Nakamura et al. ROBOMECH Journal (2023) 10:11
https://doi.org/10.1186/s40648-023-00248-w

ROBOMECH Journal

RESEARCH ARTICLE

Open Access

New "iPARKO" finger extensor facilitation training device for chronic hemiplegic hand after stroke: development and verification of its effectiveness in healthy individuals

Ai Nakamura[1*], Zhou Peichen[1], Yoshifumi Morita[1] and Hirofumi Tanabe[2]

Abstract
After stroke, hemiplegic individuals have difficulty opening their hands by themselves due to paralysis. A finger extensor facilitation technique was therefore developed to increase the activity of the extensor muscle in hemiplegic individuals who cannot open their paralyzed hands by themselves. In our previous study, we created a training device prototype called the "PARKO", that imitates the finger extensor facilitation technique; however, the activity of the extensor muscle using the device was much smaller than that of the finger extensor facilitation technique. In this study, we developed a new finger extensor facilitation training device, the "iPARKO", to increase the activity of the extensor muscle during active training. We thus improved the structure of the PARKO device—including a modified method to apply force to the fingertips—and attached force sensors to the device to monitor these forces. To verify the effectiveness of the iPARKO device, we conducted active training using the device in healthy individuals. Comparing the results of the muscle activities between the PARKO and iPARKO devices among three healthy participants demonstrated that the iPARKO device increased the mean activity of the extensor muscle by 43.8%. Furthermore, the activity of the extensor muscle in two healthy individuals while moving the hand forward with the iPARKO device was 84% and 96% of the maximal voluntary contraction during the hand-opening motion without the iPARKO device.

Keywords Chronic hemiplegic, Finger extensor muscle, Hand rehabilitation, Maximum voluntary contraction, Muscle activity, Rehabilitation device

Introduction

One of the after-effects of a stroke is a motor dysfunction called spasticity, a condition wherein the hands and feet are constantly stretched and flexed due to excessive tension in the muscles [1]. Additionally, if postural abnormalities due to spasticity continue for an extended period of time, the muscles become stiff and the movement of joints is restricted, resulting in a condition called contracture [2]. In this state, it becomes difficult to open the hands, which interferes with the daily life of hemiplegic individuals. Therefore, it is necessary to treat spasticity and restore hand motor function. However, treating the hand of a hemiplegic individual is considered difficult, as the joints of the hands have 23 degrees of freedom in the joints of the hand [3], and is extremely complicated and diverse. Additionally, hand motor function is important for instrumental activities of daily living requiring detailed finger movements [4]. Therefore, defective hand motor function makes it difficult for hemiplegic

*Correspondence:
Ai Nakamura
a.nakamura.274@nitech.jp
[1] Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Aichi, Japan
[2] Department of Health Science, Shonan University of Medical Sciences, Kanagawa, Japan

individuals to improve their quality of life and return to society [5].

There are currently several studies on rehabilitation therapy for the upper limbs, including constraint-induced movement therapy [6, 7], mirror therapy [8, 9], and bilateral arm training [10]. Other therapies include repetitive facilitation exercises (RFEs) to restore the motor function of the paralyzed upper limb or hand [11]; this is based on the hemiplegic individual's desire to move their paralyzed hand, and uses multiple sensory stimuli to achieve that movement. RFEs were developed by Kawahira et al. [11], and were designed to provide focused physical stimulation sufficient to achieve the hemiplegic individual's intended movement. This stimulation was obtained by tapping or rubbing the muscle, stretching the muscles quickly and passively, or slightly resisting the intended movement. Restoration of hand motor function in hemiplegic individuals requires the repetition of voluntary movements via manual treatment by therapists, as hemiplegic individuals are unable to move their fingers by themselves. Therefore, RFEs can induce spontaneous movement and thus restore hand motor function [11].

RFEs were found to effectively reduce disability and improve the upper limb motor function in the subacute phase of stroke [12]. They also have spasticity-reducing effects in chronic stroke [13]. To restore hand-opening motor function, it is necessary to strengthen the extensor muscle, i.e., the muscle that opens the hand. To strengthen the extensor muscle, the motion of opening the hand is repeated; however, hemiplegic individuals are often unable to open their hands. Thus, we developed a manual treatment method for chronic hemiplegic individuals who cannot open their hands [14], called the finger extensor facilitation technique (hereafter referred to as manual therapy); still, this technique does not provide sufficient rehabilitation therapy due to the long treatment period and physical burden on therapists. Therefore, there is a need for a device and robot that both reduces the physical burden on the therapist and restores the hand-opening motor functions in individuals with hemiplegia. These devices and robots may replace therapists even after patients are discharged from rehabilitation hospitals.

Several devices and robots have been developed, such as the AMADEO robotic system [15] and HandCARE [16]—which are external to the body and provide the necessary resistance—HANDEXOS [17], and the exoskeleton hand robotic training device [18], worn directly on the body. Others include a glove-type robot with integrated pneumatic actuators and a soft exoskeleton [19], and single, portable, wearable soft robots [20]. Additionally, a functional recovery training device that performs RFEs has been developed [21]; the extensor muscle is stretched when the fingers are bent, and when an external force is applied, the extensor muscle contracts to protect the fingers. This is the mechanism of the stretch reflex that strengthens the extensor muscle of fingers; however, few devices can strengthen the extensor muscles of hemiplegic fingers.

