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Effect of Sensory Loss on Improvements of Upper-Limb Paralysis Through Robot-Assisted Training: A Preliminary Case Series Study

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Featured Application: The present study examines the effectiveness of robot training in stroke patients with hemiplegic motor paralysis with or without complete sensory loss. Motor paralysis improvement through the use of robot training was observed in all patients examined. However, the effectiveness of robot training for patients with moderate or severe paralysis was reduced if the patient also had complete sensory loss. These results should be considered when determining the applicability and period of use of robot training.

Abstract: Sensory disorder is a factor preventing recovery from motor paralysis after stroke. Although several robot-assisted exercises for the hemiplegic upper limb of stroke patients have been proposed, few studies have examined improvement in function in stroke patients with sensory disorder using robot-assisted training. In this study, the efficacies of robot training for the hemiplegic upper limb of three stroke patients with complete sensory loss were compared with those of 19 patients without complete sensory loss. Robot training to assist reach motion was performed in 10 sessions over a 2-week period for 5 days per week at 1 h per day. Before and after the training, the total Fugl–Meyer Assessment score excluding coordination and tendon reflex (FMA-total) and the FMA shoulder and elbow score excluding tendon reflex (FMA-S/E) were evaluated. Reach and path errors (RE and PE) during the reach motion were also evaluated by the arm-training robot. In most cases, both the FMA-total and the FMA-S/E scores improved. Cases with complete sensory loss showed worse RE and PE scores. Our results suggest that motor paralysis is improved by robot training. However, improvement may be varied according to the presence or absence of somatic sensory feedback.

Keywords: cerebrovascular disease; hemiparesis; sensory disorder; manipulandum; robot-assisted training

1. Introduction

Stroke is a leading cause of disability of motor function. Recovery of arm function is essential to regain activities of daily living after stroke. Several robot-assisted exercises for the hemiplegic upper limb of stroke patients have been proposed in recent years [1]. The InMotion ARM^{TM}

Robot (MIT-MANUS/InMotion2, Interactive Motion Technologies, Inc., Cambridge, USA) has been demonstrated to be effective in neurorehabilitation therapy for the motion of shoulder and elbow joints [2–5]. In the exercise using InMotion2, a grip position of the robot arm is indicated on a display in front of the patient, who guides the grip to a specified target using the horizontal reach motion of the hemiplegic upper limb. If the patient cannot operate the robot arm sufficiently, the reach motion is performed through assistance from the robot. The reach motion is repeated >1000 times per day for stroke rehabilitation.

Neurorehabilitation training techniques are based on motor learning principles [6–9]. Motor functional recovery after stroke by the motor learning is influenced by difficulties of the training, motivation factors of the patients, transferability of a learned skill, and density and frequency of the training sessions. Especially visual and proprioceptive feedbacks, which compliment motion errors, are important for motor learning. Previous studies of reaching movements by healthy subjects revealed that sensory feedback has played an important role in motor adaptation [10,11]. In a patient study, Cole and Sedgwick reported that visual feedback complements motion when proprioception is impaired [12]. Vidoni and Boyd (2009) also augured in a clinical study that the central proprioceptive capability is important for learning patterns of movement [13]. Sensory disorder is considered a factor preventing recovery from motor paralysis. Proprioception is correlated with the perceived level of physical activity and, in combination with superficial sensation impairment, prevents the performance of activities of daily living (ADL) and upper limb motor recovery [14]. Sunderland et al. (1992) reported that patients with severe sensory disorder experience less functional improvement after stroke than patients with mild sensory disorder [15].

Staubli et al. (2009) examined the effectiveness of robot training in four chronic stroke patients and reported that, in one case of a patient with sensory disorder, the improvement in motor paralysis improvement was small [16]. Research on InMotion2 has been in upper limb paralysis motor patients [17,18], but few studies have focused on the improvement of paralysis in stroke patients with sensory disorder.

In the present study, we provided training using InMotion2 for upper limb function of stroke patients, and examined the impact of complete sensory loss on the improvement of motor paralysis in various degrees of paralysis.

