Proceeding of the IEEE
International Conference on Robotics and Biomimetics (ROBIO)
Shenzhen, China, December 2013

Modeling of Muscle Forces around the Elbow in the RITS

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***Abstract*—Muscle forces modeling and computation around the elbow are focused on in this paper when the elbow flexing and extending in the sagittal plane. The paper introduces a Rehabilitation Intelligent Training System (RITS) for restoration of motor function. The system has advantages of small size, less weight and interaction during the rehabilitation process. Furthermore, this system mainly consists of a force feedback device called PHANTOM Premium 1.5, ULERD, EEG (Electroencephalogram) based Brain-Computer Interfaces (BCI). The impaired hand wears the ULERD, so the therapist can control and move the injured hand by PHANTOM Premium in tele-operation. If the force feedback from PHAMTOM Premium is similar to the force generated by the muscle force of upper limb, the effect of upper limb rehabilitation to restore elbow motion may be suitable and satisfactory. This paper aims to computing the natural muscle forces and realizing the force which is generated by PHAMTOM and close to the computed one. Experiment has been performed to prove that the method is feasible in such robots. The development of this method can be a promising approach for further research in more effective rehabilitation to the elbow joint.**

I. INTRODUCTION

NOWADAYS there are more and more patients suffering from hemiplegia caused by stroke in China. Most of these patients can hardly move their upper limbs freely. There are two ways of upper limb rehabilitation: one is traditional, the other new. The traditional way mainly relies on the empirical of doctors. The new way always refers to the upper limb training in which rehabilitation robots assist in moving. Lots of results show that it is good for employing robots in upper limb rehabilitation process for their efficacy and economy [1]-[3].

Neuroplasticity (the brain's capacity to create new pathways) is an essential part of recovery for anyone who loses a sense or a cognitive or motor ability. For this reason, a number of researchers made efforts to contribute to the cause of development of upper limb rehabilitation by inventing many upper limb rehabilitation robots all over the world. In 2007, the MEDARM was developed by Stephen J. Ball in Queen's University [4], [5]. The robot has included actuation for both shoulder elevation/depression and retraction/protraction, allowing five degrees of freedom (DOFs) of actuated movement at the shoulder complex and one at the elbow. A new semi-exoskeleton robot with six DOFs called ARMin for arm rehabilitation has been designed by Nef in university Zurich in 2007 [6], [7]. In training process with ARMin conducted with some chronic stroke patients, improvement of motor functions were realized, such as increment in coordination of arm movements, increased range of motion (ROM) of the upper limb, enhancement of isometric muscle strength. The Maryland-Georgetown-Army (MGA) Exoskeleton, implemented by Craig Carignan in Georgetown University in 2009, had six DOFs and force/torque sensors mounted on both the upper arm and handle [8]. In 2009, Favre studied the GH-JRF calculated by their model to be estimated by the Elbow Model and pointed out that the former predicted generally higher GH-JRF during shoulder abduction [9]. In 2011, Miguel T. Silva built the muscle model that is easily adapted to connect with standard Hill-type muscle models, and solve the problems in the simulation and analysis of the redundant muscle forces. This model has particular relevance in the design of exoskeleton robot to support human locomotion and manipulation [10].In recent years, BCI (Brain-Computer Interface) systems were used in the recovery of motor function, which might provide a new means of communication for those with paralysis or severe neuromuscular disorders [11]. In 2010, researchers have found that EEG-based motor imagery BCI with robotic feedback neurorehabilitation might accelerate the recovery of motor function in stroke [12].

In China, researchers and scientists also concentrated on the researches about upper limb rehabilitation robots. A one-DOF rehabilitation robotic system with virtual environment was developed by Song Aiguo in Southeast University [13]. The actual movement was mapped to the virtual motion correctly in the virtual environment and the patient can control the virtual object through the robotic arm. Furthermore, an upper limb rehabilitation robot system based on motor imagery electroencephalography was developed [14]. Upper limb motor imagery EEG from the patient is used to control rehabilitation robot and might be effective in recovering upper limb motor function. A novel 5 DOFs exoskeletal upper limb rehabilitation robot was implemented by Sun Lining in 2009. To motivate alertness during exercise and to promote rehabilitation of an injured upper limb, a

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978-1-4799-2744-9/13/$31.00 ©2013 IEEE

control method was applied for assist action of upper limb [15]. In Taiwan's National Cheng Kung University, a rehabilitation robot with force-position hybrid fuzzy controller was designed. The robot was capable of guiding participant's wrist to move along predefined circular or linear trajectories [16].

