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Design of a Robotic Upper Extremity Repetitive Therapy Device

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Abstract— **Intensive repetitive therapy shows promise to improve motor function and quality of life for stroke patients. Intense therapies provided by individualized interaction between the patient and rehabilitation specialist to overcome upper extremity impairment are beneficial, however, they are expensive and difficult to evaluate quantitatively and objectively. The development of a pneumatic muscle (PM) driven therapeutic device, the RUPERT™, has the potential of providing a low cost and safe take-home method of supplementing therapy in addition to in the clinic treatment. The device can also provide real-time, objective assessment of functional improvement from the therapy.**

Keywords— **Repetitive therapy, pneumatic muscle, rehabilitation robot, stroke**

I. Introduction

Recent research has shown that the brain has more capability to recover function after injury than once believed. Maps from brain imaging show that motor cortical representation shrinks with inactivity following lesions and may expand with subsequent activity [1-6]. These findings form the basis for new therapeutic treatment of patients with stroke and traumatic brain injury: repetitive motor function activities. However, traditional approach and technique for neurological rehabilitation are very labor intensive and lack of consistency and objective assessment. Three to four percent of the national health budget involves personalized physical therapy [7]. There has been a continuous effort by engineers to develop a robotic system that can assist and improve the rehabilitation of patients with neuromuscular disability. The use of robotic devices to assist in these therapies is reviewed in [8]. These robotic systems tend to be expensive and are often developed for research purpose, so too complex for practical use. There is a need for affordable, practical and multi-dimensional devices to assist therapy. The device described in this paper is designed to provide active-assisted repetitive therapy to the motor functions of the upper extremity. Many important activities of daily living, such as grooming, dressing and eating depend on two-handed function [9]. The device will assist the patient to practice such coordinated bi-manual activities during therapy sessions at clinic or at home to take full advantage of the repetitive therapy.

II. Design

The design goals were to develop an upper extremity therapeutic device that provides training of reaching and feeding motions. The device is to be compact for portability, relatively easy to use for self don and doff, capable of interacting with a personal computer based visual feedback system to capture the interest of the user, provides measurement of functional performance and has the potential to be inexpensive and amenable for home use.

The technology of the existing Hand Mentor™ air-muscle driven wrist/hand device [10] is being used to incorporate coordinated elbow and shoulder motions for the device. Rehabilitation of the affected upper extremity thus is oriented toward restoring the normal sensorimotor relationships between the joints for actually performing activities of daily living [11]. The design is given the acronym RUPERT for Robotic UPper Extremity Repetitive Therapy device.

Traditional robots are usually stiff. The use of robotic

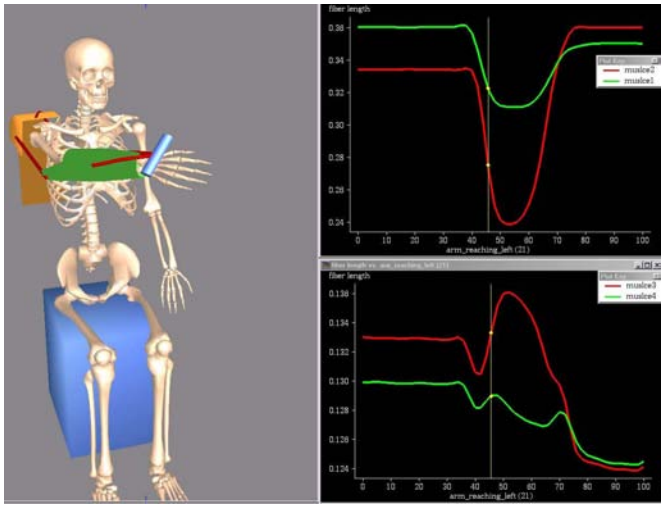

Figure 1. The length changes of 4 PMs during simulated reaching and self-feeding activities.

actuation in exoskeleton applications presents a mismatch in compliance of the actuator and the limb being moved. Impedance control of actuators has had success in addressing this problem [12, 13]. The "McKibben" type pneumatic actuators used in RUPERT provide compliant actuation and thus reduce the complexity of the control system compared to stiffer drives. These pneumatic atuators have a venerable history of use in rehabilitation devices[14-17].We used the modeling and simulation to guide the design and selection of parameters for the pneumatic muscles (PM).

A. Modeling

A kinematics model of the upper extremity was developed using SIMM (Software for Interactive Musculoskeletal Modeling). The model was used to study the effect of insertion/origin locations of the pneumatic muscles on the range of assisted joint ranges of motion and desired limb trajectories [18]. Based on the anthropomorphic data of an average man, the required lengths of PM to generate the desired range of motion are 0.37 m, 0.14 m and 0.3 m, for shoulder and elbow, wrist and pronation, respectively.

A kinetic model of the integrated human arm with the exoskeleton robot was also developed to calculate the forces required for PM to assist the desired reaching and self feeding tasks under different residual muscle forces or spastic forces in the system of a patient arm [18]. The resistance of soft tissues and possible muscle spasticity must be considered when determining the joint torques required to overcome gravity as determined by the model. To minimize possibility of eliciting spasm when assisting arm movement, the air flow to the PM is restricted by the joint rotation speed of 2.5 to 5.0 °/sec. (depending on load). Based on the dynamic simulation using various assumptions on residual muscle and spastic forces we have determined to set the torque to be 5 Nm for the hand and elbow and 8 Nm for the shoulder at 210 KPa. To increase efficiency, shoulder and elbow air muscles were attached to cables that lay on cams. This increased the moment arm during extension. If clinical testing indicates stronger torque is required, larger diameter air muscles or higher pressures can easily be incorporated.

