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Walking Practice Combined with Virtual Reality Contributes to Early Acquisition of Symmetry Prosthetic Walking: An Experimental Study Using Simulated Prosthesis

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Abstract: Virtual reality (VR)-based rehabilitation has been used in lower limb amputees; however, the extent to which VR is effective in reacquiring symmetrical gait in lower limb amputees is unclear. The purpose of this study was to confirm whether a VR intervention is effective in obtaining a simulated prosthetic gait. The participants were 24 healthy males who had never worn a simulated prosthesis. They were divided into three groups: VR, tablet, and control groups. The intervention consisted of 5 min of in situ stepping on parallel bars and watching a video of a simulated prosthetic leg walker on a head-mounted display or a tablet. Measurements included Gait Up parameters during a 10-m walk and immersion scores. After the intervention, there was a significant interaction between walking speed and leg swing speed in the VR group. The rate of improvement in walking speed and immersion scores was significantly higher in the VR group than in the other two groups, and there was a significant positive correlation between the rate of improvement and immersion scores. Compared to the tablet and control groups, the VR group showed the highest rate of immersion and improvement in walking speed.

Keywords: rehabilitation; virtual reality; lower limb amputee; gait ability; symmetry

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1. Introduction

The majority of lower limb amputations are vascular disorder-related amputations (DRA) due to complications of the vascular system and diabetes [1,2]. As the number of patients with diabetes worldwide is estimated to be 170 million and is expected to increase to 366 million by 2030, the number of lower limb amputees (LLAs) is also expected to double by 2050 [3]. Lower limb amputation has a significant socioeconomic impact by reducing functional capacity, autonomy, and quality of life [4]. Lower limb prosthesis (LLP) provides support for physical function that prevents increased left-right asymmetry, which does not only improve activities of daily living (ADL) but also positively impact prognosis [5]. Therefore, rehabilitation is important to improve the performance of ADLs in LLAs.

The key goal of rehabilitation for LLAs is to restore and maintain maximum independence during mobility [6]. Furthermore, it has been reported that LLAs have a more asymmetrical gait pattern than that of healthy individuals [7], and the repetition of this pattern may pose a risk of injury to the unamputated side [8,9]. The priority of the rehabilitation process for LLAs is to retrain an optimal symmetrical gait. A systematic review on the gait of LLAs, reported positive effect after gait training [10]. Treadmill training is considered a common approach for rehabilitation, but it has some limitations such as reduced energy expenditure [11–13]. The gait training approach, the duration of training, and the types of weight-bearing and walking exercises suitable for rehabilitation in lower limb amputation is still unclear [12]. Thus, there is a lack of evidence on the most effective training method to obtain a more symmetrical gait after lower limb amputation.

The application of virtual reality (VR)-based rehabilitation in LLAs has been gaining attention. A recent study reported that walking ability and balance ability improved after using a VR game exercise together with conventional physical therapy [14]. Furthermore, a study that required patients to practice walking while watching a VR on a treadmill reported that walking ability improved more than that without watching a VR [15]. Thus, the combined use of VR has a positive effect on the reacquisition of walking ability. However, it is difficult to apply VR to the rehabilitation of lower limb amputees in clinical settings, because most interventions using VR are not direct interventions on walking ability, but interventions performed for the purpose of the effects obtained by the game. VR-based rehabilitation promotes motor learning. In a previous study that investigated the effectiveness of VR-based rehabilitation for imitation movement practice of a simulated prosthetic hand in healthy adults, the effect of motor learning was enhanced by imitating VR images rather than imitating tablet images [16]. In addition, this previous study used a head-mounted display; VR is more immersive in images, of which watching images from a first-person perspective is more effective. Although there have been studies on motor learning for upper limb amputees, to the best of our knowledge, no interventional studies have focused on motor learning for LLAs. The simulated prosthesis can be worn by a healthy person to experience the sensation of asymmetry in LLAs. Although previous studies using simulated prostheses have examined the effects of different practice methods on gait training [17], no study using VR has been conducted. Therefore, the purpose of this study was to investigate whether in situ foot-stepping in parallel bars, which is a conventional introduction to prosthetic gait rehabilitation, combined with watching a simulated prosthetic-legged proficient person can contribute to shortening the time needed to regain walking after lower limb amputation. We hypothesized that walking practice while watching a VR would be more immersive and improve walking speed than walking practice while watching a tablet.

