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Robot-Aided Motion Planning for Knee Joint Rehabilitation with Two Robot-Manipulators

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***Abstract*— In this paper, we propose a simultaneous design method of motion and external force trajectories for knee joint rehabilitation based on the biomechanical analysis of the lower limb. In this method we assume to use two robots manipulators which provide forces and moments at shank and thigh. We developed a 7 degree of freedom musculoskeletal model of lower limb with 19 muscles. The valuation function of rehabilitation efficiency e has been maximized by Genetic Algorithm (GA) that refers to the musculoskeletal model and tunes motion trajectory of the robots and forces acting on the shank and thigh.**

I. INTRODUCTION

A simultaneous design method of motion and external force trajectories has been proposed by the authors in the robot-aided rehabilitation system, which is based on biomechanical analysis of patient's musculoskeletal model [1-3]. Both the trajectories of rehabilitation motion and the applied force by the robot are simultaneously designed. In the rehabilitation training, we assumed to use only one manipulator attached to patient's foot or hand. There are several problems which are caused by the fact that the robot aided system can interact through only one body segment. The force added to the body segment tends to be large so that the force may injure the patient. It is difficult to assist the motion of all of the joints by using only one robot even if the robot has enough degree-of-freedom.

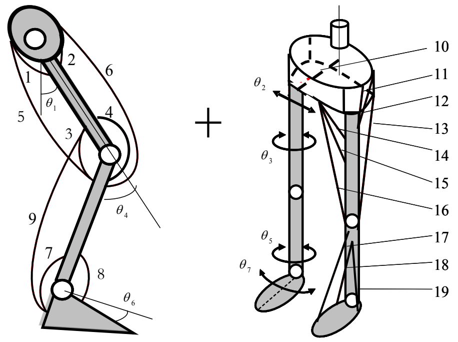
Some exoskeleton type robots such as ARMIN Ⅱ [4] provide a better support for the subject's body, and more accurate motion for each joint. But it is not easy to fit the system to the individual because it the exoskeleton systems is mechanically complex. Moreover the control systems with its complex mechanical structure make them expensive. Therefore we take here standard serial link manipulators rather than such exoskeleton type devices.

Besides of end-point type and exoskeleton type rehabilitation robots, dual robot systems have been also developed. iPAM [5] is a dual robotic system with 6-DOF for each robot, and this system is actuated by electropneumatic servovalves and low-friction pneumatic cylinders. The robots hold around the wrist of the forearm and the middle of the upper arm, respectively. The robot's motion is similar to a therapist's task in the conventional rehabilitation task, holding the patient's arm. Since the robots hold the subject's shoulder in a stable manner, the rehabilitation task can be carried out safely and reliably. REHAROB is also a dual type rehabilitation robot [6], which uses two independent 6-DOF robots to control the upper limb motion of the subject. Because of the large production volume of industrial robots and their wide range of applications, they are very reliable. Furthermore, they hold various quality and safety certificates. The development to a motion training system is easier and the cost can be low.

In this paper, we introduce a design method of motion trajectories and external forces for knee joint physical rehabilitation by using two robot-manipulators that apply forces to the patient's shank and thigh. In this paper, the rehabilitation efficiency evaluation function has been quasi-optimized by a Genetic Algorithm (GA) for the design of both the rehabilitation trajectories and the external forces. The algorithm refers to the musculoskeletal model and calculates the parameters of the curves of the motion trajectories external forces. Furthermore, by confining the knee's shear force and hip's reaction force, we can protect knee and hip joints from burdening large loads during therehabilitation task.

II. LOWER LIMB MUSCULOSKELETAL MODEL

In this study we develop a musculoskeletal model in which each leg consists of 3 rigid segments representing femur, tibia, and foot.



(a) Model of sagittal plane (b) Model of fronatal plane

Fig. 1 Musculoskeletal model

The hip and ankle joints of each leg are modeled as frictionless joints with 3 degrees of freedom. The knee joint has a moving center-of-rotation for flexion and extension,

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defined as a function of the knee flexion angle.. The muscle group that powers the leg motion in the sagittal plane are shown in Fig.1(a). Fig.1(b) presents the remaining 10 muscles that are responsible for the internal and external rotations of hip and ankle. For simplicity, in this model we ignore the Coriolis forces which are considered to be relatively small.