Although lots of upper limb rehabilitation robots have been developed and are contributive to the restore of upper limbs of patients, these robots are not portable because of large bodies. There is few researches does good job combining upper limb motor imagery EEG with Surface electromyogram (sEMG) and the force model cannot mimic the real forces of muscle during training. In this paper, a robot system named Rehabilitation Intelligent Training System (RITS) has been designed in our lab to make attempt to solve some existing problems mentioned above.

II. EXPERIMENTAL SYSTEM

A. *Overview of the robot System*

The experimental robot system RITS designed in our study mainly consists of a fore feedback device called PHANTOM Premium 1.5, ULERD, EEG based Brain-Computer Interfaces (BCI). The upper limb rehabilitation robot system is a master-slave system, allowing doctors and patient interaction with a virtual reality environment respectively (Fig. 1). Unlike robots mentioned above, RITS tend to have a comprehensive influence on the motor function area for upper limbs.

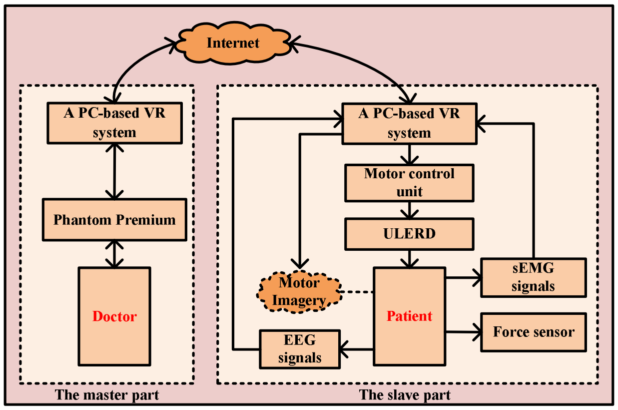

Fig.1 Block diagram of the upper limb rehabilitation robot system RITS.

To provide patients with a contextually enriched feedback, a hybrid BCI (EEG + sEMG) with multimodal feedback generated by the actual movement of the affected hand are adopted in the system. The EEG signals are acquired from the many electrodes dressed on patients' brains by BCI to control the ULERD to implement the training. Meanwhile, the sEMG signals are got from patient's upper limbs by using a EMG sensor (BioVision, Inc.), to evaluate the rehabilitation information of patients. According to the information, doctor formulates efficient rehabilitation method.

The upper limb rehabilitation robot system RITS composition is showed in Fig. 2. The impaired hand should hard bolted to the ULERD, so the rehabilitation therapist or the intact hand of patient himself can move the stylus of PHAMTOM Premium and guide the injured hand to move along certain of predefined training track [17].

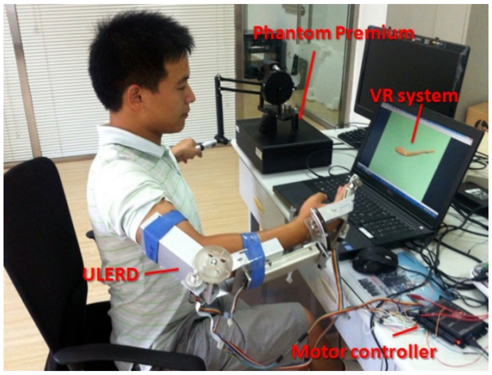

Fig.2 The upper limb rehabilitation robot system RITS composition

B. *Haptic Device (PHANTOM Premium)*

The PHANTOM Premium 1.5 (SenSable Technologies) has been widely applied to many field. As a master part, PHANTOM Premium 1.5 can provide force feedback successfully to the manipulator (Fig. 3). The programmable force feedback and large workspace (19.5x27x37.5cm) is features of the product. The arm and each joints of PHANTOM Premium move with the stylus operated by doctor. With this operation, 6-DOF position and orientation are obtained by PHANTOM Premium in real time.