2. Materials and Methods

2.1. Participants

A prior sample size calculation was performed using G*Power 3.1 [18], and to test the primary outcome, 18 participants were required to obtain 80% power ($\alpha = 0.05$, effect size = 0.40). Therefore, the study included 24 healthy men who were students at Hiroshima University. All participants met the following inclusion criteria: (1) age between 20 and 25 years, (2) no history of neurological or orthopedic diseases, and (3) no experience using simulated prostheses. The exclusion criteria were as follows: (1) those who had difficulty wearing the simulated prosthesis and (2) those with visual impairment. Thirty-four participants were screened prior to enrollment; ten participants who were unable to wear the simulated prosthesis were excluded from the study.

The study participants were randomly assigned to the following three groups using computer-generated numbers: the “VR group,” the “tablet group,” and the “control group.” This study was conducted in accordance with the guidelines proposed in the Declaration of Helsinki and approved by the Epidemiology Ethics Committee of Hiroshima University (approval ID: E-2398). All enrolled participants gave written informed consent before participating in the study. Participants were randomly assigned to three groups, after which their weight and height were measured. The weight and height scale “Digital Body Composition Analyzer with Manual Height Meter (BH-300A-N, Tanita, Tokyo, Japan)” was used to measure the weight and height.

2.2. Wearing Simulated Prosthesis

A simulated prosthetic leg (Figure 1a) was used to assess the ability to walk with the prosthesis. None of the participants had any previous experience using a simulated prosthesis. The simulated prosthesis consisted of a socket, prosthetic knee joint and foot, pylon, and their adapters. A 3R60 knee joint (Ottobock, Ltd., Tokyo, Japan) was used. Previous studies about definition of dominant leg are whether kick the ball or not [19]. The participants were instructed to wear the prosthesis on their dominant foot (the side that is used to kick a ball). Therefore, the prosthesis was worn on the dominant leg (all on the right) (Figure 1b). A skilled prosthetist and well-trained staff adjusted the tension of the belt and the angle of the joints for each participant while fitting the prosthesis.

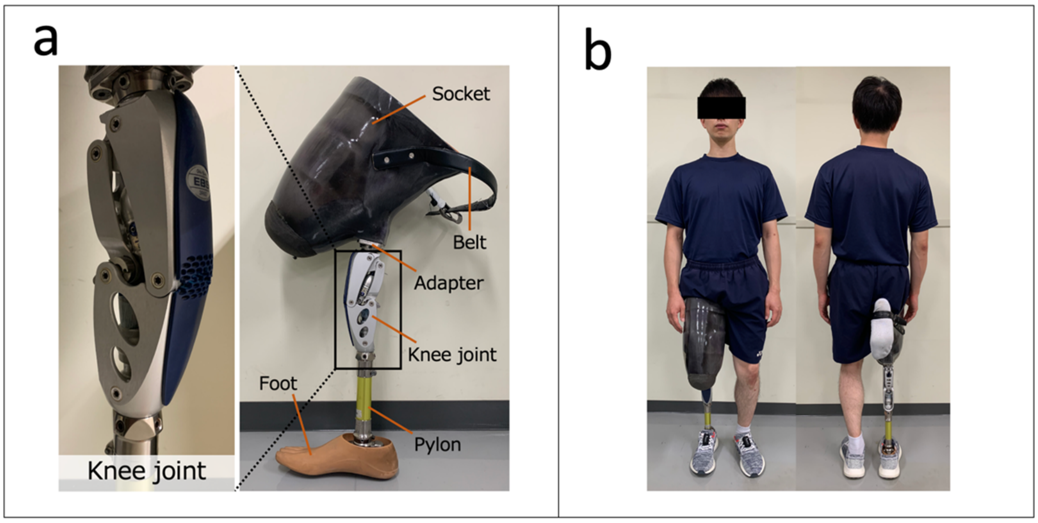

Figure 1. Simulated prothesis and wearing. (**a**) Simulated prosthesis. (**b**) All participants wore the simulated prothesis on their right lower limb. The right knee was bent, and the lower leg was inserted into the socket. The foot is fastened with the belt to prevent the lower leg from slipping out of the socket.

2.3. Intervention

The participants were divided into three groups (VR group, tablet group, and control group), and each group consisted of eight participants. The protocol used in this study is shown in Figure 2.

