Post-stroke robotic-assisted therapy

Time-variant damping coefficient based control algorithm for isotonic exercise through circular motion

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***Abstract*—In this study, the authors proposes a new rehabilitation program for post-stroke patients with disabled arm, robotic-assisted isotonic training, based on circular trajectory of motion. The robotic-assisted rehabilitation system is a 3D parallel robot, its design and characterization were introduced by the fourth author at Nagoya Institute of Technology. A constant resistance control algorithm has been applied to obtain the proposed isotonic multi-joint movement training. The experimental results have been analyzed and discussed.**

Keywords—strength training; rehabilitation robotics; upper limb rehabilitation; circular movement; isotonic exercise.

I. INTRODUCTION

Rehabilitation services are a pressing necessity with the population ageing. According to the World Health Organization that senior citizens, at least 65 years of age, will increase in number by 88 percent in the coming years [1]. Consequently, incidence of age-related diagnoses including cerebral vascular accident (stroke) will increased, as 75 to 85 percent of stroke sufferers are over the age of 65 [2]. Recovery from a stroke is often a difficult and meticulous process requiring assistance from a physical therapist and a good deal of motivation on the part of the patient. Exercise and training with effective training strategies have long been used to restore motor function after stroke [3]. Actually, not only the increased numbers of stroke patients is a challenging problem but also their associated rehabilitation costs e.g. Japan expenses relating to caring for stroke survivors is now exceeding 25 billion US dollars per year [4]. Accordingly, there is a pressing need to deploy technologies such as robotics, robotic therapy, to assist recovery. Robotic therapy saves therapist efforts, allows more intensive repetitive training, and evaluates quantitatively the improvement of motor function. In addition, robotic therapy allows therapy at a reasonable cost. In the last decade, the interest in robotic therapy research has increased exponentially and robot therapy systems have been developed worldwide for upper and lower extremities rehabilitation e.g. design and characterization of a 3D robotic-assisted rehabilitation system for patients with upper limb disability were introduced by the fourth author. This robot has a potential as an evaluation tool for the therapeutic effect [5]. Professor Morita exchanged opinions with therapists about the practical uses of the 3D parallel robot, and based on their responses, developed training systems [6,7,8] and testing systems [9,10,11].

For recovering after a stroke, stroke patient's brain must relearn skills that the stroke may have taken away because of brain damaged by the stroke. The brain is amazingly resilient and capable of adapting after a stroke. One of the methods that used for brain adaptation is repeating exercises which targeting either improving muscle performance, to recover the upper limb range of motions, and/or to tune of motor synergies. Improving the performance of stroke patient impaired arm, improving of muscle strength, can be done through strengthening training, which also called muscle contraction or resistance training. Strengthening training is exercises involve moving a body part against resistance and hence progressively strengthen its muscles. Muscle strength can indicated by the active force that is generated by muscle contraction in response to resist the external forces, which can be classified into static strengths (isometric strengths) and dynamic strengths. Isotonic and isokinetic contractions, which are muscle contractions with a constant resistance and muscle contraction in a constant speed, respectively, are two types of dynamic strength of a muscle. Rehabilitation programs, which are based on muscle contraction, presuppose not only well understanding for the types of muscular contractions but also knowledge for which exercises utilize those contractions.

A. Isotonic Exercise

An exercise can be called isotonic exercise, if the muscles exert a constant force during carrying out the exercise against a resist, even constant or variable, and with muscle shortens or lengthens through the available range of motion i.e. with variable velocity. Isotonic exercise mainly used to increase dynamic strength, muscle endurance and power and can classified into two types, concentric and eccentric isotonic exercise. Isotonic concentric if the force is exerted as the muscle is shortened when an external force is applied while isotonic eccentric if the force is exerted as the muscle is elongated when external force is applied.