Similarly, we developed a training device called the "PARKO" to imitate manual therapy, and verified its effectiveness in healthy individuals and one hemiplegic individual [22]. Still, the PARKO device was not accurate enough to imitate manual therapy. This device had a lower extensor muscle activity than manual therapy—meaning that the muscle was not sufficiently trained—and was unsuitable for the recovery of hand motor function. The PARKO device only has one component to secure the fingers, leading to an inability to accommodate differences between individual fingers. Preliminary experiments have shown that the sum of the force applied to each fingertip is proportional to the muscle activity of extensor muscle. To increase muscle activity, the force applied to each fingertip must be uniform within the tolerance limit. Therefore, it is required to individually secure the fingers and adjust the force applied to fingertips using a new device.

In this study, we developed a novel finger extensor facilitation training device (iPARKO) that solves the problem of low extensor muscle activity. We verified the effectiveness of the iPARKO device in healthy individuals before applying it to chronic hemiplegic individuals. Specifically, we compared the activity of extensor muscle between the PARKO and iPARKO devices. We also compared the activity of the extensor muscle of the iPARKO device with that of maximum voluntary contraction (MVC) [23] when opening the hand. The extensor muscle activity using the iPARKO device was evaluated in regard to MVC.

Materials and methods

Finger extensor facilitation technique

The finger extensor facilitation technique (or manual therapy) we used is shown in Fig. 1. To strengthen the extensor muscle in healthy individuals, the hand-opening motion is repeated with load to the muscle. However, since hemiplegic individuals are unable to open their hand, it is necessary to train the extensor muscle using a motion different to opening the hand.

In rehabilitation after a stroke, it is generally considered effective to increase muscle activity, but not spasticity, through muscle strengthening exercises [24]. To this end, it is necessary to avoid increasing abnormal muscle tone and spasticity in the antagonist flexor muscles when training the extensor muscles of hemiplegic individuals. Manual therapy is one way to train the extensor muscle

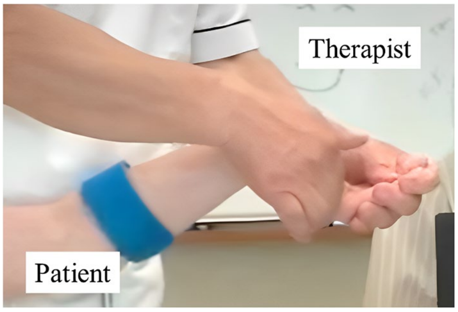

Fig. 1 Finger extensor facilitation technique

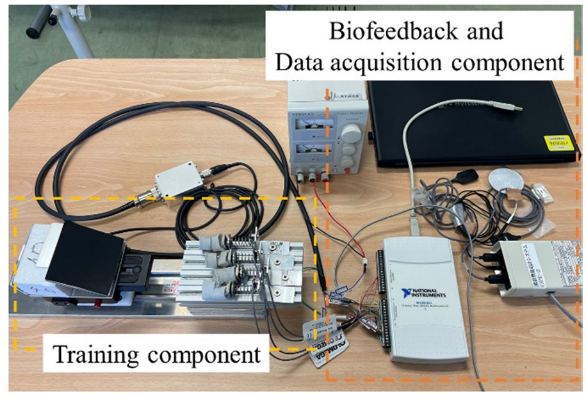

Fig. 2 iPARKO finger extensor facilitation training device

of hemiplegic individuals, and until then, no significant recovery of extension function is obtained with severely paralyzed hands. Thus, we developed a new method to restore hand motor function to open the hands of severely hemiplegic individuals while avoiding increasing abnormal muscle tone and spasticity in the antagonist flexor muscles.

Manual therapy has provided satisfactory results for severely hemiplegic individuals [25]. Therein, the therapist keeps four fingertips of the hemiplegic individual's paralyzed hand in hyperextension, excluding the thumb; when the hemiplegic individual moves their hand forward, the therapist applies the appropriate resistance to their fingertips. This resistance increases the activity of the extensor muscle, while the activity of the flexor muscle can be reduced because the fingertips are kept in hyperextension. Repeating this training—which applies the physiological contraction mechanism of muscles—improves the strength of the extensor muscle. When the fingers are kept in hyperextension, there is no freedom in the direction of a finger flexion; only the muscle in the direction of a finger extension can be contracted. By applying a force to the fingertips in that state, the activity of the extensor muscle can be increased, verifying the reduction of spasticity and effectiveness in hemiplegic individuals [26].

Manual therapy can be used to open the hand in two to three minutes [25], and although at least one hour of training per day is required to maintain the therapeutic effect until the next day, the maximum training time without breaks by the therapist is approximately ten minutes. Thus, several therapists can take turns conducting training (which is a physical burden).

Development of iPARKO

The goal of developing the new iPARKO device was to increase the extensor muscle activity during training with the new device, compared with the old PARKO device. During manual therapy, the therapist holds four of the hemiplegic individual's fingers together (excluding the thumb), and applies force to each fingertip. Conversely, when using the PARKO device, the force is applied using a brace that fixes the four fingers together; however, it was unclear whether the appropriate force is applied to each fingertip. Additionally, it is considered that the method of applying force is insufficient, as it does not correspond with the difference in finger length and individual differences. Therefore, the iPARKO device adopted a slide mechanism that changes the position of the pressing plate for each fingertip, making it possible to measure the fingertip force; thereby, it responds to individual differences by adjusting the fingertip force. We thus expect that the activity of the extensor muscle will improve when using the iPARKO device compared with the PARKO device.

