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ANALYSIS OF REACHING MOVEMENTS WITH THE ADDITION OF RESISTANCE FORCES IN THE HORIZONTAL AND VERTICAL PLANES USING A ROBOT ARM IN NON-DISABLED INDIVIDUALS

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Abstract
A new, simpler, quantitative evaluation method, with higher reproducibility and validity than the conventional method used to evaluate hemiplegic upper extremities, is needed. The general properties of reaching movements were examined in healthy subjects by adding resistance forces to establish a new evaluation method using robotic technology. The subjects included 14 non-disabled males and 2 non-disabled females whose average age was 25 years. Their reaching movements were measured in both the horizontal and vertical planes with resistance force to add disturbance using a robot arm. Then, the jerk cost, the largest swinging distance, and the end-point displacement were calculated. Significant differences were seen between subjects with and without disturbance in the horizontal jerk cost and largest swinging distance in the horizontal plane, and vertical jerk cost and largest swinging distance in the vertical plane. The horizontal and vertical jerk costs and largest swinging distances were also greater with a larger disturbance. In the reaching movements of healthy people in the horizontal and vertical planes, when the reaching movement was subjected to orthogonal disturbance, jerk cost and largest swinging distance in the direction of the disturbance were easily affected in response to the disturbance.

Key words : Reaching movement, robot arm, resistance force, jerk cost, largest swinging distance

Introduction

Stroke is a common disease causing death among patients, and 60% to 70% of stroke survivors experience initial dysfunction of the upper extremity[1,2)]. In addition, 40% to 80% of all stroke survivors have incomplete functional recovery of the upper extremity[1,3,4)], and only approximately 15% are reported to regain useful function[5)]. This means that the upper limbs have more difficulty in recovering practical functions involved in normal activity of daily living (ADL) than the lower limbs have in regaining walking function. Therefore, rehabilitation for stroke-related hemiplegic upper limbs emphasizes an approach to the unaffected upper limbs, such as changing dominant

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hands and training for one-handed operation, by giving up on the recovery of the affected upper limbs from the early post-stroke stages.

Recent studies found that the plasticity of central nervous system was higher than previously presumed[6,7]. Some reports have described advanced rehabilitation approaches based on this plasticity, such as constraint-induced movement therapy[8,9], robotic therapy[10-14], therapeutic electrical stimulation[15], and integrated volitional control electrical stimulation[16]. These new approaches reported good results and a mechanism of recovery. Krebs and colleagues suggested a working model of stroke recovery similar to implicit motor learning from rehabilitation robotics practitioners[17]. This means that future evaluation methods for stroke-related hemiplegic upper limbs are required to focus on motor learning. There is a need to produce a new, simpler, quantitative evaluation method, with higher reproducibility and validity than the conventional evaluation method, for upper limb functions.

It is possible that application of robotic technology and the addition of measurement of movement smoothness will achieve a new quantitative evaluation method. The jerk cost, which shows the smoothness of overall movement by summation of the square of the jerk, is an index of movement smoothness[18,19]. The jerk cost is suitable for evaluation of smoothness of running[20], jaw movements[21], and upper limb movements[22,23].

There are no basic data related to the general properties of reaching movements by adding resistance force using a robot arm. To compare non-disabled people and hemiplegic patients, it is necessary to understand the reaching movements of healthy subjects. The purpose of this study was to examine the general properties of reaching movements as basic data in healthy subjects by adding resistance forces in order to be able to establish simple and accurate evaluations of hemiplegic upper extremities using robotic technology.

Methods

Experimental instruments

The robot arm is a general purpose arm (PA-10A-ARM, Mitsubishi Heavy Industries, Ltd., Tokyo, Japan) with seven joints and a weight of 35 kg (Fig. 1A). Each joint has alternate current servomotors, electromagnetic brakes, and angle detectors. It can be moved to arbitrary positions with high precision by programming. A handle was mounted at the distal portion of the robot arm as a terminal device so that subjects might move it, and a 6-axis force/torque sensor (IFS-67M25A15-14, NITTA Corp., Osaka, Japan) was installed at the base of the handle to allow impedance control of the robot arm and measurement of the force applied to the terminal device (Fig. 1B). Using the impedance control, mechanical resistances, such as inertia, rigidity, and viscosity, were managed according to the force applied to the sensor by subjects ; therefore, the robot can assist the subjects' movement and, conversely, add resistance to the movement.

