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Design of a Wearable Rehabilitation Robot Integrated with Functional Electrical Stimulation

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Abstract—**Robot-assisted rehabilitation is an active area of research to meet the demand of repetitive therapy in stroke rehabilitation. A wearable upper limb rehabilitation robot is most suitable for this task but needs to be powered by safe and compliant actuators while maintaining overall light weight and accommodating energy efficient dynamic form factor. In this study, we explore an integrative rehabilitation strategy for training patients to practice coordinated reaching and grasping functions by using a hybrid design to reduce the size and weight of the robot. The hybrid technology of the wearable upper limb rehabilitation robot and functional electrical stimulation has many technical and clinical advantages but is yet to be systematically investigated. A properly designed FES can induce active movements while inhibit abnormal reflexes. This is a promising approach to alleviate the actuation power demand of the robot, thereby the size and weight of the robot may be significantly reduced. Most important, the mechanical complexity of the robot may also be limited. We explored the concept of the hybrid design in this preliminary report. The future research is discussed for design principle of how to take advantage of each technique in developing a more energy efficient and functional effective hybrid FES and robot assisted system.**

Keywords—**rehabilitation robot, stroke, functional electrical stimulation (FES), motor rehabilitation.**

I. Introduction

Nowadays the prevalence rate of stroke in China is increasing rapidly, almost 10% annually. 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 reportedly 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 nonparetic arm[4-6]. A DC servomotor actuated 4-DoF ARM rehabilitation robot is a trombone-like device, which can assist a user to guide arm reaching movements in the horizontal plane [7]. The commercial version of MIT-MANUS called InMotion Shoulder-Elbow Robot with 2 DoFs performs the function of the shoulder and elbow joints rehabilitation training [8]. He and Koeneman et al have built a wearable device for robotic assisted upper extremity repetitive therapy (RUPERT) [9-10]. The RUPERT has five actuated DoFs driven by compliant pneumatic muscles (PMs) on the shoulder, elbow, and wrist joints. The device can also provide real-time, objective assessment of functional performance. The device was tested by stroke survivors practicing several critical activities of daily living (ADL): reaching out, wiping and self feeding. Some studies investigated the effects of robot-assisted therapy on motor and functional recovery in patients with stroke, and encouraging results were observed [11].

Many stroke rehabilitation experiments show a positive role using functional electrical stimulation (FES) for recovery of motor function. FES is a method for activating sensory-motor systems by delivering electrical charge in the form of bursts of electrical pulses. By surface electrodes, FES stimulating motor or sensory nerves of muscles and facilitates motor rehabilitation and function reconstruction. Fang-Chen Wu, et al.[13], adopted a hybrid method of combining bilateral arm training with FES in patients post stroke to improve hand function, and a linear guide platform with FES feedback control is developed to execute the training of bilateral reaching movements. A robotic workstation for stroke rehabilitation of upper extremity using FES is developed by Freeman et al. [14]. They use voluntary control with the addition of electrical stimulation applied to muscles in the impaired shoulder and arm. FES can also realize the inhibition of abnormal reflexes and induce active movements [15]. However, using FES for large muscle forces and long duration force production is not desirable due to fatigue or uncomfortable sensation.

A wearable upper limb rehabilitation robot can assist the stroke patient to conduct reaching and grasping rehabilitation training in a less constrained environment or body movement. The rehabilitation robots are often driven by multiple actuators to achieve many degrees of freedom for ADL training. However, the weight and bulkiness of these actuating devices render the robot unsuitable for patients to wear, limiting widespread clinical application or at home therapy using wearable rehabilitation robots.

In this paper, we report a preliminary investigation on principles of combining a wearable upper limb rehabilitation robot with FES to reduce the size and weight for stroke patients to wear. In Section II, the attempt of exploring basic guidelines of integrating FES into the robot to reduce the demanding actuation force is described first, followed by outlining the design of experiments for coordinated shoulder flexion and hand grasping training based on integrated

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robot-assistance with FES training. Section III reports the experimental results. Conclusion and future work are shown in section IV.