Figure 2 shows the iPARKO device, while the configuration diagrams of the PARKO and iPARKO devices are shown in Fig. 3. Compared to the PARKO device, the new parts and sensors added to the iPARKO device are marked with asterisk (*) in Fig. 3. Furthermore, Table 1 compares the functions of the PARKO and iPARKO devices. Training with the iPARKO device is shown in Fig. 4. Both devices comprise training, biofeedback, and data acquisition components.

Training component

The training component of the PARKO device was designed to fix the index, middle, ring, and little fingers together. Participants applied force by pressing their fingertips against an arc-shaped plate; therefore, the PARKO device could not evenly apply the force to each finger. Moreover, it could not always maintain the fingers in hyperextension. Thus, to improve the accuracy of imitating manual therapy in the iPARKO device, we established the following specifications:

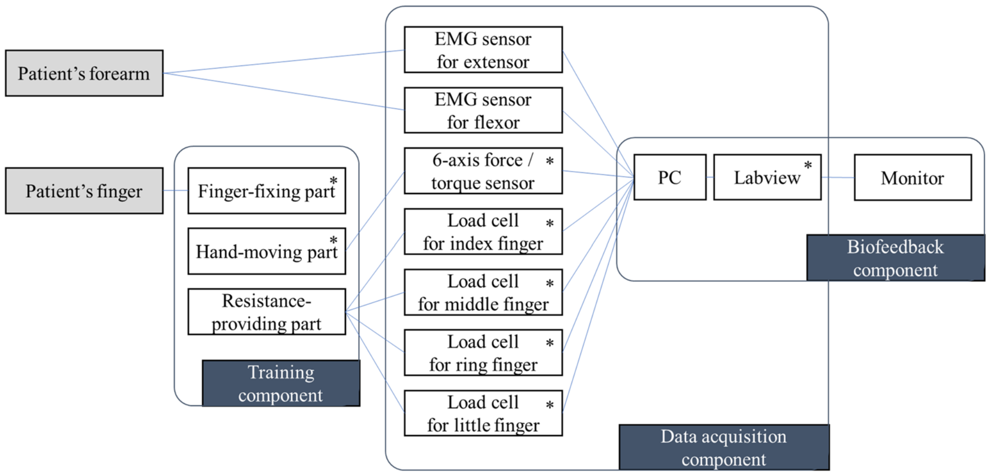

Fig. 3 Configuration diagram of the PARKO and iPARKO devices. *Denotes newly added parts in the iPARKO

Table 1 Comparison of PARKO and iPARKO device functions

	PARKO	iPARKO
Adjustment to secure each fingertip	Not equipped	Equipped
Measurement of the force applied to each fingertip	Not equipped	Equipped
Measurement of hand force	Not equipped	Equipped
Biofeedback of extensor/flexor muscles	Equipped	Equipped

The functions of PARKO and iPARKO devices are compared. As such, iPARKO device, unlike PARKO device, is equipped with the adjustment to secure each fingertip, the measurement of the force applied to each fingertip, and the measurement of hand force. Both PARKO and iPARKO devices contain information on the biofeedback of extensor/flexor muscles

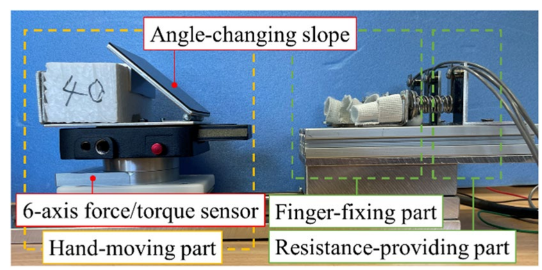

Fig. 5 Training component in the iPARKO device

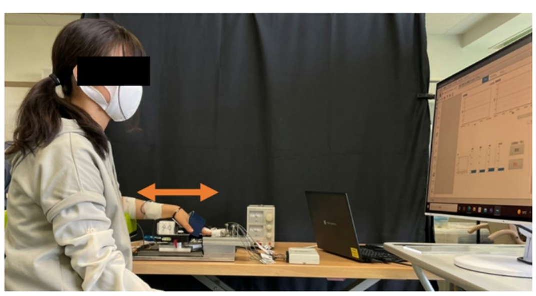

Fig. 4 Training with the iPARKO device

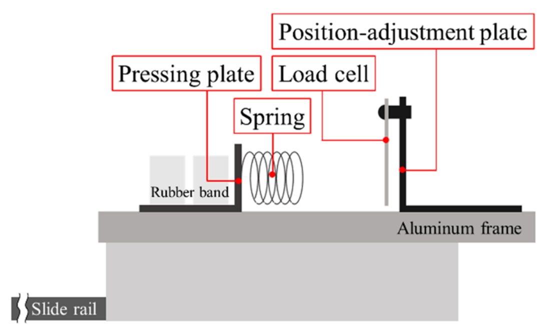

Fig. 6 Finger-fixing and resistance-providing part of the iPARKO device

1) To evenly apply the force to four fingertips of different lengths.
2) To maintain the four fingers in hyperextension. Moreover, to ensure safety and prevent injuries caused by the fingertips over-pressing, investigate therapeutic effects, and utilize the biofeedback system, the following specifications were added:
3) To measure the force applied to the four fingertips and the hand during training.

