Development and validation of immersive hand rehabilitation system using a VR rhythm game with vibrotactile feedback: an fNIRS pilot study

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Research Article

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Abstract

Background

Recently, virtual reality (VR) has been widely utilized with rehabilitation to promote user engagement, which has been shown to induce brain plasticity. In particular, contact-free hand tracking technology has been developed as a control input for VR, and there is an increasing demand for patient-specific hand rehabilitation strategies. In this study, we developed a VR-based hand rehabilitation system consisting of a user-specific gesture-controlled rhythm game with vibrotactile feedback and validated the system by measuring brain activation using functional near-infrared spectroscopy (fNIRS).

Methods

The VR-based hand rehabilitation system provides vibrotactile feedback as the user matches their hand gestures to VR targets customized to their pre-recorded hand gestures that approach according to the rhythm of the music. Cortical activation was measured via fNIRS during 420 seconds of alternating gameplay and rest in 11 healthy subjects and one chronic stroke survivor. Regions of interest (ROI) were the prefrontal cortex (PFC), the premotor cortex & the supplementary motor area (PMC&SMA), the primary sensorimotor cortex (SM1), and the somatosensory association cortex (SAC).

Results

The mean success rate of gesture matching among healthy subjects was 90% with a standard deviation of 10.7%, and the success rate of the stroke survivor was 79.6%. The oxygenated hemoglobin (HbO) cortical activation maps showed that the hemodynamic responses of HbO increased during the VR-based hand rehabilitation for all ROIs for both groups. Paired t-test analysis showed a significant increase in HbO activation values in 23 out of 51 channels that correspond to all ROIs except the left PFC and PMC&SMA, which showed high subject variability.

Conclusion

The experimental results indicate that the proposed gesture-controlled VR rhythm game and vibrotactile feedback system successfully activated brain cortical areas related to motor planning and execution, multisensory, and attention. The proposed system is expected to be effective in promoting brain plasticity by inducing brain activation in key areas for stroke rehabilitation.

1. Introduction

Persistent motor dysfunction in the hands severely affects the quality of life of stroke survivors by limiting their activities during daily life [1]. Impaired finger extension is the most common symptom after...
stroke [2] and leads to poor upper limb recovery by diminishing hand opening function [3]. Despite physical and occupational therapy, approximately 55% of stroke survivors still suffer from long-term hand disabilities after three to six months of rehabilitation [4]. Even four years post-stroke, nearly 70% of stroke survivors still experienced non-use or disuse of the affected arm [5]. These studies indicate the need for improved hand rehabilitation techniques and strategies for stroke survivors.

Although high-intensity, task-oriented, and repetitive training has been proven to be one of the best approaches to inducing neuroplastic changes for restoring hand function [6, 7], it is difficult to achieve without a high level of engagement by stroke survivors. Engagement is defined as deliberate effort and commitment to work toward the goals of rehabilitation interventions, with active participation and emotional involvement in the therapies [8]. Previous studies have suggested that the level of engagement is closely related to the level of functional improvement [9, 10]. Also, engagement has been reported to be associated with reward-related dopaminergic systems in the brain that facilitate neural plasticity and motor learning [11, 12]. However, stroke survivors are easily distracted and lose interest due to the repetitive and monotonous nature of conventional rehabilitation training, which results in a decrease in engagement [13]. Such training even leads patients to neglect the training prescribed for recovery [14]. To address this, various approaches have attempted to find ways to induce and sustain engagement during rehabilitation training.

As promising tools to promote engagement, virtual reality (VR) games have been utilized with rehabilitation programs over the past decade [15–17]. In VR games, training conditions can be modified through content manipulation, so task-oriented, high-intensity, and repetitive movements can be effectively implemented in a state of a high level of engagement [18]. In addition, using VR games in rehabilitation has proven to be effective in recovering motor function by integrating visuoauditory feedback related to movement and cognitive processes [19]. Recently, contact-free hand tracking technology has been used as a control input for playing such VR games, but there are few studies of its application in hand rehabilitation [20–22]. Even in those few cases, the number of task repetitions is insufficient to achieve neuroplastic change and functional improvement [23]. Also, the possible gestures that can be trained are limited since the condition (range of motion, degree of spasticity, etc.) of the stroke survivor’s hand was not considered.

This study presents a VR-based hand rehabilitation system that allows stroke survivors to perform various task-oriented hand gestures based on their hand condition according to a rhythm game with vibrotactile feedback. We utilized the rhythm of the music since it has a repetitive and motivating nature, and is a promising neurorehabilitation method that promotes motor recovery in stroke survivors [24]. Introducing a rhythm game is expected to encourage high repetitions of movement over a limited time and maintain a high level of user engagement during long-term interventions by varying the type of music and difficulty of the game.

