Effectiveness of mixed reality-based rehabilitation on hands and fingers by individual finger movement tracking in patients with stroke

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Abstract

Background

Stroke is a prevalent, severe, and incapacitating worldwide health issue, and a key component of patient care is rehabilitation. Mixed reality (MR) allows participants to fully submerge in a virtual space while interacting with real objects and is especially useful for hand training because of its tangible user interface. For the potential benefit of MR rehabilitation in hand training, the recognition of individual finger movements is required. We updated the MR-based rehabilitation system (MR-board 2) by adding a palm camera and specific training programs for individual fingers. This study aimed to assess the effectiveness of MR-board 2 on the self-rehabilitation of patients with stroke.

Methods

MR-board 2 comprised a board plate, a depth camera, plastic-shaped objects, a monitor, a palm-worn camera, and seven gamified training programs. All participants performed 20 self-training sessions (5 days per week for 4 weeks) involving 30-min training using MR-board 2 in a research intervention room. The outcome measurements for upper extremity function were the Fugl–Meyer assessment (FMA) upper extremity score, repeated number of finger flexion and extension (Repeat-FE), Box and Block Test score (BBT), Wolf Motor Function Test score (WMFT), and Stroke Impact Scale (SIS). MR-board 2 recorded the finger active range of motion (AROM) during training.

Results

Except for the FMA-proximal score, other FMA scores, BBT score, Repeat-FE, WMFT score, and SIS stroke recovery were improved significantly during MR-board 2 training and were maintained until follow-up (4 weeks after the intervention). All AROM values of the finger joints changed significantly during training.

Conclusions

MR-board 2 self-training, which includes natural interactions between humans and computers using a tangible user interface and real-time tracking of the fingers, improved upper limb function across impairment, activity, and participation. MR-board 2 could be used as a self-training tool for patients with stroke, improving their quality of life.

Trial registration

This study was registered with the Clinical Research Information Service (CRIS: KCT0004167).
Background

Stroke is a prevalent, severe, and incapacitating worldwide health issue, and a key component of stroke care is rehabilitation (1). Continuous and sufficient rehabilitation is required to elicit functional improvement (2). Several augmented and virtual reality apps have been implemented to enhance rehabilitation (3). Mixed reality (MR), which blends virtual reality and physical things, allows participants to fully submerge themselves into a virtual space by interacting with real objects, thereby maintaining their sense of reality. Previous studies have demonstrated the feasibility of Mixed reality-based rehabilitation (MRR) specifically for upper limb rehabilitation among participants with stroke (4, 5). The real physical objects of MRR play the role of tangible user interfaces, enabling more engagement, active participation, and effective learning (6, 7). MRR might be especially meaningful for hand rehabilitation because the physical interfaces provide a haptic sense to the contacting hand, which is a gate for the interaction of the body with objects.

The potential benefits of the MRR can be achieved through complex hand movements that require individual finger movements. Colomer et al. presented an MRR program that included finger tapping, pincer grasping, and mass grasping (5). However, recognizing individual finger movements is challenging in previously introduced MR systems because they are only sensed using a depth perception camera. Capturing the entire finger movement is particularly difficult for stroke participants because they commonly experience spasticity, dystonia, or deformities, which impede adequate movement perception from the camera. Various types of sensors, including wearable and flexible sensors and inertial measurement unit (IMU) sensors, have been used for fingers (8–10). However, sensing using an IMU sensor is affected by attachment location, and wearable-type sensors are difficult to wear by participants with stroke.

To address the above mentioned issues, we updated the MRR system (MR-board 2) by adding a palm camera (TapSix) and specific training programs for fingers (11). The original MR board, which confirmed the feasibility of a self-rehabilitation tool for the upper extremities in participants with stroke, provided interventions regarding gross hand movements only and did not include individual finger training (FT) (12). The newly developed MR-board 2 can provide finger-relevant training, allowing for more hierarchical training according to the participants’ capabilities and goals. When participants could not train their fingers at the initial stage, they received gross hand training, such as grasping, releasing, and object manipulation. If they regain finger function, they can move on to individual FT.