First, all participants were fitted with a simulated prosthesis, and then they practiced walking with the simulated prosthesis in parallel bars for 5 min. Based on a previous study that investigated the effects of VR intervention on walking and balance abilities, which was conducted for 5 min per set [14], we selected a 5-min intervention time. Subsequently, a pre-intervention evaluation of a 10-m walk test was conducted, after which the participants rested for 5 min. The participants then performed in-situ foot stamping for 5 min in the parallel bars [13]. The three groups underwent the intervention as follows:

(1) VR group: Participants wore a head-mounted display (HMD, Mirage Solo with Daydream, Lenovo, Hong Kong, China) and watched VR images while walking with 3D images of 180° vertically and horizontally and 180° stereoscopic view. The participants were instructed to watch the 3D images as if they were walking and step on the spot along with the images themselves.

(2) Tablet group: A tablet terminal (Tablet, iPad 5th generation, Apple, CA, USA) was set up at eye level, and the participants watched a 2D video on tablet. The participants were instructed to watch the video as if they were walking and step on the spot along with the images themselves.

(3) Control group: Participants were instructed to only step on a spot for 5 min.

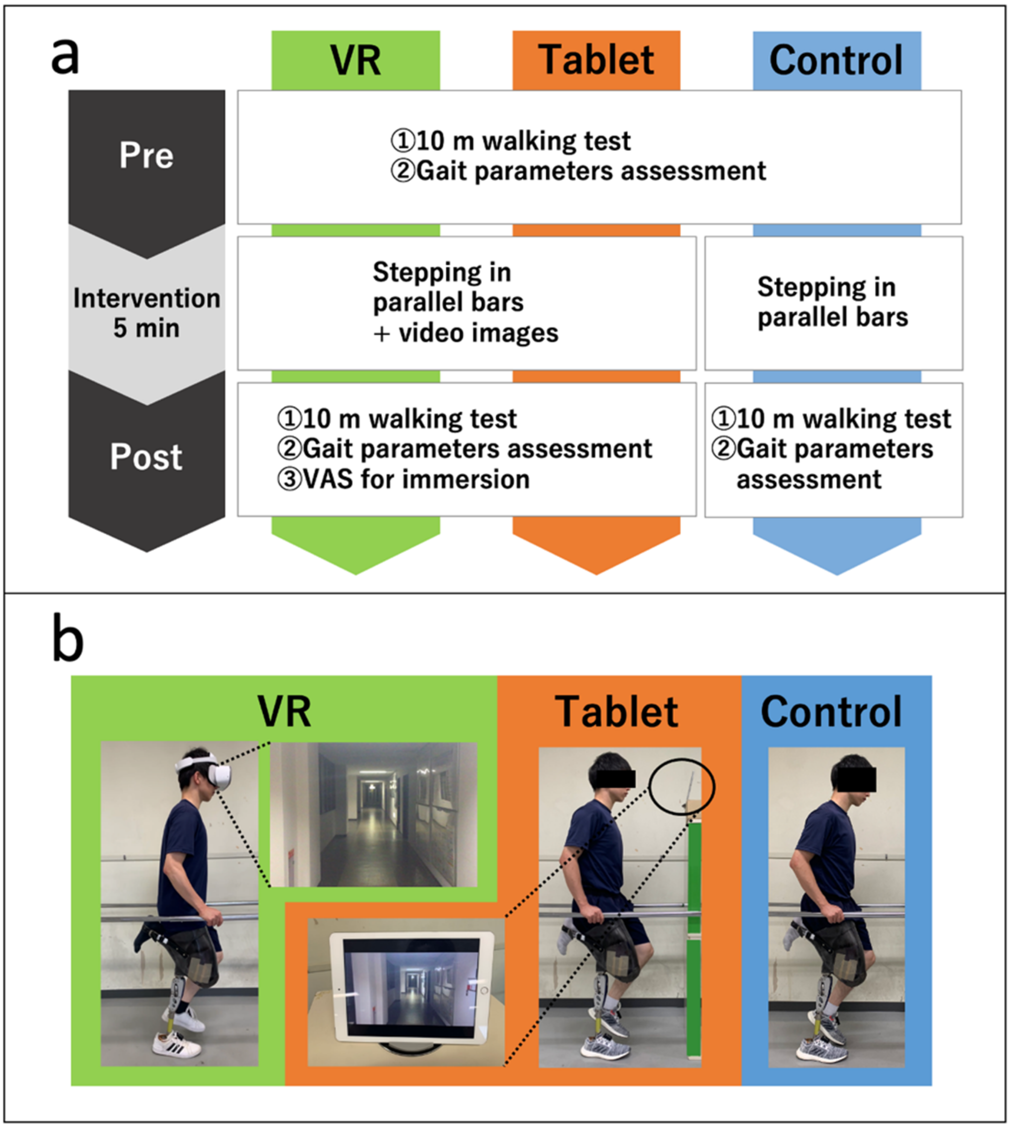

Figure 2. The flow of intervention in this study. (**a**) The protocol of this study; (**b**) the method of intervention.

