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FULL PAPER

Development of VR platform for cloud-based neurorehabilitation and its application to research on sense of agency and ownership

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ABSTRACT

Recently, neurorehabilitation that uses virtual reality systems is being applied in clinical settings to deal with issues such as phantom limb pain (PLP) as an alternative to mirror box therapy. One of the weak points of mirror box therapy is that the desired analgesia effect might not be confirmed in some patients. One hypothesis to explain this phenomenon is that the subjective sense of the length of a phantom limb is different from that of an intact limb. Since the gap between body representation in the brain and actual sensory feedback is considered one of the causes of PLP, different lengths of a subjective phantom limb are a serious problem for mirror box therapy and similar VR-based rehabilitation methods. We are thus developing a VR system that displays an avatar that has the same length as the subjective phantom limb. The purpose of the current study is to determine the feasibility of the VR system – specifically, whether it has enough effect on sense of agency (SoA) and sense of ownership (SoO) for healthy subjects – before conducting experiments for actual phantom limb patients. To this end, we developed a VR system in which a virtual avatar performs a motion identical to that of the subject by means of a motion capturing device (Kinect V2). The subject wears a 3D head mounted display (Oculus Rift DK2) to experience seeing through the eyes of the avatar. Six conditions of avatar representation were used: two appearances of a normal human arm and a robot arm and three lengths of the arm (short, medium, and long). The subject executes elbow flexion-extension movement of the right arm, which causes the same movement in the VR avatar's arm. After the induction movement, the subjective sense of the length of the right arm is measured by a pointing gesture of the left hand. Twelve subjects participated in this experiment. Results showed that the subjective length of the arm was changed according to the length of the displayed arm in the VR environment. From the results of a questionnaire, we found that there is no negative effect on SoA. SoO when the subjects watch the natural human avatar is stronger than when the robot arm is shown. These results are positive, thus confirming the basic potential of the proposed VR system. In conclusion, the change of self-body appearance of a VR avatar has enough effect on subjective sense of arm length. Since the subjective sense of arm length is strongly related to body representation in the brain, we believe that the system can be a platform for research on embodied-brain science systems.

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Virtual reality; neurorehabilitation; cloud computing; sense of agency; sense of ownership

1. Introduction

Visual information is increasingly being used in rehabilitation for motor impairment and sensory deficit after damage to the central and peripheral nervous system. One of the targets of such applications is a symptom known as phantom limb pain (PLP), which generates the illusional feeling of a missing limb after amputation and is often accompanied by pain in the area that the limb used to be. The most well known and effective therapy for PLP is mirror box therapy [1,2], whereby patients attempt to control their phantom limb in accordance with a mirror image of the intact limb. Another therapy for PLP is imitation therapy [3], where patients attempt to manipulate their phantom limb to follow a movement given by a real or computer graphics movie of the intact limb. If the patients succeed in controlling the phantom limb by imitating the movements in the movie or in the mirror, PLP can be relieved. Hemiplegia is another common rehabilitation target of virtual reality systems. One of the therapies for hemiplegia uses virtual images that are controlled by movements of the paralyzed limbs that can be modified in accordance with the status of the symptom. Since these therapies often use virtual reality systems [4,5] featuring the application of head mounted displays, sensor groves [6], myoelectric sensors [7], and so on, the relationship between computer graphics and virtual reality technologies has been gaining attention [1,8].

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One of the problems with such therapies is that the concrete mechanism behind the therapies has not been fully explained. For example, mirror therapy and imitation therapy have larger individual differences of the analgesia effect among the patients. One reason for this is the telescoping phenomenon, whereby the phantom limb becomes shorter than the original length of the limb and the intact one. Since mirror therapy corrects the mismatch, considered to be the cause of PLP, between body representation in the brain and actual body by providing the vision of the intact limb as visual feedback of the amputated one, the telescoping leading to different lengths of the phantom limb is a serious problem for mirror therapy and similar VR-based rehabilitation methods. In the case of rehabilitation for hemiplegia, a detailed strategy in terms of what kinds of movement/visual stimulus should be shown to patients is difficult to be explained. In fact, individual strategies for each patient are typically considered and designed by physical therapists in each clinical field, which results in a further lack of uniformity or clarity.

If we can identify the mechanism behind a therapy and design an algorithm to determine the appropriate movement of the virtual limbs, the situation of the clinical setting will be improved. However, a major barrier to this goal is the huge cost involved in collecting the paired data of the reaction of patients and the movement of virtual limbs given to the patients. Therefore, we propose a cloud-based immersive virtual reality system that enables us to amass a huge clinical database for neurorehabilitation.