Fig.3 PHANTOM Premium1.5 haptic device（SenSable Technologies）

C. *The Upper Limb Exoskeleton Rehabilitation Device (ULERD)*

ULERD has three active DoFs including the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension in elbow and wrist joint. As a slave part, the motivation of designing such device is to provide effective training to the patients with motor dysfunction to re-learn their motor function. Design process of ULERD can be obtained in detail from reference [18]. The structure of the ULERD from upper view is showed in Fig. 4. Furthermore, ULERD is also a hand rehabilitation device which has been developed for finger movements [19]-[21].

Meanwhile, due to comfortable and portable for home-rehabilitation to patients, decreasing the mass of such device as light as possible is in need. For this reason, BLDC motor (Maxon Technology) is used for its high power density. Meanwhile, main parts of this device are made of aluminum board. The total weight is only 1.3kg.

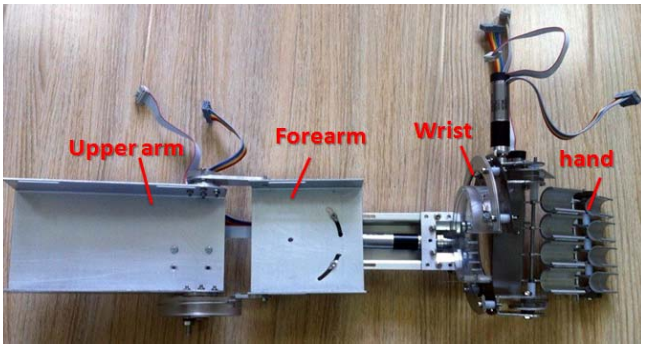

Fig.4 The prototype of the upper limb exoskeleton rehabilitation device

III. MUSCLE FORCE MODELING IN THE ELBOW JOINT

In this section, muscle forces modeling and computation in the elbow joint are focused on when the elbow flexing and extending in the sagittal plane. If the force feedback from PHAMTOM Premium is close to the natural force, the effect of upper limb rehabilitation to the elbow joint is suitable and satisfactory. In order to realize the aim, human muscle force modeling located the elbow joint is essential. Considering security reasons, the speed of flexion and extension motion of the elbow joint should be low during the upper limb rehabilitation process. Therefore we assume that the speed in the model is less than 0.025 rad/s (1.433°/s).

A. Model Equation

On the basis of the principle of anatomy, the basic muscles in the elbow joint include biceps brachii (BIC), brachialis (BRA), brachioradialis(BRD), pronator teres (PRT), triceps brachii (TRI). Among them, BIC, BRA, BRD, PRT are flexor muscles and TRI is extensor muscle.

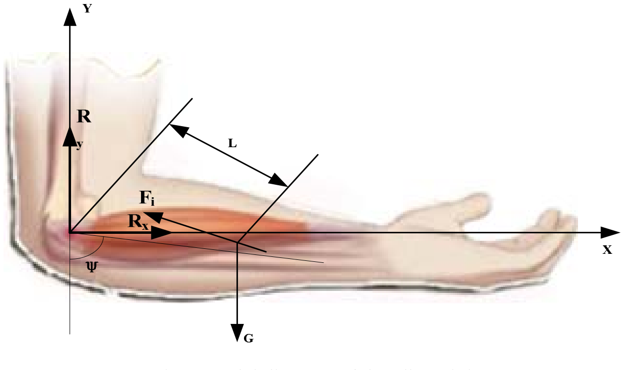

Fig.5 Model diagram of the elbow joint

Model diagram of the elbow joint is given in Fig. 5.The picture shows that humerus, ulna and radius are considered as rigid bodies. Humerus is immobile while ulna and radius flexing and extending in the sagittal plane. The plane of motion is the X-Y plane, the Z axes is perpendicular to the X-Y plane.

