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Robot-aided Rehabilitation Task Design For Inner Shoulder Muscles

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Abstract— **In this paper, we propose a simultaneous design method of motion and external force trajectories for shoulder inner muscles in the robot-aided rehabilitation system, based on a biomechanical analysis of patient's body. The rehabilitation efficiency evaluation function was maximized by Genetic Algorithm (GA), where the structure of spline curves parameters are pre-defined, and the structural parameters are explored to design smooth rehabilitation motion and external force trajectories.**

I. Introduction

For inner muscles rehabilitation, open kinematic chain exercises by using thera-band and rubber band and closed kinematic chain based on the constrained motion of a rehabilitation system have been reported [1-2]. These studies evaluated the rehabilitation effects of the tracking motion trajectory, based on a biomechanical analysis of human body and showed that the efficiency and safety of the rehabilitation therapy can be improved significantly if the rehabilitation procedure includes precise motion trajectory and external force trajectory. Such enhanced therapeutic effect can be achieved with the usage of robot-aided rehabilitation systems that can generate trajectories and forces in full consideration of the symptomatic state and damaged segment of the patient.

Pei et al. presented a sequential design method of 3 dimensional motion trajectory and external forces trajectory generated by robot-aided rehabilitation system for lower limbs rehabilitation in [3], where rehabilitation efficiency evaluation function was maximized to design the rehabilitation motion, and then external forces were determined in order that the constraints related to each joint's range of motion and each muscle's maximal muscle force may be satisfied. But the designed trajectories and external forces were not optimized in the same planning stage. In this study, we propose a simultaneous design method of motion and external force trajectories for a shoulder inner muscles' robot-aided rehabilitation system based on biomechanical analysis of a patient's body. The rehabilitation efficiency evaluation function was quasi-optimized by Genetic Algorithm (GA) for design of both rehabilitation motion and external force trajectories. In order to yield a practical application of robot-aided rehabilitation system, smooth rehabilitation motion and external force trajectories are desirable. In this study, structures of spline function based motion and force trajectories are first pre-defined in consideration of sufficient motion degree-of-freedom, and then their parameters were searched by GA so that both trajectories are optimized in the same planning stage. The computational results show that the rehabilitation motion and external force trajectories were successfully obtained without violating any constraint, and improved rehabilitation efficiency was improved. This implies that the developed trajectories are safe from the biomechanical viewpoint in full consideration of each joint's torque, each muscle's force, and each joint's reaction force.

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II. Upper limb musculoskeletal model

A. *Mechanism of shoulder joint motion*

Shoulder motions for flexion/extension, abduction/adduction, and outward/inward rotation are concerned with humerus, scapular, and clavicle. The coordinated motion between humerus and scapular was called scapulohumeral rhythm by Codman [4]. The coordinated motion was further investigated in [5], where in "setting phase" of shoulder motion that is confined to less than 60 degree in flexion motion and 30 degree in abduction motion, Inman et al. insisted that the rotation angles of glenohumeral and scapulothoracic joints coordinate by 2:1 ratio, and scapular motion in setting phase becomes stable. In 1976, Poppen [6] pointed out that scapular has compound 3 dimensional motion. However, the scapular's motion has not been accurately verified yet. For development of reliable rehabilitation motion, therefore, we confined shoulder angle to have smaller than 60 degree in flexion motion and 30 degree of abduction motion in this study.

B. *Upper limb musculoskeletal model*

Kizuka [7] investigated the activities of shoulder muscles based on the analysis of electromyographic signals during adduction/abduction motion and outward/inward rotation motion of shoulder from 0 degree to 120 degree, respectively. Subjects were laid on their backs, and the load acting on shoulder was increased by 2Nm up to 20Nm using a dynamometer. When the load was smaller than 10 Nm, the outward motion when the rotation angle was smaller than 45 degrees, and the abduction motion when the rotation angle was smaller than 30 degrees, the activities of inner muscles were strong. This result shows that when the motion angle is smaller and the load is lower in both outward rotation and abduction of the shoulder, inner muscles are well-trained.

Therefore, in this study, we first determine shoulder motion range in which the scapular can be assumed to be stationary. By developing the shoulder rehabilitation motion in consideration of the scapular's stationery motion range, we can reduce uncertainty in identification of scapular motion. We developed an upper limb musculoskeletal model shown in

Fig.1, where shoulder has 3 degree of freedom (DoF), elbow has 1 DoF, and wrist has no DoF. Figure 2 shows the muscles modeled in the developed upper limb musculoskeletal model.

