

# DEVELOPMENT OF TABLETOP ROBOT FOR REHABILITATION OF UPPER LIMB PARALYSIS AND APPLICATION TO ASSESS UPPER LIMB FUNCTION

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## Abstract

Rehabilitation robot systems for upper limb training of hemiplegic individuals are generally large, difficult to carry, and expensive. There is the need for design of a compact, low-cost robotic system appropriate for widespread dissemination and use. The purpose of this study was to design and construct a new compact and portable rehabilitation robot, and to compare the upper limb function of patients with stroke-induced hemiplegia and healthy volunteers. The subjects were six patients with hemiplegia due to stroke in chronic stage and seven healthy adult volunteers. The upper limb function of each subject was investigated using the new robot system. The parameters for the assessment were Maximum swerve, Average speed, Jerk cost X (horizontal) direction, and Jerk cost Y (Straight) direction. All parameters calculated from the robot trajectory. In stroke group, differences were observed between affected and non-affected sides for both Maximum swerve ( $p = 0.027$ ) and average speeds ( $p = 0.045$ ). In control group, there are no differences between dominant and non-dominant hand in all parameters. Comparing affected side in stroke group and dominant side in control group, differences were observed for Maximum swerve, Jerk cost X. The results show that the new device is effective as an assessment instrument objective measurement of upper limb function. Maximum swing width and Jerk cost X is useful parameters to evaluate upper limb function by this device.

**Key words** : rehabilitation robot, hemiplegia, upper limb function

## Introduction

Stroke is a major cause of death in Japan and other countries, and about 70% of the surviving patients pres-

ent at least temporary functional impairment of the upper limb<sup>1</sup>. It has also been reported that high rate of stroke survivors suffer functional failure of the upper limb<sup>2,3</sup> and that only about 15% are left with useful function<sup>4</sup>. Stroke is important disease because it results in disorders that require caregiving and rehabilitation for functional recovery and maintenance.

Appropriate assessment is an integral part of physical rehabilitation, because the therapist can plan the effective training strategy from it<sup>5</sup>. In the stroke rehabilitation field, the most common scoring systems for motor per-

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formance is the Fugl-Meyer Motor Performance Assessment<sup>6)</sup>. And, the disability of stroke patient is most commonly measured using the Functional Independence Measure (FIM)<sup>7)</sup>. Although these measures are widely accepted, standardized and validated, they are still subjective and suffer from low resolution which is typical of ordinal scales<sup>8)</sup>.

Recently, various kinds of robotic technologies have been developed for more accurate assessment of reaching movement<sup>9)</sup>. Robotic assessments can be objective, quantitative, and continuous scales with less floor or ceiling effects compared to conventional clinical tools<sup>10)</sup>. In general, rehabilitation robotic systems for upper limb evaluation and training of hemiplegic individuals are large, difficult to carry, and expensive. The stroke patients are required to visit the hospital or other facility to evaluate and train their paralyzed upper limb by such robot devices. Recently, we developed a compact, readily transportable rehabilitation robot for upper limb. It is appropriate for widespread dissemination and use in the

stroke upper limb rehabilitation field.

The aim of this study was to design and construct a new compact and portable rehabilitation robot for upper limb rehabilitation, and evaluate quantitative upper limb function between the patients with stroke-induced hemiplegia and healthy volunteers by the robot.

## Materials and Methods

### 1. Participants

Six stroke patients (mean age ;  $63.0 \pm 12.1$  years, 5 men and 1 female, time since stroke ;  $63.6 \pm 45.6$  months) in the chronic phase of stroke-induced hemiplegia (induced by cerebral hemorrhage in three and by cerebral infarction in three ; Brunnstrom stages III-VI) (Table 1, 2) and seven healthy adult volunteers (mean age ;  $41.1 \pm 22.7$  years, 5 men and 2 female) participated in this study. The exclusion criteria were secondary motor neuron dysfunction complication, unstable disease control, and lack of motivation for participation in the ex-

Table 1. Demographic and clinical information of stroke patients

Number of patients	S1	S2	S3	S4	S5	S6
Age	55	49	83	62	59	70
Gender	M	M	F	M	M	M
Type of lesion	Inf	Inf	Hem	Hem	Inf	Hem
Side of lesion	Right	Right	Left	Left	Left	Left
Time since onset (months)	76	42	129	7	30	98
Brunnstrom stage (arm)	4	4	5	4	5	5
Brunnstrom stage (finger)	5	4	5	5	5	5

M : male, F : female  
Hem : hemorrhagic stroke  
Inf : infarction stroke

Table 2. Summary of the characteristics of stroke patients

Characteristic	N = 6
Age, mean $\pm$ standard deviation (range)	$63.0 \pm 12.1$
Type of disease	
Cerebral infarction	3
Cerebral hemorrhage	2
Subarachnoid hemorrhage	1
Days after the onset of hemiparesis, median (range)	$63.6 \pm 45.6$
Brunnstrom stage-arm, median (range)	$4.5 \pm 0.6$
Brunnstrom stage-finger, median (range)	$4.8 \pm 0.4$

periment.