So far, several cloud-based rehabilitation systems have been proposed. For example, Tsuji et al. [9] proposed a motion database system for cloud-based rehabilitation. Okada et al. [10] proposed a home rehabilitation system for Parkinson's disease using Kinect, an easy motion capture system. We feel that such home rehabilitation systems using cloud computing will form the basis of rehabilitation systems in the next generation. In the current study, we focus on sense of agency (SoA) and sense of ownership (SoO) as the initial verification targets toward the realization of neurorehabilitation systems. SoA is the subjective awareness that one is initiating, executing, and controlling one's own volitional actions. SoO is the pre-reflective awareness or implicit sense that one is the owner of a movement. Both of the keywords are essential issues to understand perception and motion planning mechanism in the brain [11]. Since abnormal SoA and SoO often arise for PLP and hemiplegia, neurorehabilitation systems have to preclude the negative effect of SoA and SoO. Especially, one of our future challenges is to ensure a flexible length of an avatar's arm for PLP rehabilitation in order to fill any gap between the length of a phantom limb and an intact limb. If the movement of an avatar that has a modified length of arm has a negative influence on SoA and SoO, the challenge will be difficult to overcome. Therefore, we determine the feasibility of the VR system – specifically, whether it has enough of a positive effect on the subjective sense of body (such as SoA and SoO) for healthy subjects, when the same subjective length of the phantom limb is shown – before conducting experiments for actual phantom limb patients.

In this paper, we propose a cloud-based VR platform for neurorehabilitation that can collect 'big-data' for neurorehabilitation and research on body representation in the brain. The purpose of this study is to determine the feasibility of the immersive VR system, specifically, whether the VR system has enough effect on SoA and SoO for healthy subjects, before conducting experiments for actual phantom limb patients. In Section 2, the basis of our VR-based neurorehabilitation system and the evaluation method are introduced. The results are given in Section 3. We discuss the results and future works in Section 4, and conclude with a brief summary in Section 5.

2. Method

2.1. Cloud-based virtual reality system

Recently, virtual reality systems have become common tools for a variety of research and applications. However, almost all virtual reality systems are working as stand-alone systems that are not connected to each other through the Internet. With respect to developing applications for rehabilitation, many systems have already been proposed [12–14], but these are also stand-alone systems that use exclusive and expensive devices such as sensor groves, motion capture systems, and so on. Thus, patients have to go to a hospital or laboratory to use them, which can create a bottleneck in the case of popular VR-based rehabilitation methods. If a VR-based rehabilitation system could be developed that uses cheap and simple devices, everyone would be able to use it at home. Additionally, if this system were connected to a cloud system, rehabilitation procedures could be managed from a server operated by therapists or artificial planning systems using feedback from the rehabilitation results. We choose the SIGVerse system [15] to establish such a cloud-based virtual reality system for neurorehabilitation.

SIGVerse was originally developed as a cloud-based simulator for human–robot interaction research. Users can 'login' to a personal avatar through an immersive user interface such as a head mounted display or motion