2. Materials and Methods

We recruited first-stroke patients without severe cognitive impairments (i.e., severe aphasia and/or unilateral special neglect), who were able to be intervened for 2 weeks and could stably sit (Functional Independence Measure—bed/chair transfer item score of 4 or higher) for the present pilot study. Consequently, 22 stroke patients with a supratentorial lesion participated in this study (Table 1). The patients were admitted to the Fujita Health University Nanakuri Memorial Hospital between June 2013 and June 2014 and had agreed to training using InMotion2. The study design was compliant with the provisions of the Declaration of Helsinki and was approved by the appropriate ethics review boards of Fujita Health University (approval number: 15–132).

The subjects included three patients with complete sensory loss (0 points for both the tactile, "anesthesia", and proprioceptive senses, "no position change is detected", on the Stroke Impairment Assessment Set (SIAS)—Light Touch and Position Senses, respectively [19,20]) and with Fugl–Meyer Assessment scores for shoulder and elbow, excluding tendon reflex (FMA-S/E, perfect score: 30 points), of 8 points, 23 points, and 30 points, respectively. The other 19 patients had FMA-S/E scores similar to those of the three patients with complete sensory loss, but had scores of 1 point or higher for both the tactile and position senses on the SIAS.

The patients were divided into three groups by the motor paralysis according to the upper-extremity subscale of FMA (FMA-UE). For the classification, we referred to a previous FMA study [21] which classified the motor paralysis of the upper extremity as severe (0–27 points), moderate (28–57 points), and mild (58–66 points). In the present study, the FMA-UE score excluding the items of the coordination and tendon reflex was used for the evaluation as for the total FMA score of the upper extremity (FMA-total, perfect score: 54 points). In the modified scores (FMA-total), the classification ranges were 0–15, 16-45, 46–54 points, respectively. By assuming the rate of scores for shoulder and elbow excluding tendon reflex to the FMA-total (30/54), the borders of the three groups in FMA-S/E (perfect score: 30 points) were defined at 9 and 25 points, respectively. Patients with the FMA-S/E scores of less than 10 points were placed in the severe motor paralysis group (10 patients), patients with scores of 10 to 25 points were placed in the moderate paralysis group (eight patients), and patients with scores of 26 or higher were placed in the mild paralysis group (four patients). For each group, one patient had complete sensory loss. The effectiveness of robot training for patients with complete sensory loss was compared with that for patients without complete sensory loss for each motor paralysis level.

Table 1. Characteristics of participants at the start of robot training.

Paralysis (Range)	Sex, Age	Days	Stroke Type (Lesion), Paretic Side	SIAS U/E		Sensory Loss
				LT	Pos	
Severe (1–9)	M, 36	78	Hemorrhage (Putamen), R	0	0	Complete
	M, 56	59	Hemorrhage (Thalamus), R	1	1	-
	M, 58	62	Hemorrhage (Putamen), R	1	2	-
	F, 61	77	Hemorrhage (Thalamus), L	2	3	-
	M, 75	54	Ischemic (Basal ganglia, Corona radiata), L	3	3	-
	M, 58	70	Hemorrhage (Putamen), L	3	3	-
	M, 75	58	Ischemic (Putamen, Corona radiata), L	3	3	-
	M, 58	70	Hemorrhage (Putamen), R	3	3	-
	M, 71	63	Hemorrhage (Putamen), L	3	3	-
	M, 52	69	Hemorrhage (Thalamus), L	3	3	-
Moderate (10–25)	M, 59	74	Hemorrhage (Putamen), L	0	0	Complete
	M, 61	78	Hemorrhage (Subcortical), L	1	1	-
	F, 59	77	Hemorrhage (Putamen), R	2	2	-
	F, 30	54	Hemorrhage (Putamen), L	2	2	-
	F, 65	71	Hemorrhage (Putamen), L	2	2	-
	M, 58	45	Ischemic (Middle cerebral artery), R	2	2	-
	M, 62	67	Ischemic (Putamen), R	3	3	-
	M, 83	71	Ischemic (Internal carotid artery), L	3	3	-
Mild (26–30)	M, 75	69	Ischemic (Internal carotid artery), L	0	0	Complete
	M, 79	89	Ischemic (Atherothrombotic brain), R	2	2	-
	M, 66	50	Ischemic (Basal ganglia lacunar), L	2	2	-
	F, 61	52	Hemorrhage (Thalamus), L	3	3	-

Range, Range in Fugl–Meyer Assessment score—shoulder and elbow score excluding tendon reflex; M, male; F, female; Days, days from stroke onset; R, right; L, left; SIAS, Stroke Impairment Assessment Set; U/E, upper extremity; LT, Light Touch (0–3); Pos, Position (0–3).