II. METHODS

A wearable upper limb rehabilitation robot with 5 DoFs is designed. The robot is based on human anatomy architecture using the exoskeleton structure whose joints accord with joints distribution of human upper limb. According to the requirements of actual rehabilitation training, the most basic and most important 5 DoFs of the upper limb are selected, including shoulder flexion/extension, shoulder abduction/adduction, elbow flexion/extension, wrist flexion/extension and finger flexion/extension. PM is used as the driving actuator in this design for both its compliance and also relative light weight, in addition to lower cost. However, the size and weight of the wearable upper limb rehabilitation robot still need to be reduced for stroke patients to accept. Normally, the size and weight of the robot is determined by the driving mechanism. Driving devices of shoulder and fingers play a main role in the size and weight of the rehabilitation robot. How to reduce the demand of actuation force for a certain robot rehabilitation movement of shoulder and finger joints becomes critical.

A. *FES assistance theory and controller designed*

Skeletal muscles generally work as flexor/extensor pairs to generate bi-directional movement of each joint. When co-contraction is not desired such as the case in quick withdraw from a noxious stimuli, the flexors perform strong contraction and the extensors realize relaxation. This comparative fixed relationship is the characteristics of spinal reflex. In general, the flexor and the extensor are mutually inhibitive. Figure 1 shows the most basic muscle feedback control circuit.

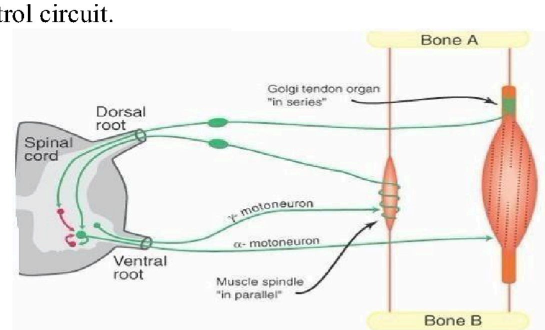


Figure 1. muscle feedback control circuit[16].

However, for stroke patients the neural modulation becomes abnormal. Suffering a stroke usually leads to two conditions including flaccid paralysis and tetany. Flaccid paralysis is a clinical manifestation characterized by weakness or paralysis and reduced muscle tone without other obvious cause (e.g., trauma)[18]. Tetany is a case of involuntary muscle convulsion. It is a muscular physical state at which action potentials from nerves arrive to the skeletal muscle motor end plate rapidly enough in succession to cause a steady contraction.

FES delivers stimulating current to related nerves in the target muscles to produce desired active force. Specifically, we can use FES to activate extensor muscles in coordination with the robot during rehabilitation training. FES activates extension-related peripheral nerves while the muscle spindle receptors are activated, which give relative inhibition neural signals to the corresponding antagonistic muscles. For stroke patients with tetany, FES can also be used for the inhibition of abnormal reflexes while assisting active movements. Combination of the robot and FES can possibly alleviate the effect of the antagonistic muscle abnormal modulation in stroke patients. So this integrated method can cut down the demand of actuation force for a certain movement of the robot, by which the size and weight of robot may be significantly reduced as shown in Figure 2.

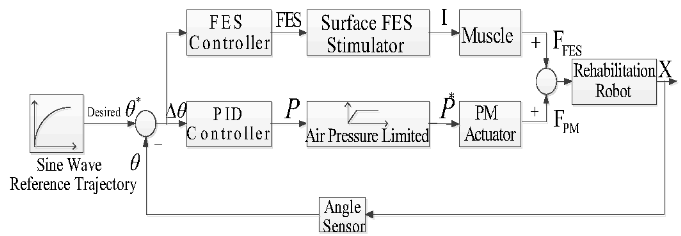


Figure 2. FES assisting the rehabilitation robot control diagram.

The complex nonlinear dynamics of the pneumatic muscle and many uncertainties in the device make this device driven by the PM actuator difficult to control, and it is very difficult for us to build the overall mathematical model of the device for model based control. To realize the device controlled, a PID controller is taken for the robotic device shown in Figure 3. Where Δu(k) is the control increment at the k-th sampling time, and e(k) is the deviation of the system at the k-th sampling time.

