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A Novel Upper Limb Rehabilitation System with Hand Exoskeleton Mechanism

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Abstract **–The exoskeleton robot is a comprehensive technology that is combination of sensing, control and information. Based on the upper limb exoskeleton rehabilitation device (ULERD), this paper describes a novel hand exoskeleton mechanism for using in rehabilitation field and aiming at helping varieties of hemiparalysis patients recover motor function of the whole-arm. This system consists of exoskeleton device, haptic device (PHANTOM Premium), motors, motor controllers and work station. And the hand exoskeleton mechanism is portable, wearable and adjustable for patients doing home rehabilitation training. Through using the finite element software (ANSYS), the main components of the hand exoskeleton are studied by force simulation analysis. And it shows that the exoskeleton device have the ability to resist deformation and sustain patients' fingers to implement rehabilitation training. Except that, a finger model is established to simulate the force status in different flexion angles of the proximal interphalangeal (PIP) joint and the metacarpaophalangeal (MCP) joint. From the analysis of the finger joint, the optimal joint activity range of device is presented that the PIP joint is less than 60^{o} and the MCP joint is less than 75^{o}. These experiments demonstrate this exoskeleton can provide a scientific rehabilitation method for the hemiparalysis patients and force influence of the exoskeleton device should be considered and reduced. In the future, with the mechanism structure improvement, this system will have a promising application prospect in the rehabilitation field.**

Index Terms - Hand exoskeleton rehabilitation robot, ANSYS, Force simulation analysis

I. INTRODUCTION

According to the World Health Organization (WHO), approximately 700,000 people experience stroke or cerebrovascular accident in the Europe and United States every year [1]. Typically, stroke is not lethal, especially with the improvement of medical treatment, and the survival rate is further improved. Studies show that about 60 ~ 75% of stroke patients can survive [2]. However, in these survivors, 80 ~ 90% people will be left with motor function defect of upper or lower limbs even hemiplegic, thus losing the ability of activities in daily living [3].

Since the last century seventy's, robot techniques are applied in the field of rehabilitation, and they successfully replace the traditional physical therapist and can provide high repeatability and high strength training for patients to recover motor function. One of the earliest robotic called MIT-MAUNS that can offer two degrees of freedom for upper limb including shoulder, elbow and wrist movement by performing task-oriented training [4], [5]. Through passive and active rehabilitation, it improves motor function in the hemiparetic upper limb of acute and chronic stroke patients in clinical trials [6]. The mechanism is simple, but it can't aim at mainly joint of upper limb. The ARMin that studied by University Hospital Balgrist can provide rehabilitation strategy based on the impedance control and admission control to achieve passive motion rehabilitation, casual games rehabilitation and task-oriented rehabilitation [7]. Hand Mentor is the first clinical application equipment of the active wrist and finger joints rehabilitation training. It mainly consists of a single degree of freedom pneumatic exoskeleton mechanism and a display controller [8]. CPM rehabilitation of injured fingers equipment that developed by Harbin Institute of Technology adopts the exoskeleton joint unit based on connecting rod mechanism, through three independent exoskeleton joint units connected in series to form a whole fingers exoskeleton [9]. The finger rehabilitation device developed by the Beihang University adopts the exoskeleton joint unit based on parallel slide structure, through the same sheath wire transmission to drive the finger joints. Its characteristic is the feedback signal by means of joint position sensor and a strain type force sensor to active rehabilitation therapy [10].

These rehabilitation robots have many advantages in rehabilitation training with multiple degrees of freedom, enough range of movement and precise control method. However, they also have some disadvantages. For example, firstly they are large and complex, and not appropriate for home rehabilitation. Secondly, they can't combine hand exoskeleton with the upper limb exoskeleton to achieve the whole-arm rehabilitation training and some hand exoskeleton devices achieve only one finger motion. Besides, they also don't analyse force impact of exoskeleton device for the whole-arm.

