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Exoskeleton with EMG Based Active Assistance for Rehabilitation

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Abstract—**The development of a prototype robotic system to facilitate upper extremity (UE) rehabilitation in individuals who sustain neurological impairments such as cervical level spinal cord injuries (SCI), acquired brain injuries (ABIs) or stroke (CVA) is described. A control system based on Electromyography (EMG) signals has been implemented to provide the appropriate amount of assistance or resistance necessary to progress a patient's movement recovery. Use of EMG signals has potential advantages over systems based only on torque and position sensors. The prototype system includes programmable mechanical impedance, adjustable thresholds and control gains. This robotic rehabilitation device would be used to provide repeated motor practice in an effort to promote neurological recovery and improve functional use of the UE.**

Keywords—**Rehabilitation Robotics, Exoskeleton**

I. INTRODUCTION

Engineering approaches are being developed to assist in improving upper extremity (UE) function in individuals who sustain neurological impairments secondary to spinal cord injuries (SCI), acquired brain injuries (ABI) or cerebral vascular accidents (CVA). While many devices will substitute for non-functioning or poorly functioning limbs, or will provide passive movement of paralyzed or inactive limbs, limited effort has been directed to optimizing and facilitating functional recovery in individuals with the potential for improving function. Examples of individuals with the potential for functional recovery include those with weak muscles, or poor sensory input,or those who are unable to perform movements independently, or who fatigue easily after a few repetitions. The overall purpose of the described work is to develop an innovative computer-controlled powered orthotic device. The device will utilize online information regarding muscle force output, UE joint angles, and Electromyography (EMG) feedback signals to make "smart" decisions about how to progress a patient in motor practice. This will provide repeated motor practice for individuals unable to perform these movements enough independently and/or repeatedly, which should facilitate a change in the neuro-motor system and improve strength or control. This goal is motivated by two key findings in the literature. The first is that clinical research in humans with movement disorders secondary to CVA, in particular have demonstrated the ability to improve strength and functional use of the UE with repeated motor practice [1-3]. A device such as the one described here, that augments traditional therapy and provides for increased and concentrated movement practice, may assist therapists in achieving greater functional levels at a time when lengths of stay continue to decrease.

The second piece of evidence is provided primarily by literature related to what type of activity is required to strengthen muscles. Passive movement may be useful when an individual is not able to generate force in a muscle to cause movement of the limb. Passive movement alone, however, will not restore strength to the same degree as performing active or resisted movement when the ability to contract the muscle is actually present. Often an individual with weak muscles is unable to perform active movement throughout the entire range of motion, or is unable to initiate a movement but may be strong enough at varying points in the range of motion to actively perform the motion. Simply providing passive motion in these cases will miss the potential that exists in the individual, whereas providing assistance to intiate the movement but allowing for the individual to perform that motion when able, may provide for improvement in movement control and strength. A robotic device that can sense the amount of ability the individual has, or the force one can generate in the muscle, will be "smart" enough to determine the amount of assistance or resistance the machine should provide to facilitate the greatest functional change in muscle strength or coordination. Development of robotic devices that interact with patients for rehabilitative purposes is limited, however, by the ability of the machine to sense volitional movement and either assist or resist the motion.

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. Another successful rehabilitation robotic device is the MIT-MANUS, a 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.

The use of EMG signals as a control input to rehabilitation systems is being developed at many centers toward several goals. Reference [6] describes an EMG controlled orthotic exoskeleton for the hand. The goal of this research was not meant to be a rehabilitation system to promote motor recovery, but rather an assistive device to provide pinching movements to patients with reduced muscle strength. The system features cables and springs as the mechanical devices closest to the human fingers, and employed several EMG control strategies to allow fine control of finger motion. The EMG of the biceps was used as a surrogate for the missing finger flexion and extension EMG signals. Reference [7] describes the use of EMG to provide variable amounts of assistance for a 1 degree of freedom (DOF) elbow joint. This UE exoskeleton is based on the existing patient's muscles, where the amount of assistance can be adjusted from minimal assistance through high resistance based on the patient's capabilities. Finally a myosignal based exoskeleton for force amplification has been described in Reference [8]. Their work discusses that in an exoskeleton driven by EMG signals, the human and the machine are directly linked and the kinematics and dynamics of the neuromuscular control system and the exoskeleton share the same constraints. The research was concentrated on the use of EMG signals as control signals for force amplification in able bodied humans. The exoskeleton described in this paper provides an opportunity to capitalize on the information available from EMG to drive the robotic device. The advantage of the EMG is that it can isolate the muscles needed to move the device without the interactions of adjoining muscles. It can also detect the extent of active participation of the patient, and use this information to either decrease or increase assistance and resistance as is appropriate to progress the patient.

