Improvement of Sense of Agency During Upper-Limb Movement for Motor Rehabilitation Using Virtual Reality

Kei Aoyagi, Wen Wen, Qi An, Shunsuke Hamasaki, Hiroshi Yamakawa, Yusuke Tamura, Atsushi Yamashita, and Hajime Asama

***Abstract*— Sense of agency refers to the feeling of controlling one's own body. Many patients surviving from a stroke lose the sense of agency over their body. This is due to impairments in both motor control and sensory brain functions. As a result of this lack in the sense of agency, stroke patients tend to lose the intention of moving the paralyzed limb, which results in further deterioration of brain functions and worsening muscles and joints. The present study proposes a motor rehabilitation system using virtual reality to improve the sense of agency during upper-limb movement which is required for various daily life activities such as eating meals and operating devices. Specifically, participants were instructed to move their hand to track a moving target ball in a virtual reality environment, while the position of their real hand was measured via a motion capture system. Participants were shown another ball presenting the position of their hand in virtual reality. We tested the proposed system with healthy participants, of which the motor control was disturbed by a 1-kg weight attached on the wrist. Participants reported their sense of agency after each trial. The results showed that the sense of agency was enhanced by the proposed intervention. Our results pointed out a potentially useful method to improve the sense of agency during body movements using modified visual feedback, which may contribute to the development of rehabilitation for stroke patients.**

I. Introduction

In recent years, the need for rehabilitation systems for stroke patients increased due to aging population. Stroke is one of the highest incidences observed in elderly people. The most common after effect of stroke is hemiplegia. Stroke patients suffering from hemiplegia tend to avoid using the paralyzed side bodies, since they lose the control of the paralyzed limbs and feel very poor sense of agency. Moreover, less-used paralyzed side bodies are at risk of a declining conscious experience of the body as ones' own [1]. This tendency makes their condition more serious because less-used paralyzed limbs lead to further deterioration of brain functions and worsen the condition of muscles and joints. In order to avoid this situation, an ideal rehabilitation system should be able to promote efficient use of paralyzed limbs. Recent studies proposed that the motivation of moving paralyzed limbs can be improved by using game-like virtual reality tasks [2]. However, stroke patients still suffer from poor sense of agency during those tasks. Also, the motivation may decline quickly when the task is no longer novel and attractive.

Here, the present study sheds light on the sense of agency. The sense of agency refers to the subjective feeling of controlling one's own body, and through it, external events. In our daily life, the sense of agency is a default state when we move our body. In other words, healthy people usually do not need any extra effort for feeling the sense of agency. The classic view in cognitive science suggests a comparison account for the sense of agency (Figure 1). Specifically, when people intend to move their body, the brain automatically generate a predicted state of the sensory output (e.g., where the body should be after the movement). After performing the action, the actual sensory feedback is compared with the prediction. The sense of agency emerges if there is no prediction error (i.e., mismatch), and diminishes if there are large prediction errors [3-4]. Furthermore, recent studies showed that the higher level of cognitive processes that compare the intention (or a goal of action) with the outcome also contribute to the sense of agency [5-7]. In summary, to generate strong sense of agency, the actual sensory feedback should match both the low-level predicted sensory feedback and the high-level expected sensory feedback.

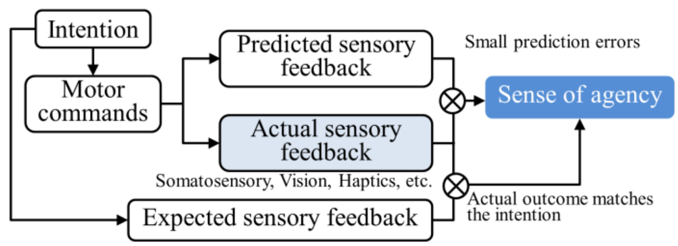

Figure 1. The model of sense of agency

In the case of stroke patient, the sense of agency fails in both low-level and high-level comparisons. Previous studies showed that the sense of agency is linked with motivation [8-9]. People tend to prefer actions that cause matching consequences to the sense of agency. Therefore, the sense of agency is considered to be an internal reward [10], which can be the motivation for those actions in long-term. Here, the present study proposes a motor rehabilitation system using virtual reality, in which modified visual feedback efficiently improves the sense of agency during hand movements.

