Virtual reality-based action observation facilitates acquisition of body-powered prosthetic control skills

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Abstract
Background Regular body-powered prosthesis (bp-prosthesis) training often facilitates acquisition of skills through repeated practice but requires adequate time and motivation. Therefore, if there are auxiliary tools, such as indirect training, skill acquisition may be easy. In this study, we examined the effects of action observation (AO) using virtual reality (VR) as an auxiliary tool. We examined two different modalities during AO, VR and tablet device (Tab), and two perspectives, first- and third-person perspectives. This study aimed to examine whether AO training using VR is effective in acquiring bp-prosthetic control skills in the short term.

Methods Forty healthy right-handed participants simulated bp-prosthesis with the non-dominant hand. They were divided into five groups with different interventions and displays for AO: first-person perspective on VR (VR1st), third-person perspective on VR (VR3rd), first-person perspective on Tab (Tab1st), third-person perspective on Tab (Tab3rd), and control group (Con) without AO. Participants of VR1st, VR3rd, Tab1st, and Tab3rd observed the video image of experts operating prosthesis twice, 10 min each time. We evaluated the immersion during the video observation using the Visual Analog Scale. Prosthetic control skills were evaluated using the box and block test (BBT) and bowknot task (BKT).

Results In BBT, no significant enhancements of prosthetic control skills between groups were found. In contrast, the BKT change rates of prosthetic control skills in VR1st and VR3rd were significantly higher than those in Con (p < 0.001). Additionally, immersion scores of VR1st and VR3rd were higher than those of Tab3rd (p < 0.05), and there was a significant negative correlation between immersion and BKT change rate (Spearman’s rs = -0.47, p < 0.01).

Conclusions In BKT (bilateral manual dexterity), VR video viewing led to significantly better short-term prosthetic control acquisition than Con. Additionally, it was suggested that the higher the immersion, the shorter the BKT task execution time. Our findings suggest that VR-based AO training is effective in acquiring bp-prosthetic control in the short term. Especially, it is effective for bilateral prosthetic control, which is necessary in the daily life of upper limb amputees.

Background
A body-powered prosthesis (bp-prosthesis) is often used by upper limb amputees. However, upper limb amputees have difficulty acquiring control of the bp-prosthesis at the initial time of skills training and often refuse to use the prosthesis. Appearance or presence of pain is one of the reasons of refusal. Additionally, insufficient training of prosthesis handling at the initial time is another reason for refusal [1-3]. A previous study reported that repeated training with the bp-prosthesis at the initial time promotes the use of the prosthesis and improves a wide acceptance of prosthesis use [4]. However, repeated training needs longer time and motivation. Therefore, it is necessary to establish training in which prosthetic control can be acquired in a short time.

Regular bp-prosthesis training often facilitates acquisition of skills through repeated practice, and if there are auxiliary tools, skill acquisition will be easier. Huinink et al. reported that indirect grip force adjustment practice is effective in acquiring bp-prosthetic control [5]. Additionally, another study revealed similar results for myoelectric prosthesis [6]. Therefore, indirect training on bp-prosthetic control may promote skills acquisition.

Action observation (AO) is an application of the phenomenon in which observing the behavior of another person produces the same neural activity as that performed by oneself. Previous studies showed that AO enhances performance, such as the dart throwing [7, 8], standing balance [9], and hamstring force [10]. Therefore, observing the operation of a prosthetic expert may facilitate the acquisition of bp-prosthetic control. Additionally, virtual reality (VR) is technology used to simulate an environment that users experience as being comparable to the real world [11]. Previous studies showed that VR training promotes recovery of upper limb functions in patients with stroke or Parkinson’s disease [12-14]. Therefore, VR training may be used in acquiring bp-prosthetic control. If indirect skill training using AO by VR is effective in acquiring bp-prosthetic control in the short-term, this training may help several upper limb amputees.

In this study, we examined the effects of AO using VR as an auxiliary tool. We examined two different modalities during AO, VR and tablet device (Tab), and two perspectives, first- and third-person perspectives. We hypothesized that AO by VR is effective in acquiring bp-prosthetic control in the short term. The focus point of this study is whether VR is superior to the Tab and whether the
first-person perspective is more effective than the third-person perspective.