B. Circular Motion

It is known from literature that, circle drawing, movement along circular trajectory, is a multi-joint movement, in which the muscles crossing the elbow and the shoulder are sequentially activated, in addition, successful circle drawing, 360º movement through circular trajectory, requires coordination of both the shoulder and elbow joint [12 and 14]. Consequently, one can predict that circular movement training has an important advantage for upper arm rehabilitation i.e. rehabilitation training movement in a circular manner may positively affect recovering the upper limb range of motions, improving muscle performance, and/or in some cases brain adaptation for relearn lost skills.

In this research, the proposed method for upper limb rehabilitation is isotonic contraction training obtained through circular movement exercise. Accordingly, the final goal of this study is implementing constant resistance control algorithm to perform an isotonic exercise through repetitive circular movements for the disabled arm of stroke survivors.

II. ROBOTIC-ASSISTED REHABILITATION SYSTEM

The 3D robotic-assisted rehabilitation system is a 3D-force display parallel robot as shown in Fig. 1, which is used for upper limb rehabilitation training/testing. The design and characterization of the robot were introduced in [6]. The patient moves the grip of the robot according to a pre-prepared training program. The patient receives the reaction force through the grip according to the control algorithm. The 3D robot is driven by three direct drive motors (rated power: 209 W) and belt reduction drives. Maximum force of 50N can be generated with respect to each direction of the grip. The training space is available in 3D space (500×500×500[mm]). A 6-axis force/torque sensor is attached between the grip and the end effector to measure the force/torque exerted by the subjects. The parallel link mechanism is adopted to get higher robot structural stability.

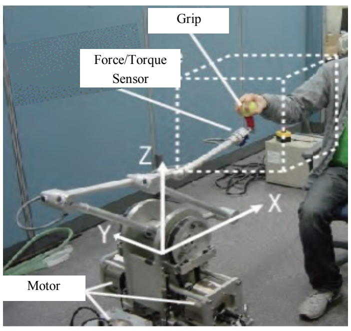

Fig. 1. 3D robotic-assisted rehabilitation system.

III. CONTROL ALGORITHM

A. Position-based Impedance Control

Impedance control algorithm has been widely used for practical robotic applications. For many robotic therapy applications, position-based impedance control algorithm replaces the impedance control algorithm not only to avoid the strong dependence of the impedance control on the robot dynamic model but also to improve the robustness of the controller against system disturbances and uncertainties [15]. Position-based impedance control is a force control loop overlapping a position controller i.e. there is an inner position controller to track the reference trajectory of the impedance model. The model of the position-based impedance control is determined according to the following equation as a summation of inertial, viscous, and elastic force components:

$$\mathbf{F}_{\mathrm{r}} = \begin{bmatrix} \overline{F}_{rx} \\ \overline{F}_{ry} \\ \overline{F}_{rz} \end{bmatrix} = \mathbf{M}_{\mathrm{r}}\,\ddot{\mathbf{r}}_{\mathrm{d}} + \mathbf{D}_{\mathrm{r}}\,\dot{\mathbf{r}}_{\mathrm{d}} + \mathbf{K}_{\mathrm{r}}\,\mathbf{r}_{\mathrm{d}}\,, \tag{1}$$

where $\overline{F}_{rx}$, $\overline{F}_{ry}$, and $\overline{F}_{rz}$ are the components of the measured exerted forces in direction of x, y, and z, respectively, and related to motion coordinate system, as shown in Fig. 2. Where $\mathbf{M}_{\mathrm{r}}$, $\mathbf{D}_{\mathrm{r}}$, and $\mathbf{K}_{\mathrm{r}}$ are mass, damping, and spring coefficients matrices, respectively, and are expressed as:

$$\mathbf{M}_{\mathrm{r}} = \begin{bmatrix} M_x & 0 & 0 \\ 0 & M_y & 0 \\ 0 & 0 & M_z \end{bmatrix},\ \mathbf{D}_{\mathrm{r}} = \begin{bmatrix} D_x & 0 & 0 \\ 0 & D_y & 0 \\ 0 & 0 & D_z \end{bmatrix},\ \mathbf{K}_{\mathrm{r}} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix},$$