Therefore, we hypothesized that MR-board 2 could benefit upper-limb self-rehabilitation, especially for hand rehabilitation, including FT and capturing entire finger movements. This study aimed to apply MR-board 2 to participants with stroke as a tool for self-rehabilitation and explore its effectiveness across every domain (impairment, limitation, and restriction) of the International Classification of Functioning, Disability, and Health (ICF) (13). We also recorded and analyzed each joint involved in the entire finger movement during FT.
Methods

The present study was performed at a single rehabilitation hospital using a pre-post design. The institutional review board of our rehabilitation hospital approved this study (NRC-2018-04-026), and all participants provided written informed consent before enrollment.

Participants

The inclusion criteria were as follows: (1) age > 19 years; (2) unilateral upper limb functional deficits secondary to first-ever hemispheric stroke as identified from the medical record; (3) participants with chronic stroke, as defined by stroke duration > 6 months; (4) participants who did not receive any other physical rehabilitation interventions other than MR-board intervention during the present study; (5) Brunnstrom’s motor recovery stage in the affected arm and hand ≥ 4 (14); (6) the Medical Research Council scale of muscle strength for wrist flexion/extension, forearm pronation/supination, and finger flexion/extension strength ≥ 3 (15); (7) cognitive ability to understand and follow instructions (mini-mental state examination score ≥ 24) (16). The exclusion criteria were as follows: (1) stroke of bilateral brain lesions; (2) any neurological disorders other than stroke; (3) modified Ashworth scale (MAS) score of upper limb spasticity ≥ 2 (17); (4) predisposing severe pain in the upper limb that could impede training; (5) any severe medical condition; (6) inability to follow instructions because of cognitive impairment or severe aphasia.

Apparatus

Instrument description

The original version of the MR board comprised a board plate, a depth camera, plastic-shaped objects, and a monitor (12). The board surface can be applied differently with multiple textures, providing various haptic senses (rough or soft) to the participants’ fingertips. MR-board 2 was updated by adding a palm-worn camera (TapSix system) to record individual finger movements and a finger-specific training program (11). The TapSix system was placed on the palm of the participants, specifically in the hypothenar area, instead of making them wear a camera on the wrist, which requires a wide range of motion (RoM), allowing a stable angle of view without missing finger images owing to the occlusion of the camera. The primary components of the TapSix are a Raspberry Pi Zero with a Broadcom BCM2385 processor, an inexpensive camera sensor (OV5647, Omnibus), and a Bluetooth module with support for human interface devices (FB155BC, Firmtech). A silicone band fixes the camera without occlusion of finger movement. The TapSix battery lasted for 3 h with 580 mA of current and 1700 mAh of capacity. Through image processing, TapSix identified the fingertip apart from the surrounding environment on various surfaces and determined finger tapping on the tactile surface by computing the shortest distance between the fingertip position and the surface edge. Hand-pose estimation technology, which can extract every finger joint, was used to analyze the movements of the participants’ hands. The detailed components of MR-board 2 are illustrated in Fig. 1.
Contents of training programs

MR-board 2 contains seven gamified training programs, which are categorized into 1) training with a bare hand (virtual hand training; ViHT), 2) training using tangible objects (tangible hand training; TaHT), and 3) training for individual finger movements (FT). ViHT and TaHT are explained in detail in a previous study (12). The descriptions of each training program are as follows. The seven gamified training programs were intended to offer a step-by-step approach based on the progress of the participants.

ViHT consists of “placing arm” and “grasp and release.” The participants were asked to move their arms and grasp and release their hands according to the instructions provided on the monitor.

TaHT consists of “matching the same shape,” “moving the object,” and “stacking the objects.” Six different objects were used in each training session. The objects consisted of three different shapes (triangles, squares, and circles) and colors (red, blue, and green) and two sizes (large and small). Participants were asked to move a specific object to a specific area reflected on the monitor.

FT consists of the “single finger tapping task” and “multi-finger tapping task” (Fig. 2). Five pipes were displayed on the screen, and each pipe reflected the movement of each finger. The "single finger tapping task" involves pressing one leaked pipe among five pipes by tapping a finger. The "multi-finger tapping task" involves rescuing the fish by blocking the entrance of pipes with four fingers except for the pipe in which the fish was located.