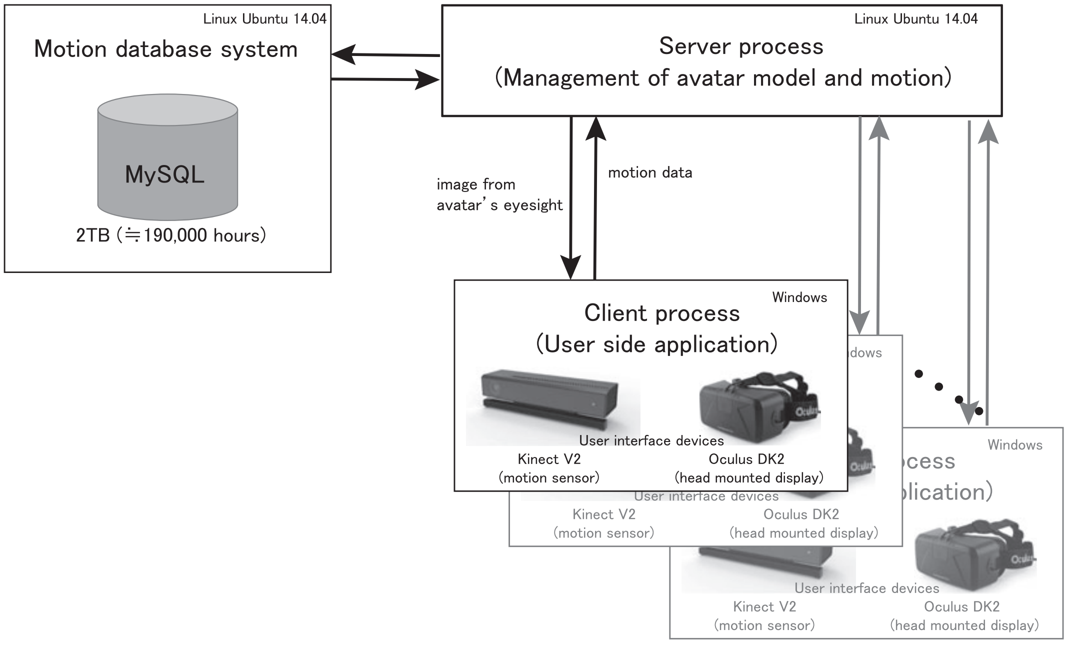

Figure 1. System configuration of the cloud-based virtual reality system with motion database.

capture system and then interact with robots [16]. An overview of the SIGVerse system is shown in Figure 1. This system consists of server and client processes. The status of environments and a patient avatar in the VR environment are controlled in the server process, which has connection ports to accept connection requests from arbitrary client processes. In the client process, the motion capture system and head-mounted display function as user interface devices. Motion capture systems measure the motion of real patients and send the motion data to the server process. A view from the avatar's eyesight is generated in the VR environment and is then shown in the head mounted display worn by the patients. Since the server process manages connection requests from any client, this system easily collects the reaction motion of multiple patients in the clinical field of rehabilitation. The collected motion data are stored in a database on another server.

2.2. Cloud-based sensorimotor database system

As a first prototype system, we developed a cloud-based motion database for imitation therapy in the rehabilitation of PLP. In imitation therapy, the relationship between target movements shown to a patient and response movements by the patient are useful details to design the rehabilitation program. For example, if the response movement is too slow compared with the target movement, the target movement should be slower at the next trial, since the patient could not follow the target. In contrast, if the response movement is almost identical to the target movement, the therapist can confirm that the patient has sufficient capability to follow the target movement. This database system deals with both the target and response movements in imitation therapy. Since the database system is connected to the VR platform, which has motion capture devices, it is easy to collect both of the movements. Additionally, since the system is already working on a server (OS: Linux Ubuntu 14.04) with the MySQL database server, everyone can access the database through the Internet. Maximum length of the recordable motion is about 190,000 h (810 days), and improvement of HDD will enable the database capacity to become even larger.

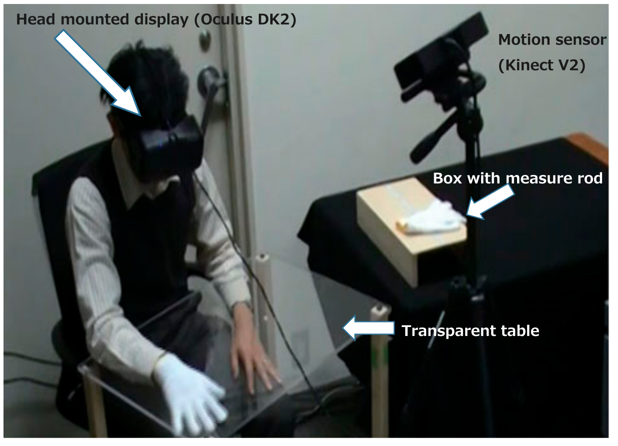

Figure 2. Overview of the experiment setup.

The database system also has a pattern search function whereby similar patterns can be extracted as a searching result with an input key pattern. Users can input an

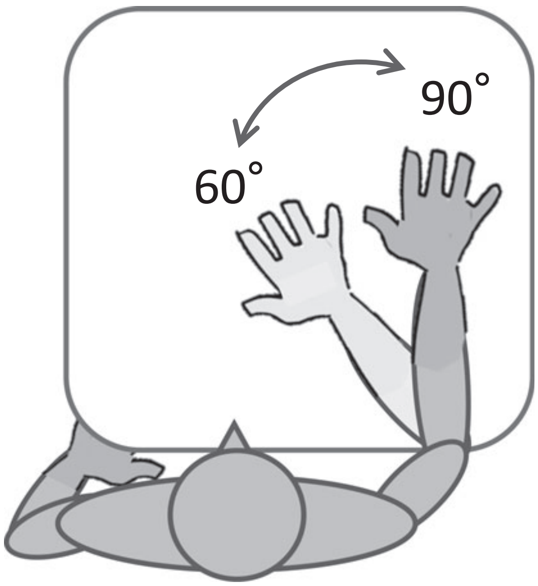

Figure 3. Requested movement for subjects.