InMotion2 robot training was performed in addition to normal occupational therapy for 10 sessions over a 2-week period at 5 days per week at 1 h per day. The normal occupational therapy, including upper limb function training and ADL training, was performed for 1 h per day, 7 days per week for 2 weeks.

Motor functions were evaluated before training started and after 2 weeks of training. The indicators of function improvement were as follows: (1) the FMA-S/E, which excludes tendon reflex (perfect score: 30 points); (2) the FMA-total, which excludes coordination and tendon reflex (perfect score: 54 points); (3) reach error (RE); and (4) path error (PE). RE and PE were calculated in the evaluation mode of InMotion2 based on the track of the recorded motion.

In the evaluation mode of InMotion2, a circular target was displayed in the center, and eight other targets were displayed at equal intervals around the circumference of a circle with a diameter of 14 cm. Each subject placed the indicator showing the grip location on the central target, then moved the indicator to the target designated on the circumference of the circle. This performance was recorded as one reach movement. After the reach motion was completed, or a specified time passed, the center point was designated as the target, and the subject moved the indicator back to the center making the total movement count as two. This task was repeated in a clockwise direction around the circle, until each outer target had been touched. This entire cycle was repeated five times, and the 80th reach motion ended the task. The RE indicated the distance from the point reached by the indicator to the target, and, whenever the indicator did not reach the target, the RE value increased. The PE evaluated the track of the indicator. Whenever the track of the indicator deviated from the optimal track, the PE value increased. The RE and PE were both averages of the values obtained during the 80 reach motions.

For statistical analysis, a range of ±1.96 of the mean values of the hemiplegic patients without complete sensory loss were set as the 95% confidence intervals and were compared against the scores of the patients with complete sensory loss.

3. Results

As shown in Table 2 and Figure 1A,B, almost all the patients without complete sensory loss improved in the FMA-S/E and FMA-total scores after the robot training. Although the pre-training FMA scores in patients with complete sensory loss were relatively higher than those in patients without complete sensory loss, their improvement tended to be less. This tendency was prominent in the FMA-total scores in the moderate paralysis group (Figure 1B).

Table 2. The upper-extremity subscale of Fugl–Meyer Assessment (FMA-UE) and InMotion2-evaluation scores in pre- and post-robot training.

Motor Paralysis	Sensory Loss	FMA-UE				InMotion2-Evaluation			
		S/E (0–30)		Total (0–54)		RE (cm)		PE (cm)	
		pre	post	pre	post	pre	post	pre	post
Severe	Complete	8	9	8	9	11.0	8.4	4.6	2.8
	-	2	2	4	4	10.9	3.4	2.3	2.1
	-	3	13	3	13	5.8	2.4	1.4	1.5
	-	5	8	6	17	0.9	0.8	1.2	1.0
	-	6	7	6	8	10.5	1.7	3.8	2.0
	-	4	4	6	6	7.6	0.8	2.0	1.3
	-	6	9	9	13	6.7	1.6	1.4	1.4
	-	8	10	9	11	4.4	1.2	2.1	1.5
	-	6	6	7	8	6.2	1.6	1.6	0.9
	-	7	7	14	15	7.7	1.0	1.9	1.0
	Avg	5.2	7.3	7.1	10.6	6.7	1.6	2.0	1.4
	SD	1.9	3.2	3.3	4.3	3.0	0.8	0.8	0.4
Moderate	Complete	23	23	42	38	2.3	0.9	2.4	1.5
	-	14	14	15	16	6.6	0.8	2.5	0.9
	-	17	22	31	44	0.8	0.9	0.9	0.7
	-	13	24	17	38	1.0	0.8	0.9	0.9
	-	23	24	35	46	0.8	0.9	0.7	0.5
	-	13	16	13	17	1.9	0.9	1.5	1.0
	-	21	21	22	22	0.9	0.9	1.0	0.7
	-	17	18	15	16	1.0	0.9	0.6	0.7
	Avg	16.9	19.9	21.1	28.4	1.9	0.9	1.2	0.8
	SD	3.9	3.9	8.6	13.7	2.1	0.1	0.7	0.2
Mild	Complete	30	30	51	52	1.2	0.8	0.9	0.7
	-	28	28	51	51	1.0	0.8	0.5	0.6
	-	29	30	52	53	0.9	0.8	0.9	0.7
	-	27	30	48	52	0.9	0.7	0.7	0.4
	Avg	28.0	29.3	50.3	52.0	0.9	0.8	0.7	0.6
	SD	1.0	1.2	2.1	1.0	0.1	0.1	0.2	0.2

