DESIGNING A ROBOTIC EXOSKELETON FOR SHOULDER COMPLEX REHABILITATION

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ABSTRACT

Frequent and repetitive functional training of the upper limb is a key aspect of regaining independence after stroke. Traditionally, this is achieved through manual one-on-one therapy, but patients are often unable to get sufficient treatment due to budget and scheduling constraints. An ideal solution may be robotic therapy, which is becoming an increasingly viable tool. Unfortunately, current rehabilitation robots ignore shoulder girdle motion, even though it plays a critical role in stabilizing and orienting the upper limb during everyday movements. To address this issue, a new adjustable robotic exoskeleton is proposed that provides independent control of six degrees of freedom of the upper limb: two at the sternoclavicular joint, three at the glenohumeral joint and one at the elbow. Its joint axes are optimally arranged to mimic natural upper-limb range of motion without reaching singular configurations and while maximizing manipulability across the workspace. This joint configuration also permits reduction to planar shoulder/elbow motion in any plane by locking all but the last two joints. Electric motors actuate the mechanisms using cable and belt transmissions designed to maximize the load capabilities of the robot while maintaining backdriveability and minimizing inertia. The device will be able to operate both as an assessment tool and as a therapy tool by monitoring and assisting movements. It will also be able to provide any level of gravity compensation. Controlling the entire shoulder complex facilitates training with more natural movements, with the added benefit of gaining the ability to observe and prevent compensatory motion.

INTRODUCTION

Over the past few years, several rehabilitation robots have been developed for the purpose of improving motor function after stroke [1,2,3]. Robotic devices present a number of benefits over traditional therapy techniques, and thus have significant potential in clinical settings. Perhaps the most significant advantage is that robots are able to repeat movements continuously without getting tired and without making mistakes. This removes strenuous manual labour from the therapist’s job, which prevents injury and allows them to focus on developing individualized treatment programs and on monitoring progress. When designed appropriately, robots can also function as assessment and diagnostic systems, providing a wealth of objective quantitative measurements during all movements. Virtual environments and complex training algorithms can be applied easily and safely. This includes any level of gravity compensation or resistive exercise.

Robotic devices are not free from limitations. One of the most obvious disadvantages for a robot is that it is difficult to build a device that can match the versatility of the human body. In particular, the human shoulder complex is a structure with extraordinary mobility that is challenging to replicate completely [4]. A robot that closely mimics upper limb motion will be able to train with more realistic functional movements. However, as a robot gains degrees of freedom (DOF), its complexity and cost increase significantly. Compliance, mass and inertia also increase, introducing other design conflicts that become challenging to solve.

Current robots neglect motion of the shoulder girdle due to its mechanical complexity. However, the shoulder girdle is an important part of upper limb motion [5], and its mobility is commonly recruited for compensatory movements and thus should not be ignored [6]. A new rehabilitation robot called MEDARM (Motorized Exoskeleton Device for Advanced Rehabilitation of Motor function) has been designed to reproduce the five most significant degrees of freedom of the human shoulder complex, including the shoulder girdle. This paper introduces the proposed design for MEDARM by describing the key design objectives used to create the final mechanical design.

DESIGN OBJECTIVES

MEDARM was designed with specific therapeutic functionality in mind. A set of design objectives required to achieve this functionality were outlined and then grouped into two categories: robot-user interface and technical design. Not surprisingly, there is significant overlap between these categories. This section describes these objectives terms of these groupings.

Therapeutic Functionality

MEDARM is intended to assist a physiotherapist with the delivery of rehabilitation services to stroke patients with upper limb motor deficits. As such, a key part of the design process involves specifying the types of tasks the robot should be able to perform.