We used a web camera, Qcam Orbit MP (QVR-13R, Logitech International S.A., Apples, Switzerland) to give the subjects visual feedback of the target trajectory of reaching movements and the handle position of the robot. This camera can be turned 189° in the horizontal direction and 102° in the vertical direction using a motor, and it facilitates easy operation from a personal computer. Its compact size allows us to install it anywhere. In this study, two cameras were installed in two positions, anterosuperior and to the left of the subjects, and they displayed the target trajectory and the moving robot's handle on the monitor. Since the position of the target trajectory differed depending on the subjects, it was shown by narrow tape on the monitor each time.

The robot arm is preprogrammed to initiate an emergency stop if any one of its joints moves beyond the

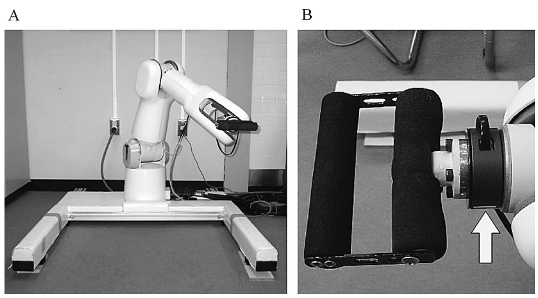

Fig. 1. A : PA-10A-ARM, a 7-axis general purpose Robot Arm (Mitsubishi Heavy Industries Ltd.). B : A handle and 6-axis force/torque sensor (IFS-67M25A15-14, NITTA Corp.).

specified angular velocity. If the terminal device of the robot arm tries to move beyond the specific scope, it is also stopped. The robot is equipped with an emergency stop button so that the operator can stop the robot at any time. Furthermore, the robot arm was wrapped with a plastic cover and incorporated urethane and limit switches inside the cover. With these, additional safety measures were added to ensure that the robot would stop if the subjects should come into contact with it.

Subjects

The subjects included 14 non-disabled males and 2 non-disabled females whose average age was 25 years (range, 21-44 years). They had no problems related to motor function, and all were right-handed. They were informed of the purpose and method of this study, and they agreed to the experiment.

Experimental setting

The reaching movement consisted of subjects sitting back in a chair while gripping the handle of the robot with the elbow joint in a flexed position at a 90° angle, and then pushing the handle forward within a horizontal plane and a vertical plane along the target trajectory shown on the monitor. The movement distance and time were preset to 50 cm and at 4 seconds, respectively, in order to allow subjects to push the handle safely while keeping their sitting balance easily. The points of the reaching movement when the subject reached the target and pressed the button were recorded, after which the robot automatically returned to the starting position.

The resistance force was also preset for the first half of the 30 cm of the movement to add a disturbance that was supposed to sweep away the reaching movement from the right and left in the horizontal plane (Fig. 2A) and upwards and downwards in the vertical plane (Fig. 2B). The disturbance had two strengths : a light resistance force that swept away at 7 cm per second ; and a strong resistance force that swept away at 12 cm per second, by viscous resistance of 25 gf/cm/s. Therefore, the resistance forces to the subjects' hands were 175 g in case of the light resistance and 300 g in case of the strong resistance when they kept the reaching movement straight against the disturbances. From the preliminary examination, the light resistance was regulated as the weakest force that the subjects could recognize and the strong resistance was regulated as the stronger force that the subjects could perform the reaching movement safely while keeping their sitting balance easily. Measurements were taken for each strength of the disturbance. The disturbance was applied to each reaching movement at random, including in the horizontal plane, no resistance, resistance from the left, and resistance from the right, and in the vertical plane, no resistance, resistance upwards, and resistance downwards. The reaching movements were repeated before each condition appeared more than three times.

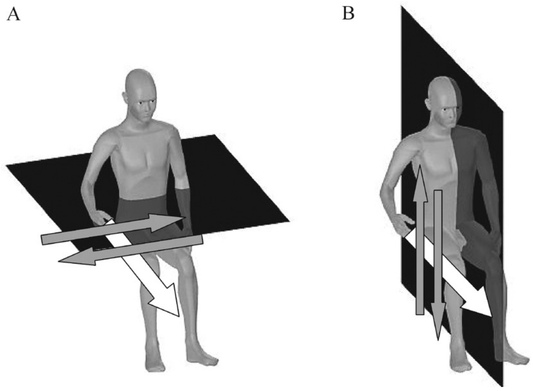

Fig. 2. The direction of the reaching movement and the resistance force in two planes. White arrow, reaching movement ; orthogonal arrows to the white arrow, resistance force ; A, horizontal plane ; B, vertical plane.