Thus, each group watched the video differently. The images used in the intervention were the same for both the VR and tablet groups. The video was captured by a 360° camera (Key Mission 360, Nikon, Tokyo, Japan) attached to the head of an individual who could walk symmetrically in a straight line with the simulated prosthetic leg. Post-intervention evaluation was then conducted.

2.4. Spatio-Temporal Parameters and Immersion Scoring

To evaluate the walking speed, a 10-m walk test was used. This test is a reliable and valid assessment tool used in various conditions including LLAs and Parkinson's disease [20,21]. The participants were instructed to walk in a straight line, down a 14-m sidewalk at their fastest walking speed. The first 2 m and the last 2 m of the 10-m walk were used for acceleration and deceleration. Walking speed was calculated by dividing the walking distance by walking time measured with a stopwatch.

The Gait Up system (Gait Up, Lausanne, Switzerland) was used to evaluate the detailed parameters during walking. The Gait Up system is a valid and reliable wearable device for evaluating gait parameters among various populations including LLAs [22–24]. The dimensions of the Gait Up sensor were 50 mm × 40 mm × 16 mm, and the weight was

36 g. Two wireless inertial sensors with 3-axis accelerometers were attached on top of the shoe (Figure 3). The spatiotemporal parameters recorded in each trial were velocity (m/s), stride length (cm), and cadence (step/min). The measurements were recorded before and after the intervention, and three trials were performed successively. Data were calculated as the mean of the three trials.

Figure 3. Two Gait Up sensors attached to each foot.

The visual analogue scale (VAS) ranging from 0 (not fully immersive) to 100 (fully immersive), was used to assess immersion in the visuals during the intervention using the VR system and tablet. Immediately after the 5-min intervention, participants provided an immersion score to rate the immersive visual experience provided by the video [16].

2.5. Statistical Analysis

The Shapiro–Wilk test was used to test for normality. After normality was confirmed, the relative changes of the 10-m walking time among the groups (VR, tablet, control) and before and after the intervention (pre, post) were analyzed using a two-way analysis of variance. Immersion scores were compared between groups (VR, Tablet) using a Mann–Whitney U test. In addition, the Kruskal–Wallis test was employed to compare the percentage of improvement in gait speed between the groups. Multiple comparisons with Bonferroni correction were used for post-hoc comparisons when a significant main effect was found. The effect size of each measure was assessed using $r(Z/\sqrt{n})$, where $r > 0.5$ indicated a large effect size [25]. Furthermore, the relationship between immersion and the rate of improvement in walking speed was examined using Spearman's rank correlation coefficient. All results are reported as mean $\pm$ standard deviation or medians [interquartile range]. Statistical analysis was performed using IBM SPSS version 27.0 (IBM, Tokyo, Japan). The significance level was set at 5%.

3. Results

3.1. Participants

Participants' age, height, body weight, and body mass index (BMI) for each group are shown in Table 1. Height and body weight were measured using the scale (height: PA-200, UCHIDAYOKOCO, Ltd., Japan; body weight: TBF-410, TANITA, Tokyo, Japan). For all these factors, no significant differences among the groups were observed.

Table 1. Participants' demographic data.

	Total (n = 24)	VR (n = 8)	Tablet (n = 8)	Control (n = 8)	p-Value *
Age	20.5 ± 1.3	20.1 ± 1.2	20.4 ± 1.1	21.0 ± 1.6	0.411
Height (cm)	170.1 ± 2.4	170.1 ± 0.9	170.1 ± 1.5	170.0 ± 4.0	0.973
Body weight (kg)	60.4 ± 5.7	59.1 ± 5.5	60.9 ± 6.1	61.3 ± 6.0	0.741
BMI (kg/m^2)	20.9 ± 1.9	20.4 ± 1.9	21.0 ± 1.9	21.2 ± 2.1	0.689

Data are presented as the mean ± standard deviation. BMI: body mass index. *: Student's t-test.