Prior to subject recruitment, review was performed by the Ethics Committee of the Akita University Graduate School of Medicine and Faculty of Medicine, and a determination of conditional approval was received (Acceptance No. 1324). All subjects gave written informed consent prior to screening procedures and recruitment.

## 2. Composition of rehabilitation robot and system

The upper limb rehabilitation device comprises the robot body, the control system, the personal computer (PC) for operation, and the monitor, together with cable connections (Fig. 1).

The robot body is very compact, disk-shaped and approximately 300 mm in diameter, 150 mm in height, and 3.5 kg in weight, with a handle on top to move it. The handle is connected internally to a six-axis force sensor that activates the internal motor in response to forces exerted on it by the subject (Fig. 2). The robot has four omnidirectional drive wheels that enable it to move in any direction on a plane (Fig. 3). An augmented reality (AR) marker on the robot is observed by a camera placed directly in front of the monitor to obtain information on the robot position and map its trajectory. The positional information is read by the PC as data related to the base coordinate axis to graphically represent the trajectory and analyze the movements. The PC provides robot operational control, trajectory recording, and related functions. The subject moves the robot while viewing the information displayed on the monitor (Fig. 4). Lateral robot movement is limited to approximately 400 mm to keep its marker within the range of positional information

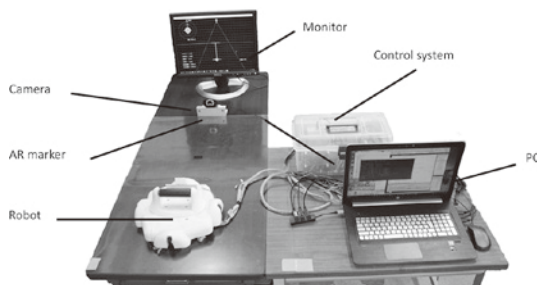


Fig. 1. Overall view of the new rehabilitation robotic system

reading via the camera. The system can be readily disassembled and transported, for operation at any location having a table approximately 400 mm square.



Fig. 2. Rehabilitation robot and AR marker placed on it



Fig. 3. Omni wheel to move the robot in all directions

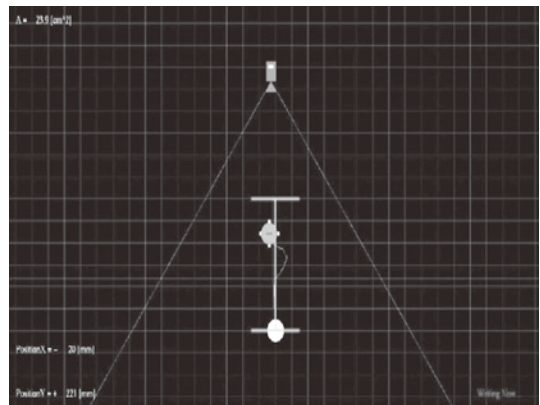


Fig. 4. Screen display on the monitor to manipulate the robot

### 3. Procedure

The participants were seated in a chair and operated the robot on the table while viewing the monitor located 500 mm ahead. The chair and table were positioned to obtain an angle of 90° in the elbow joint with the hand resting on the robot. All subjects attempted to repeat three times the forward and rearward reaching movement to and from a point 300 mm ahead without diverging from the line displayed on the monitor. Participants moved the device according to the bar going at the speed of 0.075 m/s on the monitor. They were also asked to assessment tasks using both dominant and non-dominant (stroke : affected and non-affected) hands.

### 4. Assessment parameters

The test parameters for the assessment were Maximum swerve, Average speed, Jerk cost X (horizontal) direction, and Jerk cost Y (Straight) direction. All parameters calculated from the robot trajectory. Maximum swerve was the largest absolute value (mm) recorded during trial. Average speed was the mean value of the measured speeds (m/s) recorded for forward and rearward robot movement. Jerk cost ( $\text{m}^2/\text{s}^6$ ) was calculated from Jerk, which represents smoothness, as Jerk cost =  $\int J^2 dt$  (where  $J = d^3x/dt^3$  and  $x$  is the robot X-coordinate displacement<sup>11-13</sup>).

### 5. Data analysis

Non-parametric Wilcoxon signed-rank test was used on the data of healthy participants to investigate the difference in performance between the dominant and non-dominant hand and within stroke between affected and non-affected hand. Further, the test was used to identify the combined inter-group differences in control sub-

ject's dominant hand with stroke patient's affected hand. Mann-Whitney U test was applied to compare stroke group to control group. The significance level was  $p < 0.05$ .

