Exoskeleton for Forearm Pronation and Supination Rehabilitation

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Abstract— **Loss of function after SCI, ABI or stroke has a marked affect on ones quality of life. Return of function has been a long-standing goal of physical and occupational therapy. Repeated motor practice has been identified as crucial for motor recovery. The development of a robotic device for neuromotor rehabilitation and upper extremity neuromuscular system recovery is described. The actuator mechanism allows free motion when possible, and provides programmable therapeutic levels of resistance. The sensor system allows characterization of the applied forces, and accurate measurement of the range of motion of the joint. The control system provides real time feedback of actuator commands based on sensor data, calibration routines, and operational modes.**

Keywords—**Rehabilitation Robotics, Exoskeleton**

I. Introduction

This paper describes a robotic system to support upper extremity rehabilitation in individuals who sustain neurological impairments such as cervical level spinal cord injuries (SCI), acquired brain injuries (ABIs) or stroke. This robotic assistive rehabilitation device would be used to provide repeated motor practice in an effort to promote neurological recovery and improve functional use of the upper extremity. The technical goal is development of a computer-controlled, interactive powered orthosis capable of training upper extremity movements in rehabilitation patients. A second goal is to develop training programs optimized to produce representative movement patterns involved in activities of daily living (ADLs). Control options will include multiple training protocols such as active, active-assistive and resistive modes.

Loss of function after SCI, ABI or stroke has a marked affect on ones quality of life. Return of function has been a long-standing goal of physical and occupational therapy. Recent technological advancements have spurred research into the recovery of functional movement of the upper and lower extremities. These efforts are justified not only for humane reasons but also based on fiscal responsibility, especially in light of the current economics of healthcare delivery. Given the greatly reduced lengths of inpatient stay, a need exists for robotic training devices that are clinically friendly and affordable for both rehabilitation hospital and home use.

Repeated motor practice has been identified as crucial for motor recovery [1]. This theme has stimulated several groups to develop robotic applications for neuromotor rehabilitation for upper extremity recovery. Multiple rehabilitation robotic devices have been directed at providing an individual with a robot to perform tasks under direct or indirect control [2]. A number of researchers have described the use of commercially available robots for rehabilitation applications, including the RT100 and PUMA-560 robot arms [3]. One limitation of commercial robots is their weight, size, and requirement of high torque motors near the base to move the entire robot arm. This limitation has led to the development of rehabilitation-specific manipulators.

Several researchers have described robotic devices used exclusively for training and neurorehabilitation. Reference [4] described a device to study "abstract elbow extension-flexion exercise." The user's elbow joint is placed in a servomechanism and an algorithm controls assistance with movement of the patient's elbow joint. A successful rehabilitation robotics device is the MIT-MANUS, a novel low-impedance robot for use in clinical applications [5]. A desirable feature of the MIT-MANUS is achieved using impedance control in the feedback control system. The control system provides a gentle compliant reaction to external perturbations from the patient or clinician. User-worn powered orthoses have also been developed and used with some success in patients with muscular dystrophy, spinal muscular atrophy and normal healthy adults.

II. Methodology

The figure below illustrates the mechanical design of the actuator. The actuator is driven by cables, which minimize the weight of the actuation mechanism on the patient. The forearm rotation mechanism attaches to the forearm through an orthosis. The orthosis is designed for a comfortable fit around the users arm, and provides attachment means to the mechanism. To allow for functional motion the assembly is designed to allow free motion of the elbow joint and the wrist joint. The actuator performs the same motion as the action of the biceps and the supinator during supination, and the action of the pronator quadratus and the pronator teres during pronation.

Power for the drive mechanism is in a portable base unit which includes series elastic actuators driven by an electric motor. The base unit includes load cells to measure the force on the cables. A set of angle sensors, one on the drive mechanism and a second on the forearm actuator are used to provide position feedback to the control system. A unique feature of the control system is the incorporation of series elastic elements in the drive. The elastic actuators have the advantage that even for abrupt torque inputs from the user, the system is naturally mechanically compliant. The spring constants of the elastic actuators are chosen based on the maximum forces required for rehabilitation. The series elastic actuator is based on the work of [6], and has the advantage of good force control, high force fidelity and minimum impedance.

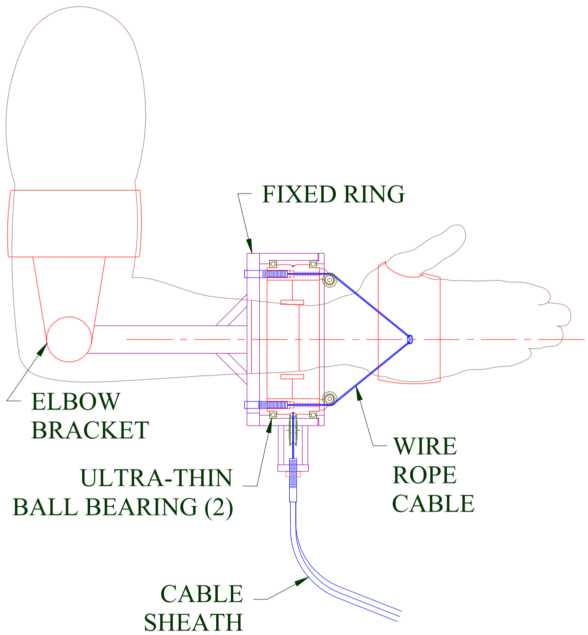

Figure 1 Forearm Rehabilitation Actuation Mechanism

The motion controller design goal was to develop fully programmable mechanical impedance-based on the combined equations of motion of the arm and the robot mechanical structure. The impedance control concept [7] is to present the user with force feedback representing a second order dynamic system. A simplified general equation describing the dynamic behavior of the forearm axis is:

$$\tau_{external} = I\ddot{\theta} + B\dot{\theta} + K(\theta - \theta_0) \qquad (1)$$