III. SIMULTANEOUS DESIGN OF REHABILITATION MOTION AND EXTERNAL FORCES TRAJECTORIES

A. Design of joint trajectories for rehabilitation motion

In this study, we assume that joint angles are changing on a smooth and cyclic manner and each joint angle is constrained between its upper bound θ_{imax} and lower bound θ_{imin} . The rehabilitation cycle T is considered as composed of two sections, named here as section 1 and section 2. During the time interval $0 \le t \le$ ti,1 , the joint angles θ_i increase. Section 2 is for $t_{i,1} \le t \le T$, where the joint angle decreases from to θ_{imax} to θ_{imin}.

In this example, for simplicity the joint angle in each section is represented by a fifth order polynomial function as follows:

$$\theta_{i,j}(t) = a_{i,j}(t-hT)^5 + b_{i,j}(t-hT)^4 + c_{i,j}(t-hT)^3 + d_{i,j}(t-hT)^2 + e_{i,j}(t-hT) + g_{i,j} \quad (1)$$

where, i is joint number as shown in Fig.1, j is the time section (j =1 or 2), T is the period of the cyclic joint motion, and h is the iteration number of the cycle. The angle of i-th joint at t= $t_{i,1}$ is $\alpha_i = \mathrm{sgn}(\theta_i)\max|\theta_i|$. Joint constrains are specified with (2) and (3) below:

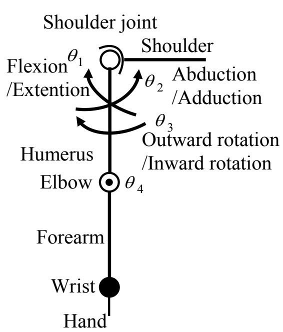

Fig.1 Upper limb musculoskeletal model

$$\theta_{i\min} \le \alpha_i \le \theta_{i\max} \quad (2)$$

$$|\theta_i(t)| \le |\alpha_i| \quad (3)$$

The maximum joint movement velocity can be represented as follows:

$$\dot{\theta}_{i\min} \le \dot{\theta}_i(t) \le \dot{\theta}_{i\max} \quad (4)$$

In order to achieve a smooth transition between the sequential sections, we assume that the angle and the speed at the end of the previous section is the same as the angle and the speed at the beginning of the next interval. That leads to the following initial conditions:

at t=0,

$$\theta_{i,1}(0) = g_{i,1}, \quad \dot{\theta}_{i,1}(0) = 0,$$

at t=$t_{i,1}$,

$$\theta_{i,1}(t_{i,1}) = \alpha_i, \quad \theta_{i,2}(t_{i,1}) = \alpha_i,$$

$$\dot{\theta}_{i,1}(t_{i,1}) = \dot{\theta}_{i,2}(t_{i,1}), \quad \ddot{\theta}_{i,1}(t_{i,1}) = \ddot{\theta}_{i,2}(t_{i,1})$$

at t=T,

$$\theta_{i,2}(T) = g_{i,2}, \quad \dot{\theta}_{i,2}(T) = 0,$$

$$\ddot{\theta}_{i,1}(0) = \ddot{\theta}_{i,2}(T), \quad \theta_{i,1}(0) = \theta_{i,2}(T).$$

Under the above specified conditions, the problem considered in this study is transformed into a search problem of α_i, T, $t_{i,1}$, $d_{i,1}$ and $d_{i,2}$. In addition to that, the above-indicated initial conditions maximize the performance function as shown in Section IV.

B. Design of external force in robot-aided rehabilitation

In spherical polar coordinates, external force acting on the end-effecter, that is, patient's hand, can be represented by $F_{ext}(t)$, $\beta(t)$, $\gamma(t)$, where $\beta(t)$ is the angle between external force and z axis and $\gamma(t)$ is the angle between the projection in x-y plane of external force and z axis. Since the external force $F_{ext}(t)$ should be a smooth periodic function, we used a fifth-order polynomial function as follows:

$$F_{ext} = a_{ext}(t-mT)^5 + b_{ext}(t-mT)^4 + c_{ext}(t-mT)^3 + d_{ext}(t-mT)^2 + e_{ext}(t-mT) + g_{ext} \quad (5)$$