Upper-limb motion in the vertical direction is especially very important because upper-limb activity is required for many situations (changing clothes, shampooing, taking actions in high places, etc). Hence, rehabilitation in a three dimensional space is needed for patients. It is difficult to intervene and help these patients because many hemiplegic

All authors are with The University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo, 113-8654, JAPAN (+81-03-5841-6456; fax: +81-03-5841-8547; e-mail: aoyagi@robot.t.u-tokyo.ac.jp)

patients have not only sensory disturbances, but also movement disorders. Here, we proposed visual intervention in three dimensional space with virtual reality via the use of a head mount display.

The system aimed to improve the sense of agency of stroke patients, who suffer from motor disabilities, and maintain their motivation for long-term motor rehabilitation. Referring to the model shown in Figure 1, the proposed system improves the match of the prediction for low-level and high-level comparisons. In order to achieve our goal, we first designed a goal-directed motor task. The participants were instructed to move their hands to trace a target ball created in a virtual reality environment, while their hands were tracked by a motion capture system in order to trigger the motion of the gray ball. The target ball moves vertically along with an 8-shape track. The vertical movement is designed according to the knowledge in rehabilitation that many daily activities require to raise arms. During the task, when a participant intends to move his hand towards the target ball, a predicted sensory feedback would indicate a hand position moving towards the target ball. Therefore, an expected sensory feedback would be a closer distance to the target ball. We also proposed an intervention condition, in which the motion of the gray ball is mixed with a participant's actual hand movement and the ideal motion (i.e., the motion of the target ball). Specifically, the position of the stimulus was presented at the mid-point between the position of the actual hand and the target ball. Such intervention can reduce both the low-level and high-level prediction errors as shown in Figure 1. In other words, by defining an intervention, people would feel that their hand is moving towards the direction they wanted it to move, and also receive a positive feedback of task performance. As a result, we expect enhanced sense of agency with the proposed intervention, compared to the condition without an intervention. In the experiment, we tested the proposed system with healthy participants, whose motions were partially disturbed by a weight attached to the wrist.

II. METHOD

The aim of this research is to demonstrate a method of visual intervention to improve sense of agency using virtual reality system. In this research, healthy subjects attached the weight on their wrist. This sections describe the hardware, software and experimental date taken from performed with subjects.

