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Stiffness Control of a Pneumatic Rehabilitation Robot for Exercise Therapy with Multiple Stages

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***Abstract*— In exercise therapy, the training program will differ depending on the degree of disability. In order to gradually transition from passive exercise to exercises with more voluntary movements, it is important to reduce the assistance provided by the therapist in stages. Since stiffness control is the key factor of assistance adjustment in robotic movement rehabilitation, this paper focuses on stiffness control as a tool to adjust the assistance in stages. It is necessary to set a proper stiffness ellipse to perform assistance with directivity, especially in the case of active-assistive exercise. The performance of the proposed stiffness control for exercise therapy is validated through experimental results.**

I. INTODUCTION

Recently, neurorehabilitation has attracted attention in the field of rehabilitation science; in particular, the effectiveness of using exercise and motion to reconstruct neural functions damaged through cerebral strokes has raised expectations. Robot-assisted arm rehabilitation, often connected to a virtual environment for task-oriented training, can be utilized as a tool to support a movement during exercise therapy. Therefore, many groups have developed arm therapy robots [1]-[3]. Pneumatic artificial muscles are attractive for rehabilitation robots since they are light weight and compliant [4], [5]. Impedance control strategies, including stiffness control, are common for rehabilitation robots [6]. Most of them also have an ability to adjust the impedance parameters. A stiffness ellipse [7] is known as a concept for adjusting spatial distribution of impedance parameters of both human and robots.

In exercise therapy, depending on the degree to which a patient is handicapped, the training program will differ with regard to passive exercise, active-assistive exercise, active exercise, and automatic resistance movement. In order to gradually transition from passive exercise to exercises with more autonomous movements, such as active-assistive exercise and active exercise, it is important to reduce the assistance provided by the therapist in stages. Models of human learning [8] suggest that the declination rate of the assistance should be faster than the forgetting rate of the human. How to adapt assistive force was studied for position error reduction of repetitive arm movements [9].

Abovementioned studies imply that high performance exercise therapy needs to adjust stiffness in each direction as the stages of the exercise shift. A number of controllers for individual stages have been proposed by now [10], [11]. However, high performance controller for pneumatic muscles have not been studied well because it is believed that pneumatic muscles with slow response is not appropriate for accurate adjustment of assistance.

Therefore, this paper focuses on stiffness control of a pneumatic robot arm as a tool to adjust the assistance in stages and describes the development of a new control strategy for rehabilitation robots. Firstly, this paper introduces stiffness control classification for rehabilitation robots. The main target patients of the rehabilitation are stroke survivors. Secondly, a control architecture for pneumatic artificial muscles is proposed. The arbitrary stiffness ellipse for guided motion can be given based on antagonistic mechanism with biarticular muscles. Since the stiffness ellipse is generated mechanically, the performance does not depend on the time response of the pneumatic artificial muscles.

II. STIFFNESS CONTROL SYSTEM CONFIGURATION

A. Design criteria for stiffness control

In case of replicating a manual exercise therapy with the robot, the robot should also replicate the stiffness of therapists in each stage. Table I displays the type of stiffness control necessary during exercise therapy. In cases like passive exercise, where a passive training routine is formulated for a patient incapable of voluntary movements, the robotic arm supporting the patient's arm requires position control to traverse the directed trajectory in order to realize the desired hand movement. In contrast, active exercises utilize the patient's own physical strength through voluntary movement; thus, the stiffness control of the robot needs to be reduced through force control. Position control is considered to be equivalent to very high stiffness in stiffness control; therefore, it is necessary to reduce the stiffness control when gradually transitioning from passive exercise to active exercise. The lower the stiffness, the more scope

TABLE I
STIFFNESS CONTROL CLASSIFICATION FOR ROBOTIC EXERCISE THERAPY

Type of exercise	Stiffness	
	movement direction	cross direction
Passive exercise	high	high
Active-assistive exercise	low	high
Active exercise	low	low

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a patient has to make voluntary movements; as a tradeoff, the assistance element is weakened. Furthermore, in active-assistive exercise where assistance is given in a specific direction only, low stiffness must be set in the direction where the patient will be exercising with his or her own strength and high stiffness in the direction where assistance is being provided.