Figure 5 shows the training component, comprising finger-fixing, hand-moving, and resistance-providing parts.

Finger-fixing part The finger-fixing part, made of four aluminum frames, is shown in Fig. 6. The size of the aluminum frames was 100 mm in length, and 20 mm in width and height. A pressing plate equipped with a rubber band was attached to each aluminum frame to fix the fingertips, which could be individually moved back and forth. Each finger was fixed to the pressing part using the finger sack shown in Fig. 7, which kept the finger in hyperextension; thus, specification (2) was satisfied. In addition, during training, the angles of the metacarpal phalangeal (MP) and proximal interphalangeal (PIP) joints are set to the participant's passive range of motion (P-ROM) and 0 degree, respectively. The angle of the distal interphalangeal (DIP) joint is 1 to 2 degrees since the participant is wearing a finger sack. P-ROM refers to the range of motion when a therapist physically moves or stretches a part of the participant's body.

Hand-moving part The hand-moving part comprised a slide rail (FBW3590XRUU + 300L; THK CO., LTD., Tokyo, Japan), 6-axis force/torque sensor (FFS055F251M-8R0A6S; Leptrino Inc., Nagano, Japan), and angle-changing slope. The slide rail could be moved back and forth as shown by the arrow in Fig. 4, and provided support allowing hemiplegic individuals to smoothly push their hands forward. The 6-axis force/torque sensor was attached to the base of the slide rail, and the angle-changing slope was attached to the 6-axis force/torque sensor. This sensor could measure the force applied to the hand, allowing for analysis of the direction of the force that increases the activity of the extensor muscle; this part is a new feature of the iPARKO device.

We found that hemiplegic individuals increase the activity of the extensor muscle by pushing their hands forward while simultaneously applying downward force [27]. The angle-changing slope was used to change the metacarpophalangeal joint angle of the participant, which could be changed in 1-degree increments by inserting Styrofoam between the plate of the angle-changing slope. Additionally, a nonslip sheet was attached to the slope, and a Velcro belt was attached to fix the metacarpophalangeal joint of the hand. Specification (3) was satisfied by attaching the load cell to the resistance-providing part, and the 6-axis force/torque sensor to the hand-moving part. During experimentation, the iPARKO device's load cell and 6-axis force/torque sensor were not used for data analysis.

Fig. 7 Finger sack

Resistance-providing part The resistance-providing part comprised four position-adjustment plates, four springs, and four load cells (LCL020; Pacific Technology Corp., Tokyo, Japan). Each spring was attached to the opposite side of the pressing plate to which the fingertip was attached; the spring constant was 1.177N/mm, and the amount of deformation during training was within approximately 10 mm. The introduction of a spring facilitates the adjustment of the force to the fingertip when securing the finger to the iPARKO device. The following procedure is used to even out the force applied to the fingertips. First, the finger is secured with rubber bands so that the finger sack is in contact with the pressing plate. Next, the force applied to the fingertip is adjusted by moving the position-adjustment plate, and when the target force is reached, the position-adjustment plate is fixed. Similarly, the position of the position-adjustment plate of the other fingers is adjusted. As a result, the force applied to the fingertip when pushing the spring can be made uniform. By introducing a spring with moderate stiffness, it is possible to fine-tune the position of the position-adjustment plate, making it easier to set the target force. Therefore, the spring is useful in adjusting the force applied to the fingertip. The rigidity of the spring was chosen through trial and error, based on the following conditions: the force to the fingertip should be adjustable, the finger should be stable and fixed, and a 10 mm forward movement should be possible.

A position-adjustment plate was attached to each aluminum frame, and a load cell was set between the spring and position-adjustment plate. In preliminary experiments on healthy individuals, the maximum force on the fingertips was determined to be about 50N. Therefore, a load cell with a range of 90N was selected.

The load cell measures the force applied by each fingertip, and the force applied to the four fingertips could be adjusted by the position-adjustment plate; thus, specification (1) was satisfied. Additionally, by observing the force applied to the fingertips with a monitor, it was possible to prevent injuries caused by over-pressing; therefore, specification (3) was satisfied.

Biofeedback component

When using the PARKO device, the electromyography (EMG) signals of the extensor and flexor muscles are displayed on the monitor as participant's biofeedback. To increase the therapeutic effect, it is necessary to increase the activity of the extensor muscle during training. In EMG biofeedback, the participant adjusts the movement of the hand so that the EMG signals of the extensor muscle increase during training. The iPARKO device simultaneously measures the force applied to the fingertip and hand, displaying the force applied to only the fingertip on the monitor screen.

By observing the activity of the muscles and the force applied to the fingertips during training, the participant may be able to increase the activity of the extensor muscle. Moreover, the participant can prevent injuries caused by over-pressing. This is our proposed biofeedback system, and thus far, the effects of training and biofeedback on the lower limbs of hemiplegic inidividuals have been tested [28, 29]. Figure 8 presents an image of the monitor screen.