In a similar way to the design of rehabilitation motion trajectory, we have 7 parameters to search, that is, a_{ext}, b_{ext}, c_{ext},

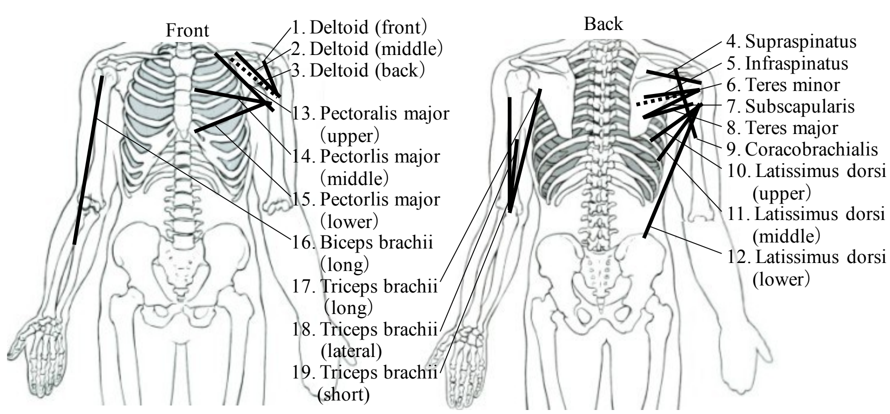

Fig.2 Muscles modeled in the developed model

d_{ext}, d_{ext}, g_{ext}, T. Here, T was considered in (1). For smoothing external force trajectory, we put following constraints.

at $t=T$,

$$F_{ext}(0) = F_{ext}(T)\ ,\ \dot{F}_{ext}(0) = \dot{F}_{ext}(T)\ ,\ \ddot{F}_{ext}(0) = \ddot{F}_{ext}(T)$$

Since we have above-mentioned three constraint conditions and 6 unknown parameters (a_{ext}, b_{ext}, c_{ext}, d_{ext}, d_{ext}, g_{ext}), we need to search three parameters among them which decide the other parameters automatically.

IV. GA BASED PARAMETER SEARCH FOR REHABILITATION MOTION AND EXTERNAL FORCE DESIGN

We verified the proposed approach for a simultaneous design of motion and external force trajectories by an example where a genetic algorithm approach was used for searching the pre-defined structural parameters of rehabilitation motion and external force trajectories.

A. Evaluate function

In order to compare the performance of the system and external force trajectories for each set of parameters generated by the GA, we introduced a performance criterion that takes into account the effect of the muscle loading and the values of jerk and joint torque changes. Jerk and joint torque change during robot-aided rehabilitation motion and their minimization leads to smooth joint trajectory. They are expressed in the following way:

$$E_\theta = \frac{1}{2}\int_{t_0}^{t_f} \sum_{i=1}^{7} \left(\frac{d^3\theta_i(t)}{dt^3}\right)^2 dt \tag{6}$$

$$E_\tau = \frac{1}{2}\int_{t_0}^{t_f} \sum_{i=1}^{7} \left(\frac{d\tau_i(t)}{dt}\right)^2 dt \tag{7}$$

The effect of the muscle loading during the rehabilitation movement can be evaluated with the integral of the generated muscle forces over the training time:

$$E_f = \int_{t_0}^{t_f} \sum_k f_k(t) dt \tag{8}$$

For the design of the motion and the external force applied to the arm we use an evaluation function E which is the weighted sum of the above-specified three indices (6), (7), and (8). The function E is given by the following equation:

$$E = E_f - k_1 E_\theta - k_2 E_\tau \tag{9}$$

As determined in (9), E maximizes if the muscle force is maximized and the components for jerk and torque change in each joint have minimum values. In order to obtain the parameters k_1 and k_2, we used a trial-and-error method as follows: we first obtain the absolute value of each term by preliminary simulation, and then decide the weight coefficients by making the sum of the absolute values of the latter terms equivalent to the absolute value of the first term. Therefore, the simultaneous design problems of motion trajectory and external force can be transformed into a parameter search problem.