**Methods**

**Participants**

Forty right-handed participants (20 men and 20 women; 21–40 years old) volunteered for the study. No participants had history of neurological or orthopedic disorders, and all had a normal or corrected-to-normal vision. They were classified as consistent right-handers according to the Edinburgh inventory [15] (all participants scored 90–100% on this scale). The purpose and procedure of this study were adequately explained to the participants, and written informed consent was obtained before enrolment. Our institutional ethical review board approved this study and performed procedures according to the Declaration of Helsinki.

**Bp-prosthetic simulator**

The participants used a bp-prosthetic simulator (Fig. 1a). All participants used this simulator for the first time. This simulator consisted of a hand hook, socket, rod, cable, and harness. This simulator could be controlled by a cable attached to a figure-of-eight shoulder harness wrapped around the contralateral shoulder (Fig. 1b). The hand hook, which is connected to the cable, is voluntarily opened by pulling the cable and automatically closed by rubber band power, releasing the cable. All participants wore the simulator on their left upper limb. They wore it on their left upper limb because prosthetic control with the non-dominant hand was highly difficult and indicated new motor learning. When wearing the simulator, they grasped a rod by their left hand; then, their left forearm was attached to the socket, and the harness was attached to their right shoulder. Thus, the hand hook opened with left shoulder flexion and scapular abduction and closed with left shoulder extension and scapular adduction (Fig. 1c, d). A skilled occupational therapist adjusted the harness tension and hook direction in adapting the prosthesis.

**Evaluation of functional performance**

We used two functional tasks to examine the functional performance of the unilateral and bilateral manual dexterity during prosthesis use: box and block test (BBT) and bowknot task (BKT). The BBT was used in the evaluation of unilateral manual dexterity during prosthesis use and performed based
on the previous report [16]. Participants stood in front of a box divided into two square compartments on a stable table, one compartment containing a total of 150 wooden blocks (2.5 cm²). The height of the table was set to the same height as the BBT kit and participants’ navel. A nonslip mat was placed under the BBT kit. Then, participants transported as many blocks as possible from one compartment to another with only their left-hand hook within 60 s [16]. The BBT score was the number of transferred blocks within 60 s.

The BKT was used in the evaluation of bilateral manual dexterity during prosthesis use. The BKT kit consisted of a box (20 cm × 10 cm × 15 cm) and five shoelaces of 15 cm length on each side. The height of the table was set to the same height as the BBT kit. A nonslip mat was placed under the BKT kit. Participants stood in front of a box placed on a stable table and knotted five shoelaces as fast as possible from far to near with the left-hand hook and normal right hand. The BKT score was the time from the start to completion of knotting the five shoelaces.

The BBT and BKT scores were measured twice in each test session, and the mean values were calculated as the score. Participants practiced for 5 min each before the start of the evaluation of the two tasks.

Evaluation of immersion

The Visual Analog Scale (VAS) was used in evaluating the immersion level during AO using VR and Tab. After AO, participants provided an immersion score on the immersive visual experience elicited by the AO. We obtained the immersion score using the VAS, which ranged from 0 (not completely immersive) to 100 (completely immersive). The immersion score was the average of the immersion during the video observation performed twice.

Video image and viewing

Participants observed the BBT and BKT videos of the prosthetic expert. We made four videos for AO training: two videos for viewing in the VR system and two videos for viewing on the Tab. Two videos for VR were recorded using a VR camera (Mirage Camera with Daydream, Lenovo). One of two videos for VR shows the first person performing the tasks of the BBT and BKT (Fig. 2 a, b); the other video shows the third person performing the tasks (Fig. 2 c, d). Two videos for the Tab were recorded using
a camera installed in the Tab (Huawei d-tab d1-01H, Huawei).

The first- and third-person perspective viewing for VR was conducted using a head-mounted display (Mirage Solo with Daydream, Lenovo). The first- and third-person perspective viewing for the Tab was conducted using the Tab with 10.1-inch display (Huawei d-tab d1-01H, Huawei). When viewing the videos, we indicated that participants performed AO with motor imagery.