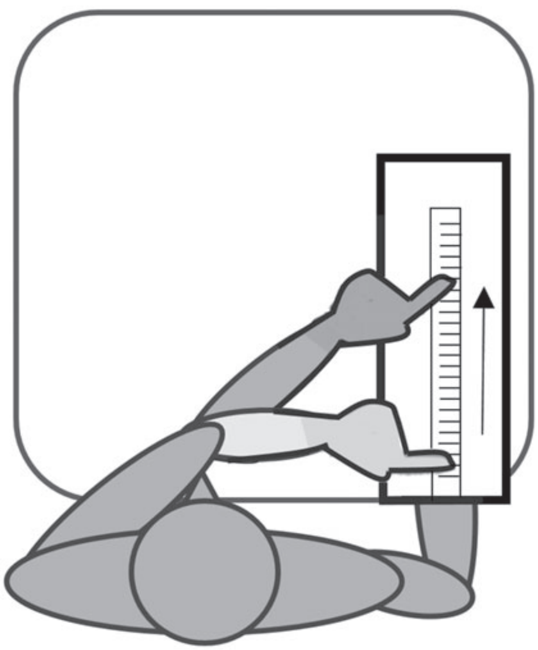

Figure 4. Measurement of sense of self for hand position.

arbitrary length of pattern data and choose a searching algorithm from a hidden Markov model (HMM) or dynamics time warping (DTW) depending on the type of application. The search result is stored in the database server with the results, which enables the system to respond to a similar query faster the next time.

Tsuji et al. proposed a motion database for rehabilitation application, but their target signal is focused on movement data and force signal. In contrast, our system has the flexibility to record not only motion data but

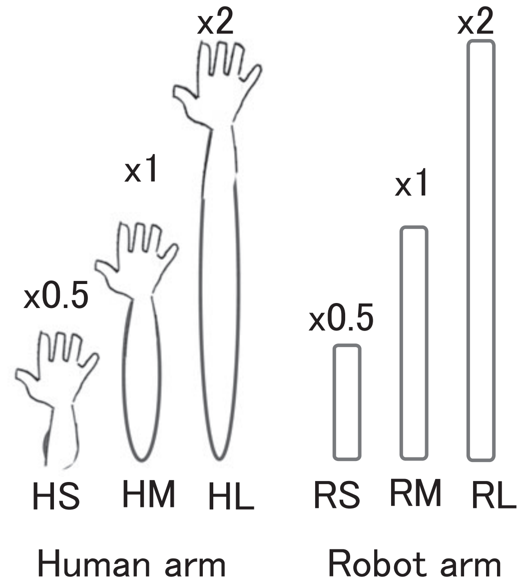

Figure 5. Six conditions of hand appearance in a virtual reality.

also arbitrary biological signals such as pulse rate and EMG. This flexibility means it can be applied to several rehabilitation applications and a future challenge on constructing computational models of body representation in the brain [17].

2.3. Participants and experimental paradigm

The subjects ($n = 12$; 8 males and 4 females, 30.1 ± 9.2 years old) took part in the experiment. Ten of them were right-handed ($+80 < L.Q < +100, 92.0 \pm 8.7$) and two of them were left-handed ($L.Q$ was -40 and -60, respectively) according to the Edinburgh Inventory [18]. All subjects provided written informed consent before the experiment. Experiments had the approval of the ethics committee of the National Institute of Informatics and were performed in accordance with the Helsinki Protocol.

In the experiment, subjects wear an HMD (Oculus Rift DK2) to login to an avatar in a virtual reality environment as shown in Figure 2. Movement of the subject is measured by a motion capture device (Kinect V2) and the motion data is sent to the virtual avatar. The requested movement for subjects is a back-and-forth movement (elbow flexion-extension) of the right hand to follow the two marks shown in Figure 3. Velocity of the hand movement is controlled by the sound of a metronome set to one elbow flexion-extension movement every four seconds. The elbow is put on a fixed point on the table to ensure that the degree of freedom of the subject's movement is just one.