B. GA-based rehabilitation motion design algorithm

In our example, the GA-based design algorithm for rehabilitation motion and external force trajectories comprises the following steps:

Step1: The trajectory of the joint angle $\theta_i(t)$ (i=1,2,3) is represented by the motion trajectory parameters $d_{i,1}$, $d_{i,2}$, $t_{i,1}$, α_i, T, and the trajectory of external force that can be defined by $F_{ext}(t)$, $\beta(t)$, $\gamma(t)$ is represented by the external force parameters a_{ext}, b_{ext}, c_{ext}, a_β, b_β, c_β, a_γ, b_γ, c_γ. In the developed GA, a set of the values of each of these parameters is defined as a gene.
Step2: The number of the individual genes as P.
Step3: Inverse dynamics approach is used for calculation of the joint torque, $\tau(t)$, muscle force, $f_k(t)$, and shoulder joint reaction force, $F_s(t)$ of each individual. Criterion (9) is used for evaluation of the system performance.
Step4: New individuals are generated by crossover and mutation. The crossover rate and mutation rate are set to 0.25 and 0.01 respectively. Calculate the evaluation values of the new individuals by using (9).
Step5: All individuals are listed in ascending order depending on their evaluate values and P individuals, which evaluation values are higher than the others are selected. The selected individuals define the individuals for the new generation.
Step6: Steps from 3 to 5 are repeating until the variation of the evaluation values of (9) remains sufficiently small for consecutive 5 generations.

V. SIMULATION RESULTS

In this section, we show the simulation results obtained by the proposed design method of rehabilitation motion and external forces trajectories for shoulder inner muscle rehabilitation in which the scapular is stationary.

A. Simulation conditions

For rehabilitation of shoulder inner muscles, inward/outward rotation motion and abduction/adduction motion are known to be efficient. For efficient realization of shoulder inward/outward rotation and abduction/adduction motions in robot-aided rehabilitation systems, elbow and wrist joints should be fixed. In this simulation, therefore, elbow joint was fixed to 90[deg], and the palmar flexion/extension, pronation/supination, radial flexion/extension of wrist joint were fixed to 0[deg] respectively. The other constraint conditions in parameter search problem are shown in table 1.

Table I . Constraint conditions

Flexion and extention range of shoulder joint	$-60 \le \theta_1 \le 0$[deg]
Abduction range of shoulder joint	$0 \le \theta_2 \le 30$[deg]
Outward rotation range of shoulder joint	$0 \le \theta_3 \le 90$[deg]
Inward rotation range of shoulder joint	$-90 \le \theta_3 \le 0$[deg]
Angular velocity range of each joint	$-60 \le \dot{\theta}_i \le 60$[deg/$s$]
External force acting on hand	$F_{ext}(t) \le 200[N]$
Training cycle	$0 \le T \le 10[s]$

B. Computational result for rehabilitation

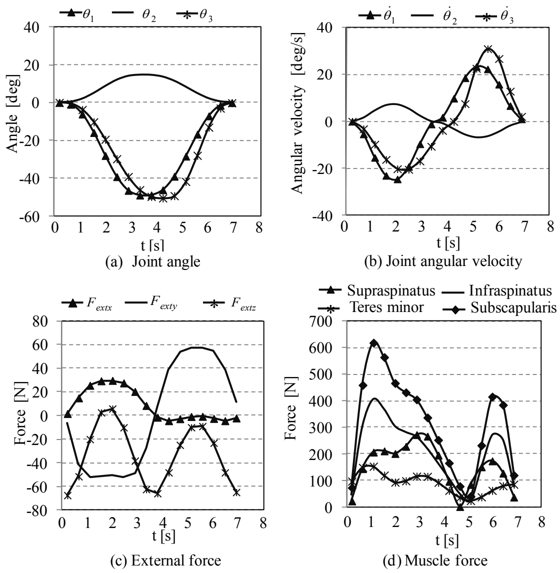

Fig.3 Calculate results

We show the computational results of robot-aided rehabilitation motion in Fig.3. For the trajectories of each joint angle, the angular velocities are shown in Fig. 3-(a), and 3-(b), respectively. The external force rehabilitation motion trajectory and external force trajectory that are acting on the contact point to the robot and inner muscle forces are shown in Figure 3-(c) and 3-(d), respectively. Fig. 4 shows a 3 dimensional trajectory of upper limb and external force. The designed motion trajectory forms smooth closed curve.