Fig. 1 shows the image of preferable stiffness ellipse for each exercise of robotic exercise therapy with exoskeleton type robot arm. The figure supposes that the subject follows a target moving from left to right. In case of passive exercise, the stiffness ellipse is large in all directions to realize the desired hand movement. Note that the subject needs larger force to move the arm tip on the direction with large stiffness and therefore higher stiffness is desirable to accomplish desired position against disturbances. On the other hand, the stiffness ellipse in active-assistive exercise has to have lower stiffness in the moving direction so that the robot does not interfere the voluntary motion of the subject. Active exercise has to have low stiffness in all directions.

In this paper, the direction orthogonal to the movement direction is referred to as the cross direction. Particularly during automatic active-assistive movement, as the stiffness settings for the movement direction and the cross direction differ, adjustment of a stiffness ellipse is necessary. Here, stiffness ellipse is an ellipse that shows every distribution of the direction of the stiffness of an arm tip. Methods for adjusting the machine's stiffness mechanism, including an actuator for setting the stiffness in a robot's hands and feedback control for recreating virtual stiffness, have been considered; the former is called mechanical stiffness, and the latter is called control stiffness. Considering the particularities of pneumatic muscles, both were set up in this study. The method for setting the mechanical stiffness of pneumatic muscles is shown below.

B. Calculation of the mechanical stiffness for muscle framework

Fig. 2 displays the rehabilitation robot used in this study. When the patient is sitting in the chair, the exoskeleton of the robotic arm is mounted on the patient's arm and used for training. The robot has three antagonistic pairs for a total of six pneumatic muscles mounted on it to simulate the placement of the functionally effective muscles [12] of the upper limbs of a human. In this study, McKibben artificial muscles are used for the pneumatic muscles. Fig. 3 shows the arrangement of artificial muscles. Although bi-articular muscles seem redundant for this 2 DOF system, they are necessary to achieve arbitrary shape of stiffness ellipse at the arm tip [13]. The following equation represents the relationship between torque T and joint angle θ.

$$\begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix} = \begin{bmatrix} k_1 + k_3 & k_3 \\ k_3 & k_2 + k_3 \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} \tag{1}$$

where Δ denotes the deflection from the equilibrium point, and k_1, k_2, and k_3 represent the angular stiffness. The subscripted numbers refer to the corresponding joints: 1 and 2 denote the shoulder and elbow mono-articular muscles, and 3 corresponds to the biarticular muscles across the two joints. The relationship between arm force $\boldsymbol{F}$ and displacement Δx and Δy in the Cartesian coordinate system is as follows:

$$\begin{aligned} \begin{bmatrix} \Delta F_x \\ \Delta F_y \end{bmatrix} &= \boldsymbol{J}^{-T} \begin{bmatrix} k_1 + k_3 & k_3 \\ k_3 & k_2 + k_3 \end{bmatrix} \boldsymbol{J}^{-1} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \\ &= \frac{1}{(det\boldsymbol{J})^2} \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \\ &= \boldsymbol{K} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \end{aligned} \tag{2}$$

Here,

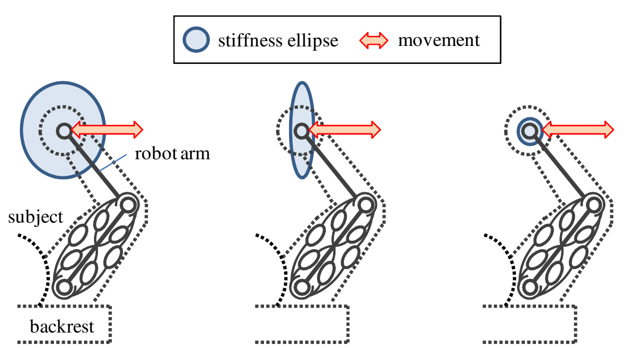
$$\boldsymbol{J} = \begin{bmatrix} -l_1 \sin\theta_1 - l_2 \sin\theta_3 & -l_2 \sin\theta_3 \\ l_1 \cos\theta_1 + l_2 \cos\theta_3 & l_2 \cos\theta_3 \end{bmatrix} \tag{3}$$