In our VR game system, players need to make the same gestures at an approaching target which is customized to their hand condition. When they perform the gestures correctly with precise timing,
multisensory feedback consisting of vibrotactile, visual, and auditory feedback is provided at the same time. Previous studies have shown that this combination of triple sensory modalities achieved better results in terms of attention than single or dual sensory modalities [25]. For these reasons, the proposed rehabilitation system is believed to enable intensive, task-oriented, and repetitive hand training with a high level of engagement.

To validate our hand rehabilitation system, we used functional near-infrared spectroscopy (fNIRS) to measure the brain activation of healthy subjects and a stroke survivor. Since brain-imaging techniques allow us to directly observe brain activity while subjects perform various motor, sensory, and/or cognitive tasks, they can demonstrate the functional reorganization and neuroplasticity of our brain in response to a rehabilitation intervention [26]. As a result, we can examine how effective our proposed rehabilitation system may be by observing brain activation. Specifically, fNIRS is a non-invasive method for measuring the hemodynamic response associated with activation of the cerebral cortex based on the intrinsic optical absorption of blood [27]. Compared to other neuroimaging techniques, fNIRS has the advantage of low sensitivity to motion artifacts and is usable in more realistic day-to-day rehabilitation settings. Until now, only a few studies have used fNIRS to measure brain activation induced by rehabilitation training using VR, and the area of interest has also been limited to motor and sensory functional areas [28]. In this study, in addition to the sensorimotor area, other areas such as the prefrontal, premotor, and somatosensory association areas that are likely to be activated while using the proposed hand rehabilitation system were set as areas of interest.

2. Methods And Material

2.1. Hand rehabilitation system

We developed a hand rehabilitation system consisting of a gesture-controlled VR rhythm game and vibrotactile feedback, as depicted in Fig. 1. For implementation, a VR HMD (Meta Quest 2, Meta Platforms, Inc., Menlo Park, CA) and vibrotactors (C2-HDLF, Engineering Acoustics, Inc., Casselberry, Fl) were used while the fNIRS system was used to measure brain activation during gameplay, for experimental validation (Fig. 1a). Compared to other VR devices, the Meta Quest 2 has the unique advantage of enabling hand tracking using only embedded cameras, without extra hardware. It can track hands at up to 60Hz by using a multi-stage process to estimate hand pose and finger joint angles in real-time [20]. Regarding the hand-tracking accuracy of Quest, Abdlkarim et al. reported an average fingertip positional error of 1.1 cm, an average finger joint angle error of 9.6 degrees and an average temporal delay of 0.038 ms [29]. To provide vibrotactile feedback strong enough to be felt even by stroke patients, we selected the C2-HDLF, a moving magnetic actuator capable of generating strong localized tactile sensations. It delivers a high displacement output range of 0.5 mm to 1.3 mm in the 50–160 Hz range.

To develop the VR rhythm game for the hand rehabilitation system, the Unity 3D game engine (version 2020.3.10f1 LTS release) was chosen as the software platform since the Meta Quest 2 has a software development kit (SDK) for development in Unity 3D, and the Oculus Integration asset (version 33.0), which
includes a hand and finger tracking application programming interface (API). In addition, TDK-API (version 1.0.6.0) was used to generate vibrotactile feedback according to events that occurred in the game.

Through the VR HMD, VR scenes are shown to the player when they play the VR rhythm game (Fig. 1b). Target gestures for each hand are generated by a target generator located in front of the player and approach the hand of the player to the rhythm of the music. The player is required to match the gesture of their hand to the approaching target. If the player makes the same gesture at the approaching target, the player’s hand color changes to the same color as the target and the target explodes in the event of a collision (Fig. 3c). When the participants perform gestures correctly with precise timing, multisensory feedback consisting of vibrotactile, visual, and auditory feedback is provided at the same time. In particular, only the hand that performed the gesture correctly is provided multisensory feedback. Two vibrotactors were attached to the volar side of the wrist since previous studies reported cerebral sensory cortex activation and restoration of sensory function when vibrotactile feedback was provided to the wrist [30, 31]. In addition to visual feedback, such as the explosive effects of the target gesture, the game score is displayed in the upper left corner of the field of view in real-time because it can support enhanced user motivation [32].

2.2. Hand gesture recognition

Our hand rehabilitation system requires the player to repeatedly perform the same gestures as the target gesture according to the rhythm of the music. As shown in Fig. 2, three gestures were selected as target gestures to be recognized: finger extension, medium wrap, and lateral pinch. The reasons for selecting the above three gestures are as follows. First, spastic clenched fist deformities can be commonly observed in stroke survivors due to spastic hypertonia of the finger flexors and weakness of the finger extensors [33], and finger extension is the motor function most likely to be impaired by clenched fist deformities [34]. Second, medium wrap and lateral pinch are the two most important types of grasp that can be used to grasp most types of objects [35].