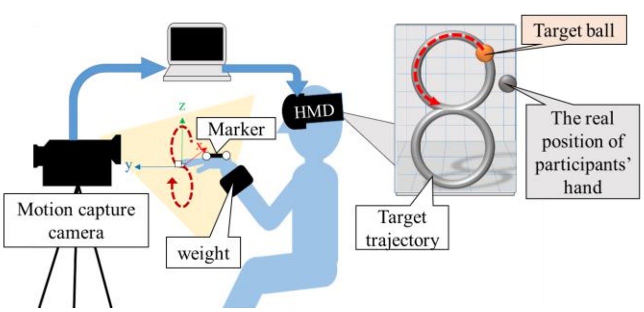

Figure 2. The components of the proposed system

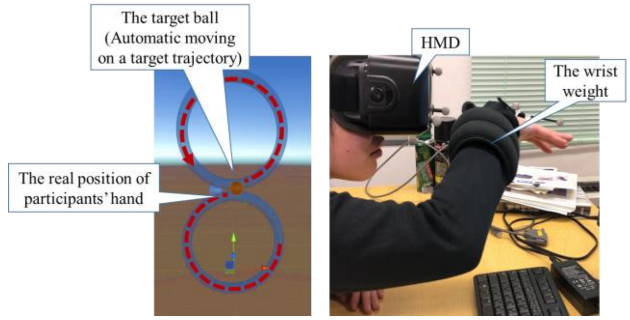

Figure 3. VR activity situation

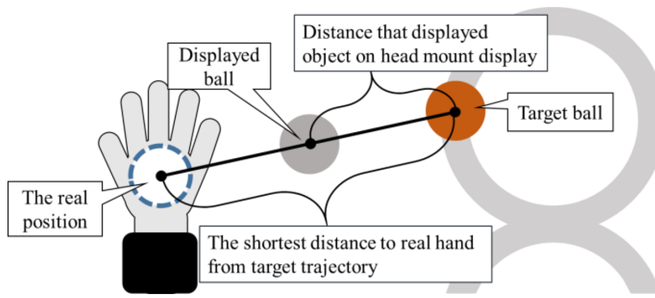

Figure 4. The design of the intervention

A. Participants

Fourteen healthy volunteers (age = 22.5 ± 3.5) participated in the experiment. Written consent was obtained prior to the participation. The study was approved by local ethics board (The University of Tokyo). All participants provided written informed consent prior to participation.

B. Proposed system

Figure 2 shows the overall setting of the proposed system. It contains a head-mount display (Oculus Rift Development Kit 2), a motion capture (V120: Trio, OptiTrack), and a platform for a virtual reality environment (Unity, 2017.2.0f3). Participants moved their hands vertically, to control a gray ball in the virtual reality to trace an orange target ball (Figure 2). Participants' hand motion was measured using V120: Trio (OptiTrack) by motion capture with a marker attached to the back of their hand (Figure 3). The target ball moved on an 8-shaped track (height 600 mm, weight 300 mm) at 235.5 mm/s. Each trail contained 4 circles (8 s/circle). In the baseline and non-intervention conditions, the gray ball was presented at the position corresponding to the real hand. In the intervention condition, the gray ball was presented at the mid-point between the actual hand position and the target ball (Figure 4). This means that the motion of the gray ball was a mixture of participants' hand movement and the target's movement at a 50/50 ratio. In addition, we can adjust the mixing ratio to modify the extent of intervention in future research to prevent from exceeding intervention (see Discussion section for details).

C. Procedure

Participants were tested individually in a quiet testing room. There were three conditions in the task: the baseline

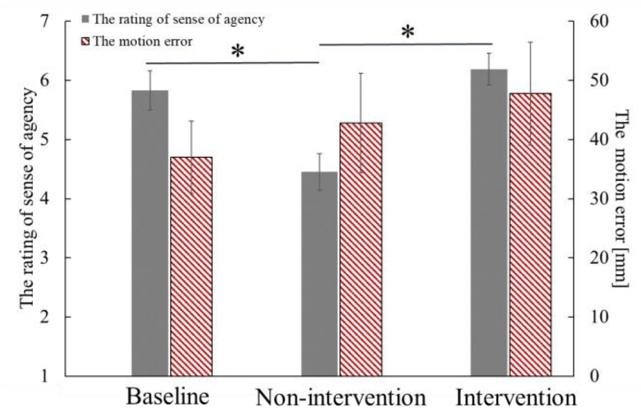

Figure 5. The rating of sense of agency *(gray bars, left hand ordinate)* and the motion error *(red stripe pattern bars, right hand ordinate)* in each condition. Error bars represent standard error.

condition, the non-intervention condition, and the intervention condition. In the baseline condition, participants did not wear any weight. The gray ball represented the real position of their hand. In the non-intervention condition, participants wore a 1-kg weight on their wrist, while the gray ball represented the real position of their hand. In the intervention condition, participants wore the weight, and the motion of the gray ball was a mixture of participants' real hand movement and the movements of the target ball.

Each participant performed 9 trials, containing 3 repeats of each condition (baseline, intervention and non-intervention). Participants were not told whether there the stimuli's motion was modified or not. The order of the intervention and non-intervention condition was counter-balanced between participants in an ABABAB fashion, and the baseline condition was conducted after completing the above two conditions. After each trial, participants rated how strongly they felt that they controlled the position of the ball that represented their hand position using a 7-point scale (1 = no control, 7 = full control). The experiment took about 32 minutes in total.