The incremental PID control algorithm is described by (1) and (2). k_p is the proportional gain. $k_i = k_p*T/T_i$ is the integral coefficient, and $k_d = k_p*T_d/T$ is the derivative coefficient. A optimum performance index is the integral of the square of the error, ISE defined by (3).

$$u(k) = u(k-1) + \Delta u(k) \quad (1)$$

$$\Delta u(k) = k_p(e(k) - e(k-1)) + k_i e(k) + k_d[e(k) - 2e(k-1) + e(k-2)] \quad (2)$$

$$ISE = \int_0^T e^2(t)dt \quad (3)$$

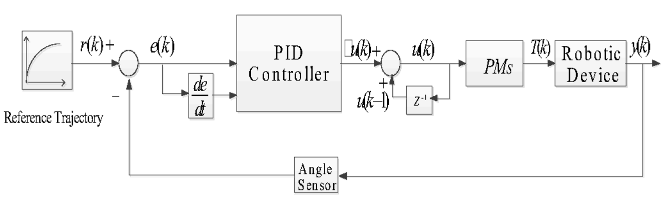


Figure 3. The control structure of the robot with reference trajectory

FES controller is an on/off system. An FES feedback control platform is designed, which allows a user to tune stimulation amplitude. The controller will turn on/off a stimulator switch according to the feedback. A controlled current stimulating device Beurer EM41 produces two channels of stimulating current pulses. When the robot joint angle reduces and runs out of the setting range, FES stops stimulating the muscles, expressed as the formula (4). θ is defined as the joint angle of the robot. Among the four FES stimulating elements, stimulus frequency is fixed to 35Hz, which can't cause muscle fatigue easily. Pulse duration is kept at 300μs and stimulus intensity is 10-25mA. The input waveform is quasitrapezoidal with biphasic, asymmetric and charge balanced characteristics.

$$FES = \begin{cases} on & 0 \le \theta \le 14, \dfrac{d\theta}{dt} > 0 \\ off & \dfrac{d\theta}{dt} < 0 \end{cases} \tag{4}$$

B. *Experimental design on shoulder and fingers*

The experiments were conducted on a non-impaired male subject with the age 28 years, with written informed consent as approved by the Institutional Review Board at Huazhong University of Science and Technology. The volunteer was instructed to relax as much as possible and to allow the stimulation to control the related motion.

a) Test on shoulder

Shoulder anteflexion motion of the rehabilitation robot is taken as the first experimental object. Realizing shoulder anteflexion motion is related to two cardinal muscles-deltoid and supraspinatus, as shown in Figure 4.

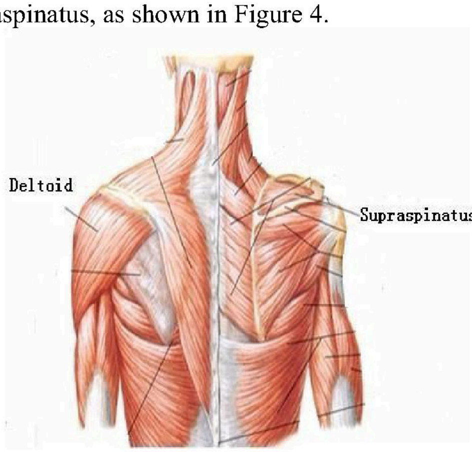


Figure 4. Shoulder anteflexion muscles-deltoid and supraspinatus.

Selection of trigger motor points is the key procedure. Surface electrodes are used as the stimulating interface of FES and neuromuscular band. Figure 5 shows the placement of electrodes on shoulder anteflexion muscles-deltoid and supraspinatus.

(a) lateral view (b) front view

Figure 5. Surface electrodes placement.

Shoulder anteflexion robot–assisted training is showed in Figure 6. The experiments consist of two contrast parts: without FES and with FES. According to the motion angle feedback of the rehabilitation robot on the shoulder, surface FES realizes switch control and current amplitude tuning, which provides stroke patients safety assurance and much better assistance effect.