where the suffixes x, y, and z are indication for the related motion coordinate directions. The vector $\mathbf{r}_{\mathrm{d}}$ is the robot's grip reference positions, which can be calculated using position-based impedance model as in [9]. The desired angles of the robot's joints $\mathbf{q}_{\mathrm{d}}$, which calculated using the inverse kinematic of the robot, are controlled by the velocity-based PID controller to generate the speed reference inputs $\dot{\mathbf{q}}_{\mathrm{ref}}$ to robot's actuators. $\dot{\mathbf{q}}_{\mathrm{ref}}$ is expressed in Eq. (2) as a function of $\mathbf{q}_{\mathrm{d}}$, $\dot{\mathbf{q}}_{\mathrm{d}}$ and joint angles $\mathbf{q}_{\mathrm{J}}$.

$$\dot{\mathbf{q}}_{\mathrm{ref}} = \mathbf{K}_{\mathrm{P}}\left(\mathbf{q}_{\mathrm{d}} - \mathbf{q}_{\mathrm{J}}\right) + \mathbf{K}_{\mathrm{I}}\int\left(\mathbf{q}_{\mathrm{d}} - \mathbf{q}_{\mathrm{J}}\right)dt + \mathbf{K}_{\mathrm{D}}\,\dot{\mathbf{q}}_{\mathrm{d}}\,, \tag{2}$$

where $\mathbf{K}_{\mathrm{P}}$ is the proportional gain matrix, $\mathbf{K}_{\mathrm{I}}$ is the integral gain matrix, and $\mathbf{K}_{\mathrm{D}}$ is the derivative gain matrix.

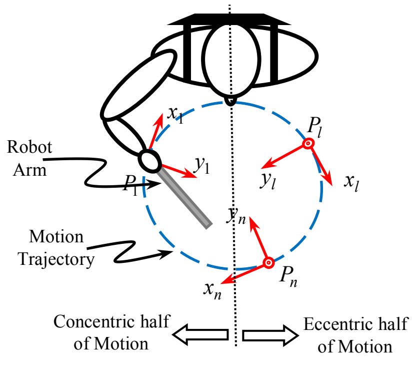

Fig. 2. System coordination (Motion in clock wise direction).

B. Constant Force Control Algorithm

The assisted robotic system is controlled in order that, a constant force pattern is applied to the patient's arm during the circular movement training, which can be achieved using time-varying damping coefficient based algorithm. Parameters of the proposed controller are designed to let a subject performance to match a predefined activation level during a repetitive training. Figure 2 shows the coordination of the system during the proposed training exercise. The block diagram of the control algorithm of isotonic training is shown in Fig. 3. It is clear from the figure that, robot's grip reference positions are calculated based on the impedance model parameters. To restrict the robot arm grip on a circular movement trajectory, the values of K_y, K_z, D_y, and D_z are chosen to be large values. The value of K_x has been taken as zero kg/sec^2 to eliminate the elastic force component, where M_x, M_y, M_z have been taken as 0.9 kg for each, these values have been chosen to minimize the value of inertial force component in the robot resistance force, but with consideration of the stability of the 3D-robot. The damping coefficient in the direction of x-axis D_x has been determined based on the following saturation function:

$$D_{\mathrm{x}} = \begin{cases} 2 & (\gamma \le 2) \\ \gamma & (2 < \gamma < 200) \\ 200 & (\gamma \ge 200) \end{cases} , \qquad (3)$$

where

$$\gamma = \left| (F_c - M_{\mathrm{x}}\,\ddot{x}) / \dot{x} \right| ,$$

F_c is the required constant reference force. The direction of x is along the circular motion guided trajectory as shown in Fig. 2, where l and n are points related to the reference trajectory, P is the cartesian coordinate frame. $\dot{x}$ and $\ddot{x}$ are the velocity and the acceleration, respectively, which are obtained by calculation and using low pass filter. Equation (3) shows that, the value of the damping coefficient between the limits of the saturation function is adaptable; consequently, the value of the viscous force component will change to generate a constant reference force, according to Eq. (1) regardless of subject's hand velocity and acceleration.

