation interface that recognizes caregiver-intended assisting actions and sends high-level action commands to remote robots for autonomous caregiving [16]; and (2) a system that monitors and relay older adults' physical, emotional, and cognitive states to caregivers through the interface, or adapts the robot's assistance autonomously, enabling personalized, responsive care. Together, these components can potentially improve remote caregiving quality and make it more human-centered.

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