In this paper, based on upper limb exoskeleton rehabilitation device (ULERD), a novel hand exoskeleton device has been designed. Through finite element software ANSYS, the force influence of exoskeleton device is studied with the simulation results of the stress and displacement distributions. Finally, by using the results, the device structure is optimized, and an optimum rehabilitation training method is drafted.

II. System Structure

A. *The rehabilitation system structure*

The system mainly consists of exoskeleton device, haptic device (PHANTOM Premium), motor controllers and work station in Fig. 1.

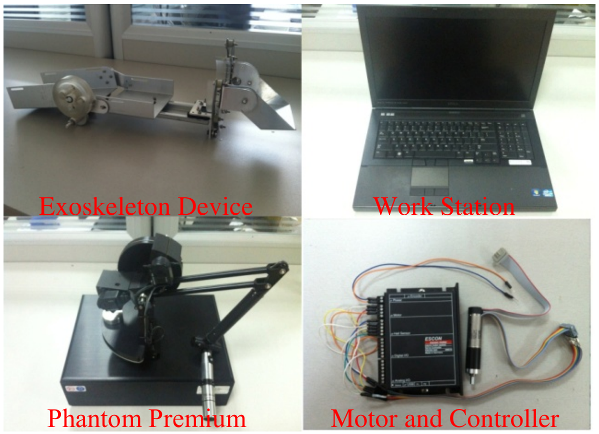


Fig. 1 The image of main parts in the rehabilitation system

The exoskeleton device is fixed on the paralysation upper limb. With the uninjured upper limb, patients change the PHANTOM Premium state to control the exoskeleton device to implement rehabilitation training (Fig.2). Meanwhile, therapist can obtain the motion information of upper limbs of patients by using inertia sensor, including Position, Velocity and Acceleration (PVA) [11]. The skin surface electromyogram (sEMG) is installed on the upper limb of patient to evaluate patient rehabilitation situation [12]. The force sensor is used to keep safety and obtain the force information in the training. By this information, therapists set up better training method for patients [13].

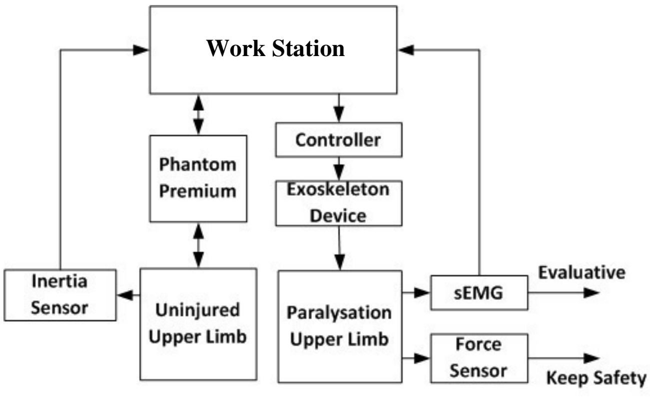


Fig. 2 The schematic of the upper limb rehabilitation system

B. *Structure and motion model of human hand*

The structure of human hand is very precise and complicated, which is mainly composed of bone, ligament, muscle, soft tissue and skin. In general, hand joint can only complete two kinds of motion, including finger flexion/extension and wrist adduction/abduction motion. The joint structure of hand is shown in the Fig. 3. Besides the thumb, the others fingers are analogous that consist of three phalanges – distal, middle and proximal phalanges, which are connected in sequence by distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint and metacarpaophalangeal (MCP) joint to metacarpal [14]. While the anatomical structure of thumb mainly consists of two phalanges, including DIP and MCP. They are connected with carpometacarpal (CMC) joint together through the metacarpal.