The simulation results of the two models assisted the initial design and adjustment of the RUPERT. The models are also modified according to the design and modification of the device and will continue to serve as a guide for the new generation of RUPERT. Further use of the model is to assist the evaluation of recovery in voluntary control by estimating the muscle torques.

B. Structure

The first working mockup verified that four pneumatic muscles could achieve the desired joint ranges of motion as well as the trajectories for reaching and self feeding tasks. Based on the experience with the mockup, Version I was fabricated as shown in Fig. 2. RUPERT I includes four air muscles (shoulder, elbow, pronation, wrist/fingers). The structure of this first prototype restricts shoulder elevation to one plane (15º lateral) and limits the elevation to 45º. The support structure has a pad that stabilizes the scapula.

The center of rotation and the length for each segment are both adjustable to accommodate the variable arm lengths and builds of the total patient population. The design goal is to accommodate the total population without having to supply multiple sizes of the device. The design is more complex with this specification: multiple adjustable components will add additional weight and demand higher mechanical strength.

Figure 2. RUPERT I. It is powered by four pneumatic muscles, has five degrees of freedom (2 at shoulder, 2 at elbow and 1 at wrist). Shown here is the version for the right arm. Lengths of both upper and lower arm segments can be adjusted to fit the size of a patient. It is easy to put on and take off.

The hand piece has the extension mechanism only on one side of the hand and each individual fingertip is supported rather than the total dorsal surface of the phalanges. This was done to make grasping objects easier. Position sensors are included in the shoulder, elbow axis and wrist axis. Together with the pressure sensors the information will be used for future design of feedback control and estimation of voluntary muscles torques from the patient in evaluation of recovery and improvement of motor function.

Based on fitting evaluations from a range of statures of able-bodied and stroke survivor volunteers and device testing of Version I at Banner Good Samaritan Regional Medical Center, Version II is being developed.

C. Modified Pneumatic Muscle

McKibben pneumatic muscles mimic human muscles by only producing a pulling force when pressurized. To control joint motion in both flexion and extension around a joint, at least two actuators are required. Springs have been incorporated into a pneumatic muscle so that the system can provide both extension and contraction. The first models had the spring over the pneumatic tube, newer models incorporate springs inside the pneumatic tube (Fig. 3).

Figure 3. Pneumatic muscles with a spring inside to provide pushing force. The spring parameters are adjustable by changing the resting length.

These muscles have been mechanically characterized and will be functionally evaluated in RUPERT II [19].

III. Results

Eight able-bodied volunteers tried on RUPERT I. Each subject's limb segment and torso lengths and the associated position of RUPERT's adjustment settings were recorded. A wide range of statures was included in the volunteers; from 5 foot tall females to males over 6 feet. Two stroke survivors tried on Version I and were able to move their limbs in the desired directions. Two stroke survivors have completed 3 week therapy protocols using RUPERT I at Banner Good Samaritan Medical Center. The purpose of these tests is to evaluate the ability of the prototype to function in a clinical environment and not focus on patient results. The evaluation by the therapists and patients has been very positive for the general design and construction. Valuable suggestions are also provided on modification and redesign. The plan for product development is to include at least two more prototypes.

IV. SAFETY

The risk to patients is minimized in this design by utilizing compliant pneumatic actuators. The first clinical evaluations were done open loop. The patient is instructed to move an individual joint, reach for an object or bring an object to their mouth. Upon completion of the self actuated motion, the air muscles are activated in a sequence to obtain the specific task being tried at that time. The device physically limits range of motion of individual joints. Force application is limited by the compliant nature of the actuators. The ASU IRB approved laboratory testing on patients and the Banner IRB approved clinic testing.

IV. Discussion and Conclusions

Stroke is the leading cause of adult disability in the United States. Many research studies, both animal and human, have shown that continued recovery of functional skills in stroke patients occurs with forced use therapy protocols, i.e., imposed use of limbs on the affected side. The functional improvement takes a long time to come back in most patients, making the rehabilitation a long and expensive therapy process. However, to control the cost, health insurers often limit or deny rehabilitation to stroke survivors claiming patients plateau several months post stroke [20]. Robotic devices that provide treatment capability in the home and clinic are a way to provide cost effective therapy to a wider population for a longer period of time. That is the purpose of the pneumatic muscle driven RUPERT device. The utility of the air muscle drive resides in its unique combination of attributes: low stiffness, low cost, lightweight, low profile, and low noise operation. There are also drawbacks for control: slow response time to force generation, lower precision than torque motor in force and position modulation, high dependence of position and movement on external load or resistance. We are working on control algorithms that will take advantage of the muscle-like properties of the PM drives for its intrinsic compliance for safety and also make the robot responsive to the demand of the repetitive therapy. A major challenge of the new control algorithm is how to make the robot respond to the intention of movement initiated by the patient, instead of robot driving the patient's arm.

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