3.2. Follow-Up

The results of the gait speed and other walking parameters are shown in Table 2. Significant main effects of the intervention were found in gait speed (F = 59.1, p < 0.01), cadence (F = 30.6, p < 0.01), stride length (F = 8.3, p < 0.01), swing speed (F = 28.5, p < 0.01), and loading (% of stance phase, F = 9.8, p < 0.01). The interaction effect was significant for gait speed (F = 9.6, p < 0.01, η^2 = 0.48) and swing speed (F = 6.0, p < 0.01, η^2 = 0.40). Thus, the participants significantly improved their gait speed and walking parameters after the intervention, and there were significant differences in gait speed and swing speed among the groups.

Table 2. Spatio-temporal parameters at pre-intervention and post-intervention.

	Pre-Intervention			Post-Intervention			Main Effect (Time)		Interactive Effect (Time * Group)		
	VR	Tablet	Control	VR	Tablet	Control	F	p-Value	F	p-Value	η^2
Gait speed (m/s)	1.1 ± 0.3	1.2 ± 0.3	1.3 ± 0.2	1.4 ± 0.3	1.2 ± 0.3	1.4 ± 0.2	59.1	<0.001	9.6	**0.001**	0.48
Cadence (steps/min)	105.3 ± 11.4	105.8 ± 9.69	110.9 ± 10.0	116.5 ± 11.3	111.5 ± 8.9	114.8 ± 12.1	30.6	<0.001	3	0.07	0.2
Stride length (cm/s)	1.3 ± 0.17	1.2 ± 0.27	1.3 ± 0.13	1.4 ± 0.15	1.3 ± 0.25	1.3 ± 0.1	8.3	0.009	1.3	0.3	0.1
Swing speed (m/s)	3.4 ± 0.7	3.4 ± 0.9	3.6 ± 0.5	3.9 ± 0.6	3.5 ± 0.9	3.7 ± 0.6	28.5	<0.001	6	**0.008**	0.4
Loading (%Stance)	13.3 ± 3.2	17.3 ± 5.0	16.8 ± 5.4	16.7 ± 4.7	18.3 ± 6.2	17.4 ± 4.3	9.8	0.005	2.8	0.08	0.2

Data are presented as the mean ± standard deviation. * p values < 0.05, considered significant interactive effects (indicated with emboldened font).

3.3. Immersion Scale

The relative changes in gait speed between each group and the comparison of immersion scores are presented in Table 3. The Kruskal–Wallis test revealed a significant difference in the rate of improvement in walking speed among the groups (p = 0.02). Subsequent post-tests showed significant differences between the control and VR (p < 0.01, r = 0.68) and between the tablet and VR (p < 0.01, r = 0.58) groups. The immersion scores were 71.5 [60.2–81.2] and 50.5 [35.7–65.7] for the VR and tablet groups, respectively, with significantly higher immersion in the VR than in the tablet group (p = 0.045, r = 0.50). The results of the correlation test between the immersion score and the improvement rate of walking speed are shown in Figure 4. There was a significant positive correlation between immersion score and the improvement rate of walking speed (r = 0.657, p < 0.01).

Table 3. The relative change of gait speed between each group and the comparison of immersion score.

	VR (n = 8)	Tablet (n = 8)	Control (n = 8)	p-Value
The improve rate of gait speed (%)	19.3 [17.4–23.5]	5.8 [3.1–10.4]	6.3 [3.2–9.4]	**<0.01** [a,b]
Immersion score (score)	71.5 [60.2–81.2]	50.5 [35.7–65.7]	-	**0.03** [a]

Data are presented as the medians [interquartile range]. Statistical analysis: Kruskal–Wallis test. Post-hoc comparisons: Bonferroni correction; * p values < 0.05, are considered significant (indicated with emboldened font). [a] Significant difference between the VR and tablet groups (p < 0.05). [b] Significant difference between the VR and control groups (p < 0.05).