In this study we refer to the muscle model proposed by Hill [7] for evaluating muscle contraction dynamics. The relationship between the generated joint torque and the muscle forces can be described with the following equation.

$$\tau_i = \sum_k r_{i,k} \times f_k \tag{1}$$

Here, $\tau_i(t)$ is the torque at the joint i, $f_k(t)$ is the muscle force generated by the muscle k, $r_{i,k}(t)$ is the minimum distance from the rotation axis of i-th joint to the segmentalized k-th muscle model.

All muscles attached to the link will work together to generate total torque of the joint. We calculate the muscular force by minimizing the evaluate function $u(f(t))$ as follows.

$$u(f(t)) = \sum_k \left(\frac{f_k(t)}{PCSA_k} \right)^3 \tag{2}$$

Here, $PCSA_k$ is the physiological cross-sectional area of the k muscle, and $f(t)=[f_1(t), \ldots, f_k(t)]$.

During the joint rotation, the muscle force f_k has upper bound f_{kmax} and lower bound f_{kmin} as follows.

$$f_{k\min} \le f_k \le f_{k\max} \tag{3}$$

III. EVALUATE FUNCTION

For the design of the motion and external force that is to be applied to the contact point to the subject, we use the evaluation function E as follows:

$$\begin{aligned} E &= E_f - k_1 E_\tau \\ &= \int_{t_0}^{t_f} \sum_k f_k(t)dt - \frac{k_1}{2} \int_{t_0}^{t_f} \sum_{i=1}^{7} \left(\frac{d\tau_i(t)}{dt}\right)^2 dt \end{aligned} \tag{4}$$

The first index (E_f) maximizes the muscle force, and the second index (E_τ) minimizes torque change in each joint.

IV. DESIGN OF THE REHABILITATION MOTION TRAJECTORIES AND APPLIED EXTERNAL FORCES

A. Design of Joint Trajectories for Rehabilitation Motion

For easy-to-use and neat robot-aided rehabilitation motion, each joint angle $\theta_i(t)$ should be smooth and cyclic. In this study, each joint angle was constrained by its upper and lower bounds (θ_{imax} and θ_{imin}, respectively). The rehabilitation cycle T is composed of following two time intervals. First time interval is $0 \le t \le t_{i,1}$ and second time interval is $t_{i,1} \le t \le T$. α_i is the angle of i-th joint at $t= t_{i,1}$, and is constrained by (5), (6).

$$\theta_{i\min} \le \alpha_i \le \theta_{i\max} \tag{5}$$

$$|\theta_i(t)| \le |\alpha_i| \tag{6}$$

In section 1 the joint angle $\theta_i(t)$ is monotone increasing or decreasing from initial value to α_i. In section 2 the joint angle $\theta_i(t)$ returns to the initial value.

The joint angle in each time interval is represented by a fifth-order polynomial function as follows:

$$\begin{aligned} \theta_{i,j}(t) = {} & a_{i,j}(t-hT)^5 + b_{i,j}(t-hT)^4 + c_{i,j}(t-hT)^3 \\ & + d_{i,j}(t-hT)^2 + e_{i,j}(t-hT) + g_{i,j} \end{aligned} \tag{7}$$

where i is the 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.

Since each muscle has the maximum contractile velocity, this constraint can be represented as follow.

$$\dot{\theta}_{i\min} \le \dot{\theta}_i(t) \le \dot{\theta}_{i\max} \tag{8}$$

A smooth transition between the two time intervals is achieved if at the beginning of each new time interval, the following conditions are satisfied:

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 these conditions, the problem considered in this study is transformed into the search problem on α_i, T, $t_{i,1}$, $d_{i,1}$ and $d_{i,2}$ which maximize the performance function as we shall see in Section C.