Procedures

All participants performed 20 self-training sessions (5 days per week for 4 weeks) involving 30 min of training using MR-board 2 in a research intervention room. They did not receive any other interventions except for the MR-board 2 training. On the first MR-board training day, an experienced occupational therapist provided brief instructions for each training program.

We developed training programs and applied them according to the participants’ hand function levels. Participants with Brunnstrom stage 4 of the hand received both ViHT and TaHT, as preferably suggested because the MR-board 2 has a special advantage for tangible user experience from MR. Participants with Brunnstrom stage 5 or 6 of the hand performed primarily FT owing to the updated characteristics of MR-board 2. In summary, the participants started with ViHT followed by TaHT. As the participants became accustomed to hand training and were able to move their fingers, FT was added sequentially. Although it varied from participant to participant, most participants were recommended to exercise in the order of ViHT, TaHT, and FT in one training session. The participants exercised their upper extremities alone, following the directions of the system presented on the monitor, without any supervision of the therapist. At the beginning of each training program, the participants determined the amount of each intervention and selected the program’s difficulty level. The therapist considered potential safety concerns and assisted participants when they needed help operating the equipment during training.
Outcome measures

An experienced occupational therapist assessed the outcomes. Evaluations were conducted four times: pre-training, mid-training, post-training, and follow-up (after 4 weeks of training). Sex, age, the affected side of paresis, and post-stroke time were collected as demographic characteristics. We collected clinical outcome measurements for upper extremity functions as follows: Fugl–Meyer assessment (FMA) upper extremity score, repeated number of finger flexion and extension (RF), Box and Block Test (BBT) score, Wolf Motor Function Test (WMFT) score, and Stroke Impact Scale (SIS) version 3.0. These outcomes reflect body function and structure (FMA, RF), activity (BBT, WMFT), and participation (SIS), thus capturing the three domains indicated by the ICF (13).

The FMA is a performance-based quantitative measure for patients with stroke, with a higher score indicating a higher motor function (18, 19). We used four outcomes of the FMA: FMA-total (33 items; score: 0–66), FMA-proximal (18 items; score: 0–36), FMA-distal (12 items; score: 0–24), and FMA-coordination (3 items; score: 0–6). In addition, we obtained Repeat-FE, the number of repeated finger flexions and extensions within 20 s, by requesting participants to flex and extend the affected fingers as quickly as possible (20). The BBT measures gross manual dexterity by counting the number of blocks that can be moved from one compartment to another within one minute (21). The WMFT is an upper extremity assessment tool that uses timed and functional tasks (22). The WMFT consists of 17 items: 15 functional abilities and 2 strength-related tasks (shoulder and grip strength). The total score on the functional ability scale (WMFT score; higher scores indicated better motor function) and the total amount of time for each item (WMFT time; shorter time indicated better performance) were obtained. We used the SIS version 3.0, a stroke-specific self-report questionnaire, to measure the health-related quality of life (HRQoL). Among the eight SIS domains, we measured five upper limb domains: strength, hand function, physical and instrumental activities of daily living (ADLs/IADLs), social participation, and stroke recovery score (23, 24). All values were normalized between 0 and 100, with higher scores indicating a better HRQoL.

The TapSix system embedded in MR-board 2 recorded the active range of motion (AROM) of fingers during FT, and 14 joints in the 5 fingers were analyzed: metacarpophalangeal (MCP) and interphalangeal (IP) joints of the thumb, MCP joint, proximal IP (PIP) joint, and distal IP (DIP) joint of the second, third, fourth, and fifth fingers. Setting the neutral position as zero-degree, finger flexion and extension were expressed as positive and negative values, respectively.

A 3D model of the hand at finger flexion and extension was presented based on the first and third quartile values of finger flexion and extension of AROM on the first and last days of FT.