FMA-UE, upper-extremity subscale of Fugl–Meyer Assessment; S/E, shoulder and elbow excluding tendon reflex; Total, total FMA-UE score excluding coordination and tendon reflex; RE, Reach error; PE, Path error; Avg and SD, mean and standard deviation excluding the patients with complete sensory loss.

InMotion2-evaluation scores are shown in Table 2 and Figure 1C,D. The RE values of the patients without complete sensory loss in the severe and moderate motor paralysis groups were scattered initially, but the values were greatly reduced after the robot training (Figure 1C). In the mild paralysis group, the RE values were slightly improved. While all the patients with complete sensory loss showed similar improvements in RE to the patients without complete sensory loss, the RE value of the patient with complete sensory loss in the severe motor paralysis group remained high after the training. As shown in the Figure 1D, in the severe and moderate motor paralysis groups, the PE values were maintained or improved in all the cases. However, for the two cases with complete sensory loss, the scores were rather higher than those for the patients without complete sensory loss at both pre- and post-training. In the mild paralysis group, the PE values were small and were slightly improved in all the cases.

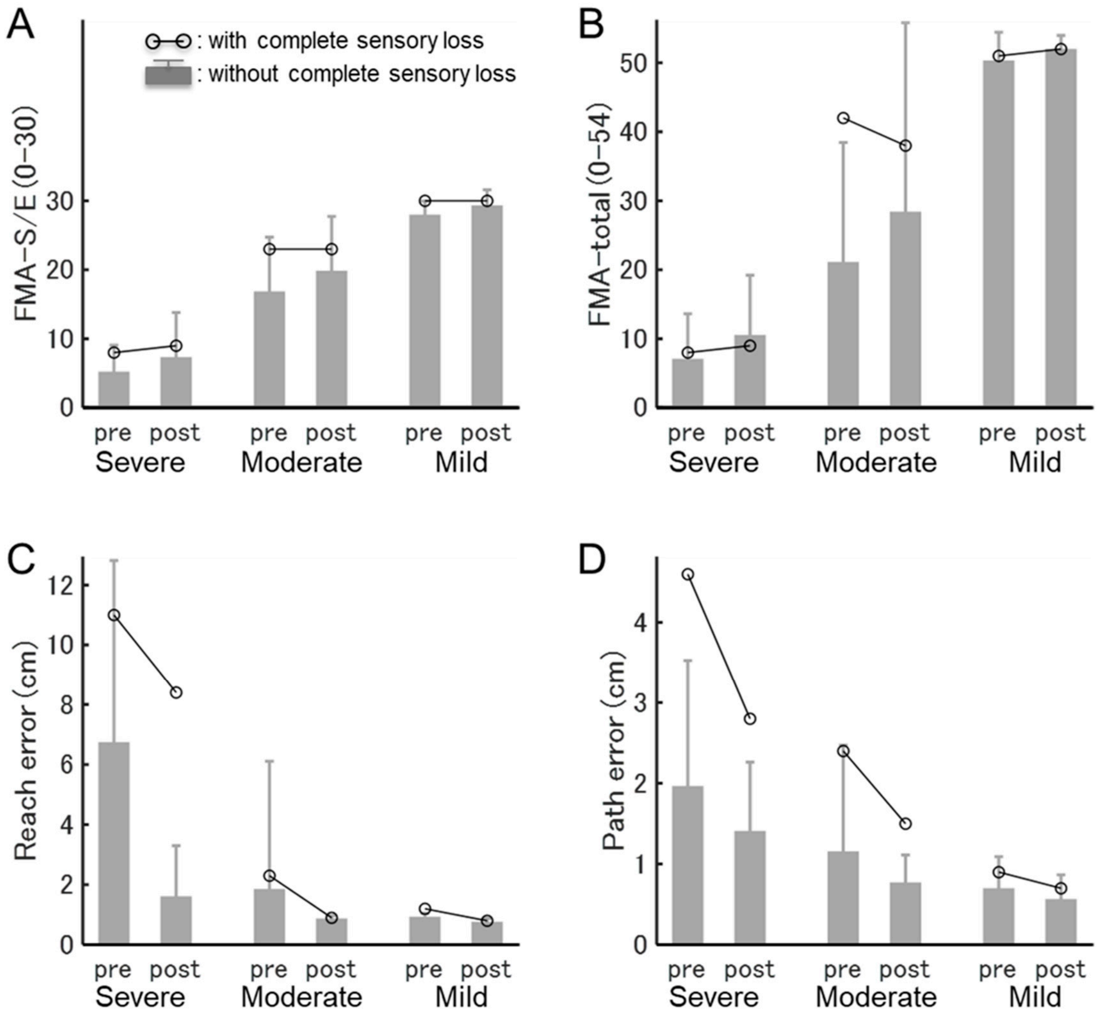

Figure 1. FMA and InMotion2-evaluation scores. FMA-S/E (**A**) is the score for shoulder and elbow excluding the tendon reflex (perfect score: 30 points), and FMA-total (**B**) is the total score excluding coordination and tendon reflex (perfect score: 54 points) of the FMA-UE. Reach Error (**C**) and Path Error (**D**) indicates the InMotion2-evaluation values, respectively. Severe, Moderate, and Mild indicate the three patient groups according to severity of motor paralysis (FMA-S/E) at the training start. For both pre- and post-session results, the means and 1.96 × the standard deviations of the patients without complete sensory loss are shown by gray boxes and bars, respectively. Scatter plots with white dots in each motor paralysis group show the scores of the patients with complete sensory loss.

4. Discussion

In the present study, we divided patients with hemiplegic paralysis caused by strokes into three groups by motor paralysis level to study differences in the effectiveness of robot training according to with and without complete sensory loss. While little impact of the complete sensory loss was observed in the mild paralysis group, in the moderate and severe paralysis groups, accuracy of the reach motion and robot-training effectiveness may be reduced in patients with complete sensory loss.