$$\begin{aligned} k_{11} &= k_1(l_2\cos\theta_3)^2 + k_2(l_1\sin\theta_1 + l_2\sin\theta_3)^2 \\ &+ k_3(l_1\cos\theta_1)^2 \end{aligned} \tag{4}$$

$$\begin{aligned} k_{12} &= k_{21} = k_1 l_2^2 \sin\theta_3\cos\theta_3 \\ &+ k_2(l_1\cos\theta_1 + l_2\cos\theta_3)(l_1\sin\theta_1 + l_2\sin\theta_3) \\ &+ k_3 l_1^2 \sin\theta_1\cos\theta_1 \end{aligned} \tag{5}$$

$$\begin{aligned} k_{22} &= k_1(l_2\sin\theta_3)^2 + k_2(l_1\sin\theta_1 + l_2\sin\theta_3)^2 \\ &+ k_3(l_1\sin\theta_1)^2 \end{aligned} \tag{6}$$

Here, $\theta_3 = \theta_1 + \theta_2$, and l_1 and l_2 indicate the lengths of the brachial region and the antebrachial region, respectively, of the robot's arm. k_1, k_2, and k_3 can be adjusted to set the tip of the stiffness ellipse.



(a) Passive exercise (b) Active-assistive exercise (c) Active exercise

Fig. 1. Preferable shape of stiffness ellipse

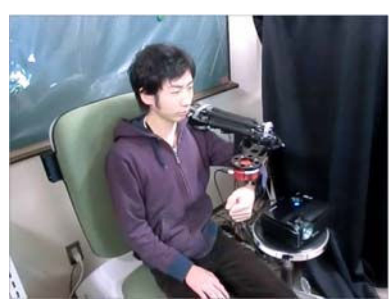


Fig. 2. Rehabilitation robot in this study

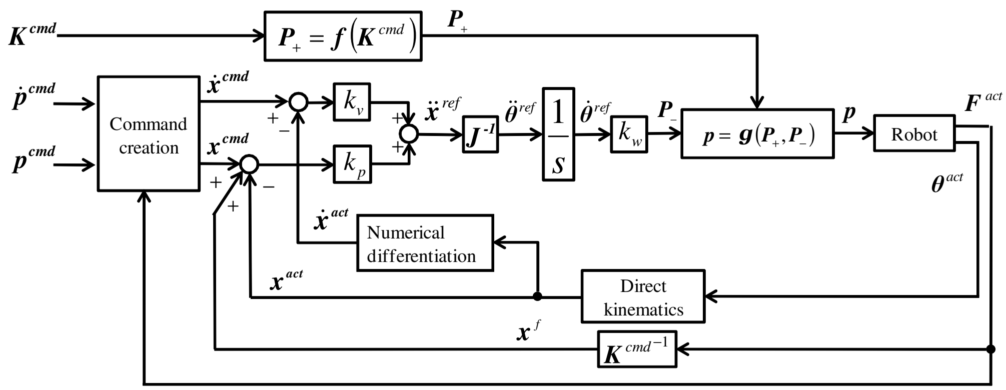


Fig. 4. Block diagram of stiffness control by pneumatic muscles

C. Structure of control system

Fig. 4 shows the block diagram of the control system for this study. Here, k_p and k_v are position and velocity gains, respectively. k_w is a constant, which relates the feedback input and the pressure command. Open loop input $\boldsymbol{P}_+$, as given by the top part of Fig. 4, is obtained from the setting of the desired mechanical stiffness.