B. Design of External Force

The external forces acting on the two contact points of the lower limb by two robots are represented by $F_{ext1}(t)=(F_{ext1x}(t), F_{ext1y}(t), F_{ext1z}(t))$, $F_{ext2}(t)=(F_{ext2x}(t), F_{ext2y}(t), F_{ext2z}(t))$, respectively. Since the external forces $F_{ext1}(t)$ and $F_{ext2}(t)$ should be smooth periodic functions, we use fifth-order polynomial functions of each external force as follows:

$$\begin{aligned} F_{ext1x}(t) = {} & a_{ext1x}(t-hT)^5 + b_{ext1x}(t-hT)^4 + c_{ext1x}(t-hT)^3 \\ & + d_{ext1x}(t-hT)^2 + e_{ext1x}(t-hT) + g_{ext1x} \end{aligned} \tag{9}$$

For the design of the force $F_{ext1x}(t)$, we have to search 7 parameters, namely a_{ext1x}, b_{ext1x}, c_{ext1x}, d_{ext1x}, e_{ext1x}, g_{ext1x}, and T. Here, T is calculated from (7). For smoothening external force trajectory, we set following constraints:

at t=T,

$$F_{ext\,1x}(0) = F_{ext\,1x}(T)\ ,\ \dot{F}_{ext\,1x}(0) = \dot{F}_{ext\,1x}(T)\ ,$$
$$\ddot{F}_{ext\,1x}(0) = \ddot{F}_{ext\,1x}(T)$$

Under these conditions, the search problem for 6 unknown parameters (a_{ext1x}, b_{ext1x}, c_{ext1x}, d_{ext1x}, e_{ext1x}, g_{ext1x}) is transformed into the three parameters (a_{ext1x}, b_{ext1x}, c_{ext1x}) search problem After the three parameters are determined, the other parameters are automatically determined.

C. GA-based Rehabilitation Motion Design Algorith

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 is defined by $F_{ext1}(t)$ and $F_{ext2}(t)$ are represented by the external force parameters a_{ext1x}, b_{ext1x}, c_{ext1x}, a_{ext1y}, b_{ext1y}, c_{ext1y}, a_{ext1z}, b_{ext1z}, c_{ext1z}, a_{ext2x}, b_{ext2x}, c_{ext2x}, a_{ext2y}, b_{ext2y}, c_{ext2y}, a_{ext2z}, b_{ext2z}, c_{ext2z}. List up these parameters and the set of each parameter is defined as a gene.

Step2: Define the number of individual gene as P and generate P individuals.

Step3: Based on the inverse dynamics, calculate joint torque, $\tau(t)$, muscle force, $f_k(t)$, hip joint reaction force, $F_{hip}(t)$, knee's shear force F_{kneeS} of each individual, and evaluate them with the function of (4).

Step4: Generate new individuals by crossover and mutation. The crossover rate and mutation rate are set to 0.25 and 0.01 respectively. Caculate the evaluation values of the new individuals.

Step5: List up all individuals in ascending order of the evaluate values, and select P individuals, whose evaluation values are higher than the others, and define the P individuals as a new generation.

Step6: Repeat step3 to step5 until the variation of the evaluation values remains sufficiently small for consecutive 5 generations.

V. MODEL CALCULATION EXAMPLE

A. Constraints

For knee jont rehabilitation quadriceps femoris should be trained because it is the great extensor of the knee joint and stabilizes the patella and the knee joint. Quadriceps femoris includes four muscles: Rectus femoris, Vastus lateralis, Vastus medialis, and Vastus intermedius. By using proposed method, we calculate hip's flexion/extension angle (θ_1), knee's flexion/extension angle (θ_4) and two external forces applied to shank (F_{shank}) and thigh (F_{thigh}).

There are several requirements on the knee joint reaction force for patient's safety. We can decompose the knee joint reaction force into two components. One is the compression force $F_{kneeC}(t)$ that acts to the direction of the shank. The other one is the shear force $F_{kneeS}(t)$ that is acts to the perpendicular direction of the compression force and the axis of knee joint. During the rehabilition of knee joint, if an excessive shear force applied to the knee may cause joint damage. For this reason, we need a small shear force to assure safety and an adequate compression force to make quadriceps femoris generate muscle forces.

