Development of virtual reality proprioceptive rehabilitation system for stroke patients

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A R T I C L E   I N F O

Article history:
Received 14 May 2013
Received in revised form 8 September 2013
Accepted 10 September 2013

Keywords:
Proprioception feedback
Computer based rehabilitation
Virtual Reality
Stroke
upper-extremity limb

A B S T R A C T

In this study, the virtual reality (VR) proprioception rehabilitation system was developed for stroke patients to use proprioception feedback in upper limb rehabilitation by blocking visual feedback. To evaluate its therapeutic effect, 10 stroke patients (onset > 3 month) trained proprioception feedback rehabilitation for one week and visual feedback rehabilitation for another week in random order. Proprioception functions were checked before, a week after, and at the end of training. The results show the click count, error distance and total error distance among proprioception evaluation factors were significantly reduced after proprioception feedback training compared to visual feedback training (respectively, \( p<0.005 \), \( p<0.001 \), and \( p<0.007 \)). In addition, subjects were significantly improved in conventional behavioral tests after training. In conclusion, we showed the effectiveness and possible use of the VR to recover the proprioception of stroke patients.

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1. Introduction

Rehabilitation training is essential for most stroke patients who have symptoms such as declined or abnormal motor control due to brain damage [1]. Generally, the elements needed for normal physical activities are motor control modulating movement in real time as well as strength. Motor control amends the motion by interaction between visual feedback that recognizes the external space or movement of oneself through vision and proprioception feedback that refers information about movement and position of body, which transverse from muscle spindles into central nervous system [2–4]. Stroke patients have difficulty in conducting exact motor control due to declined strength as well as ability to utilize feedback [5]. In particular, stroke patients showed lower accuracy of motor control compared to healthy individuals in situations without visual feedback of movement rather than with visual feedback [6,7]. In spite of these previous studies conventional rehabilitation therapy have mainly focused on strength exercise with occupational therapists support and motor control training using external stimuli with robotic or functional electrical stimulation [8,9]. Moreover, it was reported that the training effect of stroke patients could be reduced by reliance of visual feedback of their movement during training because...
the vision of patient were intact rather than proprioception [10,11].

Proprioception is evaluated by tests which measure a subject’s ability to detect an externally imposed passive movement, or the ability to reposition a joint to a predetermined position [5]. In order to improve proprioception, sensorimotor training programs have been suggested to facilitate joint position sense and dynamic joint stability using rhythmic active motion, angle repositioning and standing on an air cushion with support to stimulate muscular co-activation [12,13]. Despite recently shedding a light on the proprioception in rehabilitation, there are few studies related to rehabilitation systems focusing on the improvement of proprioception itself [14,15].

The virtual reality (VR) technique can provide various virtual environments and has been used in rehabilitation therapy that provides interaction between virtual objects and motion using motion tracking [16-22]. This technique would be more suitable for the proprioception rehabilitation because of its ability to manipulate the visual feedback of virtual objects [23]. In addition, the VR technique allows an objective assessment as well as efficient rehabilitation training because a patient can confirm his own movement without the assistance of a therapist and also view the training results in near real time.

In this study, we developed a VR proprioceptive rehabilitation system that could manipulate the visual feedback during upper-limb training and ask the subject to rely only on proprioception feedback. We also demonstrated the effect of proprioception training on stroke patients using a developed VR system that provides proprioception feedback.

