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Measurement of Immediate Effect by Therapeutic Electrical Stimulation Using a New Desktop Rehabilitation Robot

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Abstract

Objective: More frequent use of robot technology in the field of rehabilitation is driving the need for smaller, less cumbersome devices. The objectives of the present study were to evaluate and compare quantitatively the upper limb function of chronic stroke patients before and after therapeutic electrical stimulation using a newly developed rehabilitation robot.

Methods: Five stroke patients (3 men, 2 women; mean age: 66.4 ± 9.6 years; time since stroke: 36.0 ± 52.9 months) in the sub-acute and chronic phase of stroke-induced hemiplegia (induced by cerebral hemorrhage in four and by cerebral infarction in one; Brunnstrom stages III-V) participated in the study. None of them had any secondary motor neuron dysfunction or unstable disease control. Before and after 15 min of therapeutic electrical stimulation for repeated finger flexion and extension, participants performed reaching movements while moving the rehabilitation robot with their affected hand. Assessment parameters included Maximum swerve, Average speed, and smoothness of movements, as calculated by Jerk cost X (right-left direction) and Jerk cost Y (forward-backward direction).

Results: All patients were able to use the rehabilitation robot to perform the reaching movements. Clear differences were observed before and after therapeutic electrical stimulation for Maximum swerve and Average speed in the X direction, and there was a tendency for Jerk cost X to differ before and after therapeutic electrical stimulation. In contrast, there were no significant differences in either Jerk cost Y or Average speed in the Y direction before and after the stimulation.

Conclusion: The immediate effects of therapeutic electrical stimulation in chronic stroke patients can be quantified using our newly developed rehabilitation robot. Successful quantification of the effects of therapeutic electrical stimulation in stroke patients using smaller robotic systems could revolutionize the rehabilitation of these and other patients suffering from motor dysfunction or paralysis.

Introduction

Stroke is one of the major causes of death in many countries, and 70% of surviving patients present with dysfunction of the upper limbs [1]. It has also been reported that high rate of stroke survivors suffer functional failure of the upper limb [2,3], and only about 15% are left with useful functions [4]. Rehabilitation is necessary for functional recovery during the treatment of stroke. Appropriate assessment is indispensable for the rehabilitation, and effective evaluation of the patient is necessary for the therapist to know what needs to be treated [5]. Evaluation systems currently in general use include the Fugl–Meyer assessment [6] and the Functional Independence Measure [7]. These assessments are standardized and their reliability has been verified. However, these clinical measurements are subjective, and

detailed evaluation of the patient is difficult [8]. For rehabilitation, robot technology is more frequently being used for accurate and detailed patient evaluation [9]. Robot evaluation systems are objective, quantitative, continuous, and are expected as new evaluation tools compared to the conventional clinical evaluation [10]. However, many of the rehabilitation robots are large and cumbersome. To overcome these drawbacks, we succeeded in creating a small rehabilitation robot for objectively evaluating the motor function of the upper limbs of healthy volunteers and stroke patients [11].

Functional electrical stimulation (FES) is one of the most promising alternative interventions to help hemiplegic stroke survivors recover upper limb function. FES is a method of restoring functionality to the upper or lower extremities of hemiplegic stroke survivors by electrically stimulating the lower motor neurons [12]. FES training involves therapeutic electrical stimulation (TES) for the paralyzed muscles. Both FES and TES are used on the affected upper limb and are effective in improving muscle atrophy or the limited range of

motion in joints due to paralysis following stroke. There are many reports on the therapeutic effect of TES on paralyzed limbs, but few reports have examined the immediate effects objectively in detail. The aims of the present study were to evaluate and compare quantitatively the upper limb function before and after TES using our device. We hypothesized that many stroke patients would show immediate therapeutic effects after TES, and that our robot would be able to measure upper limb function in detail.