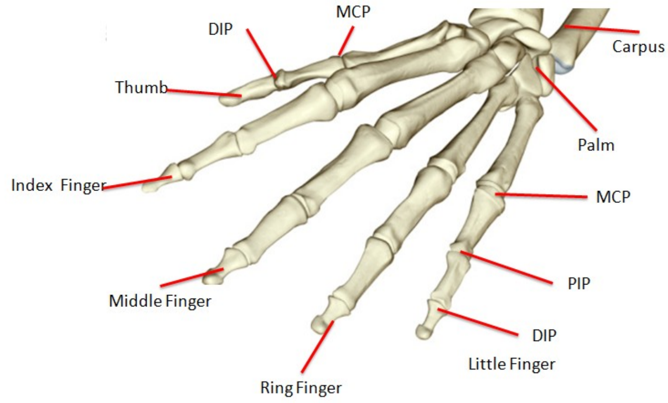


Fig. 3 The image of bones structure of human hand

Because of the complicated joint structure, the finger's kinematic model should be reasonably simplified. As shown in the Fig. 4, they are seen as the mutual movement of the index finger and thumb with open-loop type linkage mechanism. Each of the DIP and PIP has one DOF to finish flexion/extension motion, while the MCP is regarded as two independent joint with perpendicular axis and has two DOFs to finish flexion/extension and adduction/abduction motions. Accordingly some anthropometric data, the some related parameters of human hand is shown in Table I, which is used to design exoskeleton device and implement the simulation experiment [15], [16].

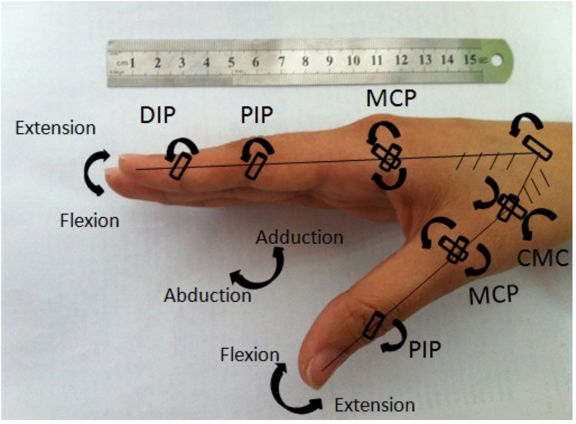


Fig. 4 The image of kinematic model of human hand

TABLE I
RELATIVE PARAMETERS OF THE HAND

	Thumb		Index Finger		
Joint	MCP	DIP	DIP	PIP	MCP
ROM (Degree)	0~50	0~80	0~80	0~100	0~85
Radius (mm)	26~29	14~17	12~15	15~17	23~26

C. The mechanical design for hand exoskeleton device

According to the clinical research, the paralysis upper limbs of patients are recovering from shoulder, followed by the upper arm and finger function recovery, with the latest. General speaking, therapist often considers the active degree of the finger joint as a recovery sign of the whole-arm motion function. However, the upper limb exoskeleton rehabilitation device doesn't achieve the movement of the fingers. So based on the ULERD, the hand exoskeleton is builded. The virtual prototype is shown in Fig. 5. The overall dimensions of the device are that the length is 120mm and the width is 83mm.