The fundamental requirement for any upper limb rehabilitation robot is to be able to perform basic therapy tasks that would otherwise be performed manually by a therapist. A significant part of typical therapy programs includes full or partial assistance with functional reaching movements [7]. Repeating and practicing these functional movements is part of the motor learning process, and is thus important for recovering the ability to perform activities of daily living. Patients with motor impairments may initially require full assistance, but the level of required assistance decreases as function is regained. As such, MEDARM should be able to provide any level of assistance, and should move passively with the patient when assistance is not needed.

Another important function of a rehabilitation robot is gravity compensation. Overcoming the forces of gravity during motion is difficult for weak patients, and removing these forces can make it easier for a patient to perform reaching movements [8]. However, it is difficult for a therapist to manually eliminate the effect of gravity. Sling systems can be used, but do not compensate equally across the upper limb workspace. MEDARM should be designed to provide any level of gravity compensation for all reaching movements.

One of the advantages of robotic technology is the ability to present the user with virtual environments. The simplest case would be to apply simple resistive loads. This type of progressive-resistive exercise is a key component of regaining strength and coordination [9]. Therefore, MEDARM should be able to simulate a range of environments, including movement through viscous fluids and picking up objects. Other more complex environments can be designed to encourage proper coordination and to prevent compensation by limiting or locking motion at specific joints. Movements may also be purposefully restricted to simpler single-joint or planar motions to reduce abnormal muscle synergies. MEDARM should thus be designed to allow joint-based control of the patient's limb.

Another aspect of rehabilitation programs is patient monitoring and assessment. Since robots provide ongoing quantitative measurements of movement and are inherently objective, they show significant potential as diagnostic and assessment tools [10]. Thus, MEDARM should be able to operate simultaneously as a therapy device and an assessment system. The robot should be able to transparently observe and record movements throughout the treatment program. This would provide an ongoing measure of progress, and this data could be stored for future use. Simplification of movements to planar motion can facilitate assessment (simpler equations of motion), so a useful feature would be able to restrict motion to simple 2DOF shoulder/elbow motion in any plane.

Robot-User Interface

Anytime a robot is used intimately with a person, there are a number of design considerations that must be made. The fact that people vary in size, shape, and motor ability makes it a tremendous challenge to accommodate everyone's needs.

Safety is of utmost importance, so MEDARM should have hardware and software limits to ensure that joints are not overextended. Other kinematic and dynamic limits should also be considered. A secure and comfortable attachment to the user should be maintained with minimal pinching, rubbing, stretching or twisting. This is particularly important in a rehabilitation setting because elderly users and patients with motor impairments are often more susceptible to injury from forced movements. Also, these users typically have more sensitive and supple skin, and/or have limited ability to sense their environment.

To provide realistic functional training, a rehabilitation robot must be able to closely mimic natural motion of the upper limb. However, there is no current robotic device that can replicate motion of the entire shoulder complex. Therefore, a fundamental goal for MEDARM's design is to provide independent control for all 5DOF of the shoulder complex (2DOF at the sternoclavicular joint, 3DOF at the glenohumeral joint). In addition, 1DOF at the elbow (flexion/extension) must also be included in order to make reaching movements, bringing the total to 6DOF. Collectively, these 6DOF should match the typical range of motion for the upper limb as summarized in Table 1 [5,11,12,13]. The remaining distal DOF could be added to or integrated into a future design, or these fine movements could be trained separately.

MEDARM should be fully adjustable to accommodate a wide range of users with limb segments of varying length, width and orientation. The vast majority of the adult population falls between the

Table1: Typical upper limb ranges of motion. (averaged from [5,11,12,13]).

Motion	Range (deg)
Sternoclavicular Joint	
Elevation/Depression	60
Protraction/Retraction	40
Glenohumeral Joint	
Flexion/Extension	160
Abduction/Adduction	150
Internal/External Rotation	120
Elbow Joint	
Flexion/Extension	140

range of 1.4m and 2.0m in height [14], so the mechanism's link lengths should be adjustable to fit this range of people.

