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Application of a Robotic Rehabilitation Training System for Recovery of Severe Plegic Hand Motor Function after a Stroke

Hirofumi Tanabe, Munehiro Ikuta, Toshimasa Mikawa, Akihiko Kondo and Yoshifumi Morita

Abstract

We have developed a rehabilitation training system (UR-System-PARKO: Useful and Ultimate Rehabilitation System-PARKO) for patients after a stroke to promote recovery of motor function of the severe plegic hand with hemiplegia. A clinical test with six patients for the therapeutic effect of the UR-System-PARKO for severe plegic hand was performed. For all patients, the active ranges of motion (total active motion) of finger extension improved after training with the UR-System-PARKO. Moreover, the modified Ashworth scale (MAS) scores of finger extension increased. Thus, the training reduced the spastic paralysis. These results suggest the effectiveness of training with the UR-System-PARKO for recovery of motor function as defined by finger extension in the severe plegic hand.

Keywords: stroke, hemiplegia, finger, rehabilitation device, motor recovery

1. Introduction

Stroke is the leading cause of disability in Japan, with more than 1 million people in Japan living with a disability as a result of stroke. Therefore, interventions that address the sensorimotor impairments resulting from stroke are important. Motor function may be restored more than 6 months after a stroke [1, 2], but these studies included patients with only moderate poststroke hemiplegia, whereas most stroke survivors have a severely plegic hand with difficulty extending the fingers [3]. This suggests that a method is needed for treatment of these severely affected cases. However, although a few studies on rehabilitation therapy for severe plegic hands have been reported, no marked recovery of ability in extension of the fingers of the plegic hands was achieved in any study [4, 5]. Proprioceptive neuromuscular facilitation (PNF) is a therapeutic method that was reported to increase the muscle strength of the plegic extremities in patients with stroke-induced hemiplegia [6]. However, since PNF is indicated for patients with a certain level of joint motion, this method has not been used for severe plegic hands where the fingers cannot extend. Thus, the first author developed a method to build up the extensor digitorum muscle strength using PNF [7, 8] for stroke patients with severe hemiplegia.



Figure 1.
The first author has developed the TANABE therapy for severe hemiplegic stroke patients.

With this therapy, he has performed repeated facilitation training using his hands on stroke patients with a severe plegic hand to help them recover their motor function, and a good treatment outcome was achieved [9, 10] (**Figure 1**).

Facilitation training uses extension of the elbow joint with resistance applied to the tips of the fully extended hemiplegic fingers to increase the force of the extensor digitorum muscle. However, this approach is time-consuming for the therapist. Therefore, development of a training system is required instead of repeated facilitation training by a therapist. The objectives of this study were to develop a training system to increase the output of the extensor digitorum muscle force and to verify the effect of training with the developed system on a severe plegic hand. The training system is called the UR-System-PARKO (a useful and ultimate rehabilitation support system for PARKO). The UR-System-PARKO was developed by remodeling the simplified training system, which developed previously for resistance training of hemiplegic upper limbs [11]. A brace for securing the plegic hand to the UR-System-PARKO was developed on the basis of repeated facilitation training by a therapist.

2. Facilitation training for finger extension

Facilitation training is indicated for patients with severely plegic hands who cannot extend their fingers. The training increases the extensor digitorum muscle force, and finger extension can be achieved with 2–3 min of manual training by a therapist. However, to retain the effect until the following day, training should be performed for at least 1 h a day, and manual facilitation training by a therapist is demanding work. However, since all of the interphalangeal finger joints should be totally maintained in the full extension position with a certain level of resistance during the facilitation training, the maximum duration of the training provided by a therapist with no break is about 10 min. Although the details of the operating procedures of the facilitation training will be explained later, several therapists will be required to provide this manual facilitation training for 1 h or more on a rotating basis. Thus, a very aggressive intervention is needed and will involve robotization of the training.