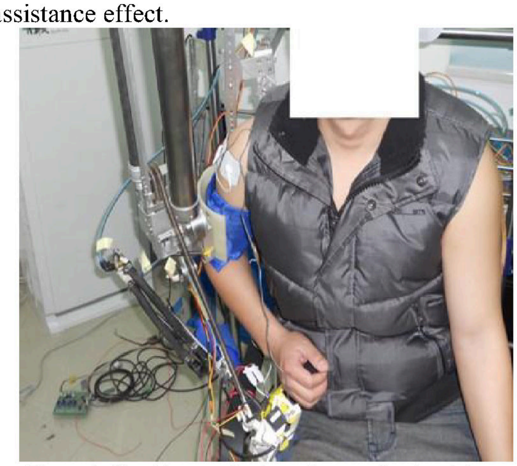
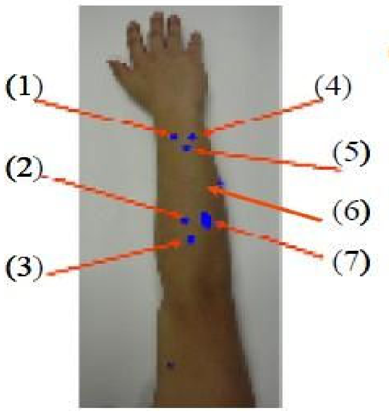


Figure 6. Shoulder anteflexion robot –assisted training.

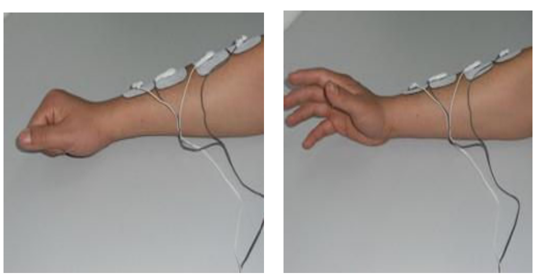
b) Test on fingers

Hand function rehabilitation of stroke patients is of great significance for achieving improved ability to perform many ADLs. However, it is also a research challenge at present due to mechanical complexity on a compact structure with so many degrees of freedom. Another challenge is the weight on the distal end of a wearable rehabilitation robot. This is another good candidate for trying hybrid approach of coordinating robotic and FES assisted therapy. Most important contribution of using FES is to simplify the mechanical structure in design of the wearable upper limb rehabilitation robot, especially for more complex grasping tasks. We performed a proof of concept experiment using the hybrid approach applied on fingers. Rehabilitation hand of the wearable robot is designed for one joint of the right hand four fingers (except thumb). It is difficult to control individually single fingers motion accurately using surface FES. Motor points of fingers are shown in Figure 7.



(1) EPB (2) ECRB (3) ECRL (4) EPL
(5) Extensor indicis (6) FDP (7) ED
Figure 7. Motor points of Fingers[17].

In general many stroke patients will form a tight fist whenever they want to perform a movement, preventing them from performing any grasp task and causing hygiene problems and skin breakdown. Hand opening using surface FES can be achieved as depicted in Figure 8.

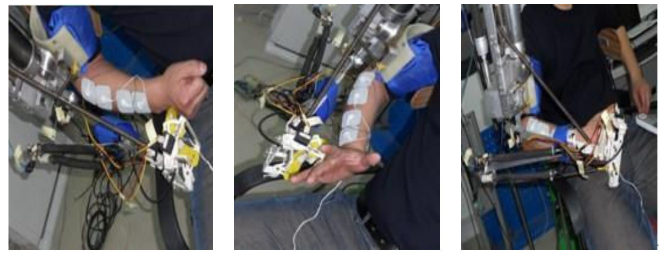


(a) hand grasping (b) hand releasing
Figure 8. Hand shape opened.

In Figure 9, we showed the locations of stimulating electrodes placement before the robot is positioned. FES performs function of opening hand when fitting the wearable robot. Then, FES can assist the rehabilitation robot to conduct fingers rehabilitation training.