Data acquisition component

The data acquisition component comprises myoelectric sensors, four load cells, and a 6-axis force/torque sensor, data acquisition device, and personal computer. When using the iPARKO device, data acquisition systems (USB6211; National Instruments Corp., Austin, TX, USA) were used for data collection. By using data acquisition systems, we were able to design the display screen, making it easier for both the hemiplegic individual and therapist to see the EMG signals and forces.

Validation experiments

Purpose of the experiments

To verify the effect of training with the iPARKO device, two experiments were conducted.

1) First, we compared the activity of the extensor during training with the iPARKO and PARKO devices.
2) Second, we evaluated the activity of the extensor muscle during training with the iPARKO device using the rate of MVC (denoted as %MVC), and clarified its relationship with fingertip forces.

EMG signals are generally normalized in relation to MVC as the reference amplitude [23]. When the iPARKO device is used in hemiplegic individuals, it is desirable to have high and low activities in the extensor and flexor muscles, respectively, to reduce the appearance of spasticity in the flexor muscle. Therefore, both the extensor and flexor muscles should be considered in hemiplegic individuals. However, since the subjects were healthy

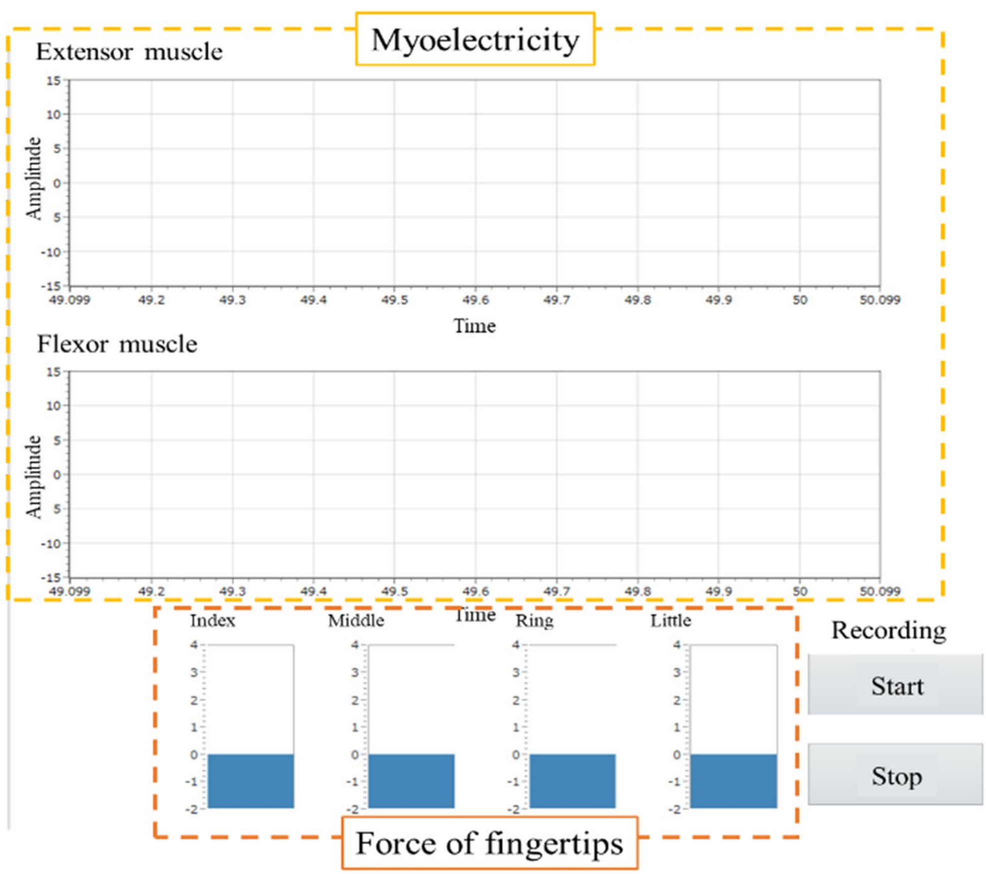

Fig. 8 Monitor for the iPARKO device

individuals in this study, only the activity of the extensor muscle was compared.

Experimental

The higher the performance of the device that increases the activity of the extensor muscle, the higher the therapeutic effect of training. Experiment 1 was intended for three healthy individuals, while experiment 2 was conducted on a different day in two healthy individuals who had participated in experiment 1 and provided consent. Information on the individuals is shown in Table 2; all participants' dominant hands were the right hand, and no medical histories were reported.

As shown in Fig. 4, the participant maintained a sitting position with their elbow resting on the upper limb stand; the training component of the iPARKO device was placed on the left side of the participant's body. The participants' knee was fixed at 90 degrees of flexion, and the ankle at 0 degrees. They were instructed to maintain a posture with no elevation angle so that the left and right shoulders were parallel to the ground, with the back straight; while the participant maintained this posture, the experimenter attached the iPARKO device to the participant. The monitor was placed in front of the participant and adjusted to a height where they could easily see the monitor with their back straight.

The experimenter then attached a finger sack to each of the participant's fingers, and attached them to the pressing plate of the finger-fixing part. The experimenter adjusted each position-adjustment plate so that the force to each fingertip was evenly applied, while observing the applied forces on the monitor screen. Next, the experimenter placed the participant's hand in a hyperextended state and fixed it to the hand-moving part; the hand was fixed to the angle-changing slope of the hand-moving part using a Velcro belt between the metacarpophalangeal joint and wrist joint. The experiment was conducted on the left hand (nondominant hand) in all participants.