C. Isotonic Training

As it was mentioned before, the concept of the isotonic training is to allow the muscles, while concentric or eccentric contraction, to exert constant forces regardless of the speed of the motion [16]. During isotonic training through circular motion, one-half of the circular movement is a half of concentric contraction of the muscles and the other is eccentric contraction half i.e. the circular movement training program includes both concentric and eccentric contractions in one repetition of motion.

During isotonic training exercise through circular motion, to avoid muscular injury due to overtraining and overload activation of the muscles, the range of motion and the constant load value should be chosen carefully according to the subject's physical conditions and his/her stroke severity. Which can be done by considering the followings:

1) Many muscles activated during the isotonic training through circular motion. The maximum activation force are different for each one, and the maximum activation should be according to most weaken muscle.

2) During eccentric contraction, muscle able to produce a greater force than during concentric contraction.

IV. RESULTS AND DISCUSSION

To verify the effectiveness of the proposed control algorithm, subjects are asked to perform isotonic exercises using the 3D robot. At this point of research healthy peoples played the role of patients. The following procedure has been followed:

1) The range of motion and the value of constant resistance force that applied during training program are decided according to the subject's physical conditions and his/her stroke severity.

2) The subject uses his/her disabled arm to grasp the grip and asked to move the grip slowly during the training to trace a circular trajectory, motion may be in clockwise or counter clockwise directions.

3) The subject repeats the training, the number of training repetition also is decided according to the subject's physical conditions and his/her stroke severity.

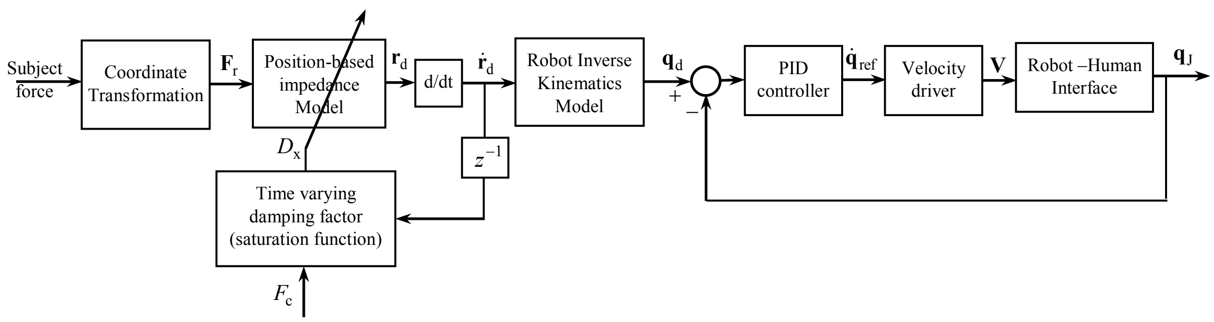

Fig. 3. Isotonic training control algorithm.

Results for two repetitions of the isotonic exercise, eccentric and concentric contractions, with desired exerted forces of 15, and 20 N are shown in the Figs. 4~6. From Fig. 4, position circular trajectory, isotonic training's motion trajectory, can be observed with a radius of 165 mm. It is clear from Figs. 5 and 6 that, isotonic training using the 3D-robot can be achieved by applying the proposed control technique i.e. during the exercise, the subject's hand velocity was changing according to his/her motion and intention where his/her excreted forces were mostly constant regardless of the change of his/her hand velocity.