II. METHODOLOGY

To determine the feasibility of EMG active assistance, an exoskeleton driven by EMG signals combined with an impedance control algorithm has been fabricated. Figure 1 shows a mechanical diagram of the actuation mechanism.

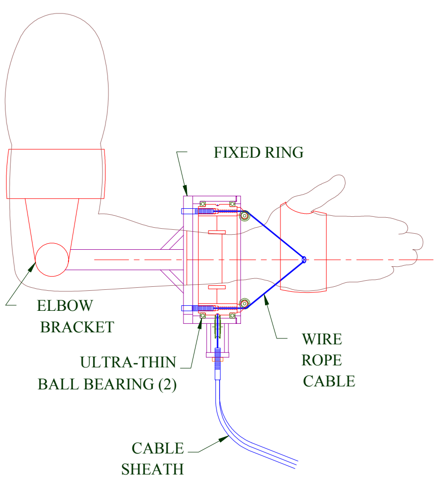

Figure 1 Forearm Rehabilitation Actuation Mechanism

An actuator is driven by cables, which were selected to minimize the weight of the actuation mechanism on the patient. The forearm rotation mechanism attaches to the forearm through an orthosis. The actuator is designed to provide the same torques as 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 an electric motor and 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 programmable dynamic impedance as originally described in [9]. The resulting elastic actuation has the advantage that even for abrupt torque inputs from the user, the system is naturally mechanically compliant.

Additionally two EMG recording sites are chosen to collect data. One set of electrodes can be placed over the pronator teres to obtain pronation commands and the second set can be placed over the biceps or supinator to obtain supination commands which will be used to alter the position.

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 is to present the user with force feedback representing a first order dynamic system. Figure 2 shows the dynamic impedance control loop which is configured to provide apparent impedance described by:

$$\tau = Bs(\theta - \theta_0) + K(\theta - \theta_0) \qquad (1)$$

Where θ is the rotation angle of the forearm, τ the torque applied externally to the simulated impedance, B the linear damping component, and θ_o represents the natural angle of rotation of the mechanism with no applied torques. During the start of a repetition θ_o is set to an initial value and then is adjusted based on the EMG activity and B and K are defined depending on the desired motion. In operation, the processor samples position and force data, calculates an actuation force, compares the EMG data obtained to a predefined threshold, and then provides an actuation command to the motor drive.

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 [10] where pneumatic actuators were used for arm movement. The measured torque is calculated based on inputs from 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 programmed dynamic impedance. The output of the filter is the rotation angle corresponding to the programmed dynamic impedance. A position loop is closed around the forearm angle of rotation to match the forearm rotation angle with the rotation angle corresponding to the dynamic impedance. Additional details of the implementation of this control system are described in [11].

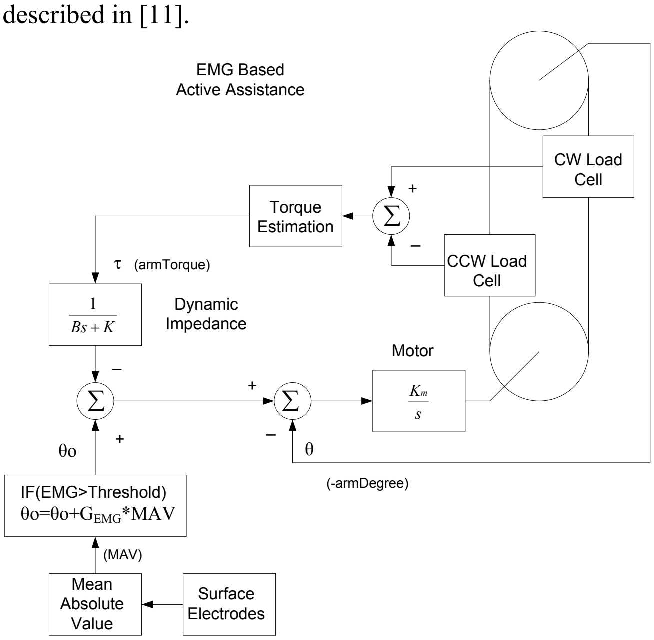

Figure 2 Impedance Control System

This 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++.

The EMG signal is sampled at a 1 kHz rate and the mean absolute value (MAV) of the signal is calculated as described in [7]. The MAV is evaluated every 30 ms interval to synchronize the MAV results with the dynamic impedance control calculations. The impedance control calculations are updated every 30 ms and are used to provide drive signals to the motor.