The present study is positioned as a preliminary case series study for a robot-aided rehabilitation aiming to improve the paralyzed arm function of stroke patients. In the current clinical practice, there is less applicability criterion of robot rehabilitation. For the reaching movement, vision and proprioception differently contribute to the planning of the motion [22]. Sarlegna et al. (2009) revealed that visual information mainly contributes to defining the kinematic plan and proprioception is for the transforming kinematic profile into the neural commands [22]. Ingemanson et al. (2019) suggest the importance of baseline somatosensory integrity for improving hand function after stroke [23]. Further, the combination of light touch and proprioception impairment has been revealed to relate with the upper limb motor recovery after stroke [14]. For the patients with a sensory disorder, therefore, the effectiveness of new technology on the neurorehabilitation should be discussed carefully. Especially in patients with complete loss of touch and position senses, there is no feedback other than vision in reach motion, thus a significant decrease in effectiveness could be predicted. In the present study, therefore, the effectiveness of robot rehabilitation for patients with complete sensory loss was compared with that of patients with similar paralysis and without complete sensory loss. In addition, it is difficult to investigate the role of proprioception in a study of healthy subjects because the proprioception cannot be completely masked experimentally. Thus, the present pilot study may be important to disseminate robot rehabilitation though there are few subjects.

In the moderate and severe motor paralysis groups, the benefits of robot training for the FMA-total tended to be small for patients with complete sensory loss. Sensory disorder has been shown to reduce the degree of improvement of motor paralysis [14], and the improvement of paralysis through upper limb robot training in one case was small [16]. Our results are similar to those of previous studies and suggest that somatic sensory feedback contributes greatly to the improvement of motor paralysis through upper limb robot training. As shown in the patient with moderate motor paralysis and complete sensory loss, the FMA-total score was decreased by robot training. Dobato et al. (1990) reported that sensory disorder causes dyssynergia, resulting in patients becoming prone to dropping objects, bradykinesia, and clumsiness [24]. In this patient, the performance of grasping and/or manipulation did not improve sufficiently, and as a result, the FMA-total score including the functions of wrist and fingers might not improve.