III. Result

A. Sense of Agency Rating

Figure 5 shows the results of the rating of sense of agency (left hand coordinate). A repeated-measures ANOVA of the three experimental conditions (i.e., baseline condition, non-intervention condition, vs intervention condition) revealed a significant effect of the condition ($F(2, 30) = 25.48$, $p = .001$).

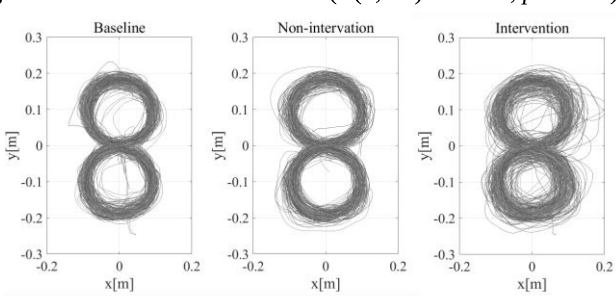

Figure 6. Motor performance of the hand movement by all participants

Post-hoc comparisons (Bonferroni-adjusted t tests) showed that the sense of agency in the non-intervention condition was significantly weaker than those in the baseline and intervention condition (Bonferroni-adjusted ps < .001). However, there was no significant difference between the baseline and the intervention conditions (Bonferroni-adjusted $p = .533$). The results showed that the 1-kg weight attached to the wrist impaired the sense of agency during the movement. However, with the proposed intervention, participant reported comparable level of sense of agency to that in the baseline condition (i.e., no weight), even when they were still wearing the wrist weight. This result showed that the proposed system is efficient in improving the sense of agency during such goal-directed movement.

B. Motion Error

The black bars on right hand coordinate in Figure 5 show the averaged distance between the participants' real hand position and the target ball. This reflects the actual motor performance of the hand movement, regardless of what the participants saw. The error was calculated by measuring the absolute distance between the hand position and the target ball, and was averaged across time. Figure 6 plots the hand movements of all the participants from all the trials in each condition.

A repeated-measures ANOVA (baseline condition, non-intervention condition, vs intervention condition) revealed a non-significant effect of experimental condition ($F(2, 26) = 2.49$, $p = .103$). Therefore, regardless of whether there was a weight or not, or whether they visual feedback was modified or not, participants managed to perform equally well among those three conditions. The 1-kg weight on the wrist decreased the sense of agency as expected, although the actual performance was intact. Combining with the results of the agency rating, it can be concluded that the subjective feeling of agency could actually be dissociated from the actual motor performance. In other words, even when people actually perform rather poorly (or well), appropriate visual intervention could change the subjective feeling of agency to some extent regardless of the motor performance. The proposed method of intervention improves motor control feeling under motion impairment.

IV. Discussion

In the present study, we proposed a motor control task in virtual reality, improving the sense of agency via modified visual feedbacks. The task was designed to be goal-directed. In the intervention condition, participants were shown a mixed motion of their own hand and the ideal movement (i.e., movement of the traced target) in the virtual environment. Such intervention is considered to improve the sense of agency in the conditions with difficulties in impaired movement, such as the cases of stroke patient. We tested the system with healthy participants, whose movement was partially disturbed by a 1-kg weight attached to their wrist. The results showed that although the weight did not result in worse motor performance, it indeed significantly decreased the sense of agency. Most importantly, the proposed intervention significantly enhanced the sense of agency to a comparable level when people did not wear the weight.

In our system, the improved sense of agency was due to result in more successful comparisons with the sensory feedback (i.e., visual feedback in the virtual reality), the predicted (i.e., moving toward the target ball) and expected (i.e., successfully tracing the target ball with a minimal distance) sensory feedbacks. In our system, participants always need to actually move their hand to trigger the motion of the ball. Since none of the participants in our experiment had any motor disability, they performed rather well even when wearing a 1-kg weight on the wrist. This means, the absolute extent of intervention was small, because the error itself was small. However, patients who are suffering from motor disability will not be able to trace the target ball very well. With a large extent of motion error, if the system still maintains a 50/50 intervention ratio, people would still see a ball representing their hand somehow following the target ball in the head mount display, even if they could barely move their hand. Such of exceeded intervention would obviously cause a great loss sense of agency. Therefore, in the case of large motor disability, the system should make the intervention ratio flexible regarding the extent of motor disability and the actual motor ability, to provide a just-helpful-without-been-noticed intervention to enhance the sense of agency in future research.