Intervention group

In this study, an intervention was divided into five groups: 1) VR\textsubscript{1st}, 2) VR\textsubscript{3rd}, 3) Tab\textsubscript{1st}, 4) Tab\textsubscript{3rd}, and 5) Control groups, consisting of 8 participants.

1. The first group was the VR first-person perspective group (VR\textsubscript{1st}). VR\textsubscript{1st} used VR for intervention. The VR video was viewed using a head-mounted display. The VR video watched in 3D 180° vertically and horizontally. Participants watched the videos of prosthesis skills and imaged them as if they were performing prosthetic operations. The video was a point of view as if one was performing a prosthetic operation (first-person perspective) (Fig. 2a, b).

2. The second group was the VR third-person perspective group (VR\textsubscript{3rd}). VR\textsubscript{3rd} used VR for the intervention. Participants watched videos of prosthesis skills and imaged them as if they were performing prosthetic operations. The video was a viewpoint from which movement of the scapula to the forearm was easy to observe when performing a prosthetic operation (third-person perspective) (Fig. 2c, d).

3. The third group was the Tab first-person perspective group (Tab\textsubscript{1st}). Tab\textsubscript{1st} used the Tab for intervention. Participants observed the same videos as those in VR\textsubscript{1st} on a Tab and imaged them as if they were performing prosthetic operations. The video was a point of view as if one was performing a prosthetic operation (first-person perspective) (Fig. 2a, b).

4. The fourth group was the Tab third-person perspective group (Tab\textsubscript{3rd}). Tab\textsubscript{3rd} used
the Tab for intervention. Participants observed the same videos as \( VR_{3rd} \) on the Tab and imaged them as if they were performing prosthetic operations. The video was a viewpoint from which movement of the scapula to the forearm was easy to observe when performing a prosthetic operation (third-person perspective) (Fig. 2c, d).

5. The fifth group was the control group (Con). Con was evaluated for BBT and BKT without intervention.

Protocol (Fig. 3)
The participants were divided into five groups for the intervention. As a pre-intervention (Pre) evaluation, BBT and BKT were evaluated. The first and second interventions were Session 1 (S1) and Session 2 (S2), respectively. The groups, except for the control group, imaged BKT and BBT videos while watching them for 10 min. Participants were allowed to remove the simulator and move their hands during video observation. During video observation, they were instructed to imagine themselves as if they were performing a prosthetic operation.

We performed the BBT and BKT after the first and second interventions, which were Post 1 (P1) and Post 2 (P2), respectively. We obtained an immersive evaluation at P1 and P2 in four groups: \( VR_{1st} \), \( VR_{3rd} \), \( Tab_{1st} \), and \( Tab_{3rd} \).

Statistical analysis
To clarify the effects of intervention, we used the following: 1) BBT change rate, 2) BKT change rate, and 3) immersion score.

BBT change rate is an increased rate of the BBT scores of P1 and P2 when Pre is set to 0. BKT change rate is a decreased rate of the BKT score of P1 and P2 when Pre is set to 100. The immersion score was the average of the immersion during video observation of S1 and S2.

Initially, each data was confirmed for normality using the Shapiro-Wilk test. After normality was confirmed, BBT and BKT change rates were analyzed using two-way ANOVA for factors of groups (\( VR_{1st} \), \( VR_{3rd} \), \( Tab_{1st} \), \( Tab_{3rd} \), and Con) and sessions (Pre, P1, and P2). Immersion was analyzed using one-way ANOVA for factor of groups (\( VR_{1st} \), \( VR_{3rd} \), \( Tab_{1st} \), \( Tab_{3rd} \)). If a significant main effect was
found, the Holm’s method was used for post hoc comparisons. Then, we investigated the relationships among BBT and BKT change rates (Pre to P2) and immersion score using Spearman’s rank correlation test. All results are reported as means ± standard deviations. Statistical analysis was performed using IBM SPSS version 23.0. The significance level was set at 5%.

