Cooperation of electrically stimulated muscle and pneumatic muscle to realize RUPERT bi-directional motion for grasping

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Abstract—**Robot-assisted rehabilitation is an active area of research to meet the demand of repetitive therapy in stroke rehabilitation. Robotic upper-extremity repetitive trainer (RUPERT) with its unidirectional pneumatic muscle actuation (PMA) can be used by most stroke patients that have difficulty moving in one direction because of a weak agonist or hyperactive antagonist. In this research, to broaden the usage of RUPERT, we not only add grasping functionality to the rehabilitation robot with the help of surface Functional Electrical Stimulation (FES) but also realize the robot joint bi-directional motion by using a PMA in cooperation with surface FES evoked paralyzed muscle force. This integrative rehabilitation strategy is explored for training patients to practice coordinated reaching and grasping functions. The effectiveness of this FES electrically evoked bio-actuator way is verified through a method that separates the mixed electromyogram (MEMG) into the electrically evoked electromyogram (EEMG) and voluntary electromyogram (VEMG). This is a promising approach to alleviate the size and mechanical complexity of the robot, thereby the cost of the joint bi-directional actuator rehabilitation robot by means of their own characteristics of stroke subjects.**

I. INTRODUCTION

Nowadays the prevalence rate of stroke in China is increasing rapidly. Stroke survivors with various degrees of motor dysfunction not only endure inconvenience of the daily lives but also feel great psychological pressure, in addition to economical burden on the family and society. Many types of rehabilitation robots have been developed to assist rehabilitation in individuals with stroke. The MIT-MANUS is a well-known upper limb rehabilitation robot that is reported to help users to realize reaching tasks and practice supported movements of the shoulder and elbow joints[1-2]. The development of Bi-Manu-Track is to realize wrist and elbow training including wrist flexion and extension, and bilateral elbow pronation and supination [3]. The MIME robot with a 6-DoF arm can realize the bilateral practice of a 3-DoF upper arm while the paretic arm follows the non-paretic arm [4-5]. A DC servomotor actuated 4-DoF rehabilitation robot ARM is a trombone-like device, which can assist a user to guide arm reaching movements in the horizontal plane [6].

J. He, et al. have built the wearable exoskeleton device RUPERT for stroke patients with right-hand-side hemiplegia in collaboration with Kinetic Muscles Inc. (Tempe, AZ) since 2005 [7-10]. The current version of the robot (RUPERT IV) has five unidirectional DoFs: shoulder flexion, the humeral external rotation, elbow extension, forearm supination, and wrist extension. RUEPRT has two unique features that distinguish it from the other therapy robots currently available for the upper-extremity. The first and most important feature of RUPERT is that it is a wearable exoskeleton robot that allows a greater degree of mobility to the patient. The second unique feature of RUPERT is its unidirectional actuation. Most stroke patients have difficulty moving in one direction because of a weak agonist or hyperactive antagonist. Each DoF of RUPERT is actuated by a single PMA, thus resulting in unidirectional actuation in different DoFs, which encourages patients to do voluntary rehabilitation training without any resistance force. The actuation in the other direction is achieved either through gravitational pull on different segments of the robot or through the patient's existing motor control. This under-actuated design might not be a good approach for subjects with very weak muscle control, especially in a situation that it needs stable posture for assisting patients to reach and grasp a real 3D object in reaching range. In order to broaden the usage of RUPERT, we explore an integrative rehabilitation strategy for training patients to practice coordinated reaching and grasping functions. Biceps muscle stimulated through a pair of surface stimulation electrodes can assist RUPERT elbow joint to realize the elbow flexion against PMA direction. Pectoralis major muscle is stimulated through a pair of surface electrodes for humeral internal rotation. The shoulder joint bi-directional motion is realized by use of PMA against its own gravity. Fingers extensor digitorum muscles and flexor digitorum muscles are individually stimulated for hand releasing and power grasping, respectively.

Recently, K. L. Meadmore, et al. [11] have developed an upper limb stroke rehabilitation system consisting of electrical stimulation, commercial exoskeleton robot and virtual reality to assist stroke patients in performing virtual 3D objects reaching and grasping tasks. The commercial robot is a purely passive 'un-weighing' system which supports the patient's arm against gravity via two springs. This rehabilitation system cannot provide the function of assisting stroke patients in performing a specified real 3D object reaching and grasping tasks.