2.1 Plegic hand fingers always bend

Human fingers are constructed so as to prioritize flexion to extension movement in order to grab objects. Thus, fingers are lightly bent, even at rest. After a stroke, the upper limb and fingers on the plegic side are usually controlled by synkinesis of the flexor muscles, and this often results in clenching of the fingers. Our hypothesis is that contraction of the muscle for extending the fingers (extensor digitorum) is inhibited by strong contraction of muscles bending the fingers (flexor digitorum profundus, flexor digitorum superficialis) in severely plegic hands. We have found that contraction of the flexor muscles is inhibited and that of the extensor muscle is induced by fixing all fingers in a hyperextended position and extending the elbow joint while applying resistance to the fingertips. The reason why the plegic hand fingers are able to extend under these two conditions is explained below.

2.2 Why are severe plegic hands unable to open?

- a. Flexor and extensor muscles are present in pairs in the joints. For joint movement, neither the flexor nor the extensor muscle contract alone, but both contract simultaneously, giving smooth and accurate movement. The balance of the two muscles in joint movement is not 0 vs. 100%, but about 46 vs. 54% or 44 vs. 56%, and the slight dominance of either muscle again results in smooth movement [12]. However, in poststroke plegic hands, the flexor muscle tone is excessive and the finger flexor muscle contracts more strongly than the extensor muscle. Therefore, as a plegic hand is opened to grasp objects, the appropriate balance of the two muscles is not present. This inability to grasp objects is due to the stronger contraction of the flexor muscles, which results in strong hand clenching.
- b. Marked extensor digitorum muscle contraction is induced by fixation of the plegic hand in a hyperextended position, and this contraction is further increased by extending the plegic hand forward while applying resistance to the fingertips of this hand. Hogan stated that simultaneous contraction increases stiffness of the joint and maintains the position of the plegic hand [13]. Muscle spindles that sense the muscle length are adjusted by γ motor neurons. The length of the flexor muscles gradually shortens as finger flexion is induced by contraction of these muscles, but simultaneous actions of α and γ motor neurons prevent sensitivity reduction of muscle spindles (α - γ linkage). When the fingertips push an object with the fingers fixed and extended, the flexor and extensor muscles contract simultaneously to stabilize the joint. The muscles cancel out the tension on each other, and there is no change in muscle length, while the α - γ linkage prevents a change in muscle spindle sensitivity. Thus, muscle spindle sensitivity is increased by afferent contraction compared with that in muscle shortening, which increases the roles of the finger flexor and extensor muscles in the stretch reflex. The flexion activity of the hyperextended fingers is reduced, despite the contraction of the finger flexor muscles. In contrast, this contraction easily extends the fingers, resulting in marked contraction of the finger extensor muscle (**Figure 2**).

Additional resistance applied to the fingertips increases the output of the finger extensor muscle force. The flexion/extension torque of the interphalangeal joint varies depending on the finger joint angle, despite the similar forces of the flexor and extensor muscles of the fingers. This position is significant for flexion movement (**Figure 2a**). The torque of joint rotation in the extension direction decreases because the extensor digitorum muscle tendon is in contact with the bone. Conversely, the torque of rotation in the flexion direction increases because