2. Methods and materials

2.1. Subjects

In order to evaluate the developed proprioception feedback virtual environment system, we recruited 10 stroke patients (age: 54.7 ± 7.83 years, onset: 3.29 ± 3.83 years) as shown in Table 1 and 10 healthy age-matched subjects (age: 56.4 ± 4.53 years). The stroke patients; (1) who had suffered a primary ischemic or hemorrhagic stroke as diagnosed by magnetic resonance imaging image scans or computed tomography; (2) presented mild to severe paresis of the upper extremity and lacked any additional neurological disease causing motor deficits; (3) can perform the active flexion of affected elbow more than 50°; (4) who was in more than 10 weeks from stroke onset because most motor recovery is almost completed within 10 weeks poststroke [24,25]; (5) showed no deficits in visual field by visual field examination; (6) showed no severe defects in cognitive function with a Mini-Mental Status Examination score [26] >24; (7) showed no neglect by Albert test [27] or apraxia [28]; (8) showed no serious depression by the Beck Depression Inventory test [29]; (9) had no pain and dysfunction of upper extremity by peripheral neuropathy, a rotator cuff tear of shoulder and complex regional pain syndrome; and (10) A summary of demographic variables and clinical measure for the stroke group is included in Table 1. Most patients had low BDI scores (9–28). All subjects that consented to participate in this study were informed about the experimental protocol,
which was approved by the Department of Rehabilitation of Eulji Hospital. Healthy subjects had no history of neurological diseases.

2.2. VR proprioception rehabilitation system

The virtual environment was designed to switch visual feedback on/off during upper-limb training. The subjects’ arms will be positioned below an upper board to be out of view as shown in Fig. 1. The affected hand positions were tracked with a magnetic 3D position sensor (patriot 6-DOF tracker, POLHEMUS, USA). On screen, a virtual cylinder moved according to the position of the subject’s hand under the board. With the other hand, a button was installed for the subject to respond to designed tasks. VR tasks were programmed with 3D Game Studio (Conitec Datasystems Corp., Germany).

2.3. VR proprioception rehabilitation tasks

Two types of VR training tasks were designed to evaluate the effect of the proprioceptive focused training compared to visual feedback focused training. The VR environment was designed like a living room environment which patients were accustomed. And the cylinder was used as a waste box in the room in order to enhance the skill of daily life. In the visual feedback virtual environment (VFVE) task, there is a semi-transparent cylinder showing the present position of the affected hand and opaque cylinder as the target position as shown in Fig. 2a. The subjects were asked to move their affected hand into the position of the opaque cylinder. The subjects could see the semitransparent cylinder moving according to their arm’s movement as a visual feedback. The subjects pressed the mouse button when they believed the affected hand position corresponded to the target position. If the distance between the affected hand position and target position were within a predefined criterion, the opaque cylinder would reappear. If they failed, repeated the process till they succeeded. On the contrary, in the proprioception feedback virtual environment (PFVE) task, both semi-transparent and opaque cylinders are shown at staring point but the transparent cylinder disappears as soon as they start to move their hand into target position. Thus, they have to estimate the current position and get to the target position by relying on their own proprioceptive feedback information. Similar to VFVE, the subjects pressed the mouse button when they believed they reached the target position. If they failed, the semi-transparent cylinder will be shown for 500 ms for the subjects to check the current hand position and continue till they reached the target position. In both environments, twenty target positions were provided. For performance analysis, the total number of trials was counted during twenty target tasks, which was the total number of mouse button clicks. In addition, error distance measured the distance between target position and affected hand position when subjects pressed initial-button. Total error distance was calculated by accumulating error distance every time the subjects pressed the mouse button as confirmation. Lastly, movement distance was measured from start position to affected hand position moved initially. The total movement distance was measured by summing the total movement distance from start position until the affected hand reached the target position successfully.

2.4. Experiments

2.4.1. Evaluation of characteristics of proprioception feedback virtual environment

In order to evaluate whether parameters measured in PFVE are related with proprioception function, all stroke patients subjects performed the PFVE task as well as an elbow angle assessment task previously developed for the assessment of proprioception function [23]. All parameters from PFVE were compared with error angle from angle assessment task, which has a close relationship with proprioception function [23,30]. In addition, occupational therapist measured the upper extremity FMS (Fugl-Meyer Assessment Scale) [31] and Box and Block test [32], Jebsen-Taylor Hand Function test [33] to measure the upper extremity function in stroke patients. Healthy subjects only performed the PFVE task in order to compare with the behavioral characteristics of stroke patients.