Development of (2) yields:

$$\begin{aligned} \boldsymbol{J}^{-T}\begin{bmatrix} k_1+k_3 & k_3 \\ k_3 & k_2+k_3 \end{bmatrix}\boldsymbol{J}^{-1} &= \boldsymbol{K} \\ \begin{bmatrix} k_1+k_3 & k_3 \\ k_3 & k_2+k_3 \end{bmatrix} &= \boldsymbol{J}^T\boldsymbol{K}\boldsymbol{J} \end{aligned} \quad (7)$$

Suppose $\boldsymbol{K}^{cmd}$ is the command stiffness matrix on the arm tip, the antagonistic muscle stiffness $\boldsymbol{k}_{cmd} = [k_{1cmd}, k_{2cmd}, k_{3cmd}]^T$ is given by the following equation:

$$\begin{bmatrix} k_1^{cmd}+k_3^{cmd} & k_3^{cmd} \\ k_3^{cmd} & k_2^{cmd}+k_3^{cmd} \end{bmatrix} = \boldsymbol{J}^T\boldsymbol{K}^{cmd}\boldsymbol{J} \quad (8)$$

Then, the average pressure of antagonistic muscles $\boldsymbol{P}_+$ is calculated from the antagonistic muscle stiffness $\boldsymbol{k}_{cmd}$ by (9). For coefficients a, b, and c, the parameters identified in the preliminary experiment in [14] are used.

$$\boldsymbol{P}_+ = \begin{bmatrix} P_{+1} \\ P_{+2} \\ P_{+3} \end{bmatrix} \begin{bmatrix} a_1k_1^{cmd2}+b_1k_1^{cmd}+c_1 \\ a_2k_2^{cmd2}+b_2k_2^{cmd}+c_2 \\ a_3k_2^{cmd2}+b_3k_3^{cmd}+c_3 \end{bmatrix} \quad (9)$$

On the other hand, the feedback loops at the lower part of Fig. 4 is where stiffness control is performed. When the stiffness control should be set to 0 with the created command value given in the next subsection, a position command is created. The command value creation stands for the feedback loop at the lowest part of the figure. The open loop input and the feedback loop input are linearly added and given as pressure inputs $\boldsymbol{p}$ [15].

D. Command value creation process

As shown in Table I, during exercise therapy, stiffness is increased only in the cross direction; in the movement direction, it is necessary to reduce the stiffness in order to simplify movements. Ideally, the stiffness should be set to 0 to recreate the state of no assistance; however, in an actuator driver system, it is difficult to set the mechanical stiffness to 0. Furthermore, in order to improve the control characteristic effect by opposing forces, the stiffness should be increased to an extent and the opposing tension in the muscle should be maintained. In other words, in an antagonizing driver system based on artificial muscles, it is possible to set an optional mechanical stiffness; however, there is a limit to the range of suitable control performance that can be achieved.

Thus, in this study, we introduced a method that sets the stiffness control to 0 from the creation of a command value. When an external force is generated, a command value is created, and the command position is moved only toward a specific direction. On the basis of such a process, static control stiffness becomes 0 only in the movement direction for the command value, and directional assistance and free movement in the direction of advance become possible. In the command value creation part, each of the command values is generated by a different method depending on the type of training.

First, during passive exercise, a position command fixed at a high stiffness position is given. In order to increase stiffness, no command value is created during passive exercise only. Position command $\boldsymbol{p}^{cmd}$ in time t is achieved as follows:

$$\boldsymbol{x}^{cmd} = \boldsymbol{p}^{cmd} = \begin{bmatrix} p_x^{cmd}(t) \\ p_y^{cmd}(t) \end{bmatrix} \quad (10)$$

Here, subscripts x and y denote the elements corresponding to the x- and y-axes, respectively, of the vector.

For active-assistive exercise, a limited command value is created where the operator can only move in the direction in which the target is moving. In the cross direction, a command value that does not depend on external forces is given so that it does not go off the trajectory. Similar to the experiment presented in this paper, when the movement of the target is limited to the y-axis direction, the command value of the position is given by the following equation.

$$\boldsymbol{x}^{cmd} = \begin{bmatrix} p_x^{cmd}(t) \\ \int v_y^{cmd}dt \end{bmatrix} \quad (11)$$

$$\boldsymbol{v}^{cmd} = v^{max}\frac{\boldsymbol{F}^{act}}{|\boldsymbol{F}^{act}|} \quad (12)$$

In active exercise, since the robot creates the command value in the direction in which the operator applies discretionary force, the command value is achieved as follows.

$$\boldsymbol{x}^{cmd} = \int \boldsymbol{v}^{cmd} dt \quad (13)$$

Equation (12), which is also used for deriving active-assistive exercise, is used to find $\boldsymbol{v}^{cmd}$.