Results

Participants

Demographic data of sex, age, and Edinburgh inventory score in each group are shown in Table 1. No significant differences in age and Edinburgh inventory score between groups were found. Additionally, participants’ educational background was > 12 years (during university or graduated from a vocational school or university). It was the first time for all participants to use the bp-prosthetic simulator and perform the BBT and BKT tasks.

| Participant | VR1st | VR3rd | Table 1st | Table 3rd | Control |
|-------------|-------|-------|-----------|-----------|---------|
| Participants| 8     | 8     | 8         | 8         | 8       |
| Sex (Male/female) | 4 / 4 | 4 / 4 | 4 / 4     | 4 / 4     | 4 / 4   |
| Age Mean (SD) | 25.4 (3.7) | 26.1 (5.9) | 27.9 (6.9) | 25.1 (4.9) | 27.1 (4.0) |
| Edinburgh inventory score | 98% | 98% | 93% | 98% | 94% |

This table shows the demographic data of sex, age, and Edinburgh inventory score. No significant differences in age and Edinburgh inventory score between groups were found.

Unilateral manual dexterity: BBT

The results of the BBT change rate are shown in Table 2. The BBT change rate is an increased rate in the BBT scores of Post1 and Post2 when Pre is set to 0. In Pre, the BBT raw score was not significantly different between the groups. All five groups tended to increase the number of transported blocks with increasing sessions. The transition of BBT change rate is shown in Fig. 4. A significant main effect for sessions was found (F (2, 14) = 109.769, p < 0.001); however, there was no significant main effect for groups in the ratio (F (4, 28) = 0.424, p = 0.790), nor was the interaction significant (F (8, 56) = 0.512, p = 0.842). Thus, in unilateral manual dexterity, all groups significantly acquired prosthetic control with increasing sessions. However, there were no differences in the acquisition level between the groups.
Table 2
Box and block test change rate

|                  | Pre  | Post1 Mean (SD) | Post2 Mean (SD) |
|------------------|------|-----------------|-----------------|
| **BBT change rate (%)** |      |                 |                 |
| VR₁st            | 0    | 33.1 (8.8)      | 47.3 (11.6)     |
| VR₃rd            | 0    | 23.6 (11.9)     | 44.5 (18.7)     |
| Table 1st        | 0    | 23.3 (10.7)     | 40.2 (12.9)     |
| Table 3rd        | 0    | 19.4 (11.5)     | 40.0 (13.6)     |
| Control          | 0    | 33.0 (30.8)     | 44.6 (37.4)     |

Mean (SD), SD = standard deviation

This table shows the BBT change rate in Post1 and Post2 based on the Pre score. A significant main effect for sessions was found (F (2, 14) = 109.769 p < 0.001); however, there was no significant main effect for groups in the ratio (F (4, 28) = 0.424, p = 0.790), nor was the interaction significant (F (8, 56) = 0.512, p = 0.842).

Bilateral manual dexterity: BKT

The results of the BKT change rate are shown in Table 3. BKT change rate is a decreased rate in the BKT score of Post1 and Post2 when Pre is set to 100. In Pre, BKT raw score was not significantly different between the groups. All five groups tended to shorten the time with increasing sessions. The transition of BKT change rate is shown in Fig. 5. The two-way ANOVA indicated significant differences in change rate in the main effect for sessions (F (2, 14) = 176.935, p < 0.001) and groups (F (4, 28) = 3.792, p = 0.014). Moreover, the two-way interaction between groups and sessions was not significant (F (8, 56) = 1.863, p = 0.084). Post hoc tests showed that VR₁st (p < 0.001) and VR₃rd (p < 0.001) had significantly reduced rates of change compared to Post2 in Con. Thus, in bilateral manual dexterity, the VR₁st and VR₃rd showed significantly better acquisition of prosthetic control skills compared to Con.

Table 3
Bowknot task change rate

|                  | Pre  | Post1 Mean (SD) | Post2 Mean (SD) |
|------------------|------|-----------------|-----------------|
| **BKT change rate (%)** |      |                 |                 |
| VR₁st            | 100  | 67.9 (9.7)      | 54.9 (6.1) *₁    |
| VR₃rd            | 100  | 74.2 (14.0)     | 58.8 (9.2) *₂    |
| Table 1st        | 100  | 81.9 (16.9)     | 68.3 (19.3)      |
| Table 3rd        | 100  | 86.7 (12.9)     | 71.8 (14.0)      |
| Control          | 100  | 87.2 (15.8)     | 78.1 (8.7) *₁ *₂ |

Mean (SD), SD = standard deviation

*₁) VR₁st vs Control p < 0.001  *₂) VR₃rd vs Control p < 0.001

This table shows the BKT change rate in Post1 and Post2 based on the Pre score. There was main effect of group (F (4, 28) = 3.792, p = 0.014). Among groups, VR₁st (p < 0.001) and VR₃rd (p < 0.001) showed higher rates than the Control (Con). There was main effect of sessions (F (2, 14) = 176.935 p < 0.001). The two-way interaction between groups and sessions was not significant (F (8, 56) = 1.863, p = 0.084).