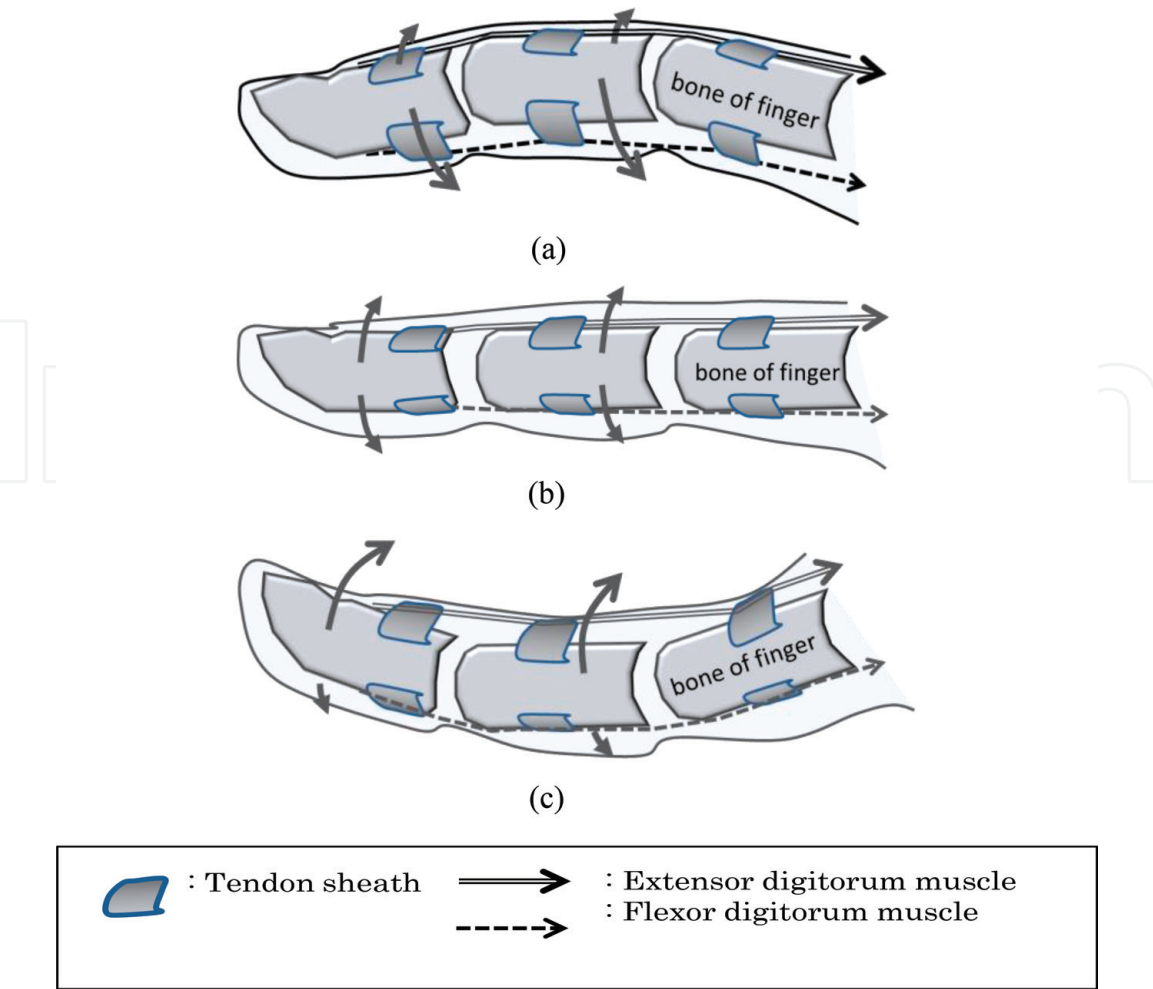
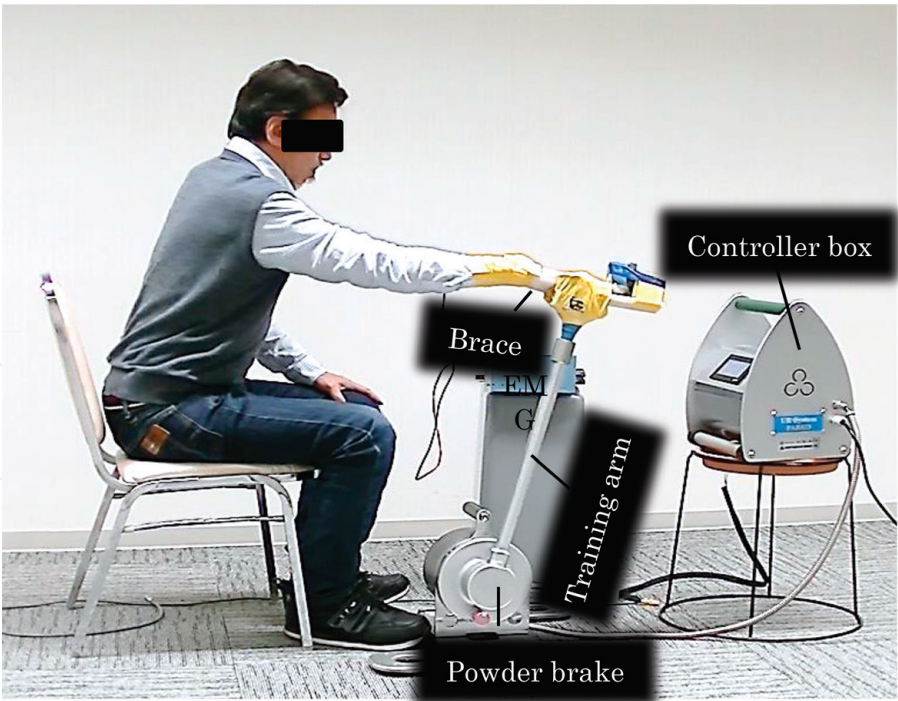


Figure 2. Differences in the torque of joint movement in finger extension and flexion between the flexor and extensor muscles of the fingers. (a) Position with light flexion of the finger; (b) position with extension of the finger; and (c) position with hyperextension of the finger.