Materials and Methods

Participants

Five stroke patients (3 men and 2 women, mean age: 66.4 ± 9.6 years, time since stroke: 36.0 ± 52.9 months) in the sub-acute and chronic phase of stroke-induced hemiplegia (induced by cerebral hemorrhage in four and by cerebral infarction in one; Brunnstrom stages III–V) were included in the study (Tables 1 and 2). They were all right-handed, and the paralyzed side was the left hand on the non-dominant hand side. The exclusion criteria were secondary motor neuron dysfunction, unstable disease control, and lack of motivation for participation in the experiment.

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

	S1	S2	S3	S4	S5
Age	66	62	83	62	59
Gender	F	M	F	M	M
Type of lesion	Hem	Hem	Hem	Hem	Inf
Time since onset (months)	4	10	129	7	30
Brunnstrom stage (arm)	3	4	5	4	5
Brunnstrom stage (finger)	4	5	5	5	5

Table 1: Demographic and clinical information (*Hem: Haemorrhagic stroke; *Inf: Infarction stroke).

Characteristic	N=5
Age, mean ± standard deviation	66.4 ± 9.6
Sex, male//female	3//2
Type of disease	
Cerebral infarction	1
Cerebral haemorrhage	4
Days after the onset of hemiparesis, median (range)	36.0 ± 52.9
Brunnstrom stage-arm, Mean ± SD	4.2 ± 0.84
Brunnstrom stage-finger, Mean ± SD	4.8 ± 0.45

Table 2: Characteristics of the participants (SD: Standard Deviation).

Rehabilitation robot and system

Our upper limb rehabilitation device comprises a robot body, a control system, a personal computer (PC) for operation, a monitor, and cable connections (Figure 1).
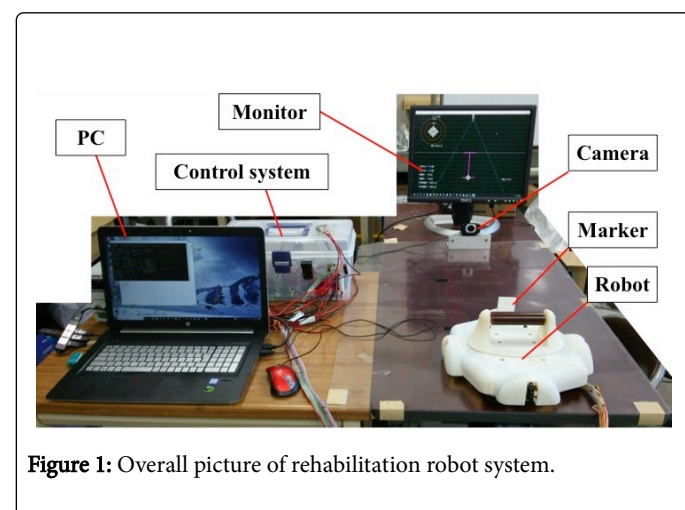

Figure 1: Overall picture of rehabilitation robot system.

The disk-shaped robot body is very compact, approximately 300 mm in diameter and 150 mm in height, and weighs 3.5 kg. The handle, which is used to move the robot, is connected internally to a six-axis force sensor that activates the internal motor in response to forces exerted on it by the subject (Figure 2).
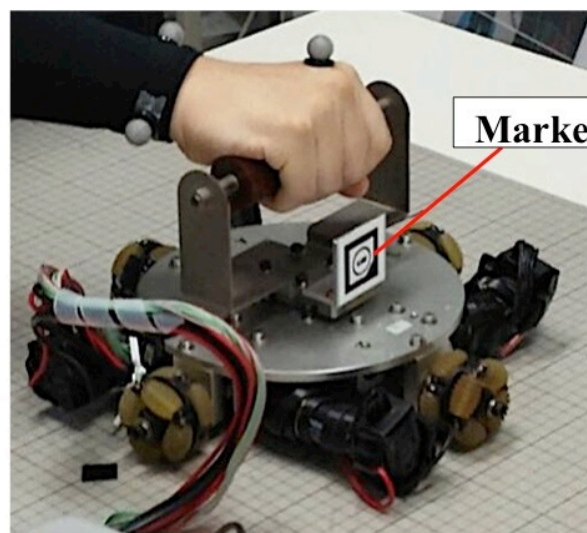
Figure 2: Rehabilitation robot and AR marker placed on it.