Statistical analysis

One-way repeated measures analysis of variance (ANOVA) was used to compare repeatedly measured outcomes, and the following normality was confirmed. The Bonferroni correction was used for the post hoc test. For finger AROM, Dunnett’s test was used for pairwise comparisons. Statistical analysis was
performed using R 4.2.2 (http://www.r-project.org; R Foundation for Statistical Computing, Vienna, Austria). A p-value of < 0.05 was considered statistical significance.

Results

A flow diagram of the study procedure is shown in Fig. 3. In total, 21 participants with hemiplegic stroke (10 with left hemiplegia and 11 with right hemiplegia; 9 females aged 56.7 ± 14.2 years) participated in this study. The time from stroke onset was 32.7 ± 34.8 months.

One participant dropped out during intervention due to pneumonia, irrelevant to this study. Table 1 shows the changes in clinical outcomes according to ICF domains. Based on one-way repeated-measures ANOVA and its post hoc test, except for the FMA-proximal scores, other FMA, Repeat-FE, BBT, and WMFT values were improved significantly following MR-board 2 training as they underwent the pre-, mid-, and post-tests. Post hoc analysis demonstrated that the variables were improved throughout the MR-board 2 training and did not change from post-test to follow-up, indicating that these variables were maintained after training until follow-up. SIS stroke recovery was improved throughout training and follow-up; in contrast, other SIS outcomes did not show significant changes.
<table>
<thead>
<tr>
<th>Outcome measurements</th>
<th>Pre-test</th>
<th>Mid-test</th>
<th>Post-test</th>
<th>Follow-up</th>
<th>p-value</th>
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<tr>
<td><strong>Body function &amp; structure</strong></td>
<td></td>
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<tr>
<td>FMA-proximal</td>
<td>29.0 ± 5.4</td>
<td>29.4 ± 5.4</td>
<td>29.7 ± 5.8</td>
<td>29.6 ± 5.9</td>
<td>0.617</td>
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<tr>
<td>FMA-distal</td>
<td>16.1 ± 6.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18.1 ± 5.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.1 ± 5.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>19.0 ± 4.8&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>FMA-coordination</td>
<td>2.3 ± 2.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.8 ± 2.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.6 ± 1.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.7 ± 1.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
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<tr>
<td>FMA-total</td>
<td>47.5 ± 11.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>50.3 ± 10.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>52.4 ± 10.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>52.2 ± 10.0&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
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<tr>
<td>Repeat-FE</td>
<td>14.2 ± 7.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.5 ± 8.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.2 ± 8.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>18.5 ± 8.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
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<tr>
<td><strong>Activity</strong></td>
<td></td>
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<td>BBT</td>
<td>16.9 ± 11.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.0 ± 12.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>22.0 ± 12.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>22.3 ± 13.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>WMFT score</td>
<td>45.2 ± 11.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>48.4 ± 11.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>50.9 ± 11.2&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>51.3 ± 11.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
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<tr>
<td>WMFT time (s)</td>
<td>251.9 ± 232.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>210.0 ± 215.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>174.0 ± 193.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>194.8 ± 197.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>WMFT shoulder strength</td>
<td>9.8 ± 5.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.2 ± 5.8&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>12.0 ± 7.3&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>12.8 ± 7.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>WMFT grip strength</td>
<td>8.4 ± 6.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.0 ± 6.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.0 ± 7.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.6 ± 7.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Participation</strong></td>
<td></td>
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<tr>
<td>SIS strength</td>
<td>34.1 ± 15.8</td>
<td>37.1 ± 12.9</td>
<td>35.3 ± 13.9</td>
<td>38.2 ± 16.4</td>
<td>0.45</td>
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<tr>
<td>SIS hand function</td>
<td>36.5 ± 25.9</td>
<td>36.0 ± 28.8</td>
<td>40.3 ± 29.3</td>
<td>37.8 ± 29.2</td>
<td>0.441</td>
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<td>SIS ADL and IADL</td>
<td>77.0 ± 18.2</td>
<td>73.8 ± 16.4</td>
<td>74.6 ± 16.3</td>
<td>76.4 ± 15.4</td>
<td>0.342</td>
</tr>
<tr>
<td>SIS social participation</td>
<td>46.7 ± 22.3</td>
<td>45.6 ± 25.1</td>
<td>49.0 ± 26.0</td>
<td>53.6 ± 22.3</td>
<td>0.264</td>
</tr>
<tr>
<td>SIS stroke recovery</td>
<td>44.5 ± 17.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>55.8 ± 12.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>58.3 ± 14.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>60.0 ± 17.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

FMA, Fugl–Meyer assessment; BBT, Box and Block Test; WMFT, Wolf Motor Function Test.

