Compliant Robots for Next-Generation Human-Robot Interaction

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***Abstract*—While traditional robotics provides solutions to many problems involving human-robot interaction, there is one large and critical area in which traditional robotics has fallen short: the combination of affordable and portable robotic systems with sufficient performance is currently an unsolved problem in robotics [1]. Most robots that physically interact with humans are heavy and expensive, severely limiting the widespread integration of the benefits of robotics into everyday life. In this paper we discuss possibilities for introducing the constrained compliance of compliant mechanisms to dramatically improve the portability, affordability, performance, and safety of robotic systems for physical human-robot interaction.**

Keywords*—*Robotics, Rehabilitation, Compliant Mechanisms.

I. INTRODUCTION

Traditionally, rehabilitation of movement disorders (stroke, traumatic brain injury, etc.) has been provided by skilled therapists and is usually time-consuming and labor-intensive. Because of limits in reimbursable health care, rehabilitation usually ends before a patient is fully rehabilitated, leaving the patient partially disabled. In the US there are 5 million stroke patients alone, while the increasing size of the aging population (expected to double by 2050) creates an urgent need for technology to support the increasing demand for rehabilitation. To fill this need, the field of rehabilitation robotics has rapidly developed and many engineering groups have created robotic devices to supplement traditional therapy. Robots can provide consistent and repeatable therapy over long periods without fatiguing, holding the potential for improved patient outcome at reduced cost [2]. Accurate sensors and intelligent algorithms can evaluate the severity of a patients movement deficits and quantify (and even adapt to) progress during rehabilitation. Finally, rehabilitation robots can provide augmented feedback and challenge users in ways not possible with traditional therapy [1]. These and other potential advantages have led to the development of a variety of rehabilitation robots [3, 4], and initial clinical trials show that robotic rehabilitation can be as effective as traditional therapy [5].

However most commercially available rehabilitation robots do not see widespread use because they are too expensive (on the order of \$50,000 - \$250,000). Few clinics can afford them and patients can only use them on-site. This challenge is compounded by the current approach to rehab robotics that the development of more sophisticated robots will allow them to become integrated into hospital and rehab centers. The high cost of these devices puts them out of financial reach for most of consumers and at odds with other accepted medical therapies, which are typically better reimbursed by third-party payers. Thus, the financial model for providing robot-aided rehabilitation to the large number of potential recipients with neurologic disorders remains problematic in the United States [2].

II. OBJECTIVE

Instead of improving robotic rehabilitation by increasing the sophistication of the robots, this research aims to explore the possibility of portable, low-cost robots that allow a large number of patients to benefit from unlimited therapy time. The justification for this approach comes from the fact that the benefit of robotic rehabilitation is likely more related to the amount of practice than the sophistication of the device [1], and because simpler devices see more widespread use [4]. In other words, we expect a simple and inexpensive device that is available for more practice time and to more people to be more effective than the current model of sophisticated, expensive devices. While we focus in this proposal on neurological disorders, the results of this work are applicable to rehabilitation from biomechanical injuries as well (sprains, strains, contractures, scarring, immobilization, etc). Although we focus here on rehab robots for the upper limb, advances in this area can be extended to lower limb rehabilitation and to allied fields such as assistive robotics, orthotics, and prosthetics. Therefore, this work, if successful, will have a positive impact on millions of patients; stroke alone is a leading cause of long-term disability, with roughly 5 million stroke survivors in the US today [6].

III. PRELIMINARY STUDY

A preliminary study showed that low-cost, portable rehab robots are feasible. Last year, I worked as a member of a team of six mechanical engineering students for my senior capstone design project. We were challenged to develop a take-home rehab robot for the upper extremity that could be built for less

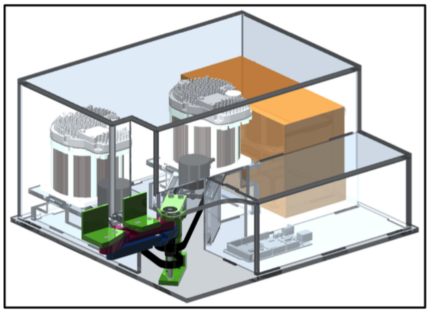

Fig. 1. First prototype of the low-cost rehab robot developed at BYU

than \$3000 (a significant drop compared to the usual price tag of tens to hundreds of thousands of dollars). A needs analysis showed a demand for a take-home robot to rehabilitate flexion-extension of the wrist and metacarpophalangeal (MCP) joints since these DOF are critical to grasping and manipulating objects (a component of most activities of daily living) but tend to take the longest to rehabilitate following stroke. Within 8 months, our team created a rehab robot that 1) allowed patients to move through nearly the full unimpaired range of motion in these two DOF, 2) was capable of providing assistance close to the maximum voluntary torque in these two DOF, and 3) exhibited mechanical output impedance sufficiently low for patient-initiated movements, even for weak patients (the torque to back-drive the robot was on the order of 1% of the unimpaired maximum voluntary torque.