2.4.2. Evaluation of the therapeutic effects of proprioception feedback virtual environment

Ten stroke patients participated in the experiment for evaluation of the effects of proprioception feedback virtual environment training. They were randomly assigned into two groups (five patients per group) in order to randomized the order of training. One group performed VFVE five times during the first week. Then, the week after, the group did PFVE training five times. The other group performed the tasks in reverse order. All patients performed the VFVE task and PFVE task three times in order to check the improvement of proprioception function. The Box and Block test and Jebsen-Taylor
hand function test was conducted with PFVE before and after training.

2.5. Data analysis

The Pearson’s correlation has been used to compare between FMS score or error angle and parameters measured in PFVE using the SPSSWIN 18.0 software package. In addition, the independent t-test has been used to compare the behavioral characteristics between stroke patients and healthy control from PFVE. The repeated ANOVA and one sample T-test have been used in order to compare the training effects between VFVE and PFVE.

3. Results

3.1. Characteristics of proprioception feedback virtual environment

Comparison between an elbow angle assessment task and PFVE, is shown in Table 2. The error angle from the elbow angle assessment task had a significant relationship with the error distance ($r = .640, n = 10, p = .046$) and total movement distance ($r = .751, n = 10, p = .012$). Whereas in PFVE, it had no correlation with movement distance, click count or the total error distance. The two parameters (error distance and total movement distance) also significantly correlated with FMS score reflecting the severity of stroke, respectively $r = -.662, p = .037$ and $r = -.726, p = .018$. In addition, FMS score correlated with total error distance $(r = -.714, p = .002)$ and click count $(r = -.659, p = .038)$ but not with movement distance among the parameters measured in PFVE.

The comparison between stroke patients and healthy control subjects in PFVE shown in Table 3 below shows that the total movement distance of stroke patients increased significantly compared to healthy control group ($t = 1.87, p = 0.044$). Additionally, movement distance in stroke patient group increased compared to the healthy control group ($t = 1.818, p = 0.043$). However, the click count, error distance and total error distance of stroke patients did not significantly increase compared to the healthy control, click count of stroke patients showed an increase pattern rather than healthy control ($t = 1.488, p = 0.077$).

3.2. Therapeutic effect of proprioception feedback virtual environment rehabilitation

In order to evaluate the therapeutic effect of PFVE, we compared VFVE and PFVE after training stroke patients for two

<table>
<thead>
<tr>
<th>Table 2 – The correlation between two assessments (elbow angle assessment, FMS) and parameters from proprioception feedback virtual environment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error angle</td>
</tr>
<tr>
<td>-------------</td>
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<tr>
<td>Error distance (r/p-value)</td>
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<tr>
<td>Error angle</td>
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<tr>
<td>FMS score</td>
</tr>
</tbody>
</table>

* p < 0.05.
Table 3 – Comparison of behavioral characteristics between stroke patients and healthy control in proprioception feedback virtual environment.

<table>
<thead>
<tr>
<th></th>
<th>Stroke patients affected (N = 10)</th>
<th>Healthy control affected-cor (N = 10)</th>
<th>t</th>
<th>p-Value (1-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Click count (number)</td>
<td>3.34 ± 1.31</td>
<td>2.58 ± 0.95</td>
<td>1.488</td>
<td>0.077</td>
</tr>
<tr>
<td>Error distance (cm)</td>
<td>10.58 ± 3.48</td>
<td>9.02 ± 2.06</td>
<td>1.214</td>
<td>0.120</td>
</tr>
<tr>
<td>Movement distance (cm)</td>
<td>42.20 ± 9.08</td>
<td>36.53 ± 3.82</td>
<td>1.818</td>
<td>0.043</td>
</tr>
<tr>
<td>Total error distance (cm)</td>
<td>27.32 ± 15.29</td>
<td>18.75 ± 10.12</td>
<td>1.477</td>
<td>0.078</td>
</tr>
<tr>
<td>Total movement distance (cm)</td>
<td>64.89 ± 32.41</td>
<td>44.43 ± 8.44</td>
<td>1.878</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Affected, affected upper extremity of stroke; Affected-cor, corresponding upper extremity of age-matched control.