†One-way repeated-measures analysis of variance for comparisons of changes with Bonferroni correction of post hoc tests.

‡Data are presented as mean ± standard deviation.

§<sup>a</sup>, <sup>b</sup>, <sup>c</sup>Same letters indicate statistically non-significant based on Bonferroni correction.
We collected finger movement data on the first and 20th days of FT; 12,432 and 22,104 data points were obtained on the first and 20th training days, respectively, indicating an increase in FT time. All AROM values of finger joints significantly changed throughout the MR board intervention ($p < 0.001$), and the mean value shifted toward less flexion (more neutral position) in finger joints except the DIP joints of the index and middle fingers. Both fingers’ minimum and maximum values of AROM became further increased from zero degree on the 20th day compared with the first day, indicating increased AROM (Fig. 4). Figure 5 depicts the 3D hand reconstruction based on the first and third quartile data of joint AROM values.

**Discussion**

This study demonstrated that MR-board 2 self-training, an MR-based rehabilitation program involving FT, significantly improved upper limb functions in terms of impairment level (FMA, RF), activity (BBT, WMFT), and participation (stroke recovery item of SIS), and these effects were maintained for 4 weeks after training. Also, individual finger AROM values showed improvements. These results indicate that MR-board 2 self-training in participants who were in the chronic phase of stroke and did not receive interventions other than MR-board 2 training resulted in functional improvements across a variety of domains.

The effects of the MR-board 2 self-training became more evident than those of the original MR board training used in a previous study (12), possibly because the MR-board 2 training included FT, enabling more complex training for an extended duration. For example, participants with a Brunnstrom motor recovery of stage 5 or 6 received FT in addition to gross hand training. The variety of training embedded in MR-board 2 enabled a tailored approach. FT was executed using TapSix, a camera-based computer vision technology; in contrast, most FT programs in virtual rehabilitation commonly use wearable glove-type devices (25–27). Participants easily wore the TapSix on their hypothenar area with a strap without gloves on individual fingers, and all participants in the present study could wear the TapSix by themselves. Moreover, TapSix can detect subtle finger movements using position values and does not require specific movements, such as contacting sensing pads between fingers (28). Additionally, the ViHT provided haptic feedback to boost motor learning (29), which was impossible in training using a glove. Sensory feedback from tangible objects during TaHT and various surfaces during FT enables the experience of a realistic sense of touch and proprioception in MR, leading to motor control enhancement.

The maximum and minimum values of finger AROM values increased (Fig. 4), indicating an increased ROM in each finger, and the participants moved their fingers more frequently after training. In addition, hand posture was normalized more successfully in the last training session than in the first one, indicating that finger movements of the participants became more natural after FT. The mean of all joint ROM values became less flexed after the training, except for the index and middle finger DIP joints of the 14 finger joints. This observation might be attributed to the fact that the posture became more relaxed and natural throughout the training, and the DIP joints in the index and middle fingers, critical for hand manipulation, played more active and focused roles (30).
We collected finger joint ROM data during FT using the TapSix system. The finger is a unique and complex structure in which many joints are proximate in small areas. Therefore, we attached the TapSix to the hypothenar area, allowing for a more stable image without restricting wrist motion. Wrist-based camera devices may lose images of the hands and fingers because they are out of angle when the wrist is extended (31, 32). TapSix was robust under various lighting conditions. Owing to the proximity of the camera to the fingers, the lightness values of the fingers were significantly higher than the hue and saturation values. Furthermore, TapSix uses a 940-nm emitting IR LED (and filter), which is a convenient system for noise processing. These features enable TapSix to extract finger data by distinguishing the finger from the surface.