Experiment 1 was performed in the following order: measurement using the PARKO device, a 3-min break, and measurement using the iPARKO device. During the experiment, the activity of the extensor and flexor muscles were measured by two myoelectric sensors. A total of 10 trials were performed in each participant; each lasted 4 s, and involved pushing the spring-loaded pressing plate for 2 s, and weakening for 2 s. When measuring using either device, the fingertip force was assumed to be the participant's own maximum force.

Experiment 2 was performed in the following order: MVC measurement, a 3-min break, and measurement using the iPARKO device (measured as described in Experiment 1). During MVC measurement, the activity of the extensor muscle was assessed when the participant opened their hand force for 2 s with the maximum force, as shown in Fig. 9. The activity of muscles was normalized using the absolute mean value of the EMG signal during MVC measurement. Evaluation of muscle activity during training with the iPARKO device by %MVC was performed in Participants No. 1 and 2; additionally, we measured the force applied to the fingertip during training.

In both experiments, a metronome announced the timing at 2 s intervals. The sampling interval for the measurements was 0.001 s.

Table 2 Information of the three participants

Participant No.	Sex	Age	Dominant hand
1	M	26	R
2	F	21	R
3	F	26	R

The sex, age, and dominant hand of the three healthy individuals are shown

Results and discussion

The full-wave rectified waveform of the EMG signal for the extensor muscle of Participant No. 3 is shown in Fig. 10 as an example. Compared with the resting state, the EMG signal was found to increase when force was

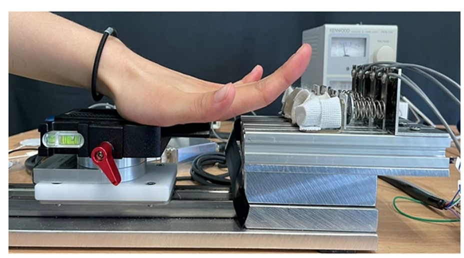

Fig. 9 Opening hand at maximum voluntary contraction

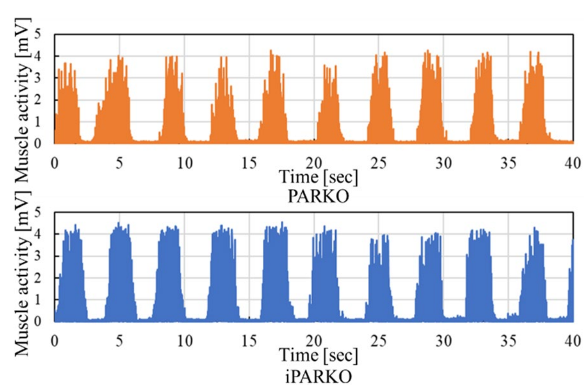

Fig. 10 Raw waveform of the activity of the extensor muscle in Participant No. 3

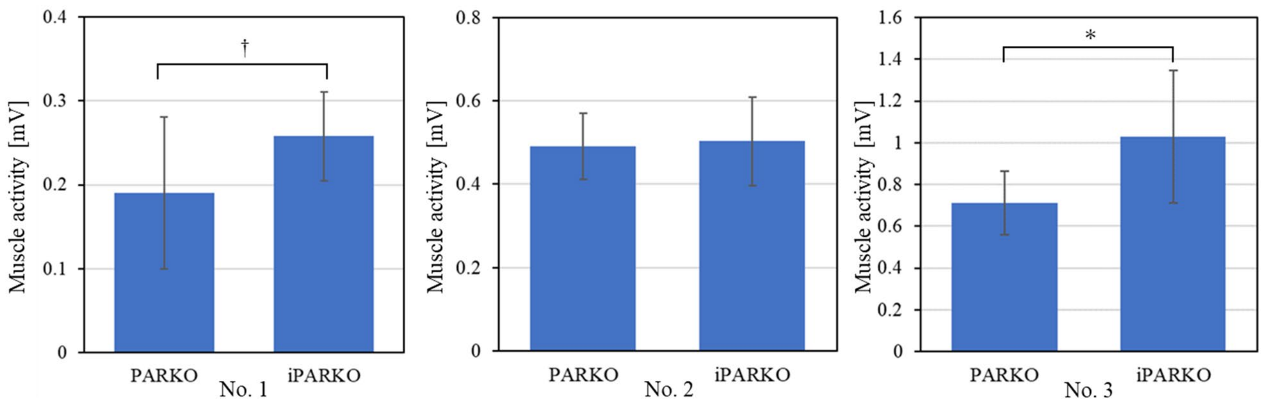

Fig. 11 Mean value of the activity of the extensor muscle in healthy individuals

applied to the fingertips. The absolute mean value of the EMG signal was calculated every 2 s when the force was applied to the fingertips, and the mean value was then calculated to determine the absolute mean value of 10 trials. The mean value was defined as the muscle activity during training.