Immersion
The results of the immersion score in the four groups are shown in Table 4. The scores of the VR\textsubscript{1st}, VR\textsubscript{3rd}, Table 1\textsubscript{st}, and Table 3\textsubscript{rd} were 75.2±10.9, 71.8±11.5, 60.8±11.7, and 55.4±15.94, respectively. The one-way ANOVA indicated significant differences between groups (F (3, 28) = 4.916 p = 0.007). Subsequent post hoc tests revealed a significant difference between Table 3\textsubscript{rd} and VR\textsubscript{1st} (p = 0.012) and VR\textsubscript{3rd} (p = 0.045).

| Table 4 | Immersion |
|---------|-----------|
|         | Mean (SD) | VR\textsubscript{1st} | VR\textsubscript{3rd} | Table 1\textsubscript{st} | Table 3\textsubscript{rd} |
| Mean    | 75.2 ± 10.9 | 71.8 ± 11.5 | 60.8 (11.7) | 55.4 *± 15.94 |

Mean (SD), SD = standard deviation

*1) VR\textsubscript{1st} vs Table 3\textsubscript{rd} p < 0.05

*2) VR\textsubscript{3rd} vs Table 3\textsubscript{rd} p < 0.05

The table shows the immersion of action observation (AO) in each intervention. The one-way ANOVA indicated significant differences between groups (F (3, 28) = 4.916 p = 0.007). Subsequently, post hoc tests between the four groups showed significant difference between VR\textsubscript{1st} and Table 3\textsubscript{rd} (p = 0.012) and VR\textsubscript{3rd} and Table 3\textsubscript{rd} (p = 0.045).

Moreover, the results of the correlation between immersion and BKT change rate (Pre to Post2) are shown in Fig. 6. There was a significant negative correlation between immersion and BKT change rate (Spearman's rs = -0.47, p = 0.007). There was no correlation between immersion and BBT change rate.

Discussion

In this study, AO using VR was more effective in acquiring bp-prosthetic control compared to Con. The results depended on the task, and the abovementioned results were confirmed in the bilateral manual dexterity task (BKT) but not in the unilateral manual dexterity task (BBT). Furthermore, higher immersion score was shown in the VR\textsubscript{1st} and VR\textsubscript{3rd} than that in Table 3\textsubscript{rd}. There was a significant negative correlation between immersion and BKT change rate.

Effect of AO using VR

The BKT change rate was significantly higher in VR\textsubscript{1st} and VR\textsubscript{3rd} than that in Con (Fig. 5). This result suggested that AO using VR facilitates the acquisition of bilateral prosthetic control. Additionally, the immersion score was higher in VR\textsubscript{1st} and VR\textsubscript{3rd} than in Table 3\textsubscript{rd}, and there was a significant negative correlation between immersion and BKT change rate. Thus, VR is more immersive than Tab, and the higher the immersion score, the shorter the execution time of BKT. These results indicated that VR
leads to ease in immersion during AO and acquisition of prosthetic control skills. Crosbie et al. reported the impact of immersion on reach and search movement of virtual objects in patients with stroke. They concluded that those with higher immersion tend to perform better [17].

Moreover, using VR can increase the motivation for patients to participate in rehabilitation and their involvement in treatment tasks [18]. Rohrback et al. reported that “enjoyment,” “motivation,” and “engagement” are involved when using VR [19]. Lewis et al. revealed that the level of engagement and motivation in performing tasks is posited as a factor in determining the success of rehabilitation interventions using VR [20]. From these, it is presumed that the use of VR improved the enjoyment, motivation, and engagement of participants during AO and facilitated motor learning. However, since these indicators have not been evaluated, it is desirable to evaluate them in future research.