Evaluation of the reaching movement

The data of the position and time of the robot arm were gathered with a sampling frequency of 50 Hz, and three evaluation items were calculated from the data : the jerk cost, the largest swinging distance, and the endpoint displacement. The calculated results were compared for the reaching movement in the horizontal and vertical planes under the three disturbance conditions (no resistance, light resistance, and strong resistance).

The jerk cost is the sum total of the square of the jerk, which is obtained by differentiating the acceleration, as well as an index for smoothness of movement that is shown in the variation of acceleration[18,19]. We examined

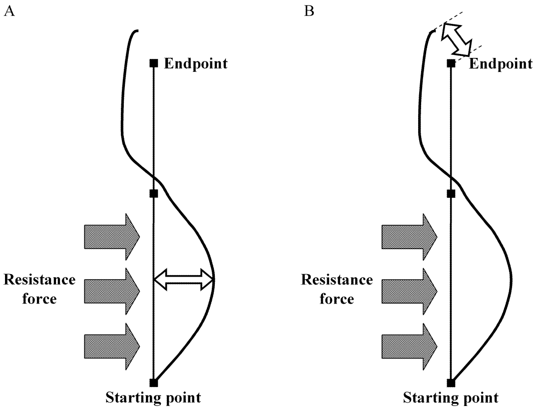

Fig. 3. The diagrammatic representation of A, the largest swinging distance, and B, the endpoint displacement.

this jerk cost in terms of the anteroposterior and horizontal directions for the reaching movement in the horizontal plane, and in terms of the anteroposterior and vertical directions for the reaching movement in the vertical plane. Since jerk cost depends on velocity[24), in this study, reaching movement was done under the same time and movement distance conditions. However, because the time for each trial differed, jerk cost was obtained after normalizing data by time. The largest swinging distance represented the furthest distance swayed by the disturbance (Fig. 3A). The endpoint displacement was the distance between the target endpoint and the actual point reached when errors occurred in the reaching points (Fig. 3B).

Data analysis

Mean values in each disturbance condition were obtained for the evaluation items calculated from the subjects' reaching movements, and these were taken as the values for the subjects. We first investigated whether there was an effect from disturbance. For comparison depending only on whether there was disturbance, the results without disturbance for bilateral upper limbs were combined and taken as the no disturbance group, and, in the cases of both light and strong resistances, the results with disturbance from two different directions in bilateral upper limbs were combined and taken as the disturbance group. Next, items that should be noted from this comparison were recorded, and the effect of the size of the disturbance was examined. The Kruskal-Wallis test was used to identify significant differences in the three different evaluation items. Then, the average values were compared under the three disturbance conditions with every evaluation item using the Games-Howell post hoc test. Statistical analyses were done using StatView 5.0 for Windows (HULINKS, Inc., Tokyo, Japan), and the significance level was set at P less than 0.5.

Results

Effect of presence or absence of disturbance

Table 1 compares the anteroposterior jerk cost, horizontal jerk cost, largest swinging distance, and endpoint displacement with and without disturbance in the horizontal plane. With light resistance, there was no significant difference in the anteroposterior jerk cost with and without disturbance. With strong resistance, the anteroposterior jerk cost was significantly larger when there was disturbance than when there was no disturbance. With both light and strong resistances, the horizontal jerk cost and the largest swinging distance were significantly larger when there was disturbance than when there was no disturbance. No significant difference was seen in endpoint displacement with and without disturbance, regardless of the strength of the resistance.

Table 2 compares anteroposterior jerk cost, vertical jerk cost, largest swinging distance, and endpoint displacement with and without disturbance in the vertical plane. There was no significant difference in the anteroposterior jerk cost with and without disturbance when the resistance was light. With strong resistance, the anteroposterior jerk cost was significantly larger when there was disturbance than when there was no disturbance. With both light and strong resistances, vertical jerk cost and the largest swinging distance were significantly larger when there was disturbance than when there was no disturbance. No significant difference was seen in endpoint displacement with and without disturbance, regardless of the strength of the resistance.