The algorithm for gesture recognition is as follows (Fig. 2). Through the built-in camera of the Meta Quest 2, the 3D distances ($DIST$) between the reference point and 22 hand points are used for gesture recognition for both hands. First, before playing the VR game, the player's 22 $DIST$s for each of the three gestures are measured and stored as pre-recorded $DIST$ in advance. After that, the player starts to play the game, and real-time hand tracking occurs. For all $i$, if the difference between the $DIST(i)$ of the current gesture and the $DIST(i)$ of the pre-recorded gesture is less than a certain threshold value, it is recognized as the corresponding pre-recorded gesture and the hand color will be changed as well. In this study, the threshold value, which means how accurate the recognition should be, was set to 2 cm. Since the gesture is being recognized in real-time, it is necessary to maintain the corresponding gesture until the target and hand come into contact, and it is also necessary to continuously change the gesture during the gameplay. The pattern of the approaching target gesture changes randomly in accordance with the music rhythm.

2.3. Validation experiment
2.3.1. Participants

Eleven healthy subjects (25.4 ± 4.4 yrs) and one ischemic stroke survivor with mild left-sided hemiplegia (22 yrs) were recruited for the validation of our hand rehabilitation system. The demography is shown in Table 1. As to the stroke survivor, finger opposition and flexion could be well performed; finger extension was not smooth, but still possible. The experimental protocols were approved by the Institutional Review Board at the Korea Advanced Institute of Science and Technology (KH2022-001); written informed consent was obtained from each subject before participation. The experiment was conducted in accordance with the latest Declaration of Helsinki.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Sex</th>
<th>Age (yrs)</th>
<th>Time since stroke (months)</th>
<th>Affected (Stroke) or dominant (healthy) side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>M</td>
<td>22</td>
<td>336</td>
<td>Left</td>
</tr>
<tr>
<td>S1</td>
<td>M</td>
<td>22</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S2</td>
<td>M</td>
<td>21</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S3</td>
<td>M</td>
<td>25</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S4</td>
<td>M</td>
<td>28</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S5</td>
<td>M</td>
<td>34</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S6</td>
<td>F</td>
<td>28</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S7</td>
<td>M</td>
<td>26</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S8</td>
<td>F</td>
<td>21</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S9</td>
<td>F</td>
<td>19</td>
<td>-</td>
<td>Right</td>
</tr>
<tr>
<td>S10</td>
<td>F</td>
<td>29</td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>S11</td>
<td>F</td>
<td>26</td>
<td></td>
<td>Right</td>
</tr>
</tbody>
</table>

2.3.2. Experimental setup and procedure

To measure brain activation, NIRSport 2 (fNIRS, NIRx Medical Technologies, Glen Head, NY, USA) with continuous near-infrared light of two wavelengths (760 nm & 850 nm) was used. After establishing a region of interest (ROI) in the cerebral cortex, a custom channel montage was employed to measure task-related brain activation. Based on the international 10–20 system [36], the optodes and channels are arranged as shown in Fig. 3. The distances between source and detector were kept to 3 cm and the channel was placed in the center between them. 16 detectors and 16 sources constructed 51 channels in
total and the channels were divided into 4 groups to cover the ROIs as follows: The primary sensory-motor cortex (SM1), the premotor cortex & the supplementary motor area (PMC&SMA), the somatosensory association cortex (SAC), and the prefrontal cortex (PFC).

Based on the block design paradigm [37], detailed in Fig. 3c, measurements were performed with a total of 10 repetitions in a block consisting of 20 seconds rest, 20 seconds task of VR-based hand rehabilitation, and an additional 20 second rest section. In the task section of the block, subjects played a VR rhythm game with the music. In the rest section of the block, the music stopped and subjects were asked not to move and rest. In this manner, a session comprises 21 blocks, taking 420 seconds. Note that the target gestures given to the player are totally randomized for each subject.

The song "Believer" by Imagine Dragons was selected as the music for the VR rhythm game since it has a strong beat and is widely used in many commercialized rhythm games. The song is about 200 seconds long and has a tempo of 125 bpm. A total of 200 target gestures were generated per second, and for each participant, the number of missed targets was counted, and the success rate was calculated.

Details of the measurement procedure and instructions provided to the subject are as follows. As a subject enters an experiment room insulated from noise and light, he or she is asked to sit down in a chair facing the wall. Then the subject is instructed on how to wear the VR HMD, and the operator attaches vibrotactors to both wrists of the subject. After placing the optode holder cap on the subject’s head and inserting the optodes into the cap, we give a few instructions before the measurement starts, such as “close your eyes during the rest section” and “do not voluntarily move the other body parts except your hands.” These instructions essentially complete the preparation for the measurement.