According to a report by Sale et al. (2014), robot training of recovering stroke patients resulted in improvement of motor paralysis in 3 weeks (15 sessions) [18]. However, our results demonstrate a similar degree of paralysis improvement in only 2 weeks (10 sessions). The appropriate number and length of training sessions for robot training is unknown, and future studies must examine whether continued robot training achieves further improvements or whether the effects reach a plateau after 2 weeks.

The RE and PE values are worse in cases with complete sensory loss than in cases without complete sensory loss for moderate to severe motor paralysis levels. These results suggest that the reach motion skill level and effectiveness of robot training are impacted by the degree of somatic sensory feedback. Changes in RE after 2 weeks differed according to the presence of complete sensory loss only in the severe motor paralysis group, suggesting that somatic sensory feedback contributes greatly to the improvement of reach motion in severely paralyzed patients. On the other hand, the RE scores of patients in the moderate and mild paralysis groups with complete sensory loss were within the range of patients without complete sensory loss. Thus, among patients with voluntary control of their shoulder and elbow on the paralyzed side, repeated robot training improves reach motion regardless of whether sensory disorder has occurred.

Similar to the results for PE of patients with moderate and severe motor paralysis in this study, Ghez et al. (1995) reported that errors in the track during reach motion were great among patients with sensory disorder [25]. Thus, feedback of somatic sensation contributes greatly to the fine corrections of errors. Sarlegna et al. (2009) stated that visual information plays an important role in reach motion of patients with somatic sensory disorder and hypothesized that mild motor paralysis patients can compensate for errors caused by somatic sensory disorder through visual feedback [22]. They concluded that moderate and severe paralysis patients have difficulty in correcting errors based only on visual feedback. However, because a tendency is seen for PE to diminish, long-term robot training may result in further improvement. Vidoni et al. (2009) stated that, in continuous motion, the excellence of proprioception was positively correlated with motor learning effects [13]. In our study, a similar relationship was observed in the severe motor paralysis group as a result of continuous robot training. These results suggest that, assuming sensory disorder has occurred, the effects of motor learning equal to that in patients without sensory loss can be obtained if the motor paralysis is not severe.

The present study had encountered difficulties enrolling a sufficient number of patients with complete sensory loss. Therefore, we compared each evaluation score of the patients with complete sensory loss with the 95% reference range calculated using scores of the patients without complete sensory loss. Patients with moderate to severe motor paralysis have relatively large lesions [26,27], so that cognitive dysfunctions often appear. In several cases, to diagnose the sensory disorder which is assessed by listening to the patient's sense was difficult because of aphasia. The patients with cognitive dysfunctions also often had difficulty understanding the robot operation. For these reasons, it was difficult to recruit a sufficient number of patients with moderate to severe paralysis who had severe sensory impairment. On the other hand, for the patients with mild paralysis who marked high FMA scores at admission, some task-oriented and/or skill trainings rather than the robot training are performed in the clinical manner. Therefore, the number of patients with mild paralysis was small regardless of the presence or absence of sensory impairments. To further popularize robot training in clinics in the future, it will be necessary to ensure adequate numbers of samples, to verify effectiveness according to the length of the training period, and to optimize the effectiveness of robot training according to whether a patient has or has not suffered sensory loss.

5. Conclusions

Results of the present study reveal differences in the effectiveness of robot training according to whether a patient with hemiplegic motor paralysis caused by a stroke has complete sensory loss. In addition, InMotion2 is able to evaluate errors in the track of reach motions and can be used to examine differences in improvement effects according to the presence or absence of sensory disorder. Motor paralysis improvement through the use of robot training was observed in all cases, but, while the impact of complete sensory loss was not observed in the mild paralysis group, the effectiveness of robot training for patients with complete sensory loss was reduced in the moderate and severe paralysis groups. These results should be considered when determining the applicability and period of use of robot training.

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