At frequencies higher than the control bandwidth, an error resulting from the difference between mechanical stiffness and control stiffness often occurs. To reduce this problem, the mechanical stiffness should be brought as close as possible to the control stiffness□

III. Experiment

A. Outline of Experiment

The details of experimental devices are shown in Table II.

The scene of the experiment is shown in Fig. 5. The patient operates the rehabilitation-aiding robot while looking at the display and carries out the training. A marker indicating the moving target and the position of the patient's arm is shown by computer graphics in real-time on the display. The patient operates the arm so that the marker traces the target. In this experiment, healthy people were designated as the subjects. Control of the robot differed depending on the training type, as mentioned previously; the target position was entered in the command value of the position control so that the robot could guide the arm of the patient by position control in the cross direction. In this experiment, the command value of the position control was given as follows:

$$p_x^{cmd}(t) = 350 \quad (14)$$
$$p_y^{cmd}(t) = 160 + 40\sin(\omega t) \quad (15)$$

Here, the units of position and time are millimeters and seconds, respectively, and $\omega = 0.1$.

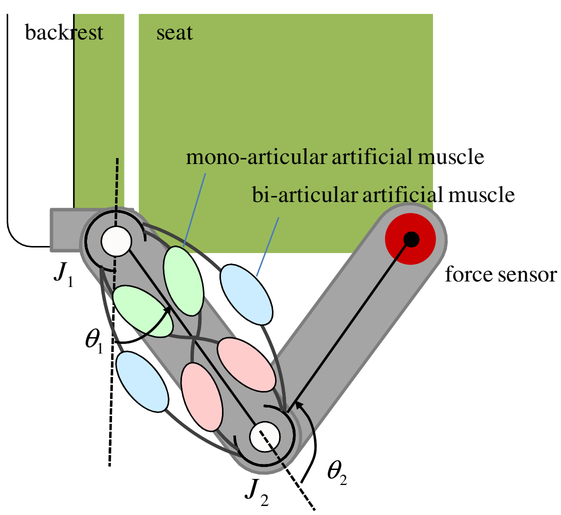


Fig. 3. Muscular arrangement of robot arm

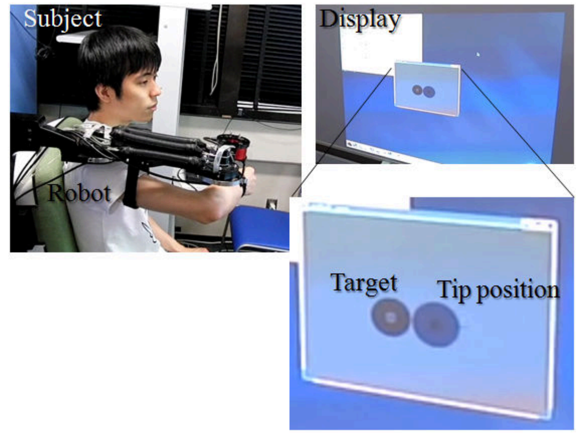


Fig. 5. Overview of the experiment

B. Experimental Results

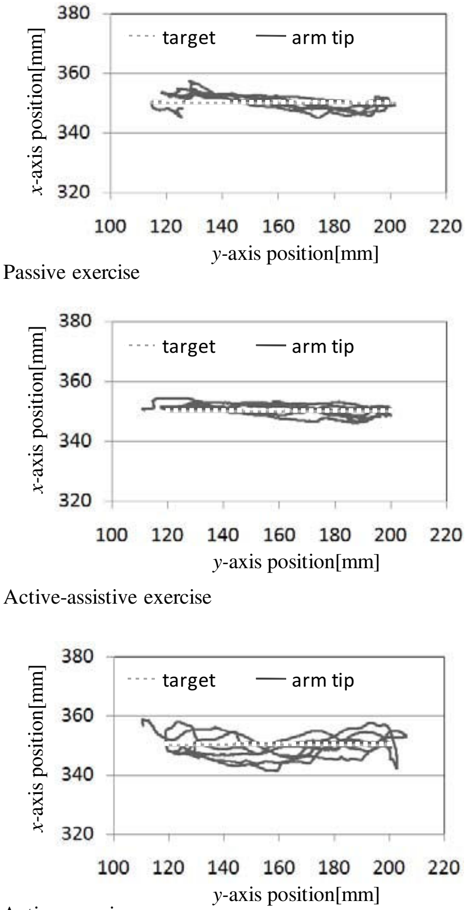
Fig. 6 shows the target and arm trajectories for active exercise, active-assistive exercise, and passive exercise during the experiment. The mechanical stiffness of the robotic arm was consolidated to 83 N/m. During active exercise, there was an even greater error in the x-axis compared to the other results since there was no intervention by the robot.

Fig. 7 shows the tracing error for passive exercise. During passive exercise, the target position was input as the command value of the position control, and the robotic arm traversed to that position. Regarding the three examples where mechanical stiffness was changed through adjustment of $\boldsymbol{P}_+$, the average pressure of the antagonistic muscles, the results obtained were compared on the basis of tests with no subject and a healthy subject. The no-subject results showed that increasing the mechanical stiffness produced a clear improvement in the tracing performance.