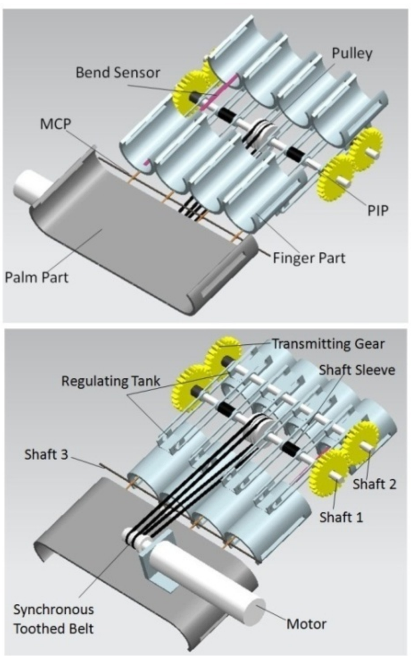


Fig. 5 The drawing of the virtual prototype of the hand device

The hand rehabilitation device mainly provides four fingers flexion/extension movement in the Fig. 6. And the Fig. 7 is shown the device flexion on the basis of the principle of linkage mechanism [17], [18]. According to ergonomic characteristics, the finger part is designed as cylinder to increase the force area for finger. The regulating tanks make finger part be adjustable for different length fingers. The transmitting gears are used to connect Shaft 1 with Shaft 2 to achieve PIP joints flexion/extension movement by the synchronous belt transmission with the BLDC (Maxon) motor on the palm part. The synchronous belt transmission is stable transmission, low friction consumption and can achieve the reciprocating motion Moreover, the quality of the motor is so light that don't increase the burden for patients. Regardless of the different PIP joints positions of each finger in the extension situation, the PIP joints are designed in a line to achieve motion. The shaft3 is used to connect hand exoskeleton with ULERD. By using the motor in the wrist joint, the finger device can achieve MCP joints flexion/extension and the whole-arm movement. Besides, some bend sensors are fixed on the exoskeleton to measure the angle changing for obtaining the motion information and keeping safety. And the skin surface electromyogram (sEMG) is mounted on the finger for evaluating the rehabilitation situation.

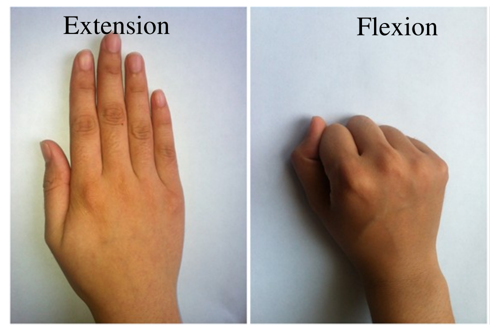


Fig. 6 The image of the work principle of the hand device

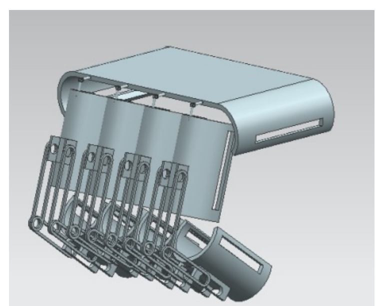


Fig. 7 The drawing of the flexion action of the hand device

D. Bending sensor

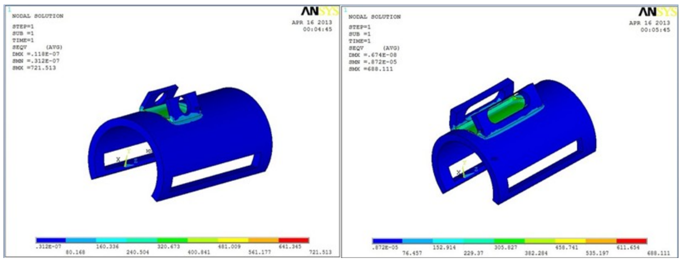
As shown in Fig. 8, bending sensor (Spectra Symbol), which consists of a flexible circuit board, force sensor, and elastic packaging materials, is connected to the signal processing circuit through a conducting wire. Through changing the curvature radius of sensor, the bending angles of single finger joint are measured.

Fig. 8 The image of the bending senor (Spectra Symbol)