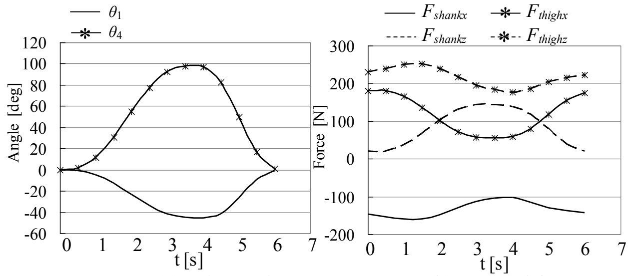
In addition, it is desirable if the ventral hip muscles generate limited tensions during the therapy exercise. These requirements can be met by limiting the range of the hip joint and hip joint reaction force. We design such attainable movements by limiting the upper bounds for the angular velocities of the joints. All the constraints are shown in table 1.

TABLE I. CONSTRAINTS IN PARAMETERS SEARCH

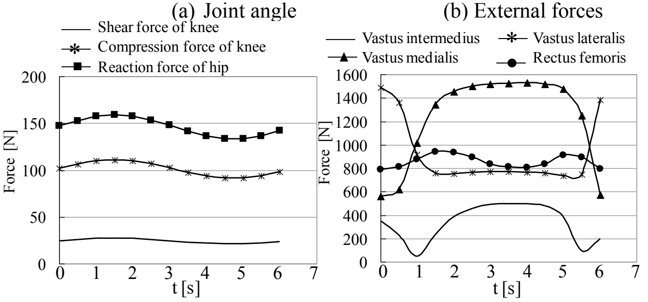
Flexion and extension range of hip joint	$-60 \le \theta_1 \le 0$[deg]
Extension and flexion range of knee joint	$0 \le \theta_4 \le 130$[deg]
Angular velocity range of each joint	$-180 \le \dot{\theta}_i \le 180$[deg/$s$]
Training cycle	$0 \le T \le 10[s]$
Shear force at the knee joint	$-30 \le F_{kneeS} \le 30[N]$
Compression force at the knee joint	$-200 \le F_{kneeC} \le 200[N]$
Hip joint reaction force	$-200 \le F_{hip} \le 200[N]$

B. Calculation results

The calculation results are shown in Fig.2. The trajectories of each joint angle are shown in (a). The applied external force is shown in (b). The knee's shear force and the knee's compression force and hip's reaction force are shown in (c). The generated muscle forces of rectus femoris and vastus are shown in (d). These calculation results show that all constraints on the motion are satisfied.



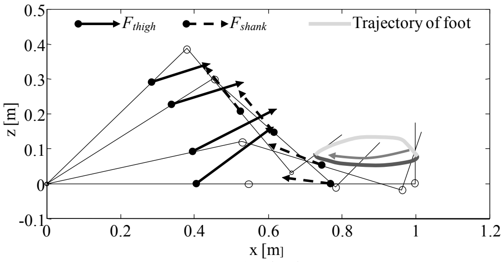
(a) Joint angle (b) External forces



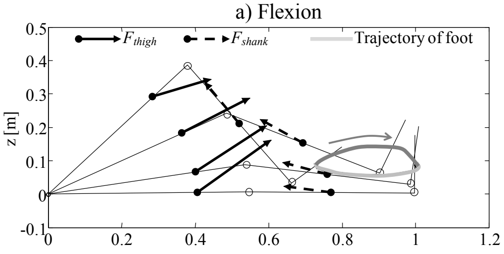
(c) Force acting on knee and hip (d) Muscle force

Fig. 2 Calculation results for angle trajectory, external force, load at knee joint, and muscle forces.