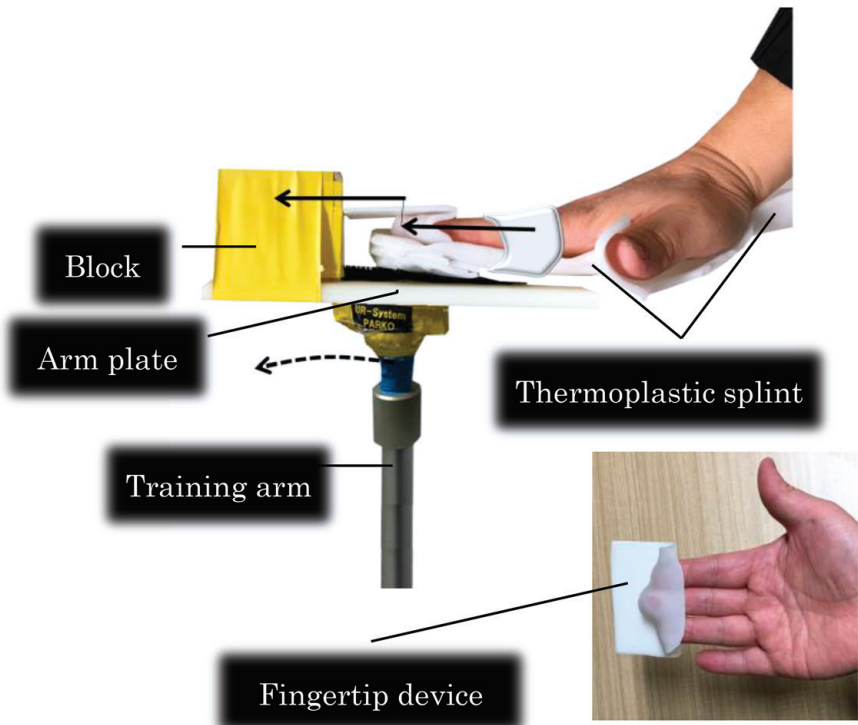
the flexor digitorum muscle tendon acts to pull the tendon sheath away from the bone. The torques of rotation of the interphalangeal joint in the flexion/extension direction of the flexor and in the extensor muscles are the same (**Figure 2b**) and this position is significant for extension movement (**Figure 2c**). The torque of joint rotation in the extension direction increases because the extensor digitorum muscle tendon pulls the tendon sheath away from the bone. Simultaneous contraction in joints increases stiffness and muscle spindle sensitivity and thus may increase the gain of the stretch reflex loop. The extensor muscle-dominant increase in output occurs because the range of motion of the fingers is greater in the flexion direction because the fingers easily bend under an external force against which output of the extensor muscle force may increase to boost stiffness.

3. Training system for recovery of motor function

The training system consists of a force display system with rotational system of one degree-of-freedom and a brace for securing the paralyzed hand. The force display system was developed in our previous work [14, 15]. The brace was developed in this work. The training system was named the UR-System-PARKO, which is shown in **Figure 3**. In order to satisfy the conditions (1) and (2) to facilitate finger extension, the force display system was used and a new brace was developed, respectively.



(a)



(b)

Figure 3.
UR-System PARKO. (a) Whole system and (b) brace.