Motion artifacts can easily be generated by movement of the subject — especially the head — causing decoupling of optodes from the scalp, which affects the measured signal [38, 39]. In order to prevent head movement, we designed all the contents provided in the VR rhythm game so that they could be viewed at a glance without head movement. In addition, the height of the desk was adjusted according to the sitting height of the subject so that the arms could be comfortably placed on the desk. We also confirmed whether any movement of body parts other than hands occurred during the experiment. After the experiments, we reconﬁrmed from all the subjects that there had been no voluntary movement except the hand.

2.3.3. Data analysis

Data analyses were carried out using the open source software Homer3 (version 1.33) implemented in MATLAB R2021a (Mathworks, Natick, MA, USA) [40]. First, the raw NIRS signals were converted into optical density (OD). Afterward, motion artifacts in the optical density data such as baseline shifts and high-frequency spikes were detected and corrected using a hybrid method based on the spline interpolation method and Savitzky-Golay filtering [41]. The data were then low-pass filtered with a cut-off frequency of 0.5 Hz in order to remove high-frequency oscillations. Subsequently, the changes in the OD signal were converted into concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) by employing the modified Beer-Lambert law with a partial pathlength factor of 6 [42].
The hemodynamic response function (HRF) of HbO (or HbR) was estimated with a general linear model (GLM) approach that uses iterative weighted least squares [43]. The HRF was modeled as a series of consecutive Gaussian temporal basis functions with a standard deviation of 1 s and their means were separated by 1 s over the time range of -2 s to 20 s [44]. After the model extraction, each HRF was normalized using the mean amplitude between -2 s to 0 s before the task onset. Then, the activation value of HbO (or HbR) representing the task was calculated by subtracting the mean HbO (or HbR) response amplitude of the baseline period from that of the task period. The baseline periods are defined as the 2 s of fNIRS measurements preceding the onset of the task period (i.e., the time to restart the VR rhythm game that was paused during the rest periods). Considering the delay in hemodynamic responses, we used intervals between 5 and 15 s after the task onset as the time window to calculate the mean response amplitude in the task period. In this way, the activation value of HbO (or HbR) was calculated for all participants and channels as an indicator for statistical analysis.

To test the assumption of normality of the activation values for each channel, the Shapiro-Wilk test was performed and found that all data followed a normal distribution for all channels at the significance level $\alpha = 0.05$. Then, the paired t-test was used to test the statistical significance of the activation value within each channel induced by the VR-based hand rehabilitation system. The findings indicated that HbO was the most sensitive to task-related hemodynamic changes and had a better signal-noise ratio, and accordingly it was selected as the main index to assess brain activation [45, 46].

A projection of the estimated hemodynamic response of HbO onto the brain cortex was carried out using the MATLAB-based software AtlasViewerGUI (version 2.16.1). It was used to transfer optode positions into Montreal Neurological Institute coordinates (MNI) [47] by registering the 3D location of the optodes and channels to the head surface of the Colin Atlas, and projecting them onto the cortical surface [48]. We then found the corresponding Brodmann Area (BA) based on the automatic anatomical labeling (AAL) database, and used that information to assign each channel to ROI [49]. Then, an image of the cortical activation was reconstructed by solving the inverse problem with a regularization scaling parameter = 0.01. Finally, the mean hemodynamic response of HbO between 5 and 15 s during the VR-based hand rehabilitation was projected onto a brain cortex.

### 3. Results

Here we present four main results regarding the success rate of the VR rhythm game, significantly activated channels, cortical activation map, and the time course of the hemodynamic response function. Group average results for the healthy subjects and the individual results for the single stroke survivor are reported.

#### 3.1. The success rate of gesture matching

The success rate of gesture matching was obtained by counting the number of missed and mismatched target gestures among a total of 200 target gestures presented in the VR rhythm game. Table 2 shows
that the success rate of gesture matching among healthy subjects ranged from 68.6–99.3% with a mean of 90% and a standard deviation of 10.7%. The success rate of the stroke patient was 79.6%.

<table>
<thead>
<tr>
<th>Subject</th>
<th>No.</th>
<th>Number of missed and mismatched target gestures</th>
<th>Success rate of gesture matching (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>P1</td>
<td>41</td>
<td>79.6</td>
</tr>
<tr>
<td>Healthy</td>
<td>S1</td>
<td>11</td>
<td>94.5</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>1</td>
<td>99.3</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>4</td>
<td>98.1</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>63</td>
<td>68.6</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>13</td>
<td>93.3</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td>54</td>
<td>72.9</td>
</tr>
<tr>
<td></td>
<td>S7</td>
<td>26</td>
<td>86.8</td>
</tr>
<tr>
<td></td>
<td>S8</td>
<td>6</td>
<td>97.1</td>
</tr>
<tr>
<td></td>
<td>S9</td>
<td>32</td>
<td>83.9</td>
</tr>
<tr>
<td></td>
<td>S10</td>
<td>10</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>S11</td>
<td>2</td>
<td>99.0</td>
</tr>
<tr>
<td>Mean (SD) of healthy subjects</td>
<td>20 (21.3)</td>
<td>90 (10.7)</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2. Significantly activated channels