Before the movement, the image of the HMD is turned off to avoid the subject viewing any visual information. During the turned off period, the subject points to the edge of the middle finger of the right hand using the left hand. To avoid touching the right hand by the left hand, a box with a measuring rod is put above the right hand, as shown in Figure 4. The measurement is conducted twice and the average of the position is kept as a reference value. After the measurement, the image of the HMD is turned on. At this time, the length/appearance of the right arm of the avatar is modified. We used two appearances of a normal human arm and a robot arm and three lengths of the arm (short, medium, and long as shown in Figure 5). Actual image of the avatar's arm is shown in Figures 6 and 7. The subject repeats the flexion-extension movement for 60 seconds while watching the modified avatar's arm. After the movement, the image of the HMD is turned off again to measure the perceived position of the edge of the middle finger by the left hand. This measurement is repeated twice. The average position is compared with the reference value in the previous one.

The subject then takes off the HMD and fills in a questionnaire containing the 10 items listed in Table 1. All items except Q1 and Q10 are based on previous studies [19–21] and are divided into four categories: ownership (Q2 and Q3), ownership control (Q6 and Q7), agency (Q4 and Q5), and agency control (Q8 and Q9). Q1 is included because participants' feeling of the length of their own right arm might change to some extent, even though the full extension of body ownership over the virtual hand does not occur (i.e. Q2 or Q3). Q10 is added to the questionnaire because the authors want to know whether the present VR system is useful for immersion of participants into virtual reality. Except for Q1, subjects reported their subjective experience during manipulation of the avatar's arm on the questionnaire with a 7-point Likert scale ranging from +3 (agree strongly) to −3 (disagree strongly). Regarding Q1, subjects rated the perceived length of their own right arm during the task, ranging from +3 (very long) to −3 (very short).

After a 5-min break during which the questionnaire is filled out, the subject puts on the HMD again and progresses to the next condition, which uses the difference between actual length and appearance of the avatar's arm. The procedure of the experiment is shown in Figure 8.

3. Results

3.1. Questionnaire

A nonparametric Friedman test was applied to analyze the questionnaire ratings. A two-way repeated measures ANOVA (i.e. visual appearance [2: human and robot] × length [3: short, medium, and long]) was used to assess proprioceptive drift.

The results of the questionnaire rating are shown in Figure 9. Each segment in the horizontal axis corresponds to one question. The vertical axis indicates the subjective sense of length in Q1. In other questions, vertical axis indicates the questionnaire ratings.

Table 1. Contents of the questionnaire.

Q1	How long did you feel your own right arm while manipulating the virtual arm/bar? −3: very short, −2: somewhat short −1: slightly short 0: unchanged 1: slightly long, 2: somewhat long, 3: very long
Q2	I felt as if the virtual arm (virtual bar) was my arm
Q3	It seemed as if I were sensing the movement of my arm in the location where the virtual arm/bar) moved
Q4	The virtual arm (virtual bar) moved just like I intended it to, as if it was obeying my will
Q5	I felt as if I was controlling the movements of the virtual arm (virtual bar)
Q6	It seemed as if I had two right arms
Q7	The virtual arm (virtual bar) began to resemble my own real arm, in terms of shape, skin tone, or some other visual feature
Q8	I felt as if the virtual arm (virtual bar) was controlling my movements
Q9	It seemed as if the virtual arm (virtual bar) had a will of its own
Q10	I felt as if I was in virtual reality

The Friedman test results demonstrated that the null hypothesis of equal medians across six conditions (i.e. visual appearance [2] × length [3]) was rejected in Q1, Q2, Q3, and Q7 (all, $\chi^2[5] > 19.8, p < 0.01$). The differences between conditions were investigated by a post-hoc Scheff's test. The summarized results are listed in Table 2. With regard to Q1 (subjective feeling of arm length), the ratings of the two long conditions (HL: 1.3 ± 0.8 [mean ± SD]; RL: 1.1 ± 1.1) were significantly higher than those of the remaining conditions (all, mean < 0), while the rating in the HS (-1.9 ± 1.1) was statistically the lowest. With regard to Q2 (body ownership), the rating in the HM (1.3 ± 1.3) was higher than those in all robot arm conditions (RM, RS, RL; all, mean < 0). Additionally, significant difference was also obtained between the HL (0.7 ± 1.2) and RM (-1.3 ± 1.4). With regard to Q3 (body ownership), the rating in the HM (1.9 ± 1.1) was higher than in the two short conditions (HS: -0.2 ± 2.0; RS: -0.8 ± 1.7). With regard to Q7 (ownership control), the ratings of the human conditions (all, means > −0.5) were significantly greater than those of the robot conditions (all, mean < 2.8), despite the arm length. Across all conditions, the agency ratings (Q4 and Q5) were quite high (all, mean > 2.1), while the ratings for agency control (Q8 and Q9) were very low (all, mean < −2.5). Similarly, the rating in Q6 (ownership control) was totally low (all, mean < −2.4). With regard to Q10 (immersion into VR), high ratings were detected (all, mean > 1.1).