This study has limitations. First, this study was not a randomized controlled trial; thus, it was not sufficient to confirm the effects of MR-board 2 training. However, our findings could indicate the feasibility of MR-board 2 because the study was conducted among participants with chronic stroke without other interventions. In addition, four tests and follow-up observations confirmed the effects of MR-board 2 training, related to improvement during the intervention and maintenance of the scores until the follow-up test. Second, the components and amount of specific training in MR-board 2 were variable among the participants because we only recommended the training structure, such as the order of training or adjustment difficulty, making it difficult to compare the effects of specific training. However, because MR-board 2 was used as a tool for in-home rehabilitation, these variations could be understood as a reflection of the participants' free will and training at home.

**Conclusions**

MR-board 2 could provide participants with immersive natural interaction between humans and computers via haptic somatosensory and visuospatial interactions. The convergence of different technologies on MR-board 2 enables effective rehabilitation, resulting in functional improvements in patients with stroke. MR-board 2 contains gamified finger and hand training programs, allowing effective repetitive movements. It is capable of recording and assessing performance and immediate feedback, enabling self-training without continuous supervision from a healthcare provider, and has no adverse effects, such as falls or pain. These features warrant MR-board 2 as a self-training tool that significantly improved the upper limb functions reflected by the impairment level (FMA, RF), activity (BBT, WMFT), and participation (stroke recovery item of SIS) based on the ICF model among people with stroke. The findings of this study provide a new approach for patients with stroke to rehabilitate.

**Abbreviations**

MR, mixed reality; MRR, Mixed reality-based rehabilitation; IMU, inertial measurement unit; FT, finger training; ICF, International Classification of Functioning, Disability, and Health; MAS, modified Ashworth scale; ROM, range of motion; ViHT, virtual hand training; TaHT, tangible hand training; FMA, Fugl–Meyer assessment; Repeat-FE, repeated number of finger flexion and extension; BBT, Box and Block Test; WMFT, Wolf Motor Function Test; SIS, Stroke Impact Scale; HRQoL, health-related quality of life; ADLs, activities
of daily living; IADLs, instrumental ADLs; AROM, active ROM; MCP, metacarpophalangeal; IP, interphalangeal; PIP, proximal IP; DIP, distal IP; ANOVA, analysis of variance

Declarations

Ethics approval and consent to participate

The institutional review board of the rehabilitation hospital approved this study (NRC-2018-04-026), and all participants provided written informed consent before enrollment.

Consent for publication

Not applicable

Availability of data and materials

Data and materials are available if requested.

Competing interests

D.Y. is employed by Neofect. Other authors declared no commercial or financial relationships that could be construed as a potential conflict of interest.

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Authors’ Contribution

Y.H. implemented the training program and wrote the manuscript in consultation with J.S. Y.C. conceived the present idea and developed the MR board. D.Y. wrote the technical section of the manuscript and printed the 3D hand model. J.S. designed and verified the analytical methods and supervised the findings.

Acknowledgments

Not applicable.

References


15. Van Allen MW. Aids to the examination of the peripheral nervous system. Archives of Neurology. 1977;34(1):61-.


Figures
Figure 1

Description of MR-board 2 components. (A) Main MR board. (B) Six objects with different shapes and sizes. (C) TapSix system worn on the palm to capture finger motion. (D) Schematic illustration of training using the MR-board 2. MR, mixed reality.
Figure 2

Views of the finger training and screenshots of each game. The participants sat in front of a monitor wearing TapSix and were instructed to move individual fingers according to the task. (A) Training of single- and multi-tapping tasks. (B) Screenshots of the single-tapping task. (C) Screenshots of the multi-tapping task
Figure 3

Flowchart of the clinical study.
Figure 4

Box plots of the range of motion of each finger joint. MCP, metacarpophalangeal joint; IP, interphalangeal joint; PIP, proximal IP; DIP, distal IP
Figure 5

Three-dimensional hand model during finger training. These images were prepared based on the whole range of motion data from the individual fingers of participants.