* p < 0.05.

weeks with 2 × 2 ANOVA analysis with two factors (pre-post and feedback methods). Because total sample size is only ten, a normality of the data was assessed and confirmed for a parametric statistical analysis using the Kolmogorov-Smirnov test. As shown in the Fig. 3(a), the error distance in FFVE significantly decreased in post-training rather than pre-training (F(1,9) = 25.194, p = 0.001). In addition, there was a significant interaction between two factors (F(1,9) = 9.924, p = 0.012). Comparing the training effects between a virtual environment with visual feedback and with proprioception, the click count, error distance and total error distance were reduced more after training in FFVE than VFVE. (Click count: p = 0.005, error distance: p = 0.001, total error distance: p = 0.007.)

3.3 Improvement of upper-limb function of stroke patients

Therapeutic effect of the VR program was proven with conventional behavioral tests (Box and Block test, Jebsen-Taylor Hand Function test). As shown in Fig. 4a, upper-limb function of stroke patients in the Box and Block test showed improvement pattern after training (n = 10, t = −2.05, p = 0.071). Because two patients had difficulty grasping a block with an affected hand (very low Box and Block test scores were shown in Fig. 4a), re-analysis was performed with eight stroke patients excluding the two. With this adjustment, Box and Block scores were significantly improved after VR training (n = 8, t = −3.567, p = 0.009). On the other hand, the unaffected hand of stroke patients did not show improvement pattern after training (n = 10, t = 0.525, p = 0.613).

Seven stroke patients completed the Jebsen-Taylor hand function test. Because two patients could not write with the affected hand and one patient did not do the post-test, three patients’ data were omitted. As shown in Fig. 4b, affected hand function of stroke patients by writing subtest of Jebsen-Taylor test improved after training (n = 7, t = 2.508, p = 0.046). On the other hand, unaffected hand of stroke patients didn’t (n = 7, t = −1.442, p = 0.199). Other tests of Jebsen-Taylor also did not improve.

Fig. 3 – Improvement effect of upper-limb of stroke patient in two different virtual environments (*: p < 0.05, **: p < 0.01) (a) Error distance decreased more in FFVE training than VFVE training (p = 0.001), (b) comparison of reduced click count between VFVE and PFVE (p = 0.005), (c) comparison of reduced error distance between VFVE and PFVE (p = 0.001), (d) comparison of reduced total movement distance between VFVE and PFVE (p = 0.007).
4. Discussion

In this study, we developed a new type of rehabilitation system that focuses on the proprioception of stroke patients using the VR technology. The developed VR system was proven to improve the motor control of stroke patients after VR proprioception feedback training.

One of the important features of the developed system is the use of proprioceptive feedback for upper limb rehabilitation by blocking visual feedback. VR proprioceptive paradigm is novel because this type of exercise system cannot be provided easily in a real environment. In order to perform a motor task, the central nervous system integrates multiple modes of sensory information, especially vision and proprioception of a healthy individual [2,34,35]. However, the multiple sensory information integration could be changed in the patient with the impairment of somatosensory information integration after stroke, whereas stroke patients can use intact visual information rather than somatosensory. Stroke patients tend to excessively rely on visual input in motor task [11]. Bonan et al. suggested that visual influence is known to become predominant when afferent input from other sources is reduced and the predominant influence of visual input constitutes a natural compensatory strategy for coping with initial stroke damage [10,11]. Traditional rehabilitation reinforces the excessive visual reliance by focusing on visual compensation rather than restoring sensory inputs that would have been normally used. Therefore, the control of visual information such as blocking visual feedback could play an important role in forcing patients to rely more on proprioception and learn movement efficiently. In addition, previous work has shown that subjects do not rely on visual feedback for learning novel movement [33,36–39]. Even congenitally blind individuals are