In the end, we succeeded in developing a rehab robot that was small ($1ft$-by-$1ft$-by-$1ft$), light ($32lbs$), and low-cost (\$1600 in parts) [7]. Figure 1 shows the prototype created as a CAD model. However, while the success of this project demonstrated that rehab robots can be made to be significantly more portable and lower cost than current rehab robots, this experience also illustrated the limits of this approach: using traditional robotic design methods is unlikely to yield robots whose weight and cost are low enough for widespread home use, not to mention wearable rehab robots, which would increase therapy time dramatically and could double as assistive devices. We also learned that the main culprits responsible for the cost and weight of rehab robots are the actuators and associated power supply; in the robot we developed, they accounted for approximately 80% of the cost and weight. Large and expensive actuators are needed to provide the desired mechanical output impedance (how the robot feels to the user).

IV. RESEARCH APPROACH

While many research groups are focused on making actuators and power sources that are lower cost and lighter, this research approach would be to attack this critical issue from the opposite end: rehab robots could be made lower cost and lighter by reducing their dependence on large actuators and power supplies by strategically integrating some of the desired mechanical output impedance into the robot hardware itself. This goal would be accomplished by taking advantage of advances in the field of compliant mechanisms, which gain their motion from the deflection of elastic components that are constrained to move in a specified way. Advantages such as low weight, the ability to integrate functions into fewer components, compactness, reduced part count, low wear, ease of manufacture, reduced backlash, and smooth motion provide powerful incentives for the use of compliant mechanisms in robotic systems.

A successful outcome of this research should create a methodology for developing low-cost, wearable rehabilitation robots by taking advantage of the low-cost and low-weight benefits of compliant mechanisms and strategically building energy storage into the robot hardware. It should also develop a library of compliant mechanisms specifically designed for wearable rehab robots (exoskeletons) for the purpose of being able to shape the mechanical output impedance of the mechanism. The library would include mechanisms specifically designed for upper-limb exoskeletons, focusing on the distal joints (forearm, wrist, fingers) that can benefit most from the space and weight advantages of compliant mechanisms. Robots with compliant mechanisms can also take advantage of the potential energy inherent in compliant joints. Replacing some of the actuators with (passive) compliant mechanisms could create hybrid systems in which the compliant joints assist or replace some of the actuators, making the system lighter and cheaper.

A. Compliant Mechanisms

Compliant mechanisms gain their motion from the deflection of elastic components that are constrained to move in a specified way, and do not require traditional motion components such as bearings. Although purposely adding compliance goes against common practice, three primary arguments support the attempt. First, systems for physical human-robot interaction have operating conditions that make them well suited for compliant mechanisms (low speed, relatively low force, and lower precision requirements). Second, because compliance has been actively avoided, there is great potential to make a large and immediate impact. Modifications to current systems and software are not well positioned to make a similar impact in safety, portability, and affordability. Third, recent advances in materials, computation, and modeling approaches have enabled the design of advanced compliant mechanisms.

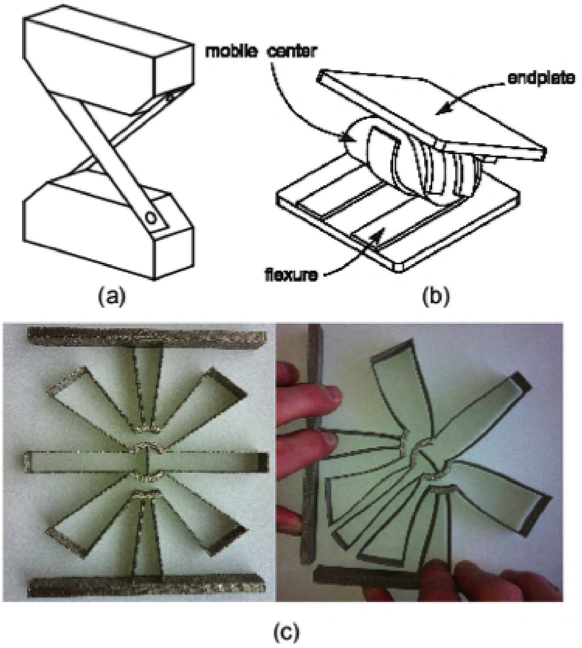

Fig. 2. Examples of surrogate bearings: (a) cross-axis flexural pivot, (b) two-DOF CORE joint, and (c) a monolithic, large deflection, titanium, compliant space hinge. Figures and photos courtesy of BYU Compliant Mechanisms Research Laboratory.