From the responses to the questionnaire, we found that the subjects could feel SoA and SoO over the avatar's arm. SoO when the subjects watched the natural human avatar was stronger than when the robot arm was shown

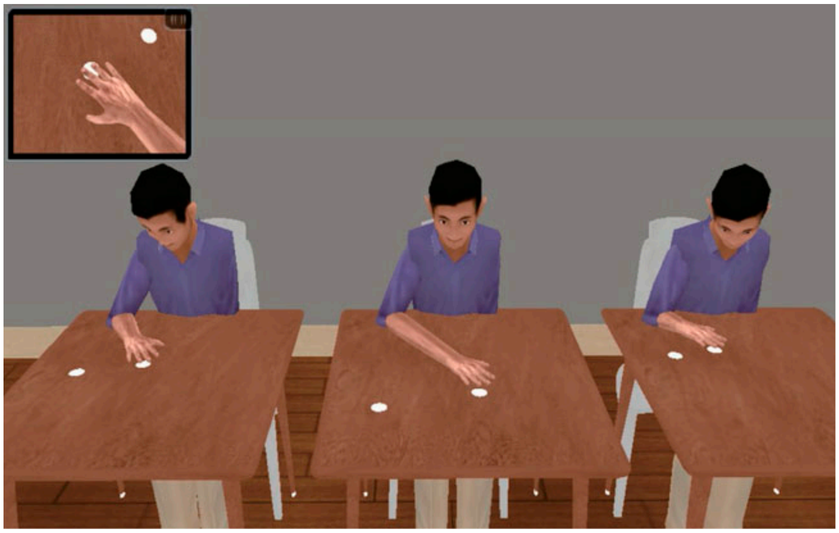

Figure 6. Avatars with three different lengths of human arm.

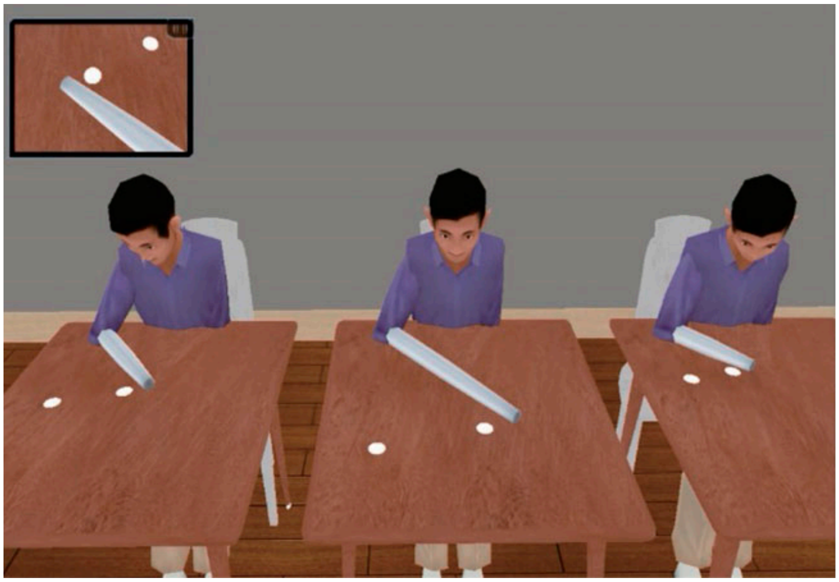

Figure 7. Avatars with three different lengths of robot arm.

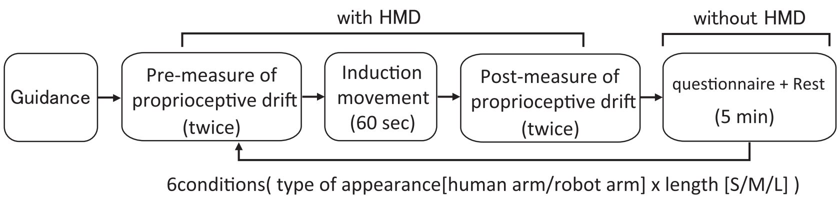

Figure 8. Procedure of the experiment.