In Fig. 4-(a), the designed robot-aided rehabilitation motion is combined with flexion, abduction, and inward rotation motion of shoulder. The external force to the direction of positive x axis assists the shoulder to flex. The external force to the direction of positive y axis generates adduction torque of shoulder, which helps supraspinatus muscle easily generate muscle force for abduction motion. In this period, subscapularis muscle is doing concentric training. supraspinatus muscle is doing concentric training. On the other hand, the external force to the direction of positive z axis generates abduction motion, which helps subscapularis muscle easily generate muscle force for adduction. The designed robot-aided rehabilitation motion in Fig. 4-(b) contains a combination of extension, adduction and external rotation motion of shoulder. In extension motion, the external force to the direction of positive x axis approaches to 0, and the action of gravity helps the shoulder easily extend. In the adduction motion, positive x axis approaches to 0, and action of gravity helps the shoulder easily extend. In the adduction motion, the external force to the direction of negative y axis generate adduction torque, which assists shoulder to adduct, as supraspinatus muscle was kept stretching. In this period, supraspinatus muscle is doing eccentric training. In abduction motion, infraspinatus muscle and teres minor muscle contract to generate muscle forces, which helps shoulder easily rotate to the outward direction. The external force to the positive z axis generates abduction torque, which helps subscapularis muscle easily generate muscle force, as subscapularis muscle was kept stretching. In this period, subscapularis muscle is doing eccentric training.

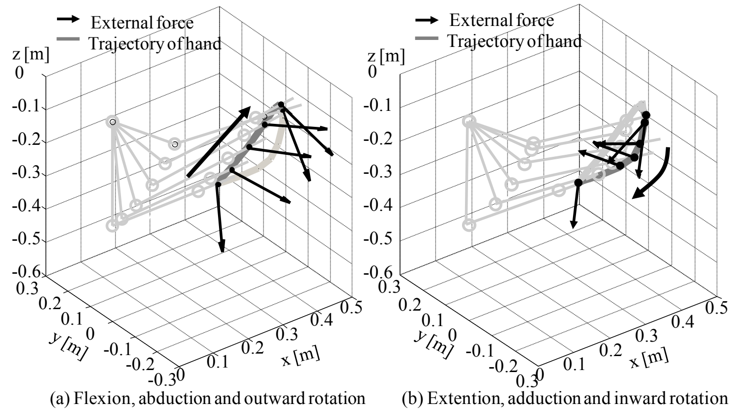

Fig.4 External force and motion trajectory of hand

VI. CONCLUSION

In this paper, we have proposed a simultaneous design method of motion and external force trajectories for shoulder inner muscles rehabilitation. We developed a 3D musculoskeletal model around shoulder and in upper limb that consists of 4 bones and 19 muscles. The number of the active DOF of the shoulder joint in the developed model was limited to 3, which is smaller than the actual motional DOF. The model was used for the calculation of the motions and forces of the robot that will generate joint motions and muscle forces as needed for the rehabilitation process. Proposed method is a model-based and allows changing the parameters of the musculoskeletal model. Individual set of joint motion and external force trajectories for shoulder inner muscle rehabilitation can be adapted easily to match the patient characteristics. During the robot motion, each joint angle and external force change smoothly within their bounds. A Genetic Algorithm-based example for searching the parameters of the rehabilitation motion and external force trajectories of the robot is presented.

References

[1] Wilk KE, Arrigo CA, et al., “Closed and open kinetic chain exercise for the upper extremity”, *Journal of Sport Rehabilitation*, Vol.5, pp.88-102, 1996.

[2] Kibler WB, “Rehabilitation of rotaror cuff tendinopathy”, *Clinics in Sports Medicine*, Vol.22, pp.837-847, 2003.

[3] Y. Pei, Y. Kim, G. Obinata, D. Stefanov, “Trajectory Planning of a Robot for Lower Limb Rehabilitation”, 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, pp.1259-1263, 2011.

[4] E. A. Codman, “The shoulder, Thomas Todd”, Boston, pp32-64, 1934.

[5] Verne T. Inman, J. B. deC. M. Saunders; LeRoy C. Abbott, “observation on the function of the shoulder joint”, *The Journal of Bone & Joint Surgery*, Vol. 26, No.1, pp.1-30, 1944.

[6] Poppen NK, Walker PS, “Normal and abnormal motion of the shoulder” *The Journal of Bone & Joint Surgery*, Vol.58, pp.195-201, 1976.

[7] T. Kizuka, H.Yamaguti, K. Takamatu, “Electromyograpjic analysis of s*houlder muscles to determine effec*tive ranges for loads and motion jpduring low-levelshoulder exercises ”, *Society of Biomechanisms Japan*, Vol.15, pp.213-223, 2000. (in Japanese)