There are a couple of important arguments for minimizing patient set-up time. First, any set-up time takes away from time a patient could be receiving therapy. Second, a long set-up time will be uncomfortable for the patient, and complicated for the therapist. The overall effectiveness of the robotic treatment will be reduced if these are ignored. Therefore, the attachment system should be quick and simple, while still maintaining adjustability for a range of people. Issues relating to patient comfort should also be considered. As much as possible, the robot should be unobtrusive. For example, placing the mechanism away from the user's head is more comfortable for the user, and will not interfere with movements.

Technical Design Objectives

The design of the mechanism itself also plays a critical role in the overall capabilities of the robot. The relative placement and orientation of the joint axes influences the robot's performance. More specifically, singular configurations must be avoided over the entire upper limb workspace to prevent the loss of one or more DOF. Furthermore, manipulability of the mechanism should be maximized over the workspace to reduce actuator requirements and improve the ability of the robot to move passively. Finally, the mechanism must not collide with itself or the user at any point in the workspace.

MEDARM should be able to drive a user's arm through a variety of functional movement patterns. Thus, as an upper limit, MEDARM's actuation system should be able generate enough torque at each joint to move the arm of a large user (up to 2.0m height and 115kg weight) with an end-point speed of up to 1m/s without any assistance from the user. At the same time, it is important that the system can be used passively as an assessment tool. In order for the robot to be powerful enough for therapy while achieving a high level of transparency for assessment purposes, the robot must be backdriveable with a high power-to-weight ratio and low friction. Making the mechanism as small and lightweight as possible without losing the structural rigidity required to provide movement assistance will also contribute to transparency.

PROTOTYPE DESIGN

Figure 1 shows a CAD drawing of the proposed MEDARM prototype. The exoskeleton itself is fixed to a structure, so a movable chair is used to bring the user into alignment with MEDARM. All electronics and motors are located behind the user, out of their way. There is plenty of room for the therapist to get beside the robot during patient setup.

There are 2DOF for shoulder girdle motion, and these joint axes intersect at the user's sternoclavicular joint. A curved track system for its second joint axis permits the robot to be located away from the user's head. An external motorized vertical cable system is used to assist with gravity compensation for the track system. The remaining 4DOF are actuated by a cable transmission that drives a spherical joint (centred at the user's glenohumeral joint) and a single rotary joint

Figure 1: A CAD drawing of a user with MEDARM. In addition to the MEDARM robot itself, the system consists of a support structure, an adjustable chair, and an external gravity compensation system.

(at the elbow). The cable drive system allows the heavy motors to be placed on the base of the system rather than on the mechanism itself. The system is therefore thin and lightweight. The cable routing scheme is optimized to provide the most efficient transmission of torque to the joints [15]. The relative orientations of the three joints that make up the spherical joint are optimized to ensure that singularity is not reached over the workspace, and that the mechanism's manipulability is maximized. The two most distal joints are parallel to allow the robot to be easily reduced to shoulder/elbow motion in any plane.

The user can be aligned with the system in a few simple steps. First, with the user sitting in the chair (away from the system), two arm cuffs are securely attached to the user's upper arm and forearm. The user is then wheeled into alignment with the robot and adjusted as needed. A linear adjustment on the curved track allows the exoskeleton's spherical joint to be aligned with the user's glenohumeral joint. Next, the arm cuffs are inserted into the mechanism and the elbow joint is adjusted and clamped in place. Finally, the arm cuffs are clamped. Only four clamps are required to secure the eight possible adjustments (not including the chair alignments).

CONCLUSIONS AND FUTURE WORK

The design proposed for MEDARM provides novel capabilities for upper limb rehabilitation and assessment. A major benefit of the design lies in its ability to replicate natural shoulder motion while maintaining a simple setup for a wide range of users. A simplified 3DOF planar version of MEDARM is currently being constructed to test the novel combination of curved track and cable transmission. Once the performance is confirmed, construction of MEDARM will begin. With a fully functioning prototype, training algorithms will be developed.

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