However, for healthy subjects who can follow the target using their own strength, the impact of mechanical stiffness for the robot was not visible because the subject followed the target voluntarily. The results of active-assistive exercise and active exercise are shown in Figs. 8 and 9, respectively. In Fig. 9, the result with no air pressure in the pneumatic muscle is displayed in the column where the mechanical stiffness is 0.

TABLE II
Details of Experimental Devices

Force sensor	Model number Load rating	WACOH-TECH DynPick 200 N
Encoder	Model number Resolution	SIKO GmbH MSK5000 0.005 mm
Proportional valve	Model number Reaction time Linearity	HOEBRIGER Techno easy 20 ms ≤2.5%
Pneumatic artificial muscles	Model number Maximum power Shortening rate	KANDA TSUSHIN KOGYO Air muscle 400 N 34%



(a) Passive exercise

(b) Active-assistive exercise

(c) Active exercise

Fig. 6. Position response during experiment

On the basis of the results of the active-assistive exercise shown in Fig. 8, not only the cross direction but also the reduction in error toward the movement direction were improved compared to active exercise. Since the improvement became prominent as the mechanical stiffnes was set higher, it can be said that the tracing error of the subject was suppressed by the stronger assistance.

During active exercise, since the command value was created such that the robot would move in the direction in which the subject applied his strength, the static control stiffness was 0. However, it was impacted dynamically by the mechanical stiffness, which depended on the antagonistic tension of the artificial muscle. Thus, a higher mechanical stiffness increased the error. On the basis of this result, it is necessary to set not just the feedback control but also the proper mechanical stiffness.

Fig. 10 compares the tracing error in each stage of exercise. Here, the distance denotes the distance between arm tip and the target. In other word, it is the vector length of the tracing error. In the experiment, average tracing errors of 5 healthy subjects were evaluated. The duration of each experiment was 100 seconds. The results show that tracing error increases as the assist given by the robot decreases.

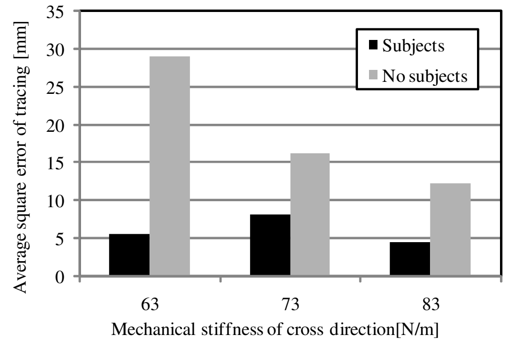


Fig. 7. Tracing error during passive exercise

Although assist was only given in the cross direction during active-assistive exercise, there was no significant difference with passive exercise on both cross direction and movement direction. It implies that the total tracing performance improves with the assist on a specific direction. Fig. 11 compares the operation force in each stage of exercise. It is quite similar to Fig. 10, while the difference to be emphasized is that the operation force on movement direction is the largest during active-assistive exercise. It suggests that the subjects were concentrated on the operation on movement direction.