In this paper, so as to make clear this integrative rehabilitation strategy — cooperation of FES electrically evoked muscle force and PMA to realize RUPERT under-actuated joint bi-directional motion, we mainly report a preliminary investigation on RUPERT elbow joint with FES for simplicity. In Section II, 3D coordinates of both specified grasping object and shoulder joint are obtained by use of

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Microsoft Kinect color cameral and depth cameral first, followed by exploring basic guidelines of integrating FES into the robot elbow joint to achieve under-actuated joint bi-directional motion, and the effectiveness of this strategy is verified through a method that separates MEMG into the EEMG and VEMG in consideration of healthy subjects participating in this experiment. Section III reports the experimental results. Conclusion and future work are shown in section IV.

II. METHODS

Three healthy subjects participated in the experiment with a written informed consent as approved by the Institutional Review Board at Huazhong University of Science and Technology. The volunteers were instructed to relax as much as possible and to allow the stimulation to control the related motion. They were fully informed of the objective, the procedures of the experiment and any potential risks that could occur during the experiment.

This proposed rehabilitation system consisted of RUPERT, FES stimulator Rehastim2 (Hasomed GmbH, Germany) , Kinetisense for EMG recording and Microsoft Kinect for Windows shown in Figure 1. We removed RUPERT wrist extension joint and forearm supination joint considering this two parts occupying hand grasping space while we took the rest as this new proposed rehabilitation system reaching part. For simplicity, RUPERT humeral rotation was fixed at internal rotation 30 degrees. PMA actuated shoulder flexion against gravity.

A. Get 3D coordinates of both specified grasping object and shoulder joint

A real-time three-dimensional (3-D) object tracking based on integration of 3-D range and color information was taken to get the yellow ball 3D coordinate. 3-D range and color information were integrated using the estimated depth and color cameras intrinsic parameters and relative transformation between the cameras [12]. After this image coordinate system was transformed, color based tracking method was used to get the yellow objects pixels. RGB image was accessed from color camera and transformed to HSV image. HSV values were tuned manually. When H-min= 19, H-max=255, S-min =175, S-max=255, V-min=156, and V-max=255, filtered HSV bin image only displayed yellow objects. The centroid coordinate of tracking object could be computed. Based on Microsoft Kinect embedded skeleton model, these 3D coordinates of shoulder, elbow, and wrist relative to depth camera coordinate system were also acquired. Both upper arm and forearm length could be computed from the above three joint coordinates.

B. Integrate FES into the robot elbow joint to achieve under-actuated joint bi-direction motion

The shoulder joint based coordinate system was derived after transformation from depth coordinate system to shoulder coordinate system. Based on the shoulder joint coordinate system, we got the reaching range of RUPERT. In order to compute real-time arm inverse kinematics, we adopt the ‘‘swivel angle’’ proposed by Tolani and Badler [13] to simplify the computation. If 3D coordinates of both object and shoulder joint were given, the elbow would be at its lowest position by use of swivel angle. Once the elbow position was fixed, the inverse kinematics problem could be solved. Shoulder flexion angle and elbow flexion angle were 45 degrees 30 degrees, respectively.

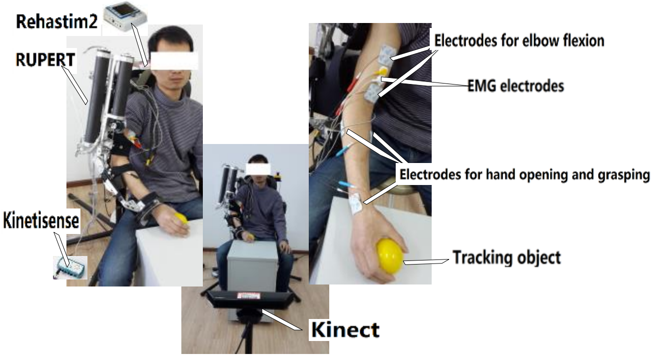


Figure 1. The proposed rehabilitation system for reaching and grasping a real 3D object

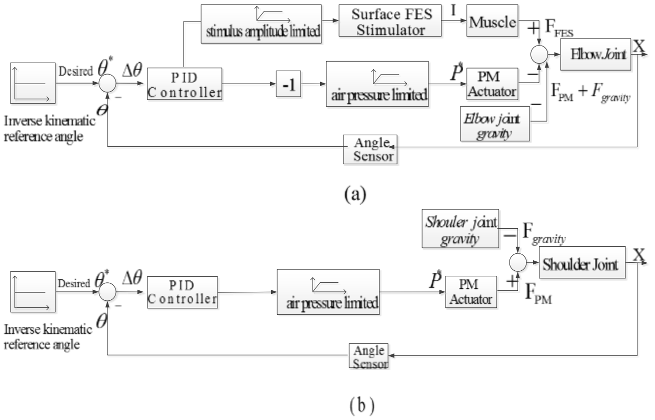


Figure 2. RUPERT specified posture reaching with humeral rotation fixed at internal rotation 30 degrees: (a) elbow joint control diagram with a PMA and FES; (b) shoulder joint control diagram.