Effect of size of disturbance

The effects of the size of the disturbance are shown in

Table 1.　Average jerk cost, largest swinging distance, and endpoint displacement in the horizontal plane

	Resistance force		Resistance force	
	Removal	7 cm/second	Removal	12 cm/second
Anteroposterior jerk cost (m^2/s^5)	20.1±7.0	25.3±14.3	18.6±7.2	44.9±34.4†
Horizontal jerk cost (m^2/s^5)	1.4±0.1	15.6±8.1*	3.3±7.2	72.7±42.0†
Largest swinging distance (mm)	15.9±6.5	34.1±9.2*	14.1±5.0	57.6±11.0†
End point displacement (mm)	24.5±12.6	24.3±11.5	20.2±11.8	28.2±17.7

NOTE.　Values are means±SD.
*Significant at $P<.05$ (removal vs. 7 cm/second) ; †Significant at $P<.05$ (removal vs. 12 cm/second)

Table 2.　Average jerk cost, largest swinging distance, and endpoint displacement in the vertical plane.

	Resistance force		Resistance force	
	Removal	7 cm/second	Removal	12 cm/second
Anteroposterior jerk cost (m^2/s^5)	18.2±8.7	22.7±9.9	21.1±8.3	34.0±21.3†
Vertical jerk cost (m^2/s^5)	2.9±1.8	17.5±11.1*	4.8±3.6	79.4±56.3†
Largest swinging distance (mm)	18.0±4.7	32.0±8.2*	20.7±7.3	54.7±11.3†
End point displacement (mm)	26.6±14.6	25.0±14.9	27.7±13.8	27.9±14.0

NOTE.　Values are means±SD.
*Significant at $P<.05$ (removal vs. 7 cm/second) ; †Significant at $P<.05$ (removal vs. 12 cm/second)

Figures for horizontal jerk cost (Fig. 4) and largest swinging distance (Fig. 5) in the horizontal plane, and for vertical jerk cost (Fig. 6) and largest swinging distance (Fig. 7) in the vertical plane, which had significant differences with and without disturbance in cases of both light and strong resistances.

The horizontal jerk cost of the left upper limb on the horizontal plane, when the direction of the disturbance was from left to right, was 1.3±0.6 m^2/s^5 (mean±SD) without disturbance, 15.5±7.5 m^2/s^5 with light resistance, and 61.9±32.2 m^2/s^5 with large resistance.　Significant differences were seen among the three disturbance conditions, with horizontal jerk cost increasing with the larger disturbance.　When the disturbance was from

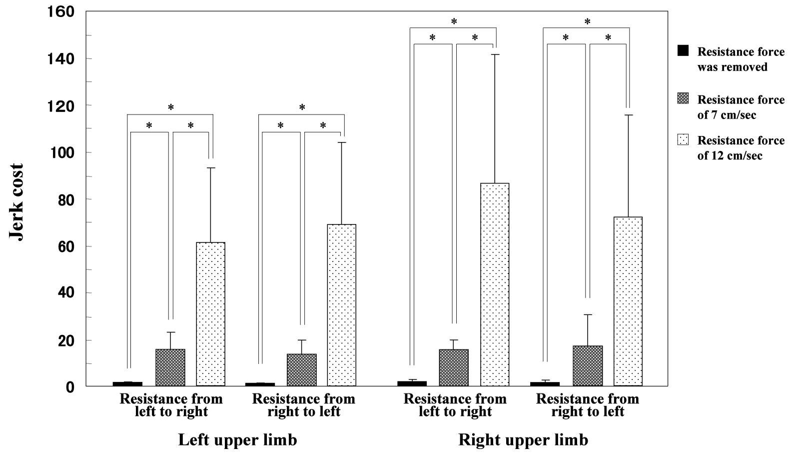

Fig. 4.　The horizontal jerk cost of the reaching movement in the horizontal plane.　*$p<0.05$; mean±SD.

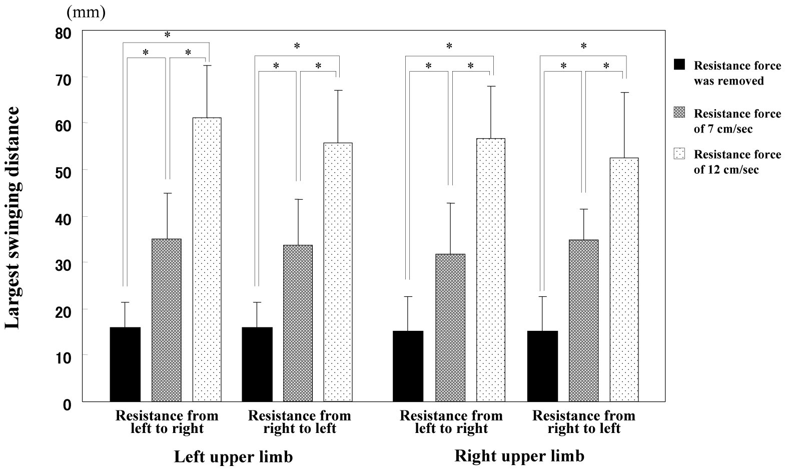

Fig. 5. The largest swinging distance of the reaching movement in the horizontal plane. *$p<0.05$; mean±SD.