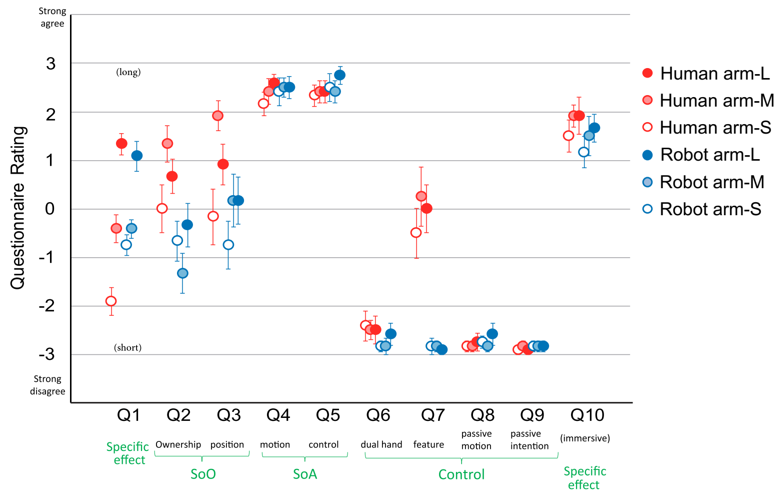

Figure 9. Results of the questionnaire. Error bars mean ± 1.0 SE.

Table 2. Order of questionnaire based on sense of length of arm length.

Q1	HS < HM, RS, RM < HL, RL
Q2	RM, RS, RL < HM
	RM < HL
Q3	RS, HS < HM
Q7	RS, RM, RL < HS, HM, HL

(in Q2, Q3). Also, when subjects manipulated the human arm, ownership ratings tended to be higher in the medium length condition than in other conditions (i.e. long and short). In contrast, high agency ratings (>2) were obtained in all conditions (Q4 and Q5). Moreover, the perceived length of the subjects' right arm during a task was altered in accordance with the length of the presented avatar's arm (Q1). These are positive results that demonstrate the basic potential of the VR system.

3.2. *Proprioceptive drifts*

The measurement results of the subjective sense of the arm length by the box with the measuring rod are shown in Figure 10. We have confirmed that proprioceptively perceived length of the subject's own arm was changed in accordance with the length of the displayed arm in the VR environment.

With regard to proprioceptive drift, a two-way ANOVA demonstrated that the main effect of length [$F(2,22) = 9.53, p < 0.01, \eta_p^2 = 0.46$] was significant, but the main effect of visual appearance ($p > 0.77$) and the interaction between them was not detected ($p > 0.88$). The post-hoc test (Tukey's HSD test) demonstrated that drifts in the long conditions (1.2 ± 1.6 cm, mean ± SD) were significantly greater than those in the short (−0.6 ± 2.2 cm) and medium conditions (middle: −0.3 ± 1.5 cm).

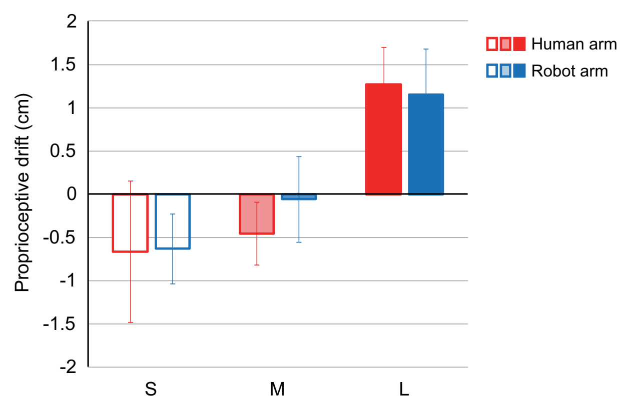

Figure 10. Results of the position gap before and after the induction movement. Error bars mean ± 1.0 SE.

We further performed correlation analysis between all questionnaire items and proprioceptive drifts across all conditions (i.e. 72 data; 6 conditions × 12 participants). Results demonstrated that there was a moderate correlation ($r = 0.33, p < 0.01$) only between Q1 (subjective feeling of arm length) and drift.

4. Discussion and future works

Delay time for displaying the arm movement on the HMD was about 200 ± 20 ms, as measured on a PC (CPU: Intel Core i7 3.4 GHz with 6 cores) while executing both server and client processes on an identical machine based on a virtual machine. This delay time is shorter than 300 ms, which is regarded as the limitation to maintain SoA [22]. Another threshold, about 230 ms, was reported as the maximum time delay to ensure SoA in Shimada's work [23], where the time delay in our system relates to sufficiently high speed. Thus, we conclude that the proposed system is fast enough to support experiments that require quality of SoA.