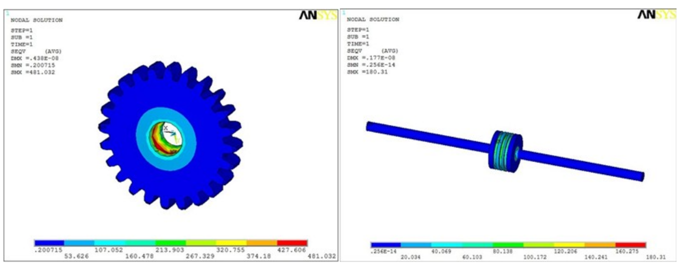
III. Experimental Setups

A. *The mechanics influence of some important components*

The driven device of the hand exoskeleton is the BLDC motor (Maxon), which is fixed on the palm part. The exoskeleton material is aluminium alloy that have some advantages, including light quality, high tensile strength and good ductility. The material property of aluminium alloy defined is EX=70GPa and PRXY=0.33. Under the action of motor, it may produce the mechanical impact for the exoskeleton device and cause the deformation and uniform stress for components. Through using the ANSYS software, some main components are simulated with a given force. The stress distribution images of components are shown in Fig. 9.



(a) Finger Part 1 (b) Finger Part 2



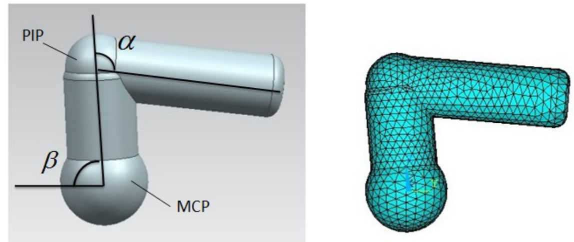
(c) Gear (d) Shaft

Fig. 9 The stress distribution of some main components

From the simulation result, it shows that the stress of finger parts mainly focus on the regulating tanks and they are enough strength to sustain patients' hands to implement rehabilitation training. Besides, it can also avoid the secondary damage for the injured hand.

B. *The mechanics influence of exoskeleton device for finger joint.*

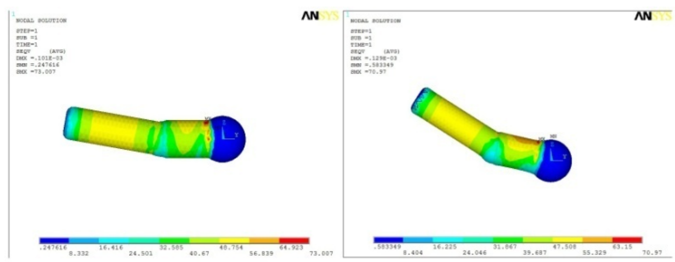
As shown in the section II, the human hand joints are complex and consist of distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint and metacarpaophalangeal (MCP) joint. Its action relies on the frictional interaction of cartilages, which can't recover and regenerate, especially the need for stroke patients. So under the frequent training action, it may accelerate loss of cartilages and the exoskeleton device should be designed to reduce the joint force [19]. In this simulation experiment, according to some related data, two cylinder models are established to simulate the human index finger and mesh the finite element (Fig. 10). The properties of bone materials defined is that EX=20MPa, PRXY=0.263 and the simulation pressure of proximal phalanx and middle phalanx is 50N [20], [21]. Besides the element type is Solid186 and the element length is 2mm. The PIP joint, proximal phalanx and middle phalanx are active, but the MCP joint is fixed. Because of the structure characteristic of the exoskeleton device, the DIP joint impact is ignored.



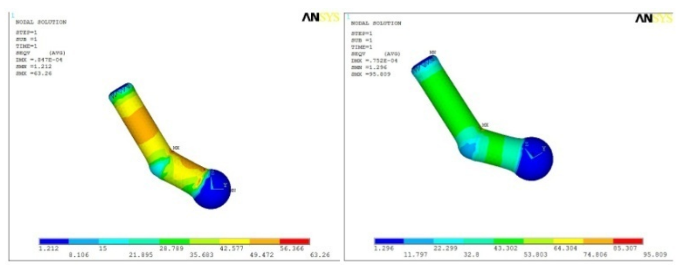
(a) The Finger Model (b) The Meshed Finger Model