Figure 9. Surface electrodes placement on the arm

The process of wearing the rehabilitation robot includes three steps as shown in Figure 10.
Step a) Selection of neuromuscular motor points of hand.
Step b) Raising of the current amplitude of the stimulator, hand is opened.
Step c) Keep the posture of hand, and help the participant wear the rehabilitation robot to do the training.



(a) hand grasping (b) hand releasing (c) fingers rehabilitation

Figure 10. The process of wear and fingers robot-assisted training.

III. RESULTS

Though the complex nonlinear dynamics of the rehabilitation robot can be derived to develop a sophisticated control algorithm, for this proof of concept experiment we used the straightforward PID close-loop control approach for all PM actuators. The sine wave trajectories are tracked by joints motion of the rehabilitation robot.

Figure 11 is the software graphical user interface (GUI) of the FES feedback control platform, and the alarm indicator light turns red when the rehabilitation robot motion angle is decreasing or more/less than the maximal/minimal angle. By use of Advantech USB-4716 multifunction high-speed acquisition card, the platform performs the function of signal input and control output. With the help of PC decision-making software control, this platform realizes closed-loop control to improve the FES control accuracy and safety.

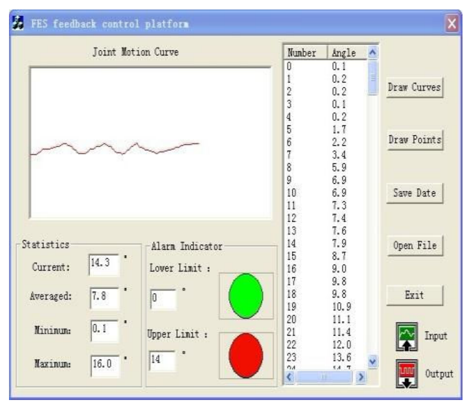


Figure 11. Functional electrical stimulation feedback control platform.

In order to achieve comparative results to evaluate FES contribution, the air pressure of PMs is specially limited below a particular value 0.16MPa. Regardless of how to tune parameter values of PID, the rehabilitation robot with FES off cannot finish the entire reference trajectory tracking task as shown in both Figure 12 and Figure 14. In Figure 12, FES can assist the rehabilitation robot to conduct the shoulder anteflexion training. Under the conditions of limited air pressure of the PM on the shoulder, the robot can accomplish the entire tracking motion with assistance from FES induced muscle force. In Figure 13, the quantitative angle tracking error is the difference value between the reference trajectory and the actual motion angle. The angle error value at the reference trajectory peak with FES on is approaching zero and is obviously less than the error value with FES off. From another perspective, it indicates that the upper limb rehabilitation robot integrated with FES can reduce the demand of the required maximum driving force for the shoulder anteflexion movement. Thus the combination of a wearable rehabilitation robot and FES can probably reduce the size and weight of the robot.

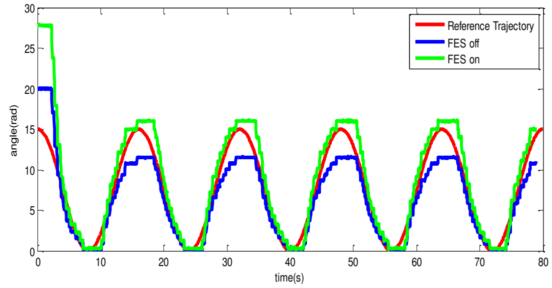


Figure 12. Shoulder anteflexion robot training without/with FES.

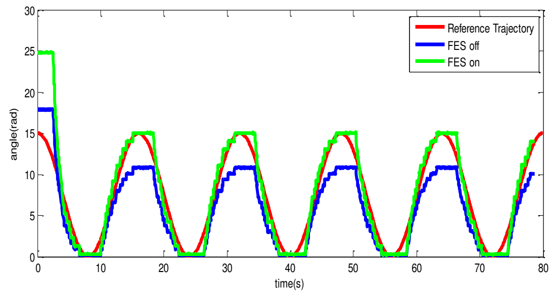


Figure 13. Shoulder anteflexion robot training tracking error with FES off/on.