B. Compliant Surrogate Bearings

The primary approach taken in this work is to develop, model, and control robotic systems based on surrogate bearings, which serve as compliant replacements for traditional rotary bearings. A straightforward surrogate bearing is a flexure [8, 9, 10, 11] that has a section with high flexibility.

Although flexures are common components in high-precision instruments, they have mainly been used in areas where only small deflections are required. Cross-axis flexural pivots [12] are used in high precision devices (Figure 2a), and some configurations are available commercially as off-the-shelf components. One of the most promising concepts for a surrogate bearing is the compliant rolling-contact element (CORE) [13, 14] a multi-DOF version is illustrated in Figure 2b [15]. A key advantage of the CORE is that it is statically balanced throughout its motion and does not tend to any particular position. It carries large compressive loads and resists off-axis loads. The BYU Compliant Mechanisms Research Laboratory has developed and licensed a related device as an artificial spinal disc [15]. Figure 2c shows a titanium space hinge designed by BYU and fabricated by NASA Marshall Space Flight Center. This hinge shows the capability of 180 degrees of rotation (plus and minus 90 degrees from its fabricated position) and is a single piece of titanium.

Because surrogate bearings can be designed to be cheaper and lighter than traditional bearings, they are a potential mechanism for transforming large, expensive robots into take-home and wearable devices. A decrease in device weight is especially important for wearable devices that travel on board with space flight crews. While the cost and weight of traditional exoskeletons increase dramatically with the number of DOF, recent advances in compliant mechanisms are making it possible to integrate multiple DOF into a single surrogate bearing, making it lighter, cheaper, and more compact.

C. Impact on Space Flight

Although this research is based on developing low-cost and low-weight rehabilitation robots, improvements in portability, affordability, safety, and performance of systems with physical human-robot interaction have direct application to space flight. Our goal is to dramatically decrease the cost and weight of human-machine interfaces through the use of compliant bearings, enabling the development of wearable devices that could reduce the sensorimotor problems caused by prolonged space flight. This project will specifically improve human-machine interfaces capable of use during space travel for exercise, self-assessment tools, and adaptation countermeasures. In addition, compliant surrogate bearings are not dependent on specific pressures like traditional bearings, allowing them to be utilized in extreme space environments. Compliant human-robot interfaces would allow astronauts to use them on board rocket ships to facilitate the adaptation to different gravitational environments and help enable future missions that focus on long-term space exploration. Flight crew members would use the robots before space travel to record current sensorimotor skills and utilize the robots throughout extended space travel to combat changes in control of movement, problems with spatial orientation, space motion sickness, or difficulty walking.

V. ANTICIPATED RESULTS

Throughout the first year of research we have completed the literature review and outlined the project goals and methods as presented above. Our future goal is to deliver a library of surrogate bearings specifically designed to serve the needs of human-robot interaction. This library would include surrogate bearings for take-home robots for common rehabilitation scenarios, allowing linear motion of the hand in 1, 2, and 3 DOF (for rehabilitation of shoulder and elbow movements) and rotational motion of the hand in 1, 2, and 3 DOF (for rehabilitation of wrist and forearm rotations). The library would also include surrogate bearings that can be used for upper-limb exoskeletons that would benefit from the space and weight advantages of compliant mechanisms.

A successful outcome of this research would include deliverables such as: (1) Results from the investigation of novel compliant rehabilitation robots, including development, control, testing, and validation. (2) A catalog of compliant surrogate bearing elements for human-robot interaction. Mathematical models, detailed design information, and testing results would be generated and disseminated for each element. (3) A critical evaluation of compliant mechanisms in robotic applications and a prioritization of compliant elements for future development. (4) Materials to facilitate widespread use of the results, including publication of the research in traditional academic venues, open-source hardware documentation, and materials to facilitate technology transfer of results.

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