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Development of Force Analysis-based Exoskeleton for the Upper Limb Rehabilitation System

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Abstract - **With the development of exoskeleton rehabilitation robotic system, the biomechanics influence of device should be considered in rehabilitation training. This paper describes a novel upper limb exoskeleton rehabilitation device (ULERD) based on biomechanics, which can be used in rehabilitation of upper limb for hemiparalysis patients. This system is aimed at helping hemiparalysis patients recover motor function of upper limb and are suitable for variety of patients. This system is portable and wearable, which consists of exoskeleton device, haptic device (PHANTOM Premium), and computer. By using finite element software ANSYS, biomechanics influence of the exoskeleton device on the patient's upper limb in the rehabilitation training is explored. Based on it, the device can be optimization design to be cylindrical type and the activity angle range of the elbow joint of exoskeleton device is proposed from 30° to 90° in the training. These experiment results demonstrate this system that can prove an advance rehabilitation approach for hemiparalysis patients and the biomechanics impact of exoskeleton device should be reduced. In the future, this system will have a bright application prospect in the rehabilitation therapy field.**

Key word- Rehabilitation Robotic System, ANSYS, Biomechanics

I. Introduction

Recently, because of stroke or cerebrovascular accident, more and more people are disability. According to the World Health Organization, approximately 700,000 people experience a stroke each year in the Europe and United States [1].Though traditional rehabilitative therapies can assist patient recover motor function and ameliorate impairment, they mainly rely on experience of therapists and give social and family heavy financial burden [2]. With the development of robotics and mechanotronics, some exoskeleton rehabilitation robots appeared to help stroke survivors to recover motor function [3]. The earliest robotic called MIT-MAUNS, which allows two degrees of freedom for upper limb including shoulder, elbow and wrist movement by performing task-oriented training [4], [5]. It can improve motor function in the hemiparetic upper limb of acute and chronic stroke patients in clinical trials by passive and active rehabilitation [6]. The structure of this robotic is simple, but it can't aim at mainly joint of upper limb. The MEDARM, studied by Canadian Institutes of Health Research (CIHR), provides five major degrees of freedom at shoulder complex based on a cable driven curved track mechanism [7]. The ARM Guide is a singly-actuated, four-DOF robotic device that consists of a hand piece attached to an orientable linear track and actuated by a DC servo motor [9]. ARMin is an exoskeleton device with six independently actuated degrees of freedom and one coupled DoFs. It can significantly support patient arm and improve significantly motor function of upper limb [10]. The Rehab-robot developed by National Taiwan University can be used for the rehabilitation of the patients. Using both EMG and force sensor signals of the patients, the robot is capable of supporting the human motion, without going through any of the ill-postures that is possible reaching the end effectors position [11]. These rehabilitation robots have many advantages in rehabilitation training with multiple degrees of freedom, enough range of movement. However, they also have some disadvantages. For example, firstly they are large and heavy, and not appropriate for home rehabilitation. Secondly, they are short of efficient and accurate rehabilitation evaluation method and do not achieve remote rehabilitation training. Besides, they also don't analyse biomechanics impact of exoskeleton device for the upper limb of patient.

In this paper, a novel upper limb exoskeleton rehabilitation device (ULERD) has been presented, and the exoskeleton device's biomechanics influence for the patient's upper limb is studied by the simulation of the stress and displacement distributions of the upper limb, using finite element software ANSYS. Besides, the device can be optimization design and an optimum rehabilitation training method will be formulated.

II. System Structure

A. *The rehabilitation system structure*

The system mainly consists of exoskeleton device, haptic device (PHANTOM Premium), and computer in Fig. 1. In the proceeding of rehabilitation training, patients can control the exoskeleton device, which is fixed on the patients' upper limb, to implement rehabilitation training by changing PHANTOM Premium state. Meanwhile, therapist can obtain the motion information of upper limbs of patients by using inertia sensor, including Position, Velocity and Acceleration (PVA). Besides, therapists use the skin surface electromyogram (sEMG), which is installed on the upper limb of patient, to evaluate patient rehabilitation situation. Based on this information, they set up better training method for patients [12].