The activity of the extensor muscle using the PARKO and iPARKO devices are shown in Figs. 11; this figure also show the standard deviation error bars. Figure 11 shows that the extensor muscle activity increased by 35.7%, 2.6%, and 44.5% using the iPARKO device compared to that observed using the PARKO device in the three participants, respectively. For Participants No. 1 and 3, t-test results showed significant differences (*$p < 0.05$) and significant trends (†$p < 0.1$) between muscle activity when using the PARKO and iPARKO devices. In Participant No.2, the mean muscle activity of the extensor muscles with the PARKO and iPARKO devices was almost identical. One possible reason for this is that the four fingertips were already equally applied a force by the PARKO device. Since the PARKO device does not have a sensor to measure the force of the fingertip, we considered this a reasonable possibility based on interviews with the participants. The rates of change in muscle activity for the iPARKO device with respect to those of the PARKO device are shown in Table 3. The mean increase rate for the activity of the extensor muscle among all three participants was 43.8%.

The %MVC of the extensor muscle in two participants when using the iPARKO device are shown in Fig. 12, revealing that the activities of the extensor muscles were 84% and 96%. The mean and standard deviation of the reaction forces acting on the four fingertips of Participants No. 1 and 2 were 10.9 ± 3.43 N and 6.37 ± 1.67 N, respectively. Therefore, it was confirmed that 84% and 96% of the muscle activity during the hand-opening motion can be obtained by applying the appropriate force to the fingertips using the iPARKO device, even if the hand-opening motion is not used.

Table 3 Increase in the extensor muscle activity when using the iPARKO device

Participant No.	Increase in the activity rate of the extensor muscle [%]
1	59.1
2	7.1
3	65.3
Mean ± SD	43.8 ± 32.0

The activity rates of the extensor muscle increased after using the iPARKO device in all three participants (59.1%, 7.1%, and 65.3%, respectively)

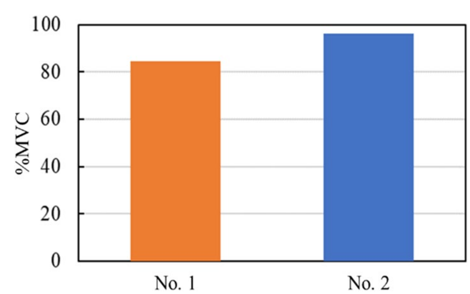

Fig. 12 Rate of maximum voluntary contraction of the extensor muscle when using the iPARKO device

This study has some limitations. The iPARKO device was applied to healthy individuals; however, hemiplegic individuals have hand paralysis. Therefore, it is possible that the application of the iPARKO device is insufficient, highlighting the need for a new brace to secure the iPARKO device in hemiplegic individuals.

In addition, a comparative experiment is required on the muscle activity between training with the iPARKO device and the manual therapy. The muscle activity with the iPARKO device should be equivalent or close to that of the manual therapy.

Conclusions

In summary, we developed a new finger extensor facilitation training device, the iPARKO, and validated its effectiveness in healthy individuals. From the verification, we found that the iPARKO device improved the accuracy of imitating manual therapy, exhibiting greater extensor muscle activity than the PARKO device.

In the future, we aim to use the iPARKO device in chronic hemiplegic individuals; the device will then be modified to accommodate the hemiplegic individual's paralysis. To this end, we plan to develop braces securing fingers and wrist for hemiplegic individuals in accordance with their disability. If the hemiplegic individuals have spasticity, fixation may be difficult. In such cases, the iPARKO device will be used after stretching and other techniques to reduce spasticity. Furthermore, we plan to compare the iPARKO device with the finger extensor facilitation technique. Second, we will utilize our newly installed load cells and 6-axis force/torque sensor to find a training method that increases the activity of the extensor muscle in hemiplegic individuals. We also plan to develop a support system to help therapists design rehabilitation programs suitable for various paralyses in this population.

Abbreviations

RFEs	Repetitive facilitation exercises
MVC	Maximum voluntary contraction
%MVC	The rate of maximum voluntary contraction

Acknowledgements

We would like to thank Editage (www.editage.com) for English language editing.

Author contributions

AN, YM, and HT proposed new device concepts. AN and ZP developed new devices. All authors performed the experiments. AN and ZP performed data analysis. All authors read and approved the final manuscript.

Funding

This research was supported by a JSPS Grant-in-Aid for Scientific Research (19K12878).

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

The study was approved by the ethics committee of Nagoya Institute of Technology: 2020–001. All participants provided written informed consent prior to measurements.

Competing interests

The authors declare that they have not competing interests.