Fig. 10 The image of the model of the finger

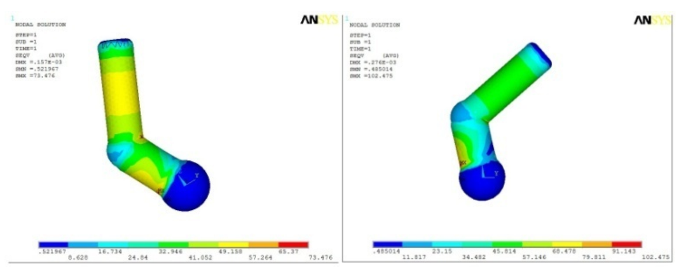
The α defined is the flexion angle of the PIP joint and the β defined is the flexion angle of the MCP joint angle. According to the clinical research, the action range of the PIP joint is the 0^o~100^o and the action range of the MCP joint is the 0^o~85^o. Using the ANSYS simulation software analyses the stress distribution of the PIP and MCP joint in the different flexion angles in Fig. 11.



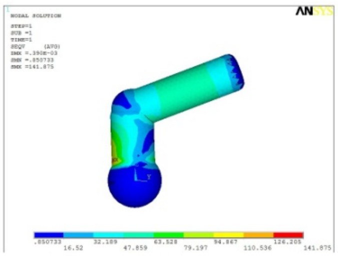
(a) $\alpha=15^o$, $\beta=0^o$ (b) $\alpha=20^o$, $\beta=15^o$



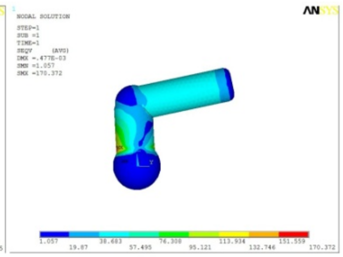
(c) $\alpha=30^o$, $\beta=30^o$ (d) $\alpha=40^o$, $\beta=45^o$



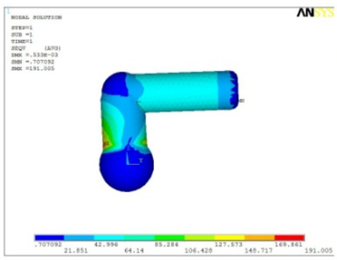
(e) $\alpha=50^o$, $\beta=60^o$ (f) $\alpha=60^o$, $\beta=75^o$