The elbow joint and shoulder joint control diagram are shown in Figure 2. This integrative strategy was used for computing a new electrical stimulation intensity in cooperation with PMA through a simple proportional-integral-differential controller. The muscles were stimulated with the biphasic rectangular pulse train. The muscle force was modulated using the pulse amplitude. The pulse width was fixed at 300μs. The pulse frequency was fixed at 40Hz to generate a fused contraction. We used the 3×3cm surface electrodes for muscles stimulation. Electrode placement for bicep stimulation would result in elbow flexion. The stimulating electrode was placed on the motor point of the biceps while the positive electrode was placed closer to the crease of the elbow as shown in Figure 1. Electrode placement for wrist and finger extension was combined for hand opening. The negative electrode of the asymmetric waveform was placed over the finger extension motor point, but enlarged to allow activation of wrist extensors. The positive electrode remains over the tendinous portion of the forearm as shown in Figure 1. Electrode placement for wrist and finger flexion was combined for hand grasping. The negative electrode was placed between the finger flexors and the wrist flexors. The positive electrode was placed over the tendinous portion of the forearm as shown in Figure 1.

C. Verify the effectiveness of this integrative strategy - separating MEMG into the EEMG and VEMG

As healthy subjects participated in this experiment, there was possibility that voluntary forces actuated the elbow joint flexion. By separating MEMG into the EEMG and VEMG, the effectiveness of this strategy of integrating FES into the robot elbow joint was verified. The experiment included two group of tests. One group was that complete voluntary forces actuated elbow joint against PMA when electrical stimulator is off. The other group was that electrically stimulated muscle force actuated elbow joint against PMA when the volunteer was instructed to relax as much as possible allowing only the stimulation to control the related motion. Comb filters have been employed to remove stimulus artefacts. The frequencies of stimulus artefacts were the multiple of stimulus frequencies. Stimulation signal was blocked for 20ms after the onset of each pulse. It was assumed that EEMG occurred during this time period. So it can be used for obtaining VEMG by removing EEMG and stimulus artefacts at the harmonic frequencies of the electrical stimulation [14].

III. RESULTS

By use of arm inverse kinematics with the smallest swivel angle, shoulder and elbow joint target angles were derived 45 degrees and 30 degrees, respectively. The shoulder joint motion curves with three subjects are shown in Figure 3. In consideration of the system control complexity, proportional-integral-differential values were manually tuned towards stable performance according to our experimental experience though not optimized. There were static errors between actual and target angles, which required more advanced control algorithms developed because of PMA nonlinear dynamics.

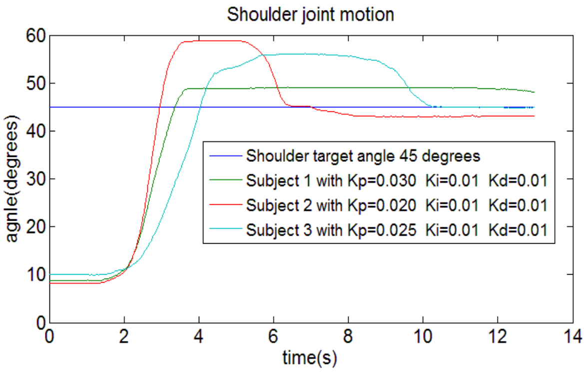
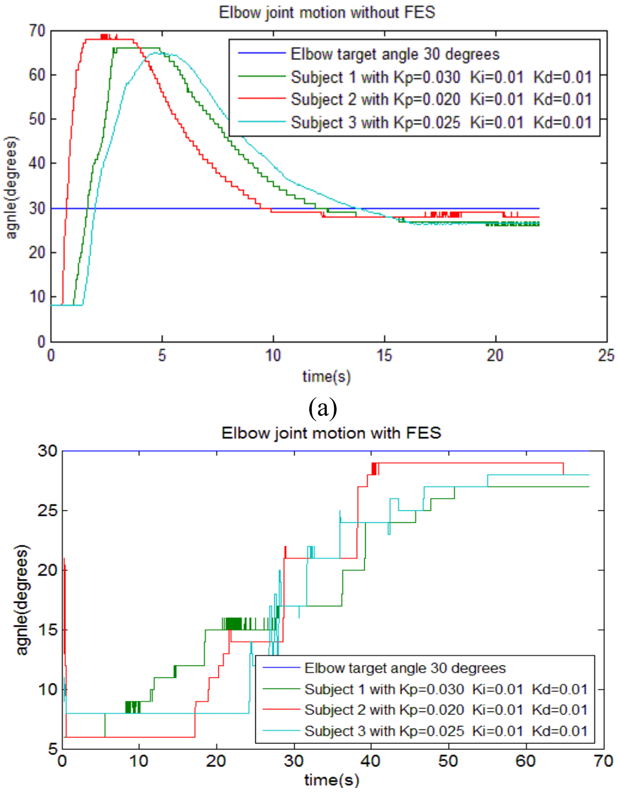


Figure 3. Shoulder joint motion for reaching the specified yellow object.