Received: 9 November 2022 Accepted: 7 March 2023
Published online: 07 April 2023

References

1. Feldman RG, Young RR, Koella WP (1980) Spasticity, disordered motor control. Year Book Medical, Chicago, pp 485–494
2. O'Dwyer NJ, Ada L, Neilson PD (1996) Spasticity and muscle contracture following stroke. Brain 119:1737–1749
3. Gustus A, Stillfried G, Visser J, Jörntell H, van der Smagt P (2012) Human hand modelling: kinematics, dynamics, applications. Biol Cybern 106:741–755
4. Kim D (2016) The effects of hand strength on upper extremity function and activities of daily living in stroke patients, with a focus on right hemiplegia. J Phys Ther Sci 28:2565–2567
5. Miller EL, Murray L, Richards L et al (2010) Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient: a scientific statement from the American Heart Association. Stroke 41:2402–2448
6. Taub E, Miller NE, Novack TA et al (1993) Technique to improve chronic motor deficit after stroke. Arch Phys Med Rehabil 74:347–354
7. Taub E, Morris DM (2001) Constraint-induced movement therapy to enhance recovery after stroke. Curr Atheroscler Rep 3:279–286
8. Arya KN (2016) Underlying neural mechanisms of mirror therapy: Implications for motor rehabilitation in stroke. Neurol India 64:38–44
9. Pérez-Cruzado D, Merchán-Baeza JA, González-Sánchez M, Cuesta-Vargas AI (2017) Systematic review of mirror therapy compared with conventional rehabilitation in upper extremity function in stroke survivors. Aust Occup Ther J 64:91–112
10. McCombe Waller S, Whitall J (2008) Bilateral arm training: why and who benefits? NeuroRehabilitation 23:29–41
11. Kawahira K, Shimodozono M, Etoh S, Kamada K, Noma T, Tanaka N (2010) Effects of intensive repetition of a new facilitation technique on motor functional recovery of the hemiplegic upper limb and hand. Brain Inj 24:1202–1213
12. Shimodozono M, Noma T, Nomoto Y et al (2013) Benefits of a repetitive facilitative exercise program for the upper paretic extremity after subacute stroke: a randomized controlled trial. Neurorehabil Neural Repair 27:296–305
13. Wada Y, Ikegami S, Ishikawa S, Furiya Y (2019) Anti-spastic effects of repetitive facilitative exercise on hemiplegic limbs of patients with chronic stroke. Rigakuryoho Kagaku 34(5):569–574
14. Tanabe H (2016) The approach of reorganization of the human central nervous system. Human Press, Tokyo, pp 88–94
15. Sale P, Lombardi V, Franceschini M (2012) Hand robotics rehabilitation: feasibility and preliminary results of a robotic treatment in patients with hemiparesis. Stroke Res Treat 2012:820931
16. Dovat L, Lambercy O, Gassert R et al (2008) HandCARE: a cable-actuated rehabilitation system to train hand function after stroke. IEEE Trans Neural Syst Rehabil Eng 16:582–591
17. Chiri A, Vitiello N, Giovacchini F, Roccella S, Vecchi F, Carrozza MC (2012) Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation. IEEE/ASME Trans Mechatron 17:884–894
18. Ho NSK, Tong KY, Hu XL, et al. (2011) An EMG-driven exoskeleton hand robotic training device on chronic stroke subjects: Task training system for stroke rehabilitation. Paper presented at the 2011 IEEE International Conference on Rehabilitation Robotics, Zurich, Switzerland. 29 June-01 July 2011.
19. Yap HK, Lim JH, Nasrallah F, Goh JCH, Yeow RCH (2015) A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness. Paper presented at the 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, USA, 26–30 May 2015.
20. Al-Fahaam H, Davis S, Nefti-Meziani S (2016) Wrist rehabilitation exoskeleton robot based on pneumatic soft actuators. Paper presented at the 2016 International Conference for Students on Applied Engineering (ICSAE), Newcastle Upon Tyne, UK, 20–21 October 2016.
21. Yu Y, Iwashita H, Kawahira K, Hayashi R (2012) Development of functional recovery training device for hemiplegic fingers with finger-expansion

facilitation exercise by stretch reflex. Paper presented at the 2014 World Automation Congress (WAC), Waikoloa, HI, USA, 03–07 August 2014.
22. Shuhan D, Tanabe H, Morita Y, Peichen Z (2019) Effect of introducing EMG biofeedback to a finger extensor facilitation training device for hemiplegic patients after strokes. Paper presented at the 2019 19th International Conference on Control, Automation and Systems (ICCAS), Jeju, Korea (South), 15–18 October 2019.
23. Meldrum D, Cahalane E, Conroy MR, Fitzgerald D, Hardiman O (2009) Maximum voluntary isometric contraction: reference values and clinical application. Amyotroph Lateral Scler 8:47–55
24. Ada L, Dorsch S, Canning GC (2006) Strengthening interventions increase strength and improve activity after stroke: a systematic review. Aust J Physiother 52:241–248
25. Tanabe H, Ikuta M, Mikawa T, Kondo A, Morita Y (2018) Application of a Robotic Rehabilitation Training System for Recovery of Severe Plegie Hand Motor Function after a Stroke. In: Küçük S, Canda AE (eds) Medical Robotics - New Achievements. IntechOpen, London, pp 1–12
26. Kondou A, Tanabe H (2019) Examination of the immediate effect of Tanabe therapy on patients with spastic hemiplegia- Preliminary study. Occup Ther Fukuoka 17:47–50 (**(in Japanese)**)
27. Nakamura A, Peichen Z, Morita Y, Tanabe H (2021) Finger Extensor Facilitation Training Device "iPARKO": Analysis of increased muscle activity in a hemiplegic person. Paper presented at the 2021 21st International Conference on Control, Automation and Systems (ICCAS), Jeju, Republic of Korea, 12–15 October 2021.
28. Sürücü DG, Tezen Ö (2021) The effect of EMG biofeedback on lower extremity functions in hemiplegic patients. Acta Neurol Belg 121:113–118
29. Woodford HJ, Price CIM (2007) EMG biofeedback for the recovery of motor function after stroke. Cochrane Database Syst Rev 2007:CD004585

Publisher's Note