The robot has four omnidirectional drive wheels that enable it to move in any direction on a plane (Figure 3). A camera placed directly in front of the monitor records an augmented reality (AR) marker on the robot to obtain information on the robot position and map its trajectory.
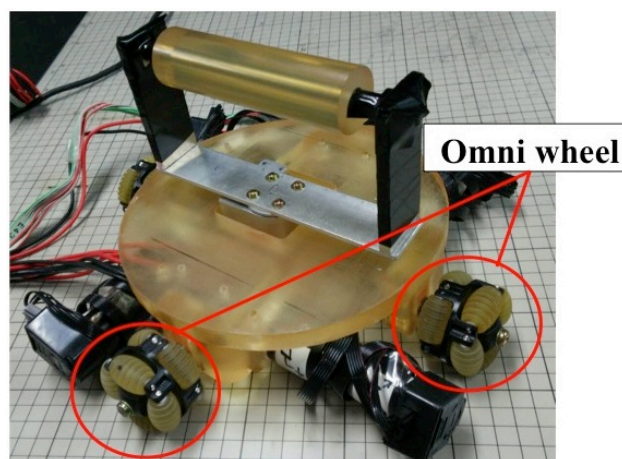

Figure 3: With the four Omni wheels mounted, the robot can move in all directions.

The positional information is read by the PC as data related to the base coordinate axis to graphically represent the trajectory and analyse 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 (Figure 4).
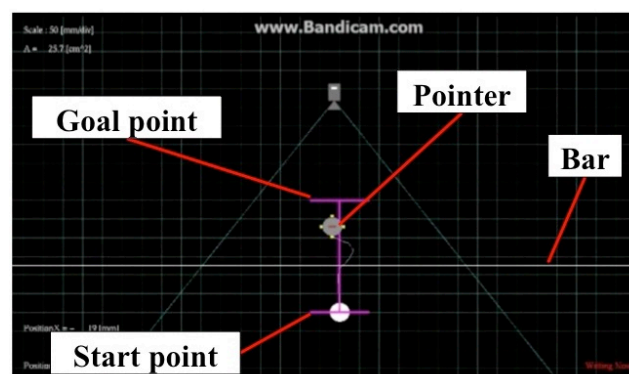

Figure 4: The subject manipulated the robot while looking at this screen displayed on the monitor. They moved the pointer from the start point to the goal point so as not to protrude from the purple line with the speed of the bar moving at the target speed as a guide.

The robot is also capable of applying a resistance to movement for training purposes. Lateral robot movement is limited to approximately 400 mm to keep the AR marker within the range of positional information being read via the camera. The system can be readily disassembled and transported for operation at any location, and only requires about 400 mm^2 of space.

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 so the elbow was bent at 90° when the participant's hand was resting on the handle of 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. Simultaneously, the robot was set to move randomly to the right or left (loaded condition) while the participants moved it. Participants moved the device according to the bar, which was moving at a speed of 0.075 m/s on the monitor. Experiments were conducted under unloaded and loaded conditions, and each participant was asked to perform the assessment tasks using his or her affected hand.

Training

The training session for each subject consisted of 15 min of TES in the exercise mode of repeated finger flexion and extension from hand joints with a pulse burst width of 0.145 ms (level 6) and a stimulation frequency of 36 Hz using the NESS H200 Wireless Hand Rehabilitation System (Bioness Inc., Valencia, CA, USA) instead of training facilitated by an occupational therapist.