(a)

(b)

Figure 4. Elbow joint motion for reaching the specified yellow object: (a) without FES and (b) with FES.

The experimental result of cooperation between FES and PMA is shown in Figure 4. It indicates that RUPERT integrated with electrically stimulated muscle adds the control difficulty to the proposed system. Figure 4(a) shows the results of complete voluntary forces actuated elbow joint against PMA when electrical stimulator is off. Figure 4(b) shows the results of electrically stimulated muscle force actuated elbow joint against PMA with FES on. By use of power spectrum analysis with comb filter by blocking stimulus signal 20ms after the onset of each pulse, MEMG was separated into the EEMG and VEMG (30ms blocking signal was analyzed alone for extracting EEMG). Figure 5(b), 5(d), and 5(f) show that voluntary force actuated elbow flexion with FES off. As the stimulator stimulus frequency was fixed at 40 Hz, EEMG frequencies around 40 Hz are shown in Figure 5(a), 5(c), and 5(e), respectively. Compared to Figure 5(b), 5(d), and 5(f), there are no EMG signals firing at around 30 Hz, which indicates electrically evoked muscle force makes main contribution to elbow flexion motion.

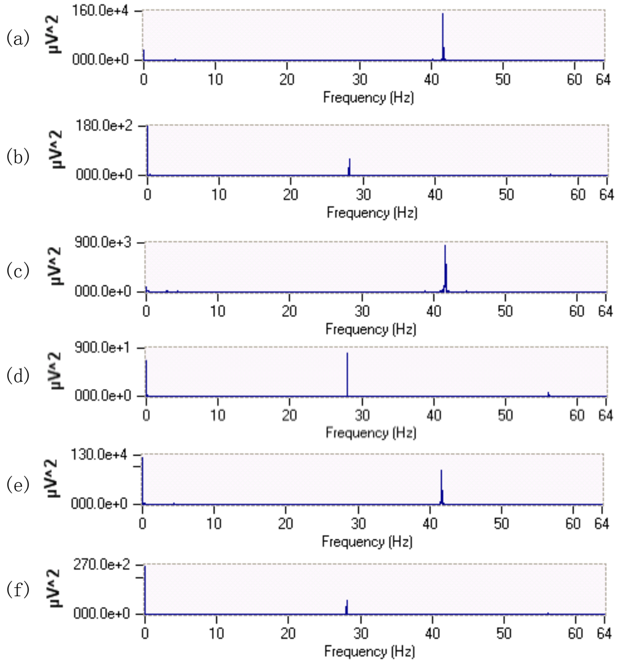


Figure 5. Biceps EMG with power spectrum analysis: (a) Subject 1 EEMG with FES and (b) Subject 1 VEMG without FES, (c) Subject 2 EEMG with FES and (d) Subject 2 VEMG without FES, (e) Subject 3 EEMG with FES and (f) Subject 3 VEMG without FES.

IV. CONCLUSION AND FUTURE WORK

Due to their high costs and large weight, most wearable upper limb rehabilitation robots are hard for stroke patients to accept and use. In consideration of their own characteristics of stroke subjects, our proposed integrative strategy is using a PMA in cooperation with surface FES electrically evoked paralyzed muscle force to realize the robot under-actuated joint bi-directional motion, which is a promising approach to alleviate the size and mechanical complexity of the robot, thereby the cost of the rehabilitation robot. FES is a method for activation of sensorimotor mechanisms, which can realize the inhibition of abnormal reflexes and induce active movements. FES stimulating hand muscles realizes hand opening and grasping, which can overcome the mechanical complexity of designing rehabilitation robotic hands. In this paper we fixed humeral rotation angle at internal rotation 30 degrees for simplifying control complexity. In order to realize the cooperation of FES electrically evoked muscle force and PMA for reaching and grasping, a simple proportional-integral-differential controller is presented. The underlying musculoskeletal system is highly sensitive to physiological conditions, including skin impedance, temperature, moisture, electrode placement, and time-varying effects such as spasticity and fatigue [15]. An advanced intelligent control algorithm needs to be developed to improve control performance.

The future research is discussed for design principle of how to take advantage of each technique in developing a more functional effective hybrid FES and robot assisted system.

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