3.1 Force display system

The force display system has a mechanical system and a controller. The mechanical system consists of a training arm and a powder brake (SINFONIA TECHNOLOGY CO., Ltd., PRB-2.5H). The brace attached to the tip of the training arm is used to secure the patient’s hand to the apparatus. The patient moves the brace forward and backward by himself/herself while stretching and bending the elbow

repeatedly. The powder brake generating a brake force serves as the resistance force during training. The maximum resistance force depends on the length of the training arm. When setting the length of the training arm to 0.75 m, the maximum resistance was 49 N. This system is extremely safe and low cost, because it is not equipped with motors. The four different resistance patterns, namely a step mode, a slope mode, a wall mode, and a constant mode, are installed in the controller. This system is mainly equipped with the two functions. The resistance display function enables therapists to perform various types of resistance training by changing the arm length and the resistance level. The touch panel parameter setting function enables therapists to easily set the parameters of the resistance patterns by pushing the buttons on the touch panel display. The parameters consist of the magnitudes and the positions of the resistance patterns. The magnitudes are selected from among nine levels. The positions are determined by moving the training arm and stopping it at the desired position. This function provides good visibility and ease of use for therapists.

3.2 Brace to facilitate finger extension

A new brace was developed to facilitate finger extension, which is shown in **Figure 3b**. The brace consists of an arm plate, a thermoplastic splint, a fingertip device, and a block. The arm plate was fixed to the tip of the training arm with flexibility. The block was fixed on the arm plate. The thermoplastic splint was made to fix the plegic hand of a hemiplegic patient in complete extension. The fingertip device attaching to the second to fourth fingers was made of a thermoplastic plate. Since the fingertip device is the important part for acting the equal resistance force to the three finger tips, it was prepared for each subject. Since contraction of the fifth finger extensor muscle is improved with facilitation of contraction of the extensor digitorum muscles of the second to fourth fingers, the fifth finger was not attached to the fingertip device. Since the fingertip device is slightly movable in the direction of travel on the rail on the arm plate, the force acting on the fingertip device moves the training arm. The movable range was 1 mm. This means that the point of action to resistance force generated by the UR-System-PARKO is the contact point between the fingertip device and the block.

4. Clinical evaluation of therapeutic effect

We conducted clinical tests of intensive training with the UR-System PARKO for severely affected hands with little or no extension of the wrist, fingers, and thumb.

4.1 Participants

The participants were six patients with chronic hemiplegia after stroke who were admitted to the clinic between September 2017 and July 2018 (**Table 1**). Before training, all participants could not extend the fingers and thumb and grasp and release the items.

4.2 Methods

All participants conducted intensive training using the UR-System-PARKO for 2 h/day and 2 weeks. The participants were requested to perform the intensive training using the UR-System-PARKO at their own pace. After each set (50 times) of the training, they took a rest for 10 min, with their hands withdrawn from the UR-System-PARKO. It took about 4–4.5 min to complete one set of the training. All participants performed the training for about eight sets. After the fourth set, they rested for 30 min, and a therapist stretched and massaged the upper extremities and fingers.

Subject	Gender	Age	Hemiplegia	Handedness	Poststroke (year)
Subject 1	M	51	L	R	8
Subject 2	M	66	L	R	2
Subject 3	F	53	L	R	2
Subject 4	M	70	R	R	4
Subject 5	F	45	L	R	3
Subject 6	M	43	R	R	3

Note: M = male, F = female, R = right, L = left.

Table 1.
Participant demographic data.

Subject		TAM (deg)		% TAM	
		Pre	Post	Pre	Post
Subject 1	Index finger	5	50	2	19
	Middle finger	5	75	2	29
	Ring finger	0	55	0	21
	Little finger	0	60	0	23
	Total	10	240	0.0	0.9
Subject 2	Index finger	5	90	2	35
	Middle finger	0	45	0	17
	Ring finger	0	45	0	17
	Little finger	0	30	0	12
	Total	5	210	0.0	0.8
Subject 3	Index finger	5	50	2	19
	Middle finger	5	75	2	29
	Ring finger	0	55	0	21
	Little finger	0	60	0	23
	Total	10	240	0.0	0.9
Subject 4	Index finger	15	120	6	46
	Middle finger	10	135	4	52
	Ring finger	0	90	0	35
	Little finger	0	80	0	31
	Total	25	425	0.1	1.6
Subject 5	Index finger	0	35	0	13
	Middle finger	0	20	0	8
	Ring finger	0	10	0	4
	Little finger	0	10	0	4
	Total	0	75	0.0	0.3
Subject 6	Index finger	5	110	2	42
	Middle finger	5	140	2	54
	Ring finger	0	40	0	15
	Little finger	0	35	0	13
	Total	10	325	0.0	1.3

Pre: before intensive training; post: after intensive training; change: difference between the results before and after training.