Figure 5 shows the results of the isotonic training with a required 20 N of exerted forces by the subject. The upper and middle graphs correspond to subject's exerted forces and the velocity along the motion trajectory, respectively. It is clear from the upper graph that, constant forces were exerted by the subject even in the concentric half of motion or in the eccentric half of motion. The lower graphs shows the adaptive values of the damping coefficient that have been calculated based on the saturation function in Eq. (3).

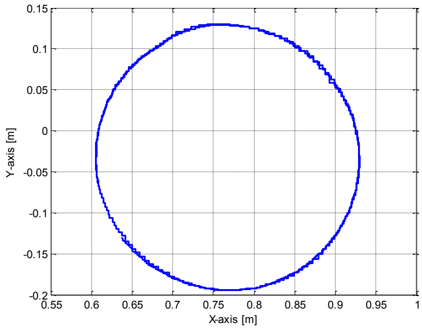

Fig. 4. Isotonic training's motion trajectory.

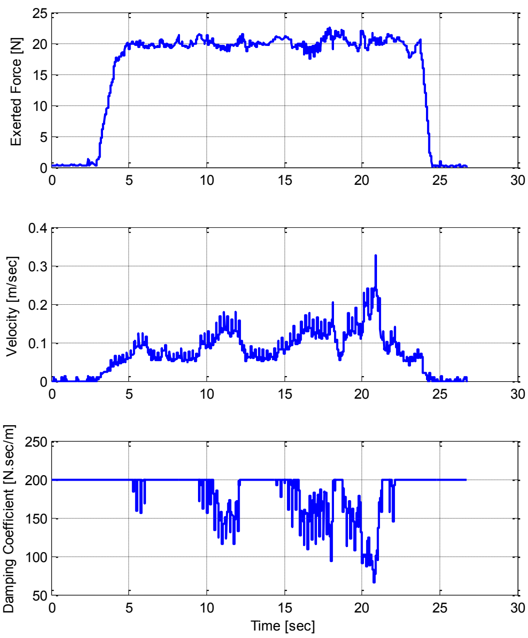

Fig. 5. Isotonic training results [F_c = 20 N].

The results of the isotonic training with required 15 N of exerted forces by the subject are shown in Fig. 6, the upper and middle graphs correspond to subject's exerted forces and the velocity along the motion trajectory, respectively. The upper graph indicates that, during the concentric and eccentric halves of motion, the subject exerted constant forces. The adaptive values of the damping coefficient are shown in the lower graph.

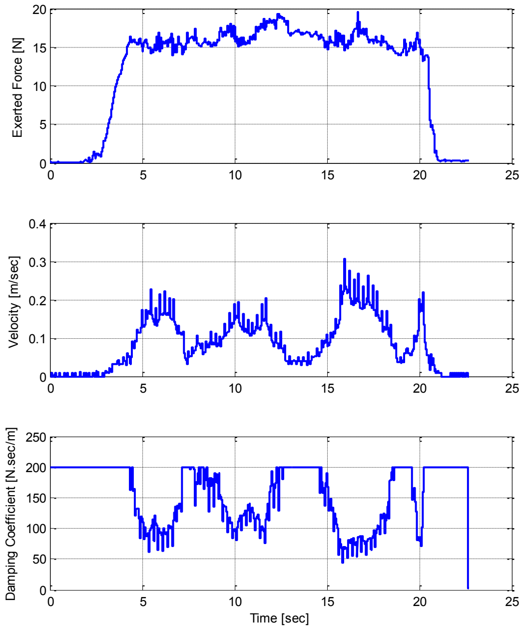

Fig. 6. Isotonic training results [F_c = 15 N].

V. CONCLUSION

In this paper, a control algorithm for isotonic training through circular motion using 3D parallel robot has been proposed. A constant resistance control algorithm have been developed based on position-based impedance control and time-variable damping coefficient technique. The effectiveness of the proposed algorithm has been verified experimentally with healthy people. Studying the activation of the muscles during the training, and applying this control algorithm for different ranges of motion and different muscle activation levels will be taken as a future work for this study.

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