The following can be concluded based on the above experimental results:

- When the subject is passive, tracing of the trajectory is improved by raising the mechanical stiffness.
- When the subject is actively doing the operation, then the mechanical stiffness may dynamically obstruct the movement of the subject.
- If assistance is such that movement is limited to a specific direction, then the accuracy of active operation by the subject is improved in both the cross direction and the movement direction.

IV. CONCLUSION

This paper proposed a new design method of a stiffness control system for exercise therapy. When using robots to

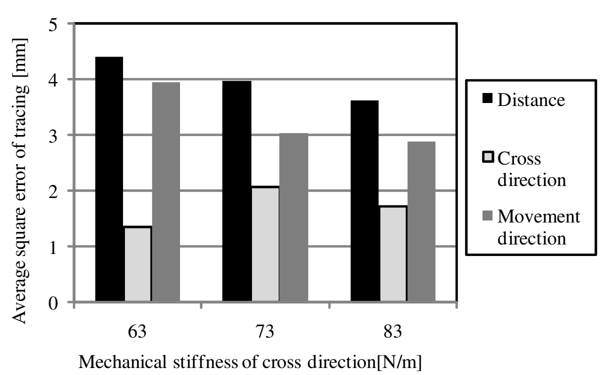


Fig. 8. Tracing error during active-assistive exercise

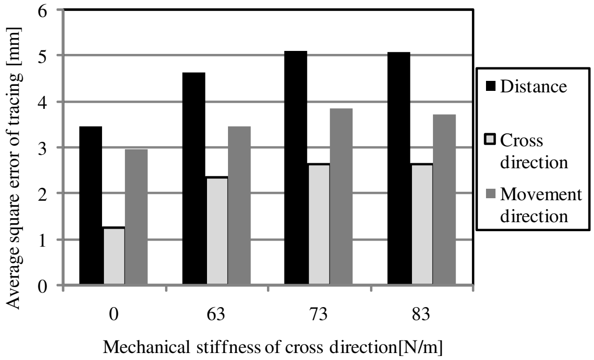


Fig. 9. Tracing error during active exercise

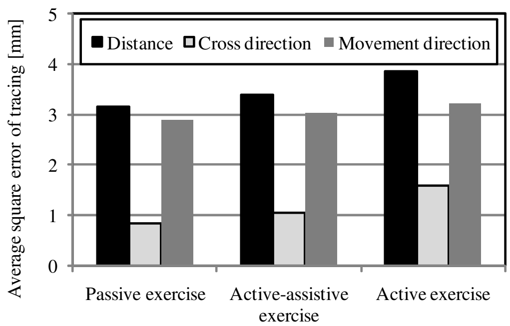


Fig. 10. Comparison of the tracing error in each stage

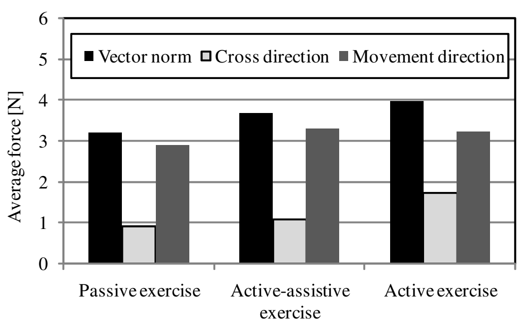


Fig. 11. Comparison of the average force in each stage

support exercise therapy, it is necessary to adjust the autonomy of movement in stages depending on the condition of the patient. Low-autonomy exercises restrain the movement of the patient, and therefore, the control stiffness should be set high; in high-autonomy exercise, the control stiffness should be set low.

It is necessary to set a proper stiffness ellipse to perform assistance with directivity, especially in the case of active-assistive exercise. On the basis of feedback, as noise is created in frequencies higher than the control bandwidth in the stiffness control, the same mechanical stiffness should be recreated rather than just the control stiffness.

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