Where θ is the rotation angle of the forearm, τ the torque applied externally to the simulated impedance, K, a stiffness component, B, a linear damping component, and I, a moment of inertia. The controller was designed so that these parameters can be defined within a useful range appropriate for the intended therapy. The parameters θ_o, M, B, and K are specified in the motion control computer system and are scripted depending on the operational mode.

The impedance control algorithm is implemented as a sampled data system in the motion control processor. The parameters describing the desired dynamic behavior are passed to the motion control processor from the user computer. The motion control processor samples position and force data, calculates an actuation force, and then provides an actuation command to the motor drive. Sensor inputs to the control system are the angle of rotation of the forearm, and the torque applied to the pronation/supination axis.

Figure 2 shows one of the control loops implemented in the motion control processor. The control loop is configured to provide apparent impedance described by:

$$\tau = Bs(\theta - \theta_0) + K(\theta - \theta_0) \qquad (2)$$

The control loop is configured to match the desired dynamic response by feeding back the measured torque and driving the forearm rotation angle. This method is similar to the method described in [8] where pneumatic actuators were used for arm movement. The measured torque is calculated based on inputs from the sensors. In the case shown in the block diagram the sensors are two load cells in series with the cables. The torque is calculated based on the difference between the measured forces in the clockwise and counterclockwise load cells and the known radius of the inner ring of the actuator. The measured torque is passed through a filter modeling the desired dynamic impedance. The output of the filter is the desired angle corresponding to the desired dynamic impedance. A position loop is closed around the forearm angle of rotation to match the actual rotation angle with the desired angle.

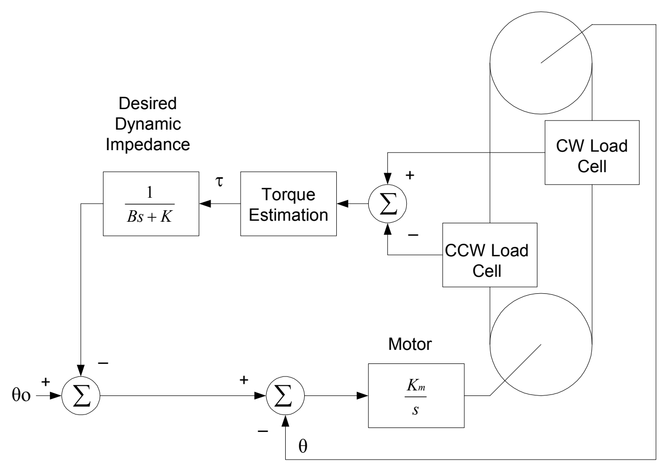

Figure 2 Impedance Control System

In operation a time sequence script from the user interface process defining the dynamics of the desired motion is passed to the real time loop. Based on the parameters in the script the actuator angle is adjusted in a closed loop fashion with feedback from the position and force sensors. The sensor data is digitized at a fixed sample rate of 1 kHz. The 1 kHz sample rate is set by a counter timer on the multifunction data acquisition card. After 32 samples are acquired the motion control equations are updated. The results of the motion control algorithm are written to a d/a converter to drive the actuator. Data are also displayed in real time on the computer screen and can be written to a file for offline analysis.

A critical element to the utility of the proposed robotic therapy is an accurate means to sense the torques applied to the joints. Evolution has not equipped the human body with a machined force plate to attach torque and load sensors. Instead there is skin, fatty tissue and muscle. The hands of a trained therapist can subjectively sense the amount of torque to apply to a joint. Several redundant sensors are used to gauge the force applied by the robot.

The first sensor is a set of load cells in line with the cables to the actuator. These cells are used to measure the force applied through the cables to the patient. The measured force also includes the weight of the arm and the exoskeleton. Use of the sensors in line with the cables can lead to measurement errors when the weight and the orientation of the actuation components creates force components larger than the actual force applied to the user. A redundant measurement of the applied force relies on the angle difference between the drive shaft and the forearm rotation angle measurement. Knowledge of the spring constant of the series elastic actuator allows calculation of the applied torque through the cable linkage. Large differences in the two measurements can be used to flag sensor faults, and disable drive to the actuator.