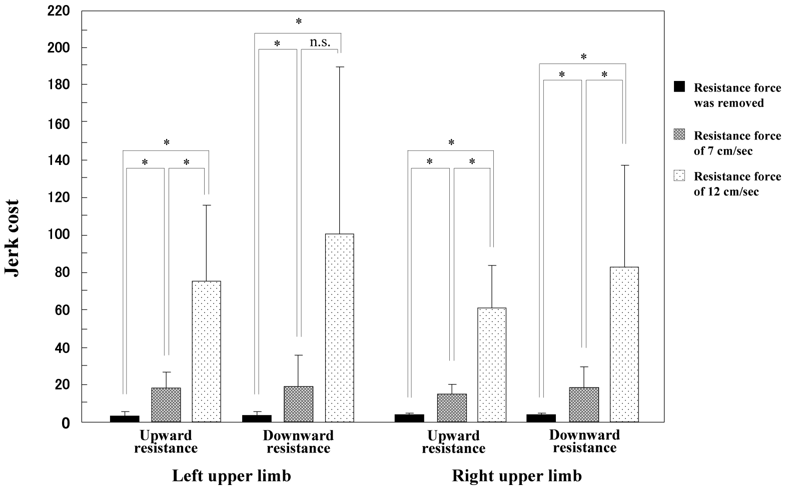

Fig. 6. The vertical jerk cost of the reaching movement in the vertical plane. *$p<0.05$; n.s., not significant ; mean±SD.

right to left, the horizontal jerk cost increased significantly with the larger disturbance. The horizontal jerk cost of the right upper limb was also significantly greater with larger disturbance, regardless of the direction of the disturbance (Fig. 4). The largest swinging distance of the left upper limb on the horizontal plane, when the disturbance was from left to right, was 35.5±9.3 mm with light resistance and 61.3±11.4 mm with strong resistance, against 16.4±5.4 mm without disturbance. It was significantly greater with the larger disturbance. When the disturbance was from right to left, the largest swinging distance was significantly greater with the larger disturbance. The largest swinging distance of the right upper limb was also significantly greater with the larger disturbance, regardless of the direction of the disturbance (Fig. 5).

The vertical jerk cost of the left upper limb in the vertical plane, when the disturbance was upward, was significantly greater with the larger disturbance. When the disturbance was downward, the vertical jerk cost was 2.9±2.0 m^2/s^5 with no disturbance, 19.1±17.0 m^2/s^5 with light resistance, and 100.2±89.7 m^2/s^5 with strong resis-

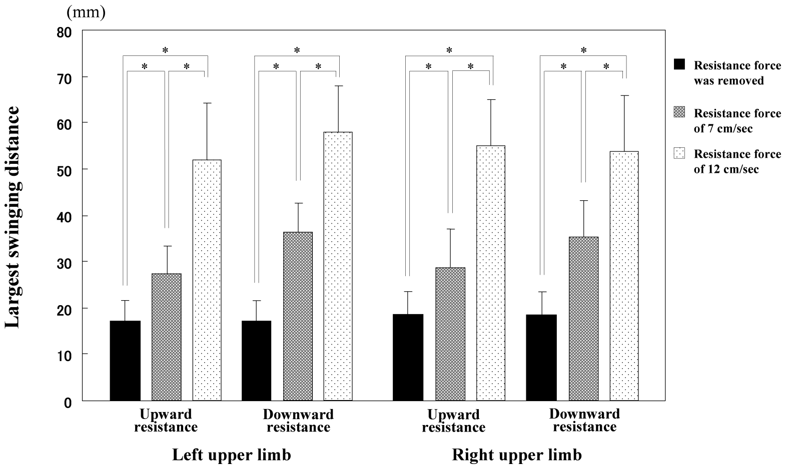

Fig. 7. The largest swinging distance of the reaching movement in the vertical plane. $*p<0.05$; mean±SD.

tance. Significant differences were seen between no disturbance and light resistance, and between no disturbance and strong resistance, but there was no significant difference between light resistance and strong resistance. The vertical jerk cost of the right upper limb increased significantly with the larger disturbance, regardless of the direction of the disturbance (Fig. 6). The largest swinging distance of the left upper limb in the vertical plane, when the disturbance was upward, was 27.5±6.1 mm with light resistance and 52.1±12.9 mm with strong resistance, versus 17.2±4.4 mm without disturbance. It was significantly greater with the larger disturbance. When the disturbance was downward, the largest swinging distance was significantly greater with the larger disturbance. The largest swinging distance of the right upper limb was also significantly greater with the larger disturbance, regardless of the direction of the disturbance (Fig. 7).