At last, the motor task was designed considering the actual requirements in rehabilitation. However, it was a rather difficult task for a stroke patient, because the target ball moved in a constant speed of 235.5 mm/s. In the case of patient who suffers from serious stroke after effect, lifting even a hand is difficult. In such a condition, a participant-paced movement is considered to be more friendly and useful. This can be done by adjusting the speed of the target ball according the participants' task performance. Additionally, the system also allows a support set-up, such as a surface on which participants can place their hand on to make the motion easier, or a physiotherapist who can partially support patients' movement. Nevertheless, the proposed system is the first to shed lights on the sense of agency, which has been shown to be an internal reward of action in rehabilitation, and is an efficient method to improve the sense of agency during motor rehabilitation.

V. Conclusion

The present study proposed a system for motor rehabilitation for patients with motor disabilities. The system contains a head mount display, a motion capture, and a virtual reality platform. When using the system, users need to perform a goal-directed movement, and a stimulus whose motion is a mixture of participants' hand movement and the ideal motion (i.e., motion of the target) is presented to the user. With a motor disability of disturbance, people usually have a poor sense of agency in such goal-directed task. However, our system can efficiently improve the sense of agency during the motion, as the presented motion of the stimulus matches the predicted and expected motion. Our experiment with healthy participants showed that the proposed intervention significantly improved the sense of agency when people did this task wearing a 1-kg weight on their wrist, compared to the condition without intervention. We also discussed the points that need to be improved in the application of rehabilitation. In this experiment, we examined the effect of sense of agency, but we did not verify the effect on the motivation for exercise activities. The effect of the proposed system on motivation should be verified in future research.

Acknowledgment

This study is partly supported by the JSPS KAKENHI Grant 2612005, 16H04293, and 18H01405.

References

[1] Burin, D., Livelli, A., Garbarini, F., Fossataro, C., Folegatti, A., Gindri, P., & Pia, L. (2015), Are movements necessary for the sense of body ownership? evidence from the rubber hand illusion in pure hemiplegic patients. PLoS ONE, 10(3), 1–12.

[2] Jurgen, B., Ann, B., Lisbeth, C., Daniel, G., Åsa, L., Hans, S., Christian, B., Katharina , S., & Martin, R. (2018), Virtual rehabilitation after stroke, Studies in health technology and informatics, 136, 77-82.

[3] Frith, C. D., Blakemore, S.-J., & Wolpert, D. M. (2000). Explaining the symptoms of schizophrenia : Abnormalities in the awareness of action. Brain Research Reviews, 31, 357–363.

[4] Blakemore, S.-J., Wolpert, D. M., & Frith, C. D. (2002). Abnormalities in the awareness of action. Trends in Cognitive Sciences, 6(6), 237–242.

[5] Metcalfe, J., & Greene, M. J. (2007). Metacognition of agency. Journal of Experimental Psychology. General, 136(2), 184–199.

[6] Wen, W., Yamashita, A., & Asama, H. (2015). The influence of goals on sense of control. Consciousness and Cognition, 37, 83–90.

[7] Wen, W., Yamashita, A., & Asama, H. (2015). The sense of agency during continuous action: Performance is more important than action-feedback association. PLoS ONE, 10(4), e0125226.

[8] Karsh, N., & Eitam, B. (2015). I control therefore I do: Judgments of agency influence action selection. Cognition, 138, 122–131.

[9] Karsh, N., Eitam, B., Mark, I., & Higgins, E. T. (2016). Bootstrapping agency: How control-relevant information affects motivation. Journal of Experimental Psychology: General, 145(10), 1333–1350.

[10] Wen, W., & Haggard, P. (2018). Control changes the way we look at the world. Journal of Cognitive Neuroscience, 30(4), 603–619.