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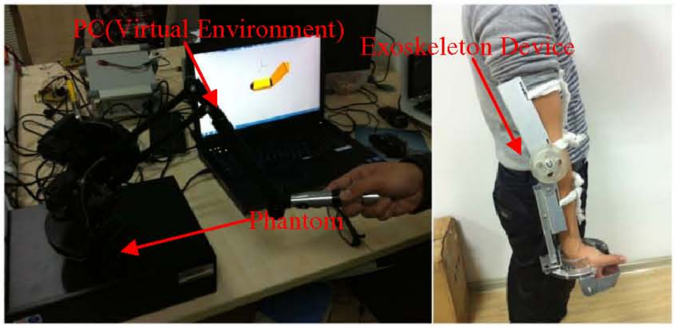


Fig. 1 The image of the rehabilitation system structure

According to different rehabilitation periods, three rehabilitation systems have been setting, including preliminary stage (Fig. 2), mid-term (Fig. 3) and later period (Fig. 4).

In the preliminary stage, patients can't implement rehabilitation training by themselves, so they should be guided under the doctor. And this system can achieve remote rehabilitation training.

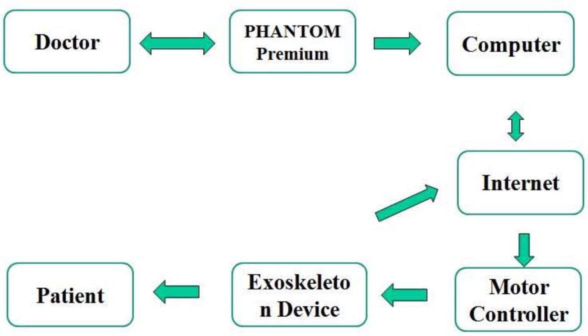


Fig. 2 The image of the preliminary stage rehabilitation system

With recovering a certain extent esthesia, they can use uninjured upper limb control Phantom to implement rehabilitation training. And some games can be setting so that they can increase interesting in the rehabilitation training.

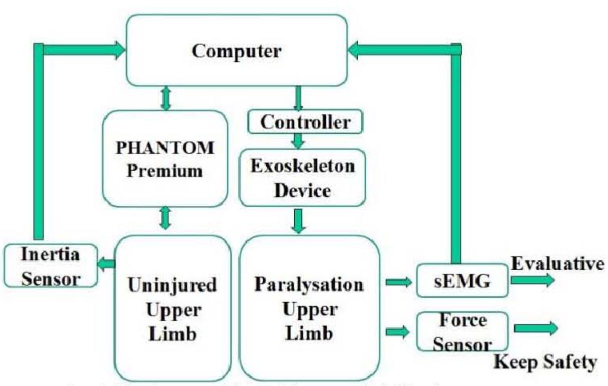


Fig. 3 The image of the mid-term rehabilitation system

In the later period rehabilitation training, patients' paralysation upper limb have ability to alone finish rehabilitation training, so some resistances can be setting to enhance training difficulty to achieve better rehabilitation effect.