Table 3 shows the results of paired t-test analysis for HbO activation values in the healthy group for each channel and the corresponding ROI. This analysis revealed significant increases in HbO in 23 out of 51 channels with a significance level of 0.05 and 10 degrees of freedom. And the ROI involving these channels were both sides of SM1 and SAC, the Left sides of PFC and PMC&SMA, and the center of the SM1 and PMC&SMA.
Table 3

The results from the paired t-test analysis for the activation value of HbO in the healthy group. The t statistics and \( p \)-value were calculated for each channel and ROI. Significant signal changes in HbO are highlighted in bold if the \( p \)-value is less than 0.05. L: left, R: right, the ROI without L or R means the center area.

<table>
<thead>
<tr>
<th>Channel</th>
<th>ROI (side)</th>
<th>HbO</th>
<th>Channel</th>
<th>ROI (side)</th>
<th>HbO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( t )</td>
<td>( p )</td>
<td></td>
<td>( t )</td>
</tr>
<tr>
<td>1</td>
<td>PFC (L)</td>
<td>-0.289</td>
<td>0.779</td>
<td>27</td>
<td>PMC&amp;SMA (L)</td>
</tr>
<tr>
<td>2</td>
<td>PFC (L)</td>
<td>-1.632</td>
<td>0.134</td>
<td>28</td>
<td>PMC&amp;SMA (R)</td>
</tr>
<tr>
<td>3</td>
<td>PFC (L)</td>
<td>1.697</td>
<td>0.121</td>
<td>29</td>
<td>PMC&amp;SMA</td>
</tr>
<tr>
<td>4</td>
<td>PFC (L)</td>
<td>1.356</td>
<td>0.205</td>
<td>30</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>5</td>
<td>PFC (L)</td>
<td>0.708</td>
<td>0.495</td>
<td>31</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>6</td>
<td>PFC (L)</td>
<td>0.131</td>
<td>0.898</td>
<td>32</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>7</td>
<td>PFC (L)</td>
<td>-0.189</td>
<td>0.854</td>
<td>33</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>8</td>
<td>PMC&amp;SMA (L)</td>
<td>0.858</td>
<td>0.411</td>
<td>34</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>9</td>
<td>SM1 (L)</td>
<td>1.256</td>
<td>0.238</td>
<td>35</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>10</td>
<td>PMC&amp;SMA (L)</td>
<td>0.322</td>
<td>0.754</td>
<td>36</td>
<td>PMC&amp;SMA (R)</td>
</tr>
<tr>
<td>11</td>
<td>PMC&amp;SMA (L)</td>
<td>-1.421</td>
<td>0.186</td>
<td>37</td>
<td>PFC (R)</td>
</tr>
<tr>
<td>12</td>
<td>SM1 (L)</td>
<td>2.334</td>
<td>0.042</td>
<td>38</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>13</td>
<td>PMC&amp;SMA (L)</td>
<td>0.758</td>
<td>0.466</td>
<td>39</td>
<td>PMC&amp;SMA (R)</td>
</tr>
<tr>
<td>14</td>
<td>SM1 (L)</td>
<td>1.286</td>
<td>0.227</td>
<td>40</td>
<td>PMC&amp;SMA (R)</td>
</tr>
<tr>
<td>15</td>
<td>SM1 (L)</td>
<td>3.057</td>
<td>0.012</td>
<td>41</td>
<td>PMC&amp;SMA (R)</td>
</tr>
<tr>
<td>16</td>
<td>SM1 (L)</td>
<td>2.567</td>
<td>0.028</td>
<td>42</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>17</td>
<td>SM1 (L)</td>
<td>2.893</td>
<td>0.016</td>
<td>43</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>18</td>
<td>SM1 (L)</td>
<td>3.353</td>
<td>0.007</td>
<td>44</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>19</td>
<td>SM1</td>
<td>3.194</td>
<td>0.010</td>
<td>45</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>20</td>
<td>PMC&amp;SMA</td>
<td>2.267</td>
<td>0.047</td>
<td>46</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>21</td>
<td>SM1 (R)</td>
<td>3.145</td>
<td>0.010</td>
<td>47</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>22</td>
<td>SAC (L)</td>
<td>3.088</td>
<td>0.011</td>
<td>48</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>23</td>
<td>SAC (L)</td>
<td>3.045</td>
<td>0.012</td>
<td>49</td>
<td>SM1 (R)</td>
</tr>
<tr>
<td>24</td>
<td>SM1 (L)</td>
<td>2.913</td>
<td>0.015</td>
<td>50</td>
<td>SAC (R)</td>
</tr>
</tbody>
</table>
3.3. The cortical activation maps