No significant differences were seen between the left and right upper limbs in anteroposterior jerk cost, horizontal jerk cost, vertical jerk cost, largest swinging distance, and endpoint displacement in the two planes, regardless of the size of the disturbance. Similarly, no significant differences were seen in these evaluation items by the direction of the disturbance.

Discussion

There have been many reports in recent years on the application of robot technology in movement training for stroke-related, hemiplegic upper limbs, but there have been no reports on specialized robots for evaluating upper limb function. Occasional reports have dealt with jerk cost to evaluate the smoothness of upper limb movements[22,23,25-28], but no studies have measured jerk cost using robots. This is the first study in which a robot arm was used and reaching movement in the horizontal and vertical planes with disturbance was evaluated using jerk cost.

The advantages of using robots to evaluate movement include: evaluations can be done easily with the use of programming; results can be quantified without difficulty; and quantitative data are objective and accurate. In addition, the difficulty of the task can be regulated by adding disturbances to the movement being evaluated. Even when obtaining the jerk index, in which jerk cost is adjusted by time and movement distance, the data needed for calculations can be gathered without the use of large instruments, such as a three-dimensional motion analyzer. In addition, robots can also be used in evaluating motor learning, which is thought to be necessary in evaluating function of paralyzed arms in the future. Thus, the application of robot technology to paralyzed upper limbs is very important, not only in training of the paralyzed limb, but also in evaluations of the paralyzed limb.

In evaluations of upper limb movements, reaching movements in the planes have a higher degree of freedom than reaching movements along a straight line. Moreover, movement to which disturbance is applied is presumed to be easily perturbed. Measurement of this perturbation is promising for the detection of mild paralysis and slight functional changes.

In this study, significant differences were seen in healthy people with and without disturbance in the horizontal jerk cost and largest swinging distance in the horizontal plane, and vertical jerk cost and largest swinging distance in the vertical plane. Jerk cost and largest swinging distance were also greater with the larger disturbance. In a study on reaching movement, Eder *et al.* developed an instrument to test coordination of paralyzed upper limbs tracing a straight line with a computer mouse, and confirmed a correlation between the standard deviation of the right-left deviation and the Ashworth Scale[29]. Schabowsky *et al.*, using a horizontal plane robot that produced disturbances, studied accommodation to a dynamic environment in a reaching movement in healthy people and showed that the reaching movement was likely to be affected by a disturbance orthogonal to the reaching movements[30]. These reports agree with our findings, and our results are thus thought to be valid.

Meanwhile, significant differences with and without disturbance were seen in anteroposterior jerk cost only when resistance was strong, and no significant difference was seen in endpoint displacement with and without disturbance, regardless of the size of the disturbance. These results show that, even when reaching movement is subjected to a disturbance orthogonal to the movement, the smoothness in the reach direction is not readily affected. With respect to endpoint displacement, even when the reaching movement is temporarily pushed off course by disturbance, under the present conditions, it was shown to be possible to adequately correct the course before reaching the endpoint.

Based on the above results, it is concluded that, in reaching movements of healthy people in the horizontal and vertical planes, when the reaching movement is subjected to orthogonal disturbance, jerk cost and largest swinging distance in the direction of the disturbance are easily affected in response to the disturbance. This result has potential application as an item to evaluate the function of paralyzed upper limbs.

This study demonstrated the characteristics of reaching movements of healthy people in the horizontal and vertical planes with disturbance. In the future, we would like to clarify the characteristics of reaching movements in hemiplegic upper limbs by evaluating the function under the same conditions and comparing the data of stroke patients and healthy people.

Conclusions

Reaching movements in the horizontal and vertical planes were analyzed by adding resistance forces with the use of robotic technology. The non-disabled subjects' reaching movements were likely to be affected by resistance forces orthogonal to the reaching movements. We realized that the stronger orthogonal resistance to the reaching movement decreased the horizontal smoothness in the horizontal plane and vertical smoothness in the vertical plane and extended the largest swinging distances.

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