Table 2.
TAM and % TAM scores before and after 2-week intensive training with the UR-System-PARKO.

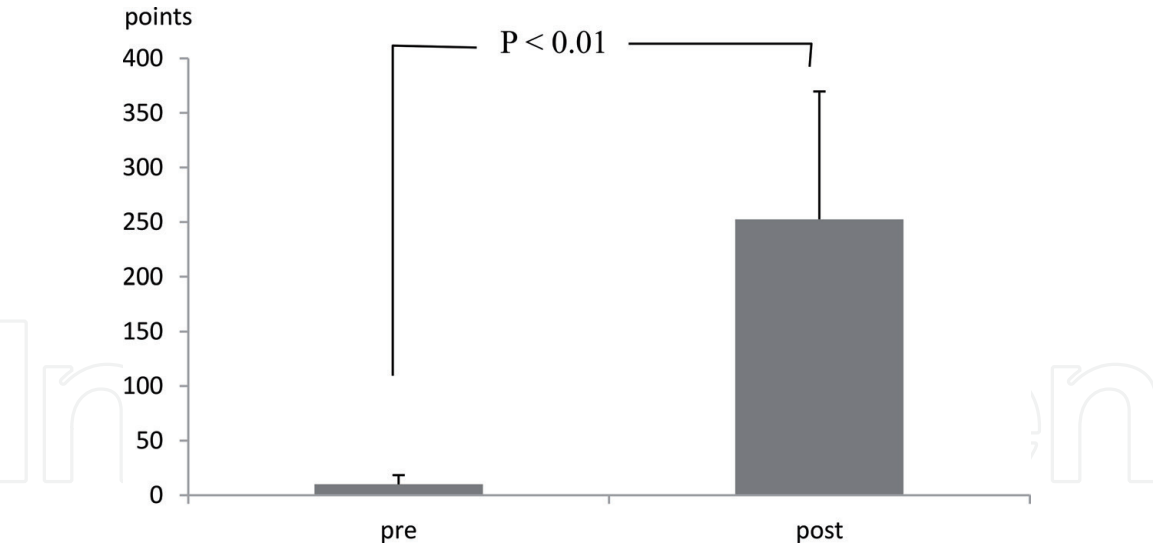


Figure 4.
TAM scores before and after 2-week intensive training with the UR-System-PARKO.