The parameter θ_o in the impedance control algorithm is set to a value that is a function of the patient's EMG activity. For active assistance in one direction, the value of θ_o is set to an initial value near one limit of the patient's range of motion. The value is then incremented by an amount proportional to the EMG activity when the EMG activity exceeds a fixed threshold. The threshold level and the proportionality constant G_{EMG} can be programmed based upon the patient's ability.

III. RESULTS and DISCUSSION

The EMG active assistance mode is demonstrated in Figure 3 where the commanded rotation angle is based on the EMG input signal. This mode can be used for repetitive training. After a successful completion of a range of motion movement in one direction, and after a programmable pause interval, the forearm is rotated back to the starting position, and the routine is repeated. When the forearm is rotated back, a low spring constant is set using the dynamic impedance to provide a gentle nudge to the forearm in the desired direction. The advantage of this is the initiation and completion of each repetition is under the control of the patient, rather than a preprogrammed scripted motion.

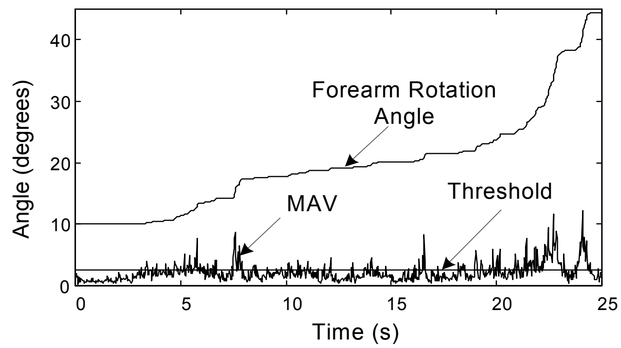

Figure 3 EMG Based Active Assistance

To provide motion in both directions, two EMG recording sites were chosen, one which has predominately pronation commands and a second which has predominately supination commands. For bi-directional operation the EMG algorithm is modified slightly. In the case where the pronation EMG signal strength is greater than a threshold the commanded angle is adjusted in the pronation direction. In the case where the supination signal exceeds a threshold, the commanded angle is adjusted in the supination direction. Figure 4 is an example recording using two EMG signals, one on the pronator teres and a second on the bicep. For this plot, the user started at a position of neutral rotation, where the palm faced medially and the thumb points superiorly, and then moved back and forth through a 60 degree range of motion. The commanded angle was limited in software to clip at +30 degrees and – 30 degrees.

Because the pronator teres is deeper in the tissue and a smaller muscle than the biceps, the MAV of the EMG activation command for pronation is smaller than for supination. To enable bidirectional control two thresholds and two scale factors were employed, one for each angle of rotation. Having two values allow independent adjustment of the control authority that each muscle has over the movement.

One of the difficulties encountered is that the surface EMG signal associated with pronation can be masked by surface EMG activity from finger flexion and wrist flexion. This is because the pronator teres is adjacent to the flexor carpi radialis, and the brachio radialis muscles. A method to eliminate movement associated with these signals would be to place multiple sensors on the forearm and to use signal classification methods to only respond to the pronator teres activation signals. Another way to manage this would be to utilize electrodes inserted into the related muscles. This, however, is less comfortable, and may not be the best tool if the desire is to use this device routinely in the clinic and at home.

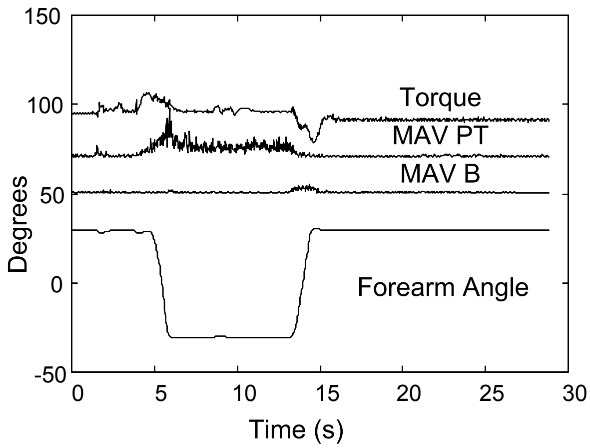

Figure 4 Bi-Directional Active Assistance

There may be cases where using nearby muscles may have a rehabilitation effect on the targeted muscles. The fact that there is volitional movement combined with proprioceptive feedback may encourage redevelopment of neuromuscular connections in the pattern generators of the spinal cord.

Further development of this device will include applying the same concepts for development of flexion/extension of the elbow, and combinations of flexion/extension and supination/rotation, to mimic and retrain functional upper extremity movements, as well as development of velocity dependent movements. Furthermore, individuals with neurological dysfunction often have other movement related impairments such as spasticity and sensory deficits. The application of this robotic device should be evaluated in terms of these impairments.

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. 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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