![Box & block test](image1)

**Fig. 4** Evaluation of improvement of upper-limb functions (**p < 0.01**). (a) Box and Block scores improved significantly after VR training (**p = 0.009**). Two stroke patients were omitted because their occupational therapists reported have trouble grasping the block with the affected hand. (b) Writing performance time of Jebsen-Taylor Hand Function test were significantly reduced after VR training (**p = 0.046**).
able to adapt to the perturbing effects of a force field produced by a rotated room.

In our results, the significant decrease of error distance and the total error distance shown after just proprioception feedback rehabilitation training, suggests that the proprioception feedback rather than visual feedback could be an effective means to enhance motor control during rehabilitation training [40]. It could be explained by the fact that cortical excitability increase in the condition without visual feedback rather than with visual feedback in our previous study [41]. To our knowledge, there are few rehabilitation systems that focus on enhancing proprioception itself in stroke patients by blocking view of arm movements. Jun et al. demonstrated the effect of proprioception feedback training without visual feedback in stroke patients [42].

One of the other advantages in the developed VR rehabilitation training is the ability to evaluate proprioception function of stroke patients as well as training itself. In order to prove this, it was compared to a previously developed upper extremity proprioceptive assessment system, which include angles assessment task which is necessary to match imposed joint positions without visual feedback to check for angle error [23]. Among all other parameters objective parameters for evaluating the proprioceptive assessment in PFVE, total movement distance had a significant relationship with error angle obtained from previous elbow angle assessment task as shown in Table 3. Most of all it significantly correlated with the FMS score (Table 2) and had higher value compared to healthy subjects (Table 3). Moreover, previous study verified the significant differences of click count and error distance between affected upper extremity of stroke group and control group in large group (n = 30) [30]. Stroke patients tend to take couple tries to reach to the target due to the damage of proprioception (the number of trials, p = 0.07) and this lead to the total movement distance and error distance which were accumulated. This explains why it could be sensitive to the functionality of the upper limb and could be used as an index parameter to evaluate proprioception of stroke patients.

Despite the results showing the improvement of proprioception function after PFVE training, careful consideration should be taken in interpretation because the PFVE was used as an evaluation tool after training session. There is a possibility that subjects became accustomed to the PFVE and knew how to adjust their arm to target without visual feedback to get a high score. A therapeutic effect was also demonstrated in the conventional behavioral tests (Box and Block test, Jebsen-Taylor test) before and after training as shown in Fig. 4, although two patients were excluded in the statistical analysis because they were not able to perform the conventional behavioral tests (Box and Block test, Jebsen-Taylor test). This corresponded to the previous study that showed improvements after rehabilitation training with sensory feedback using a VR system, even in stages [43–45].

An insufficient number of subjects and the heterogeneity of the lesions, onset time, manual dexterity, functional level may represent the limitations of our study. We did try to minimize the large variability effect due to individual difference including motor recovery influence in the experimental condition and analysis method by performing the experiment in short period, recruiting the patients who are in almost completed motor recovery. In addition, significant differences were not consistently found between stroke and age-matched control group for the major proprioceptive indices due to insufficient number of subjects. Furthermore, it is hard to generalize the efficacy of PFVE training in stroke patients because there is no comparison study with conventional rehabilitation therapeutic methods. In future investigations, clinical studies examining the effectiveness of the proprioceptive VR rehabilitation program according to various stroke subgroups, systemic experimental design, and training duration should be considered, and a method that enhances the effect via integration with other treatment methods, such as robot therapy and the various feedback paradigms, should be developed.

Conflicts of interest

None.

Acknowledgements

This work was supported by the National Research Foundation of Korea Grant funded by the Korean Government (NRF-220-2008-D00112).

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