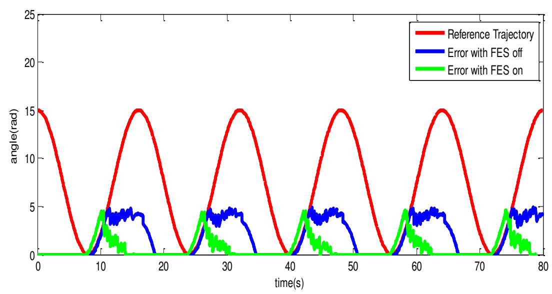


Figure 14. Fingers robot training without /with FES.

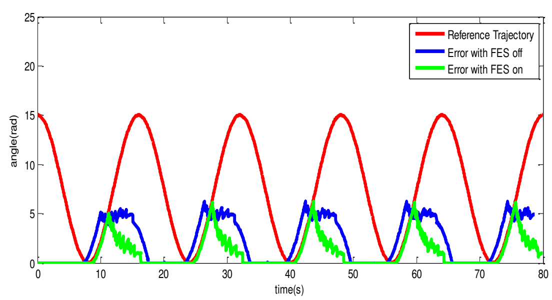


Figure 15. Fingers robot training tracking error with FES off/on.

We then tested the same approach on hand opening and close. As the air pressure of the PM on the fingers is limited, robot-assisted training can not accomplish the entire tracking motion for the hand opening and closing without FES as shown in Figure 14. FES can assist the rehabilitation robot to conduct the hand opening-closure training. When the air pressure of the PM on the fingers is limited at the same level as for Figure 14, the robot can now accomplish the entire tracking motion with FES. The angle error value at the reference trajectory peak with FES on is also approaching zero and is obviously less than the error value with FES off as shown in Figure 15. It proves that the upper limb rehabilitation robot integrated with FES can also reduce the demand of actuation force for fingers movement.

The integral of the square of the error formula shown in (3) is also taken for quantitative evaluation. Assume T as 80s, then we can obtain the equation (5). The comparison of quantitative evaluation ISE with FES off/on under the condition of both test on shoulder and test on fingers is shown in Figure 16.

$$ISE = \int_{0}^{80} e^{2}(t)dt \qquad (5)$$

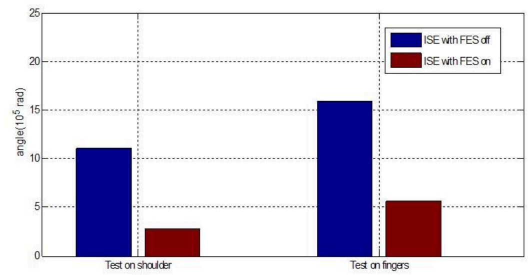


Figure 16. Quantitative evaluation ISE with FES off/on.

To sum up, the wearable upper limb rehabilitation robot integrated with FES can reduce the demand of actuation force for a certain robot rehabilitation movement, as a result to reduce the size and power of PMs, therefore the total weight and bulkiness of the robot.

IV. Conclusion and Future work

Due to its large size and weight, the current wearable upper limb rehabilitation robot is hard for stroke patients to accept and use. In that case, it prevents the clinical application of wearable upper limb rehabilitation robots. A wearable upper limb rehabilitation robot integrated with FES is designed. FES is a method for activation of sensorimotor mechanisms. Besides the above advantages FES can also realize the inhibition of abnormal reflexes and induce active movements. The combination of a wearable rehabilitation robot and FES can cut down the demand of actuation force for a certain robot rehabilitation movement, which leads to reducing the size and weight of the robot. In conclusion, the wearable rehabilitation robot integrated with FES can improve rehabilitation efficacy for more dexterous arm/hand functions but also indirectly reduce the size and weight of the robot.

It is expected that the wearable upper limb rehabilitation robot integrated with FES for smaller size and more functionality may be more easily accepted by stroke patients. It is also anticipated that functional improvement will be more significant when the patients receive the wearable upper limb rehabilitation robot integrated with FES assisted rehabilitation treatment more frequently after the clinical application.

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