According to d'Alembert principle, the equations of motion of the upper arm and forearm are

$$\sum_{i}^{6} M_O(\vec{F}_i) + M_O(\vec{G}) - I_{zz}\ddot{\psi} = 0 \tag{1}$$

$$\sum_{i}^{6} \vec{F}_i + \vec{R} + \vec{G} - m\vec{a} = 0 \tag{2}$$

where $\vec{F}_i$ (i=1,2,⋯5) is the modeled muscle forces, m and G are the mass and gravity force of forearm, $M_O(\vec{F}_i)$ is the moment of the force about the centre point O, ψ is the angle of forearm during flexion and extension, $\vec{a}$ is the linear acceleration, $\vec{R}$ is the joint reaction, I_{zz} is the moments of inertia of forearm with respect to the Z axes.

An objective function dependent on the n-th power of the muscle forces moduli: $\sum |\vec{F}_i|^n$ (n > 1) is proposed in the reference [22]. For simplifying the solving of muscle force computing, n is equal to 2 in this paper.

In order to calculate strictly positive forces for these six muscles, the unkown terms are given as follows.

$$|\vec{F}_i| = x_i^2 (i = 1,2,...,5) \tag{3}$$

$$\begin{cases} |\vec{R}_x| = x_7 \\ |\vec{R}_y| = x_8 \end{cases} \tag{4}$$

where R_x and R_y is a an x component and a y component of the joint reaction respectively.

From (1) and (2), (5) is obtained easily as follow.

$$\sum a_{1i} x_i^2 = A_1$$
$$A_1 = I_{zz}\ddot{\psi} - |\vec{G}| \bullet d\vec{G} \tag{5}$$

where a_{1i} is the arm of force $\vec{F}_i$, and A_1 is the moment of the force, $d\vec{G}$ is the arm of the force G .

And equations can also be obtained as follow

$$\sum a_{ci} x_i^2 + x_7 = A_2 \tag{6}$$

$$\sum a_{si} x_i^2 + x_8 = A_3 \tag{7}$$

where a_{ci}=cos(α), a_{si}=sin(α), α is the angle between $\vec{F}_i$ and the x axes.

Because the relation between a and ψ is

$$a_x = \frac{dv_x}{dt} = \frac{d(L\dot{\psi}\cos\psi)}{dt} = L(\ddot{\psi}\cos\psi - \dot{\psi}^2 \sin\psi) \tag{8}$$

$$a_y = \frac{dv_y}{dt} = \frac{d(L\dot{\psi}\sin\psi)}{dt} = L(\ddot{\psi}\sin\psi - \dot{\psi}^2 \cos\psi) \tag{9}$$

where L is the distance between point O and forearm.

So A_2 and A_3 can be calculated as follows.

$$A_2 = ma_x = mL\left(\ddot{\psi}\cos\psi - \dot{\psi}^2 \sin\psi\right) \tag{10}$$

$$A_3 = ma_y - \left|\vec{G}\right| = -mL\left(\ddot{\psi}\sin\varphi + \dot{\psi}^2 \cos\psi\right) - \left|\vec{G}\right| \tag{11}$$

B. Model Optimization

Because L, m, G and ψ can be measured directly, these parameters is used as known quantities. So A_1, A_2 and A_3 are obtained from (5), (10), (11), the muscle forces and the joint reactions are unknown. Furthermore, if the muscle forces are computed successfully, the joint reactions are also obtained from (6) and (7). In a word, the muscle forces computation is essential in the modeling of the elbow joint muscles.

The approach using the following optimization criterion is applied to realize model optimization.

$$Z = \sum c_i \left(x_i^2\right)^2 = \sum c_i \left|\vec{F}_i\right|^2 \tag{12}$$

where c_i are the weight coefficients. The weight coefficients at extensor muscles TRI should be negative, while at flexor muscles BIC, BRA, BRD, PRT the weight coefficient should be positive.

The Lagrange multipliers method is applied in the model to realize optimizing. An optimization of the Lagrange function is given as follow.

$$L(x_1, x_2, \ldots, x_6) = Z(x_1, x_2, \ldots, x_6) - \lambda\left(\sum a_{1i} x_i^2 - A_1\right) \tag{13}$$

where λ is a Lagrange multiplier.