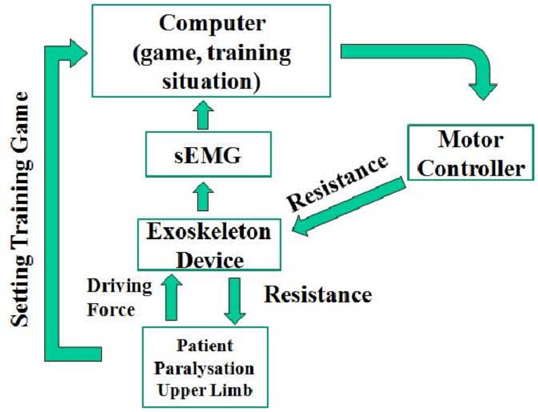


Fig. 4 The image of the later period rehabilitation system

B. The upper limb exoskeleton rehabilitation device

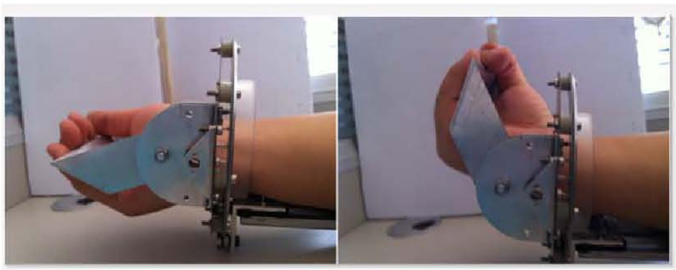
The upper limb exoskeleton rehabilitation device is designed to be wearable and portable to provide passive training and active training to the disabled patient to recover the motor function of upper limb, including elbow and wrist. The basic device structure is depicted in (Fig. 5). Three DoFs are designed and actuated in elbow and wrist, including the elbow flexion/extension (Fig. 6), forearm pronation/supination (Fig. 7) and wrist flexion/extension (Fig. 8). On the other hand, four passive DoFs are added including two DoFs (one is rotation and the other is translation) in elbow joint, other two in wrist joint with considering many factors, for example, variation of flexion/extension axis (FEA), personalized otherness in physical dimension of joint and correlation between wrist and elbow joint during elbow flexion and extension [13]-[15]. Patients are easy to contact upper limb with device by using some elastic belts passing through the component holes.

Fig. 5 The image of the exoskeleton rehabilitation device

(a) (b)

Fig. 6 The image of the elbow extension (b)/ flexion (a)

(a) (b)
Fig. 7 The image of the forearm supination (a)/pronation (b)



(a) (b)
Fig. 8 The image of the wrist extension (a)/ flexion (b)

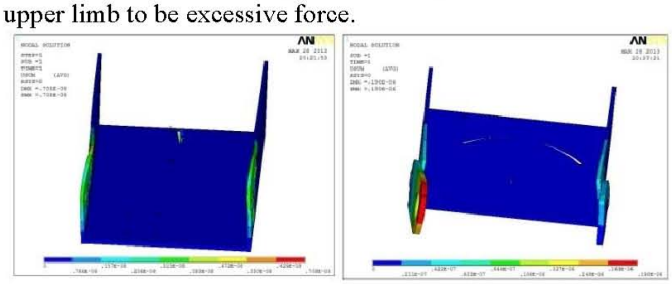
C. *Haptic device (PHANTOM Premium)*

In the system, PHANTOM Premium (SensAble Technologies) is used to be as a control and actuator device. Through Phantom, patients can control the virtual arm in the PC to make exoskeleton rehabilitation device implement rehabilitation training. Meanwhile, the information of Phantom can be displayed in the PC.

III. EXPERIMENTAL SETUPS

A. *The mechanics influence of mechanism design for the upper limb*

The exoskeleton rehabilitation device uses the BLDC (Maxon) motors with high power density. Three motors are mounted at elbow joint and wrist joint. So the motors particularly elbow joint can produce continued force influence so as to make device frame shape change (Fig. 9). Through using ANSYS software simulate component strain, the frames have adduction trend and led forearm and the upper limb to nonuniform stress. It may cause one point of forearm and upper limb to be excessive force.