Questionnaire ratings on SoA/SoO over the virtual arm and proprioceptive drifts of the actual arm length were measured in the current experiment using the VR platform. The Q1 rating showed that subjective length of the actual arm became longer when long human/robot arms were displayed, while it became shorter when a short human arm was used. With regard to SoO (Q2 and Q3), the subjects felt greater ownership (>+1) when the most natural arm (i.e. human arm with middle length) was used. With regard to SoA (Q4 and Q5), high ratings were found across all conditions (>+2). This also supports that our VR system is enough to induce SoA over the avatar. Rehabilitation effect would be correlated with SoO and SoA. Therefore, these results of SoO and SoA suggest that there is no serious problem on the rehabilitation. However, more suitable avatar should be considered. Ratings of ownership control (Q6 and Q7) and agency control (Q8 and Q9) were basically quite low (< -2). These data highlight validity and reliability of ownership and agency ratings from Q2 to Q5. The high ratings of Q10 (>+1) suggest that the subjects felt that their bodies were transported into the virtual space (i.e. feelings of immersion or presence). Through correlation analysis between all questionnaire items and proprioceptive drifts, moderate correlation between Q1 (subjective length) and proprioceptive drift is found. We therefore conclude that changes of subjective length of the actual arm during manipulations of the longer virtual arm were linked to updating of body representations.

One limitation of our system is the poor representation of realistic hand appearance, especially finger model and motion. A number of previous studies have used finger movements to induce the active rubber hand illusion [20,21,24–27], while the current study used hand (arm) movements [28]. Accordingly, it is possible that the participants might perceive their control of the virtual hand as they might their control of a computer cursor (i.e. tool use). Actually, we are now using the Perception Neuron, which can measure finger motion, and an avatar with a finger model in order to evaluate the effect of finger motion on the SoA and SoO.

Regarding the result shown in Figure 10, the drift is minus in S and M, but plus in L. We think the reason of this problem is matching error between a field of real view and virtual view displayed by the HMD. If the attachment position of the HMD to eyes is slightly changed, the proprioceptive position could be easily changed. It means a certain calibration method should be used to keep the matching accuracy. However, such an accurate matching and calibration are not so important for rehabilitation use. We thus currently do not use any precise calibration. The important result is that the order of the drift score is arranged in order of length of the arm (S → M → L).

We also proposed a cloud-based VR system for neurorehabilitation that features a simple or cheap user interface such as Kinect or 3D HMD (Oculus Rift DK2). Such a compact system has the potential to promote home rehabilitation. Large-scale records of the rehabilitation process from a variety of patients, i.e. 'big-data' for neurorehabilitation, could be collected at the server by sending the reaction of the rehabilitation patients from the client system. By analyzing the big-data for neurorehabilitation, the possibility to extract representation of body representation can be increased.

For example, imitation therapy for PLP could be improved using such big-data. The detailed parameters of a target movement in imitation therapy, such as direction, intensity, and velocity of limb, are often designed by physical therapists themselves on the basis of their own experiences. However, it could be possible to determine such parameters automatically by analyzing the big-data and extracting a relationship model between analgesia effect and reaction against the target movement.

5. Conclusion

VR-based neurorehabilitation systems for PLP are gaining a great deal attention as an alternative to mirror box therapy. One of the challenges with using a virtual avatar has been the different lengths of a phantom limb. To realize such VR systems, we need to make users feel SoA and SoO on the VR avatar even though the avatar's arm length has been modified. We developed a VR platform for neurorehabilitation that changes the length of the avatar's limb easily. Through an experiment, we confirmed that the change of self-body appearance of the VR avatar has enough influence on the subjective length of an arm. We also confirmed that sufficient SoA and SoO are felt by all subjects.

With respect to the delay time, 200 ms is considered the threshold to ensure the SoA [22]. The response of the system is fast enough, but we can decrease the delay time more using another motion capture system. For example, the delay time using the motion capture system OptiTrack[1] was 83 ± 17 ms, which is strongly immune to negative effect on SoA and SoO. Our system is also connectable with a cloud-based VR system, which means we can choose devices that best meet the needs of a specific clinical field.

We believe that our system can function as a platform for neurorehabilitation and research on embodied-brain science systems.

Note

1. https://www.optitrack.com/

Disclosure statement

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