Assessment parameters

The test parameters for the assessment were Maximum swerve, Average speed, Jerk cost X (right–left direction), and Jerk cost Y (forward–backward direction). All parameters were calculated from the robot trajectory. Maximum swerve was the largest absolute value (mm) recorded during the trial. Average speed was the mean value of the measured speeds (m/s) recorded for forward and backward robot

movement. Jerk cost (m^2/s^6) was calculated from Jerk, which represents smoothness, as Jerk cost= $\int J2dt$ (where $J=d^3x/dt^3$ and x is the robot X-coordinate displacement) [13-15].

Data analysis

The non-parametric Wilcoxon signed-rank test was used to analyse the data of stroke patients to investigate the differences in performance between before and after TES on affected hands. A p value<0.05 indicated statistical significance.

Results

Clear differences were observed between pre and post TES for Maximum swerve (p=0.043) and Average speed in the X direction (p=0.039). Jerk cost X before and after TES tended to differ (p=0.068). There were no significant differences in either Jerk cost Y (p=0.225) or Average speed in the X direction (p=0.686). There were no adverse events in all procedures (Table 3).

	Pre TES	Post TES	p
Maximum swerve (mm)	27.1	12.4	0.043
Mean speed X (m/s)	0.0168	0.0052	0.039
Mean speed Y (m/s)	0.0788	0.0628	0.686
Jerk cost X (m2/s6)	1.8	0.4	0.068
Jerk cost Y (m2/s6)	33.3	27.9	0.225

Table 3: Measurement result by desktop robot.

Discussion

There were significant differences in Jerk cost X and the largest swinging distance in the present study. In contrast, no significant differences were found in mean velocity and Jerk cost Y. Several studies have used Jerk cost to evaluate the smoothness of upper limb movements [13,14,16,17]. Jerk cost represents the smoothness of the reaching motion during a trial, and the largest swinging distance represents the furthest distance swayed during a reaching movement. Thus, the largest swinging distance indicates the accuracy of the reaching motion. The results of the present study showed that TES immediately improved the smoothness and accuracy of the movement in the X axis direction. For rehabilitation after stroke, TES has been used to facilitate the return of function and prevent complications in the upper limbs [18-22]. Another study demonstrated that TES prevented a deterioration in contractures in severely disabled patients [23]. The physical therapy literature suggests that TES might promote recovery of movement and functional ability after stroke [24]. TES can be considered as a treatment option that reduces spasticity and improves the range of motion in patients after stroke [25]. The reduction in spasticity may be explained by the actions of TES on increasing Ib afferent fiber activation via mechanisms that facilitate the Renshaw cell recurrent inhibition, on antagonist reciprocal inhibition, and on increasing cutaneous sensory stimuli [26,27]. Previous reports showed that TES for the lower limbs was useful for immediately reducing spasticity, and improving both balance and gait abilities in chronic stroke patients [28]. Similarly, our results showed that TES improved smoothness and accuracy in reaching movements. We

considered that spasticity was temporarily reduced by TES in patients who were measured using our robot.

There were no differences in Jerk cost Y in the present study. Trunk movement has been shown to affect the reaching range-of-motion in stroke patients [23]. As we did not restrict trunk movement during the test, one possible reason for the lack of any differences in Jerk cost Y may be the effect of trunk movement that helped smooth motion in the Y axis (straight) direction.

The limitations of this study include the small number of participants. Additionally, we did not restrict trunk movement during the trials. After we collect a sustainable amount of quantitative data, it will be necessary to investigate in a future study the correlation of the result measured by this robot with the clinical score to understand the clinical relevance of each measurement.

Conclusion

TES was administered to chronic stroke patients, and the immediate effects of TES were measured using our rehabilitation robot. The results showed that TES improved the smoothness and accuracy of reaching movements. Our device was able to sensitively detect the immediate effects of TES.

Conflicts of Interest

The authors have no conflicts of interest directly relevant to the content of this article.

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