(a) (b)
Fig. 9 The image of the rectangle parts' shape changes of the upper limb (a) and forearm (b)

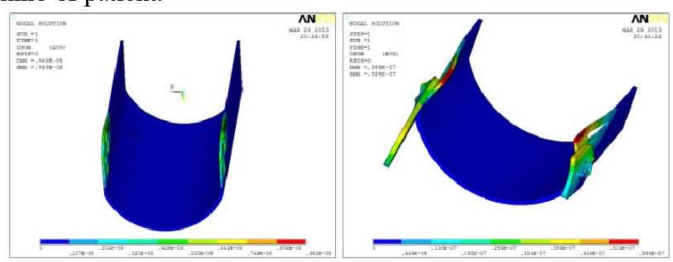
So for the sake of changing the point, cylinder parts are designed and simulated by ANSYS software (Fig. 10). Contrasted with rectangle part, though it also causes adduction trend, it increases the stress area so as not to cause one excessive force point of forearm and upper limb (Fig. 11). A point is the excessive force point. The force equation of rectangle part is described as follow:

$$F_1 = F_2 \cos\alpha + F_3 \cos\beta \qquad (1)$$

where F_1, F_2 and F_3 are the force that part gives to upper limb and α and β are the angle of force and horizontal plane. The force equation of cylinder part is described as follow:

$$F = Q_1 \cos\alpha_1 + Q_2 \cos\alpha_2 + ... + Q_k \cos\alpha_k = F_1 \cos\alpha + F_2 \cos\beta \qquad (2)$$

where from Q_1 to Q_k are the components of force F and from α_1 to α_k are the angles of force and horizontal plane. From the equation, it can show that cylinder parts increase contact area of upper limb to eliminate the excessive force point. Besides, cylinder parts accord with human body engineering and decrease shape change influence for the upper limb of patient.



(a) (b)
Fig. 10 The image of the cylinder parts' shape changes of the upper limb (a) and forearm (b)

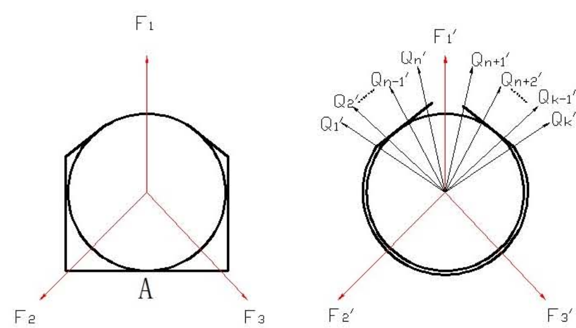


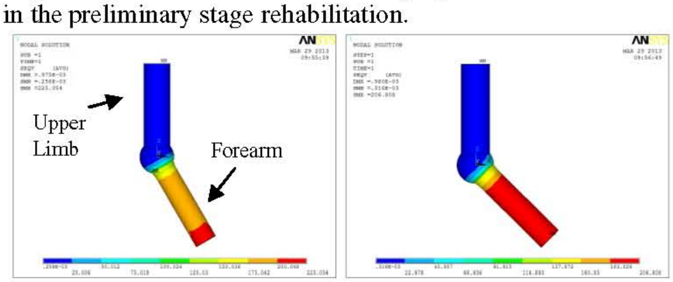
Fig. 11 The image of the force situation of rectangle part and cylinder parts

B. The mechanics influence of exoskeleton device for elbow joint

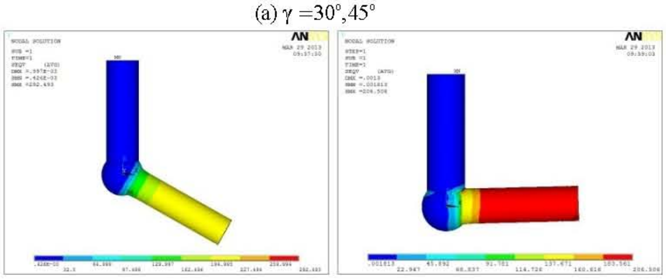
The elbow joint is a complex joint and consists of the ulnohumeral joint, the radiocapitellar joint and proximal radioulnar joint. The structure of elbow joint is showed in Fig. 12. Its activities mainly depend on the frictional interaction of cartilage, so frequent games accelerate loss of cartilage, which can't recovery, especially the need for rehabilitation of stroke patients [16]. In this experiment, two interconnected cylinder model is established to simulate the human upper limb. Defined properties of bone materials is that EX=20MPa, PRXY=0.263 [17] and the simulation pressure of forearm is 200N. The upper limb is fixed and the forearm is active. By simulating and analyzing stress conditions in different angles (γ =30°, 45°, 60°, 90°, 120°, 135°) of the elbow flexion and extension to calculate the optimal activity range of exoskeleton device in the rehabilitation training.