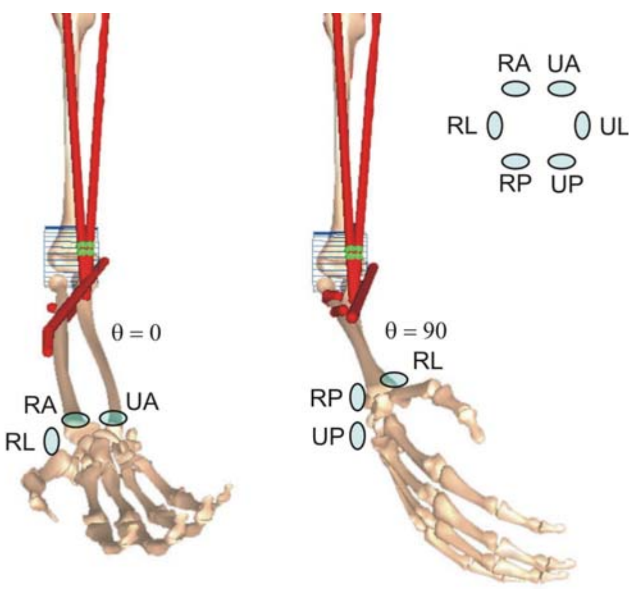

Figure 3 Contact Force Sensors

A second approach to torque measurement is based on pneumatic bladders installed in the orthosis. Six discrete pressure sensing bladders are arranged to sense the forces applied around the distal end of the ulna and the radius. One each on the posterior, lateral and anterior sides of the ulna UP, UL, UA, and one each on the posterior, lateral and anterior sides of the radius RP, RL, RA [9]. The concept is that these sensors can be used by the control system in much the same way as a trained therapist senses applied force. The pneumatic pressure sensors have the advantage that they are in very close proximity to the contact points between the robot and the user, and are compliant to motion of both the forearm and the actuator, and allow for variation in the center of rotation of the forearm at different rotation angles.

III. Results

The control system has been implemented on a laptop PC running Windows XP. A multifunction data acquisition card is used to acquire the sensor data and provide drive commands back to the motor. The control equations have been implemented in C++.

There are many control modes for the restoration of function with repetitive therapy that can be implemented with the apparatus. The following control modes have been implemented in the motion control processor.

Isometric Mode: In this mode the robot arm senses a torque from the patient. The parameter θ_o in the impedance control algorithm is set to a fixed value. In one implementation K is gradually ramped up to a high value to provide stiff resistance to movement at the fixed location. The patient is then asked to apply a constant torque to try and move the mechanism. The resulting torque is measured, stored, and plotted. This mode may also be used to measure muscle strength at fixed positions, and muscle fatigue.

Active Resistance Mode: This mode provides active resistance to motion. This mode is implemented in the controller by setting the damping coefficient B to a constant value. The action of the controller is to resist changes in position by providing a torque feedback which is proportional to the rate of change of angle. The value of the damping coefficient may be stepped as a function of angle to apply a dynamic resistance that varies as a function of angle. The resistance can be increased for eccentric motion to increase strength.

IV. Conclusion

This paper describes the development of a robotic device with the potential to greatly aid neuro-motor rehabilitation. The system is scheduled for evaluation involving clinicians and potential users at the Shepherd Center, in Atlanta GA, one of the leading rehabilitation hospitals in the United States. Future work with the system is expected to include optimization of the control modes and dynamic impedance parameters in a clinical rehabilitation environment.

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REFERENCES

[1] Hummelsheim, H. Rationales for improving motor function. *Current opinion in Neurology*. 12:697-701, 1999.

[2] Harwin, W.S., Rahman, T., & Foulds, R.A. "A review of Design Issues in Rehabilitation Robotics with Reference to North American Research" *IEEE Transactions on Rehabilitation Engineering*, March 1995.

[3] Ezenwa, B.N., Bismar, H., Bator, C. "Development of a Robot-based Work Station for OT Upper Extremity Coordination Therapy" Engineering in Medicine and Biology Society, 1993. *Proceedings of the 15th Annual International Conference of the IEEE*, 1993.

[4] Cozens, J.A., "Robotic assistance of an active upper limb exercise in neurologically impaired patients" , *IEEE Transactions on Rehabilitation Engineering,* June 1999.

[5] Krebs, H.I., Volpe, B.T., Aisen, M.L., Hogan, N. "Increasing productivity and quality of care: Robot-aided neuro-rehabilitation", *Journal of Rehabilitation Research and Development* November/December 2000.

[6] Robinson, D.W., Pratt J.E., Paluska, D.J., Pratt G.A. "Series Elastic Actuator for a Biomimetic Walking Robot" *IEEE/ASME Int'l Conference on Advanced Intellegent Mechatronics*, September 1999.

[7] Hogan, N, "Stable Execution of Contact Tasks Using Impedance Control", *Robotics and Automation. Proceedings. 1987 IEEE International Conference on* , Volume: 4 , Mar 1987.

[8] Noritsugu,T., Tanaka, T. Yamanaka, T, "Application of a Rubber Artificial Muscle Manipulator as a Rehabilitation Robot", *1996 IEEE International Workshop on Robot and Human Communication. Pg 112-117.*

[9] Forearm graphic image captured using Musculographics Software for Interactive Musculoskeletal Modeling software package, Motion Analysis Corporation Santa Rosa CA.