Then considering the conditions

$$\partial L / \partial x_i = 0 \ \left(i = 1,2,\ldots,5\right) \tag{14}$$

Therefore Six muscle forces located the elbow joint are finally obtained when the speed of flexion and extension motion of the elbow joint is less than 0.025 rad/s (1.433°/s).

$$\left|\vec{F}_i\right| = x_i^2 = \frac{A_1\left(a_{1i} / c_i\right)}{\sum a_{1i}\left(a_{1i} / c_i\right)} \qquad \left(i = 1,2,\ldots,5\right) \tag{15}$$

Based on the results, the joint reaction is also obtained as follows.

$$\left.\begin{aligned} \left|R_x\right| &= \mathrm{x}_7 = A_2 - \sum \mathrm{a}_{\mathrm{ci}} \left|\vec{F}_{\mathrm{i}}\right| \\ \left|R_y\right| &= \mathrm{x}_8 = A_3 - \sum \mathrm{a}_{\mathrm{si}} \left|\vec{F}_{\mathrm{i}}\right| \end{aligned}\right\} \tag{16}$$

C. Calculation Examples

A member (man) in our lab takes part in the computing process of muscle forces, whose weight and height are 65kg and 172 cm respectively. According to reference [23], regression equation to compute the mass of a forearm is

$$m = -0.277 + 0.016 \times x_1 + 0.0001 \times x_2 \tag{17}$$

where x_1 and x_2 are the weight (in kg) and height (in mm) of man.

So the mass of a forearm is calculated by (17) and it is equal to 0.78kg and the gravity force of forearm is

$$G = mg = 0.78kg \times 9.8N / kg = 7.65N \tag{18}$$

As mentioned above, the weight coefficients at flexor muscles should be negative ($c_1 = c_2 = c_3 = c_4 = 1$), while the weight coefficient at extensor muscles should be positive ($c_5 = -1$).

According to Reference [24], the muscle's moment arm at the elbow joint is given by a polynomial of the form:

$$a_{1i} = a_0 + a_1\psi + a_2\psi^2 + a_3\psi^3 + a_4\psi^4 + a_5\psi^5 \tag{19}$$

where ψ is in radians and moment arm in cm. A positive moment arm is an elbow flexion moment arm. The elbow angle ψ is considered as 0 in the fully extension and goes positive as it is flexed.

TABLE I gives the polynomial coefficients for the muscle moment arms for elbow flexion/extension.

TABLE I

POLYNOMIAL COEFFICIENTS FOR THE MUSCLE MOMENT ARMS

muscle	a_0	a_1	a_2	a_3	a_4	a_5
BIC	1.963	-1.440	3.031	0.887	-1.418	0.285
BRD	2.015	-0.458	3.058	-1.081	0.159	-0.0187
PRT	0.682	-0.459	1.266	-0.356	-0.149	0.0468
BRA	1.554	0.0813	-1.689	3.523	-1.811	0.276
TRI	-2.365	-1.015	1.920	-1.035	0.257	-0.0262

The speed of flexion and extension motion of the elbow joint is less than 0.025 rad/s (1.433°/s), so as to guarantee the safety of the upper limb rehabilitation process. The acceleration could be ignored and further simplifies the computation of A_1, A_2 and A_3. Therefore, (20) is given from (5), (10) and (11).

$$\left.\begin{aligned} A1 &= -\left|\vec{G}\right| \bullet \mathrm{d}\vec{G} \\ A_2 &= 0 \\ A_3 &= -\left|\vec{G}\right| \end{aligned}\right\} \tag{20}$$

TABLE Ⅱ gives values of each muscle moment arms by using (19) when ψ is 15°,⋯, 120°.

TABLE Ⅱ

VALUES OF EACH MUSCLE MOMENT ARMS (CM)

muscle	15°	30°	45°	60°	75°	90°	105°	120°
BIC	1.80	2.07	2.68	3.45	4.19	4.71	4.86	4.59
BRD	2.09	2.48	3.10	3.89	4.77	5.69	6.59	7.42
PRT	0.64	0.73	0.89	1.06	1.19	1.25	1.19	1.02
BRA	1.51	1.51	1.68	2.00	2.41	2.78	2.99	2.96
TRI	-2.52	-2.50	-2.39	-2.24	-2.07	-1.92	-1.79	-1.69
dG	-3.89	-7.52	-10.60	-13.00	-14.5	-15.0	-14.50	-13.00

TABLE Ⅲ gives the values of muscle forces through using TABLE Ⅱ and (15) when ψ is 15°,⋯, 120°.