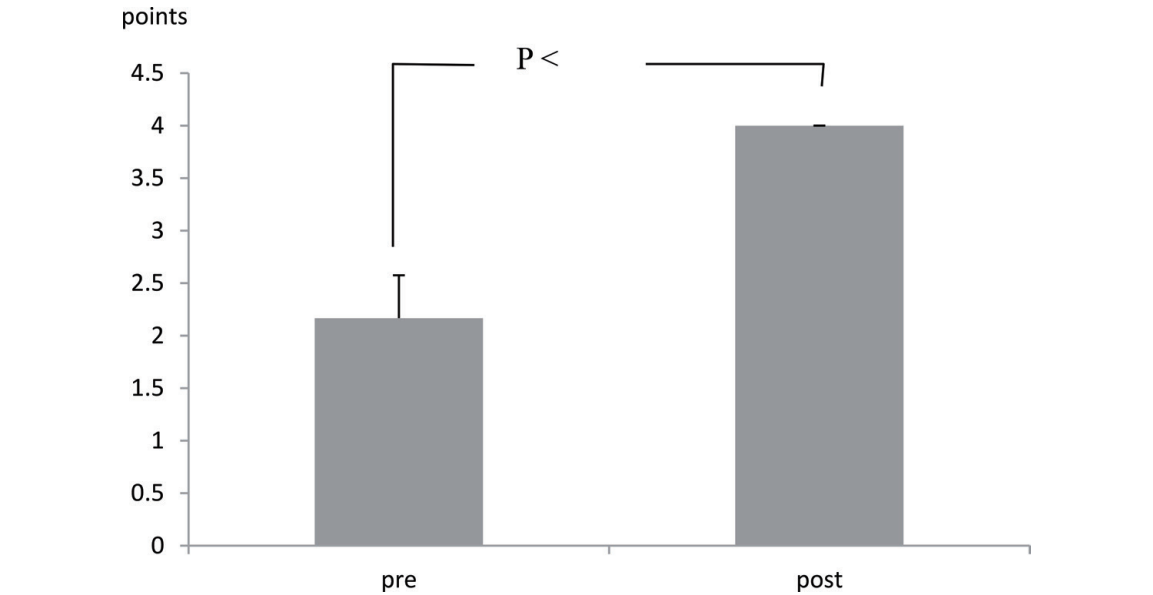


Figure 5.
MAS scores before and after 2-week intensive training with the UR-System-PARKO.

4.3 Assessment

The therapeutic effect before and after intensive training was assessed using the Total Active Motion (TAM) and modified Ashworth scale (MAS). TAM describes the full arc of motion of the digits and is measured as the total flexion of the three finger joints minus the loss of full extension of these joints: TAM = (metacarpophalangeal [MP] + proximal interphalangeal [PIP] + distal interphalangeal [DIP] flexion) – (MP + PIP + DIP extension loss). TAM was measured before the 2-week intensive training and on the day after the last day of training.

4.4 Results

All participants underwent intense intensive training according to the predetermined protocol. The TAM score for upper extremity motion showed significant improvement for participants (**Table 2, Figure 4**). Post hoc analysis indicated significant differences between pre- and posttreatment scores, and

the mean TAM scores increased by 0.003 ($P < 0.01$), respectively. The MAS scores showed a significant attenuation effect on spasticity, with post hoc analysis revealing significant differences between pre- and posttreatment scores increased by 0.001 ($P < 0.05$, **Figure 5**). The results of the study suggest that intense intensive training for severely affected hands with little or no extension of the fingers and thumbs improves the functions of the affected-side upper extremity.

5. Conclusions

The therapeutic effect of the training with the UR-System-PARKO was shown. It was found that induction of contraction of the extensor digitorum muscle of plegic hands required the following two conditions: “hyperextension of all fingers” and “extension movement of the elbow joint while applying resistance load to the finger tips.” In the clinical study with the 2-week intensive training, the motor function of the paralyzed hand was improved, and the spasticity of the flexor muscle was decreased. As a manual technique to facilitate the movement of plegic limbs of poststroke hemiplegia patients, Kabat et al. developed Proprioceptive Neuromuscular Facilitation (PNF) and showed its efficacy [16, 17]. However, these studies involved cases with mild motor paralysis and movable joints. In contrast, PNF has not been shown to be effective for severely plegic hands without finger extension.

The facilitation conditions used in the current study differ from those in PNF. Thus, the method presented here is a new type of facilitation, although the conditions of “resistance exercise of the fixed joints” and “application of pressure on the joints” are similar to 2 of the 11 facilitation conditions defined by Kabat [16]. In manual facilitation, contraction of the extensor digitorum muscle does not occur, and facilitation fails if an interphalangeal joint is bent. In the method used in this study, the wrist, interphalangeal, and other joints must be fixed, but many joints in the hand are flexible, which makes complete manual fixation difficult. Moreover, passive joint compression transiently excites spinal motor nerve cells [18], which suggests that the facilitation effect of the extensor digitorum muscle will not occur without application of homogeneous pressure to all the interphalangeal joints. Therefore, a thermoplastic splint that fitted the hyperextended plegic hand fingers was made for each subject. This custom-made splint was important for ensuring that the facilitation effect was obtained. The site and resistance to be applied during pushing of the plegic hand have to be determined by the therapist beforehand, and each subject may need a specific setting. Therefore, the UR-System-PARKO may be an appropriate robotic device for facilitating training of the extensor digitorum muscle in a manner that cannot be achieved by simple rehabilitation training. Further accumulation of data is required to evaluate the efficacy of the UR-System-PARKO.

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Author details

Hirofumi Tanabe^{1*}, Munehiro Ikuta¹, Toshimasa Mikawa¹, Akihiko Kondo² and Yoshifumi Morita³


¹ Shonan Medical Sciences, Japan

² Aso Rehabilitation College, Japan

³ Nagoya Institute of Technology, Japan

*Address all correspondence to: hirofumi.tanabe@sums.ac.jp

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