Figure 4 shows the results of the cortical activation maps for the healthy group and one stroke survivor stimulated by the VR-based hand rehabilitation system with vibrotactile feedback. An increased HbO response is highlighted in red while a decreased HbO response is highlighted in blue. Regardless of whether the subject was a healthy subject or a stroke survivor, increased cortical activation was observed for all ROIs (i.e., both sides of SM1, SAC, PFC, and PMC&SMA). In the stroke survivor, the SM1 activation area was wider on the contralateral side than on the ipsilateral side. In addition, a widespread decrease in HbO response was found in both lateral sides of the brain of the stroke survivor, compared to healthy groups.

3.4. The time course of hemodynamic response function

Figure 5 and Fig. 6 present the temporal change in the HRF of HbO (or HbR) related to the VR-based hand rehabilitation task and vibrotactile feedback in 4 ROIs. The averaged HRF time course with confidence bands for the healthy group is depicted in Fig. 5. It is observed that both sides of the brain have similar time course trends in all ROIs except the prefrontal cortex. In the SM1 and SAC areas, HbO showed a tendency to increase after the start of the task and then gradually decreased until the end of the task, and HbR showed the opposite tendency. Regarding the PMC&SMA area, a temporary increase was confirmed immediately after the start of the task, but a tendency to decrease rapidly was observed. While PFC showed a tendency to increase in the right brain, it was found that there was almost no change throughout the task in the left brain.

The individual HRF time course of a single stroke survivor is shown in Fig. 5. A similar time course was observed in both sides of SM1, right PFC, left PMC&SMA, and left SAC; HbO showed a tendency to increase after the start of the task and then gradually decreased until the end of the task, and HbR showed the opposite tendency to HbO. However, the right SAC showed a similar trend to the above-mentioned area except for the initial decrease after the start of the task. The left PFC and right PMC&SMA showed a similar trend, with both HbO and HbR gradually increasing and decreasing.

4. Discussion

In this study, we proposed an immersive hand rehabilitation system based on VR rhythm games and vibrotactile feedback, which is capable of performing task-oriented, repetitive, and intensive tasks with a high level of engagement. Compared with previous studies that developed VR-based hand rehabilitation
systems using contact-free hand-tracking technology, our study has the following three differences [21, 22].

First, the target gestures can be personalized using gesture recognition algorithms, and how precisely the gesture should be performed can be adjusted by changing the classification threshold value. As shown in Table 2, with a recognition threshold value of 2 cm, the gesture matching success rate of the stroke survivor was 79.6% and the average success rate of 11 healthy was 90% (SD = 10.7%). A similar accuracy was found in the study by Yuan et al. [50], in which the accuracy ranged from about 75 to 90% when novice players played a commercial rhythm game four times. This indicates that an appropriate threshold value for gesture recognition was selected and that all participants, including the stroke survivor, performed the gestures correctly according to these criteria. Previous studies have utilized built-in hand recognition functions which could recognize only limited hand gestures, such as poke, pinch, and finger opposition, and didn't consider how accurately the hand movements were being performed. In contrast, for this study three training motions—lateral pinch, medium wrap, and finger extension, among the many possible hand motion options, were selected. These motions have proven to be the most commonly used postures for gripping and releasing objects of various shapes and sizes in daily life [35], and have also been adopted as target movements in recently developed soft and exoskeleton robots [51, 52].

Second, a rhythm game was selected as the VR game content to facilitate intensity control and repetitive training. Previously, Ogun et al. selected daily life behaviors such as handling cubes, picking up vegetables from a bowl, and kitchen experience [21]; Pereira et al. selected farm activities such as harvesting crops, milking the cow, and making cheese [22]. Those studies reported that high user engagement was successfully induced, however, the number of repetitions of tasks was insufficient to achieve neuroplastic change and functional improvement [23]. It has been reported by previous research that the number of repetitions must be at least 300 times a day to induce neuroplastic changes and functional improvement of the upper extremity [53]. Our system induced the stroke survivor to perform 200 gestures for about 420 seconds, so it is considered to be sufficient for inducing a high rehabilitative effect. In addition, the intensity of training could be easily adjusted by manipulating the type of song and the frequency or pattern of the target appearance.

Third, vibrotactile feedback was used to induce a high sense of immersion. It is now widely used in video games and VR games to the extent that it is difficult to find products without vibration tactile feedback among commercial game controllers, and it has been reported to provide a stronger sense of immersion than audio-visual feedback alone [54]. It was attached to the median nerve of the wrist to provide vibration without interfering with hand tracking, and the effect of vibrotactile feedback will be discussed in detail using the brain activation results described later.