Fig. 3 shows the lower limb motion and erternal foreces applied to shank and thigh. The lower limb is represented as a stick figure. The vectors of the forces applied to the thign and shank for the sequential moments of the flexion and extension are shown in the same figure. During the knee's flexion phase, as shown in Fig. 3(a) the external force applied to shank assists the flexion that causes small knee's shear force and the thigh quardriceps do eccentric training. During the knee's extension, as shown in Fig. 3(b) the external force applied to shank is a resistance of extension which makes the thigh quardriceps generate large muscle force in way of concentric training. The external force applied to thigh generates an extension torque to hip while the external force applied to shank generates a flexion torque to hip which effectively reduces the reaction force at hip.



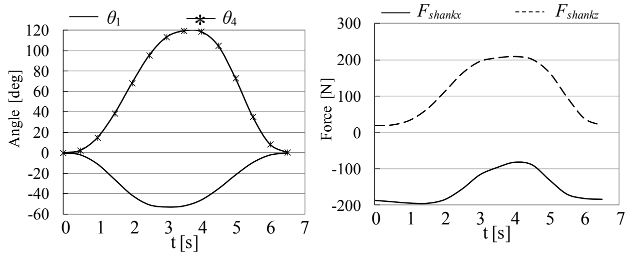
a) Flexion



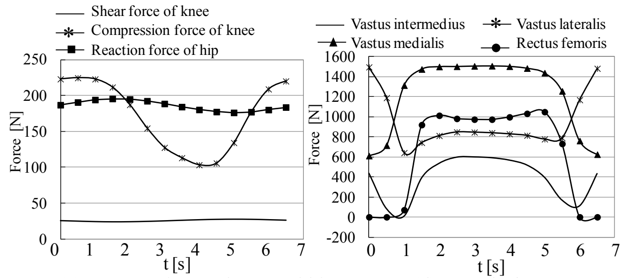
b) Extension

Fig. 3. External force and trajectory of foot.

C. *Comparision of the calculation results with the results of one robot based system*



(a) Joint angle (b) External forces



(c) Force acting on knee and hip (d) Muscle force

Fig. 4 Calculation results of one robot based system

In order to show the merits of the proposed system that uses two manipulators, we compared with the one robot-manipulator based method. Fig.4 shows the calculation results of one robot based system and table 2 shows the comparison results. Knee's share force and muscle force of the target muscles do not indicate great differences between one and two manipulators aided system. However, hip's reaction force is much lower than one manipulator-based system. Furthermore, the rehabilitation efficiency of the two robot based system is 36.37%, while that of the one robot based system is 24.63%. This results show the superiority of the two robot-manipulator based rehabilitation system. Hip's torque and reaction force are lower than one manipulator-based system that assures the two robots –based system is more safety and higher efficiency.

TABLE II. COMPARSION OF TWO ROBORS BASED SYSTEM WITH ONE ROBOT AIDED SYSTEM

Comparation terms		One robot	Two robots
Maximum hip's reaction force [N]		224.62	110.89
Average hip's reaction force [N]		167.67	101.01
Maximum knee's shear force [N]		27.37	27.27
Average knee's shear force [N]		25.39	24.12
Maximum muscle force [N]	Vastus intermedius	600	499.57
	Vastus lateralis	1496.36	1488.26
	Vastus medialis	1502.72	1527.58
	Rectus femoris	1052.33	946.11
Average muscle force [N]	Vastus intermedius	389.14	332.21
	Vastus lateralis	898.19	871.15
	Vastus medialis	1286.32	1276.36
	Rectus femoris	689.76	861.61
Rehabilitation efficency $\eta = \frac{E_m}{E_A} = \frac{\int_{t_0}^{t_f} \left| f_k(t) r_{i,k} \dot{\theta}_i(t) \right| dt}{\int_{t_0}^{t_f} \sum_{i=1}^{7} \left| \tau_i(t) \dot{\theta}_i(t) \right| dt}$		24.63%	36.37%

VI. CONCLUSION

In this paper, we proposed a design method of trajectory and external force for two robot- manipulators based system. We have calculated the trajectory and external forces applied to shank and thigh for knee joint rehabilitation by using proposed method. Furthermore, we compared it with one robot-based system, the lower hip's reaction force and higher rehabilitation efficiency showed the superiority of the proposed two manipulator -based rehabilitation system.

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