VR effect depending on task difficulty

The BBT change rate was not significantly different among the groups (Fig. 4). This result shows that VR and Tab intervention has little effect on unilateral prosthetic control skills. This is because the characteristics of the BBT task influenced it. The BBT score is the number of blocks moved in 1 m on the one hand. Previous studies have reported an age-averaged score for BBT in healthy adults [16, 21]. However, there is no study showing the average age of BBT for prosthetic users. Previous studies have reported an average of 25–30 blocks in assessing prosthetic control skills using BBT [22, 23]. In this study, the average score of each group in Post2 is 25–28 blocks. This result suggests that the BBT score had a ceiling effect. Furthermore, the difference in AO modality does not affect the results of unilateral prosthetic control like BBT.

In contrast, the BKT change rate was significantly different among the groups (Fig. 5). BKT is the original evaluation of this study and an evaluation of the bilateral manual dexterity. In BBT, the prosthetic hook needs to open and close and be transported to one compartment. In contrast, BKT is a difficult task requiring tying up five shoelaces, cooperatively moving both hands, opening and closing the hook, and smooth operation. Comparing these two tasks, BKT is more difficult than BBT. From this result, it is presumed that AO using VR is likely to be effective in tasks with great difficulty, that is, cooperation tasks of both hands.
In many cases, a prosthetic user performs a one-handed operation in daily life with a non-amputee hand. However, tying shoelaces, cooking, washing, hobbies, etc., require the ability to move bilaterally cooperatively using prosthesis, suggesting that AO using VR can be effective. Therefore, it is suggested that using VR as an auxiliary tool is beneficial for the prosthetic user.

Comparison of VR and Tab immersion

VR\textsubscript{1st} (p < 0.05) and VR\textsubscript{3rd} (p < 0.05) had higher immersion score during AO than Table 3\textsubscript{rd} (Table 4). The results showed that VR was significantly more immersive than Tab. Additionally, there was a significant negative correlation between immersion and BKT change rate (Spearman’s rs = -0.47, p < 0.01). Therefore, the higher the immersion score, the shorter the BKT task execution time. This result was consistent with those of many previous studies [24, 25].

This is because the VR used in this study uses a head-mounted display, which can interrupt visual stimuli other than video. Since the Tab cannot completely interrupt stimuli other than video, it can be assumed that it was difficult for participants to immerse themselves in the image.

It has been reported that immersive features of technology can have a significant impact on the present experience [26]. Elsey et al. reported that 3D video with VR has a higher presence than 2D video [27]. For these reasons, VR feels more immersive than 2D movies, such as Tab, and simulated experience that exists in the video. These results suggested that using VR for AO could provide a higher immersion score and promote acquisition of bp-prosthetic control.

Clinical significance

The clinical significance of this study is as follows: The combination of VR and prosthetic training in upper limb amputees can facilitate prosthetic control skills in the short term. As a result, it is predicted that rejection of the prosthesis that occurs in the early stage of prosthesis training can be reduced, leading to an increase in continuous use. Additionally, efficient prosthetic training may contribute to reduction shortening of the training period and medical costs. We believe that the reduction in the rejection of prosthesis and increase in the use of the prosthesis in daily life will lead to an improvement in the QOL of the upper limb amputee. Furthermore, AO using VR can be performed when it is difficult to practice prosthesis operation after stump formation and skin grafting.
Study limitations

The subjects of this study were young healthy adults. Therefore, the effect may differ depending on the age. Moreover, it is necessary to apply the method to clinical research on upper limb amputees and confirm the effects. Furthermore, in this study, only two tasks, BBT and BKT, were considered, so it is necessary to consider more tasks in the future.

Conclusions

In this study, we examined whether the AO training using VR was effective in acquiring bp-prosthetic control skills in the short term. As a result, bilateral manual dexterity suggested that VR$_{1st}$ and VR$_{3rd}$ showed more effective acquisition of prosthetic control compared to Con. Additionally, the VR$_{1st}$ and VR$_{3rd}$ showed higher immersion scores during AO than the Table 3$_{rd}$, and it was suggested that the higher the immersion score, the shorter the BKT task execution time. Therefore, VR-based AO training is effective in acquiring the bp-prosthetic control in the short term. Especially, it is effective for upper limb amputees to acquire bilateral prosthetic control skills. It may help them to reacquire an ability of daily life.