For the system validation, fNIRS was used to monitor the activation of the cortical area and time course of the hemodynamic response function in four ROIs (PFC, PMC&SMA, SM1, and SAC) during the VR-based hand rehabilitation task. HbO and HbR, which measure neural activity indirectly by detecting
hemodynamic changes in the underlying cerebral cortex, are the most commonly used parameters of fNIRS [55].

As is evident from the significantly activated channels shown in Table 2 and cortical activation maps in Fig. 4, the introduction of our system gave rise to significant activations in both sides of SM1 and SAC, and the right sides of PMC&SMA and PFC. The activation of these areas means that the components of the proposed hand rehabilitation system have effectively stimulated each part of the brain as follows. First, activation of SM1 is considered to be caused by repetitive hand gestures and vibrotactile feedback during VR gameplay. There is ample evidence that the SM1 plays an important role in motor execution and sensorimotor integration during voluntary hand movements [56, 57]. Second, the activation of PMC&SMA is thought to be due to the planning and execution of the sequential hand gestures required to play the VR rhythm game that aims to remove each approaching target gesture in a sequential manner. This explanation is based on previous findings that the PMC&SMA play a critical role in the generation of sequential movements from memory with a precise timing plan [58]. Specifically, stroke survivors with PMC&SMA lesions had difficulty generating rhythmic sequential movements, even though they were provided with rhythmic auditory stimuli before the experiment. Third, vibrotactile feedback provided when the VR rhythm game was properly performed is considered to stimulate SAC activity, along with simultaneously provided audiovisual feedback. The explanation comes from previous research results [59, 60]: Reed et al. reported that SAC activation was observed when subjects performed tactile object recognition, and Yu et al. reported SAC was activated when movement-related multisensory feedback was provided. Finally, it is thought that significant brain activity was observed in PFC since the proposed hand rehabilitation system successfully induced user engagement. As an integrated hub for receiving and processing motivational and attentional information [61], it helps to voluntarily allocate attention to specific features, objects or spatial areas, and in our case, the content in the VR rhythm games [62].

As to the Group-level HRF time course of the healthy group, an increase in HbO and a decrease in HbR, the typical patterns of response to stimuli, were observed during the VR-based hand rehabilitation for all ROIs in Fig. 5. An increase in HbO means an increase in blood inflow from the artery to the activated area, and a concomitant decrease in HbR means an increase in oxygen metabolism [63]. Our findings are in line with previous studies in which the hand rehabilitation task is associated with an increase in cerebral blood flow and brain oxygenation [64].

For the individual HRF time course of the stroke survivor, the same phenomenon was observed in the bilateral SM1, right PFC, left SAC, and left PMC&SMA, as shown in Fig. 6. On the other hand, in the right SAC, HbO decreased shortly after the beginning of the task, and then returned to the baseline level and increased. Our observation of decreases in HbO in the right SAC may be caused by pathophysiological and anatomical changes in the brain after stroke [65]. In the right SAC, which can be assumed to be a degenerative brain region, there may be an insufficient increase in regional cerebral blood flow associated with a reduction of HbO during the VR-based hand rehabilitation for the sake of other brain regions [45].
There are two additional remarks worth mentioning. First, there was a difference in the interpretation of activation between the results of significantly activated channels and those of the cortical activation map. Specifically, there was no significantly activated channel in the left PMC&SMA and left PFC, however, the cortical activation maps showed an increase in HbO response for those areas. The reason for this discrepancy is considered to be high subject variability resulting in wider confidence intervals, as shown in Fig. 5. Second, both HbO and HbR tended to increase in the left PFC and right PMC&SMA of the stroke survivor, as shown in Fig. 6. A possible explanation for this phenomenon is an increase in oxygen supply due to increasing HbO and oxygen consumption due to increasing HbR, which is considered to have occurred at the same time [66]. As a further explanation for the increased HbO and HbR in the left PFC, our result is in line with the previous study that reported that a similar phenomenon occurred when performing a high cognitive task with sustained attention [67].

Although it was possible to develop an immersive hand rehabilitation system and confirm its effectiveness through the validation of brain activation, the present study is limited by the small number of participants included and the limited power of the study. In the future, a clinical intervention study should be conducted to verify the effect of the proposed system on the functional restoration of stroke survivors. Moreover, subject-specific target gestures should be applied to stroke survivors with limited hand conditions, such as range of motion and degree of stiffness for stroke survivors.