## Results

The results of upper limb performance in hemiplegic and control groups were summarized in table 3. There was no adverse events in all procedures.

In the case of stroke group, clear differences were observed between affected and non-affected sides for both Maximum swerve ( $p = 0.027$ ) and Average speed ( $p = 0.046$ ). There was no significant difference in Jerk cost X ( $p = 0.075$ ) and Jerk cost Y ( $p = 0.753$ ).

In the case of control group, the dominant and non-dominant hand performance evaluated. There are no differences between both sides in Maximum swerve ( $p = 0.204$ ), Average speed ( $p = 0.498$ ), Jerk cost X ( $p = 1.000$ ), Jerk cost Y ( $p = 0.128$ ).

Comparing affected side in stroke group and dominant side in control group, clear differences were observed for Maximum swerve, Jerk cost X ( $p < 0.001$ ,  $p = 0.014$ ). However, Average speed had no differences. Similarly in the case of stroke patients comparison, there are no difference in Jerk cost Y ( $p = 0.101$ ).

## Discussion

This study focused on investigating the evaluation of upper limb function and kinematic performance for control of stroke participants using two degrees of freedom platform. The device developed in this study is smaller, less heavy and not expensive than other upper limb rehabilitation robot reported before. The results of this

Table 3. Upper limb performance in hemiplegic and control group

	Hemiplegic patients (N=6)			Control (N=7)			<i>p</i>
	Affected	Non-affected	<i>p</i>	Dominant	Non-dominant	<i>p</i>	
Maximum swerve (mm)	27.05 (23.05-42.93)	14.95 (10.75-28.35)	0.027	12.1 (7.0-13.6)	9.1 (8.4-13.1)	0.204	0.001
Average speed (m/s)	0.104 (0.071-0.145)	0.071 (0.057-0.104)	0.046	0.083 (0.068-0.090)	0.072 (0.069-0.088)	0.498	0.295
Jerk cost X ( $\text{m}^2/\text{s}^6$ )	3.49 (1.10-11.5)	1.05 (0.458-2.300)	0.075	0.10 (0.00-0.90)	0.1 (0.0-1.6)	1	0.014
Jerk cost Y ( $\text{m}^2/\text{s}^6$ )	50.8 (31.7-67.7)	42.8 (34.2-63.6)	0.753	11.9 (4.80-45.2)	9.8 (3.3-29.5)	0.128	0.101

median (IQR)

study showed that movements performed by stroke participants were less smooth and more variable compared to healthy participants. In the following, the results of each evaluation item will be discussed in detail, and future tasks will be discussed.

In stroke group, there were differences between affected and non-affected sides for both Maximum swerve and Average speed. Although Jerk cost X had no significant difference ( $p = 0.075$ ), there was a tendency for the paralyzed side to become larger (not smooth) than on the non-affected side. However, there was no significant difference in Jerk cost Y. Trunk movement affects reaching range-of-motion in stroke patients<sup>14</sup>. We did not restrict trunk movement during the test in this study. The possible reason of no difference in jerk cost Y may be the effect of trunk movement that helps smoothness motion in the Y axis (straight) direction.

In the control group, there are no differences between dominant and non-dominant hand in all parameters same as previous study<sup>15,16</sup>. On the other hand, circle tracing task had significant differences because circle tracing task need more amount of inter-joint coordination than line tracing<sup>15</sup>. The line trace task was too easy for control group to compare dominant side and non-dominant side.

Inter-group analysis between control and stroke showed clear differences in Maximum swerve, Jerk cost X. However, Average speed had no differences. Similarly in the case of stroke patient comparison, there are no differences in Jerk cost Y.

It was reported that movements made with the unaffected limbs of stroke participants were worse than those of controls<sup>15,16</sup>. The average speed among stroke group was significantly faster on the affected side than on the non-affected side in this study. This result has two meanings, worse movement on non-affected side and uncontrollable on affected side. The possible reason of no difference in mean velocity was that the average speed became faster without controlling the affected upper limb during the operation of the trace and accordingly it became the same as the average speed on the dominant hand side of the control group. From the above, Maximum swing width and Jerk cost X is useful parameters to evaluate upper limb function by our device. On the oth-

er hand, there was room to consider about average speed.

The limitations of this study include the age difference between the control and stroke populations. As a part of future studies, we plan to conduct the experiment in elderly adult to remove any variability due to effect of aging. Additionally, the number of stroke participants is limited. We did not restrict trunk movement during trial. After we collect sustainable amount of data and some improvement, it is necessary to investigate correlation with clinical score to understand the clinical relevance of each measure in the future study.

In conclusion, the study results show that the new rehabilitation robotic system is effective as an assessment instrument objective measurement of upper limb function, and maximum swing width and Jerk cost X is useful parameters to evaluate upper limb function by this device. This novel device will be useful for examining and training of upper limb in stroke patients.

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