Abbreviations

Body-powered prosthesis, bp-prosthesis; VR, virtual reality; AO, action observation; MI, motor imagery; BBT, box and block test; BKT, bowknot task; VAS, Visual Analog Scale; Tab, tablet device; Con, control

Declarations

Ethics approval and consent to participate

This study was approved by the Ethical Review Board of the University of Kawasaki Medical School (No. 3497) and conducted in accordance with the regulations of the Ethical Review Board. We explained the content and purpose of this study to all participants and obtained written informed consent prior to participation in the experiments.

Consent for publication

We obtained written informed consent for publication from all participants.
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

The authors declare that they have no competing interests.

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Authors’ contributions

MY, HK, SD, AU, YI, SK, JH, HO, KS, KH, and TS defined the study protocol. AU cooperated in VR. MY and JH was responsible for participant recruitment. MY and SK conducted the experiments. MY, HK, and JH performed the analysis and interpretation of data and wrote the manuscript. HK, SD, AU, YI, SK, JH, HO, KS, KH, and TS provided advice on writing the manuscript.

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Figures

Figure 1

Body-powered prosthetic (bp-prosthetic) simulator a. The bp-prosthetic simulator consists of a hand hook, rod, socket, cable, and harness. b. All participants wore the simulator on their left upper limb. The simulator can be controlled by connecting a cable to the 8-shaped shoulder harness. c, d. The hand hook opened with left shoulder flexion and scapular abduction and closed with left shoulder extension and scapular adduction.
VR1st, VR3rd, Tab1st, and Tab3rd group video image a, b. The VR1st and Tab1st videos were a point of view as if one was performing a prosthetic operation (first-person perspective). VR1st watched a 3D video. Tab1st watched a 2D video. c, d. The VR3rd and Tab3rd videos were a viewpoint from which movement of the scapula to the forearm was easy to observed when performing a prosthetic operation (third-person perspective). VR3rd watched a 3D video. Tab3rd watched a 2D video.
Protocol Pre, pre-intervention; S1, Session 1; S2, Session 2; P1, Post 1; P2, Post 2; BBT, box and block test; BKT, bowknot task; AO, action observation

Before the intervention (Pre), BBT and BKT were evaluated as an evaluation of the prosthetic performance. Then, the participants were divided into five groups (VR1st, VR3rd, Tab1st, Tab3rd, Control) for intervention. After the intervention, the same evaluation as a pre-intervention was conducted. Furthermore, with the exception of the control group, the immersion during action observation and motor imagery was evaluated. This protocol was repeated twice.
Figure 4

Box and block test (BBT) change rate The graph shows the BBT change rate. This graph shows the BBT change rate of Post1 and Post2 based on the Pre score. The mean (± SD) is shown on the graph. The vertical axis of the graph shows the change rate from Pre. A significant main effect for sessions were found (F (2, 14) = 109.769 p < 0.001); however, there was no significant main effect for groups in the ratio (F (4, 28) = 0.424, p = 0.790), nor was the interaction significant (F (8, 56) = 0.512, p = 0.842).
Figure 5

Bowknot task (BKT) change rate. The graph shows the BKT change rate. This graph shows the BKT change rate of Post1 and Post2 based on the Pre score. The mean (±SD) is shown on the graph. The vertical axis of the graph shows the change rate from Pre. There was main effect of group \( F (4, 28) = 3.792, p = 0.014 \). Among groups, VR1st and VR3rd showed higher rates than Control (Con) \( p < 0.001; \ p < 0.001 \), respectively. There was main effect of group among sessions \( F (2, 14) = 176.935 \ p < 0.001 \). The two-way interaction between groups and sessions was not significant \( F (8, 56) = 1.863, p = 0.084 \).
Correlation between immersion and bowknot task (BKT) change rate The graph shows correlation between immersion and BKT change rate. The vertical axis of the graph shows the change rate from Pre. The horizontal axis of the graph shows immersion. There was a significant negative correlation between immersion and BKT change rate (Spearman’s rs = -0.47, p = 0.007).