5. Conclusions

We developed a hand rehabilitation system with a VR rhythm game that can be controlled by hand gestures and provides vibrotactile feedback. Our experimental results demonstrated that our system successfully activates brain areas associated with motor execution, motor planning, attention, and multisensory feedback. This approach is especially suitable for subject-specific hand rehabilitation because various types of target gestures can be set, based on one’s hand condition. In addition, it allows repetitive training flexibility, with higher intensity and immersion by adjusting the game difficulty, such as the frequency of target appearance, changing the rhythm according to various music, and the hand recognition threshold. Such adjustments can be based on the user's current condition, and are important to increase the volitional drive of the stroke survivor to accomplish the task. The presented system is extensible to other parts of the upper limb, such as the wrist, elbow, and shoulder. In addition, the system is a potentially useful tool for teaching proficient hand skills for various purposes in other areas.

Declarations

Ethics approval and consent to participate

This study involving human participants was reviewed by the institutional review boards of the Korea Advanced Institute of Science and Technology (approval code: KH-2022-001). All participants provided written informed consent to participate in this study. The experiment was conducted in accordance with the latest Declaration of Helsinki.
Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

Not applicable.

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Authors’ contribution

SB and H-SP conceived the study design. SB developed the VR-based hand rehabilitation system used in this study. SB carried out the experiment to identify the cortical activation during VR-based hand rehabilitation task by using functional near-infrared spectroscopy (fNIRS). SB conducted analysis of fNIRS data. SB drafted the manuscript with inputs from all other authors. H-SP contributed to the critical revision of the manuscript. HS-P supervised the data analysis and statistical analysis. H-SP supervised the study overall.

References


60. Yu, H., Q. Li, and H. Sun. *A task-irrelevant sound modulates the effects of simultaneous visual cue on visual discrimination: An fMRI study*. IEEE.


**Figures**
Figure 1

**Hand rehabilitation system.** (a) The configuration of the system. Participants wear a VR HMD and fNIRS cap on their head and vibrotactors on the volar side of both wrists. Four hand-tracking cameras built into the VR HMD recognize the participant’s hand gestures. (b) VR scenes shown to the player when playing the VR rhythm game. From the target generator, a target gesture of each hand is created and approaches the player’s hand. The player is required to match the gesture of their hand to the approaching target. (c) The process of matching gestures. When the player makes a proper gesture toward the approaching target, the color of the player’s hand changes to the same color as the target, and the target explodes in the event of a collision.
Figure 2

Gesture recognition method. There are three gestures to be recognized, and each gesture can be classified using 22 3D distances ($DIST$) between the hand point and the reference point. Before starting gesture recognition, the three gestures and corresponding $DIST$ between the $i$-th hand point and the reference point of the player are pre-recorded. During gesture recognition, if the difference between the $DIST$ of the current gesture and that of the pre-recorded gesture is less than a certain threshold value for all hand points, the gesture is recognized and the color of the player’s hand is changed.
Figure 3

**fNIRS optodes and channel configuration.** (a) Thirty-two fNIRS optodes (16 detectors and 16 sources) that formed 51 channels were used to cover 5 Regions of interest (ROI): the prefrontal cortex (PFC), the premotor cortex & the supplementary motor area (PMC&SMA), the primary sensorimotor cortex (SM1), and the somatosensory association cortex (SAC). The placement of each optode was based on the anatomical landmark location of the international 10-20 systems. (b) The 3D schematic images depicting the position of the optodes in the head scalp. Columns from left to right: lateral view of the left hemisphere, superior view, lateral view of the right hemisphere. (c) Schematic representation of the protocol. The experiment consisted of 12 tasks and 13 rests based on the block design paradigm. The duration of rest and task blocks is 20 seconds. A: anterior, P: posterior, L: left, R: right
Figure 4

HbO cortical activation map of the brain surface during the VR-based hand rehabilitation task. (a) Group mean HbO map of the healthy group. (b) Individual HbO map of 1 stroke survivor. Each reconstructed image is averaged over the time course from 5 sec to 15 sec. An increased HbO response is highlighted in red while a decreased HbO response is highlighted in blue. The color bar indicates the scale of the concentration change in micromol/L. Red dots are source optodes, and blue dots are detector optodes. A: anterior, P: posterior, L: left, R: right
Figure 5

**Group-level HRF time course of oxy and deoxy hemoglobin changes** (red and blue respectively) **of the healthy group during VR-based hand rehabilitation.** Four ROIs (PFC, PMC&SMA, SM1, and SAC) are divided into two hemispheres, and the HRF time course is averaged for the channels contained in each ROI. The shaded areas show 95% confidence bands. A: anterior, P: posterior, L: left, R: right

Figure 6

**The HRF time course of oxy and deoxy hemoglobin changes** (red and blue respectively) **of the stroke survivor.** Four ROIs (PFC, PMC&SMA, SM1, and SAC) are divided into two hemispheres, and the HRF time course is averaged for the channels contained in each ROI. A: anterior, P: posterior, L: left, R: right