Fig. 12 The image of the structure of human elbow joint

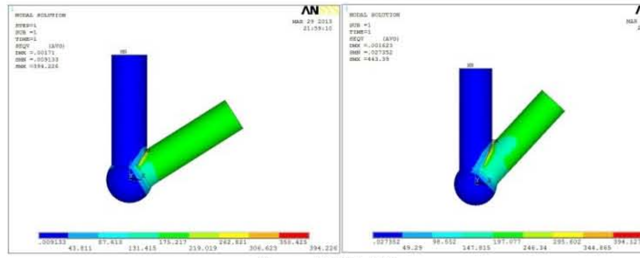
From the result of simulation (Fig.13, Fig.14), when the flexion angle γ is 135°, the stress of upper limb is maximum value 443.39MPa. When γ is less than 90°, the forearm mainly undertake the pressure that exoskeleton device gives to forearm. However, when γ is more than 90°, the elbow joint mainly undertake the pressure and the stress of elbow joint is increasing rapidly. In the situation of frequent games, it may accelerate loss of cartilage in the joint. Besides, it also shows that the stress of elbow joint is nonuniform in different angle. Generally speaking, the flexion angle range of elbow joint is form 60° to 140° in daily life. However, it is harmful for hemiplegic patients to bear large stress with their elbow joint in the rehabilitation training. So the optimal activity angle range of exoskeleton device is proposed from 30° to 90° in the preliminary stage rehabilitation.



(a) γ =30°,45°



(b) γ =60°,90°



(c) γ =120°,135°

Fig. 13 Images of the stress distribution of elbow joint in different flexion angles

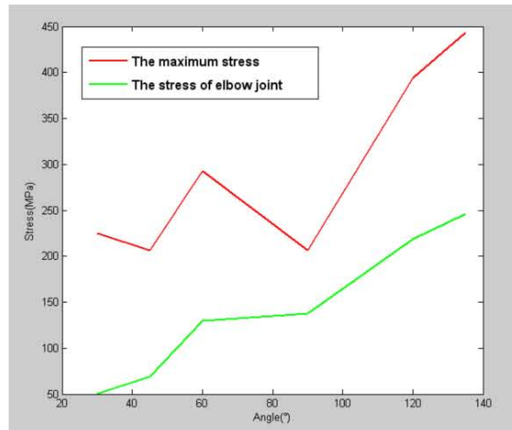


Fig. 14 The image of line graph of simulation result

IV. CONCLUSION AND FUTURE WORK

In this paper, a novel upper limb exoskeleton rehabilitation device (ULERD) is proposed. Compared with other systems, this system is more advanced and has more consideration for patients. And through using the finite element software ANSYS, it simulates and analyses the effect of mechanical structure design for patients' upper limb and the biomechanical effects of elbow joint under frequent movement. From the simulation, it shows that cylinder parts have more advantages than rectangle part, especially solving the parts deformation problem for upper limb. And the activity angle range of exoskeleton device is suggested from 30° to 90° in the training. These experiments result demonstrate that changing rectangle part to cylinder part is more useful for patient to reduce mechanical impact of exoskeleton device. Besides, biomechanics impact of exoskeleton device for patients' joint should be considered in the rehabilitation procedure. In future work, we will focus on the wrist movement by finite element analysis and select best activity range of wrist joint. Meanwhile, using structure optimization design reduces the biomechanics influence of the upper limb exoskeleton rehabilitation device on patient so as to help recovery of hemiparalysis patients.

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