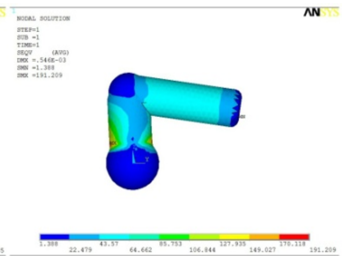
(g) α =70°, β =85°



(h) α =80°, β =85°



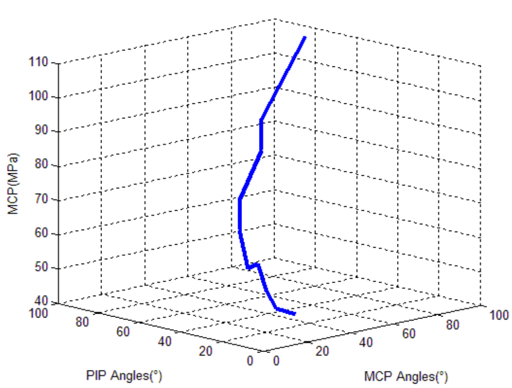
(i) α =90°, β =85°



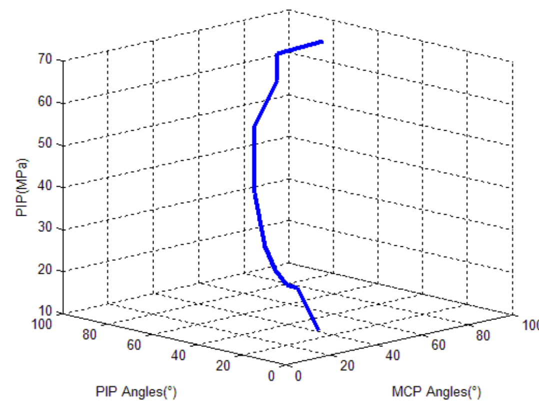
(j) α =100°, β =85°

Fig. 11 The stress distribution of the index finger in different flexion angles

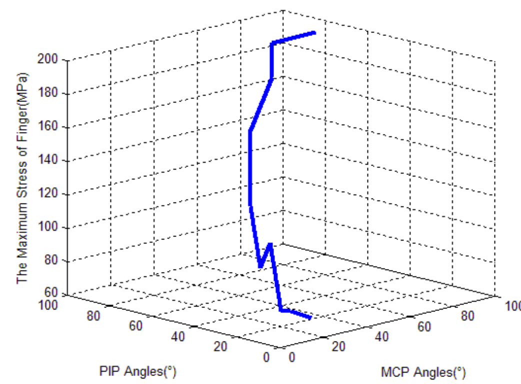
From the simulation results, as the increasing of the flexion angles of PIP joint and MCP joint, the stress in the two joints are simultaneously raised. When the α is 100° and the β is 85°, the stress in the two joints are maximum. It is that PIP joint is 64.662MPa and MCP joint is 106.844MPa. It can also been seen that when the MCP joint angle is not changing, but its stress is constantly increasing with the PIP joint rotating. So the stresses of the MCP joint and the PIP joint are interaction in the rehabilitation training. In the situation of frequent action, it can accelerate loss of cartilage so that hemiplegic patients can't have good rehabilitation effect and bring about irreparable damage. According to the simulation result, the stress curves of MCP joint, PIP joint and the maximum stress of the finger are shown in Fig. 12. From the curves images, they show that the stresses in the finger are approximately a linear relation to the joint angle.



(a) The line graph of the MCP joint stress



(b) The line graph of the PIP joint stress



(c) The line graph of the maximum stress of the index finger

Fig. 12 Images of line graph of the stress analysis

Meanwhile, the maximum stress point of hand is not at the joint, but is near to the joint position, so it should be considered that it may cause the stress increasing around the joint. When the α is 100° and the β is 85°, the stress is maximum value 191.209MPa. As shown in the simulation result, with joint angles rotating, the maximum stress is increasing rapidly, especially the α is more than 60° and the β is more than 75°. If the stress is too large, it may influence the hand rehabilitation situation and led to the patients' hands uniform stress. So according to the above analysis, the optimal activity range of exoskeleton device is proposed that the PIP joint is less than 60° and the MCP joint is less than 75°.

IV. Conclusion And Future Work

In this paper, based on the upper limb exoskeleton rehabilitation device (ULERD), a novel hand exoskeleton is proposed to help the stroke patient recovery the motor function in the finger joint. This machinery, which is connected with ULERD by Shaft 3, can achieve the four fingers joint flexion/extension movement under the motor control. It is portable and wearable for patients doing home rehabilitation training and adjustable to different hand sizes of patients. In the experiment, through using the finite element software ANSYS, it simulates and analyses the deformation and stress distribution of some main components and the force situation of the PIP joint and DIP joint in the different flexion angles. From the above researches, some conclusions are summed up as follow:

1) A novel hand exoskeleton rehabilitation based on the ULERD is presented and designed.

2) The exoskeleton device is enough strength to sustain patients' hands to implement rehabilitation training and have the ability to resist deformation.

3) The stresses of the MCP joint and the PIP joint are interaction in the rehabilitation training.

4) The optimal joint activity range of device is presented that the PIP joint is less than 60^{o} and the MCP joint is less than 75^{o}.

In the future, we will add the control method for the exoskeleton device to achieve active and passive training and select optimization training method. Meanwhile, using the ANSYS software optimizes the design of mechanism for reducing the force influence of the exoskeleton device for patients' hand so as to stimulate effectively hemiparalysis patients to recover motion function.

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