TABLE III

UNITS FOR MAGNETIC PROPERTIES (N)

muscle	15°	30°	45°	60°	75°	90°	105°	120°
BIC	13.50	17.10	15.01	12.92	11.10	9.44	7.80	6.11
BRD	15.61	20.39	17.23	14.28	12.25	10.90	9.95	9.10
PRT	4.80	6.01	4.98	3.97	3.16	2.50	1.91	1.36
BRA	11.33	12.50	9.40	7.49	6.39	5.57	4.80	3.93
TRI	18.83	20.64	13.40	8.36	5.49	3.85	2.87	2.25

The Line graph standing for the relation between muscle forces and elbow angle computed by (15) and (19) are showed in Fig. 6. Each muscle force drops after rising with the increasing of elbow angle.

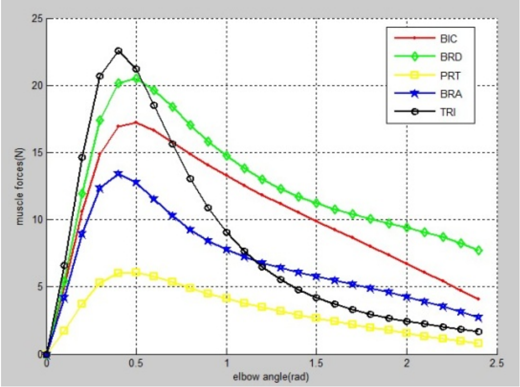

Fig.6 The relation between muscle forces and elbow angle

IV. EXPERIMENTAL RESULTS

The force is generated by PHANTOM and measured by the traditional spring-type dynamometer. Considering the maximum exertable force, the experiment results about realization of muscle force generated PRT are shown in this section. The force feedback from PHAMTOM Premium is generated by programming and the aim is to close to the natural force generated by the muscle PRT .The true force and computed force in the muscle force modeling is shown respectively in Fig. 7.

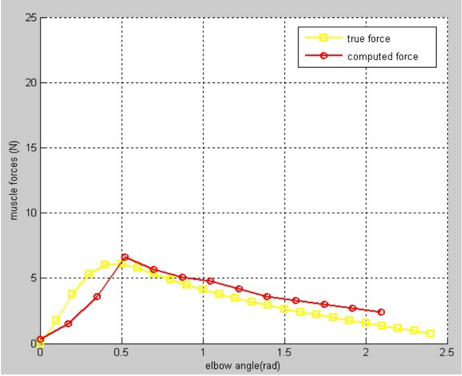

Fig.7 Line graph of muscle force

The vertical axis stands for the muscle force, and the horizontal axis stands for elbow angle. The yellow line represents the true force and the red line represents computed force in the model. The true force is close enough to the computed force in the model. Therefore, the force generated by PHANTOM can provide the natural muscle forces approximately. So the goal we proposed is achieved.

V. CONCLUSION

In this paper, a Rehabilitation Intelligent Training System (RITS) which possessed PHANTOM, ULERD, EEG based BCI was introduced. Muscle forces modeling and computation located the elbow joint were concentrated on when the elbow flexing and extending in the sagittal plane. The speed in the rehabilitation process is less than 0.025 rad/s (1.433°/s) for security reasons.

In order to program and generate the force similar to natural muscle forces through the force feedback device PHANTOM, muscle forces modeling and computation was necessary and essential to obtain the natural force values. The following conclusions can be drawn:

1) Muscle forces in the elbow joint were obtained successfully through muscle forces modeling and computation. The force close to natural muscle forces has been realized by force feedback of the device PHANTOM.

2) Experiment had been carried out to prove that the method is feasible in such robots.

The muscle force computation and modeling provided the force information of muscles in the elbow joint. The force generated by BLDCM (brushless DC motor) in the ULERD to approach the natural muscle forces should take into consideration in the future.

ACKNOWLEDGMENT

This research is supported by Tianjin Key Research Program of Application Foundation and Advanced Technology (the Natural Science Foundation of Tianjin) and National Undergraduate Training Programs for Innovation and Entrepreneurship (201310060034).

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