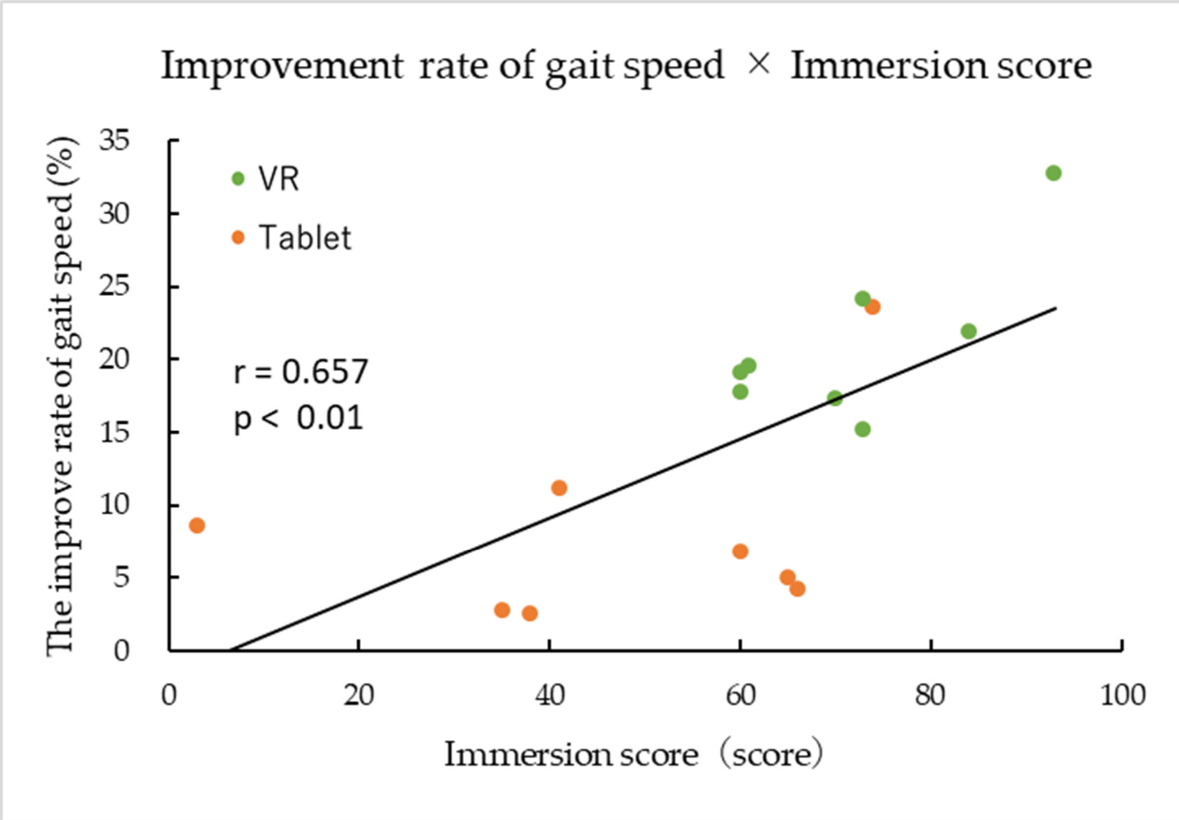

Figure 4. Correlation between the improvement rate of gait speed and the immersion score. The graph shows the correlation between the improvement rate of gait speed and the immersion score. The vertical axis of the graph shows the improved rate of gait speed. The horizontal axis of the graph shows the immersion score. There was a significant positive correlation between the improvement rate of gait speed and the immersion score ($r = 0.657$, $p < 0.01$).

4. Discussion

The purpose of this study was to investigate the effect of a VR-based practice for acquiring prosthetic gait compared with that of a conventional or tablet method. The main finding was that the combination of a VR-based and conventional rehabilitation was effective more than only a prosthetic leg gait rehabilitation. To the best of our knowledge, this is the first study to examine the effects of VR in conjunction with gait rehabilitation on the gait parameters of LLAs. A previous study reported that VR was used together with simulated prosthetic hand movement proficiency training is proficient [16]. In the current study, the focus was on a simulated prosthetic leg, but its combination with VR was shown to have a similar intervention effect.

All the parameters recorded by Gait Up showed a significant main effect after the intervention, indicating that the 5-min in-situ foot stomping in the parallel bars was effective regardless of the intervention condition. In the early stages of after the prosthetic foot is worn, it has been shown that encouraging loading on the side of the prosthetic foot improves walking ability [26]. Our results suggest that in-situ foot stamping with the simulated prosthesis was effective as walking practice with a prosthesis, even for beginners. In addition, there was a significant interaction between walking speed and swinging speed. In the post-test, there was a significant difference in the improvement rate of walking speed between the VR the other groups, indicating that walking speed can be further improved by the combination of VR with an intervention.

In addition, it has been reported that symmetry in walking is improved when the maximum walking speed is increased [27]. This suggests that the greatest improvement in walking speed with the VR-based intervention may have also improved the walking symmetry of the participants during walking. However, this is only a prediction because we did not assess walking symmetry in this study.

When observing a visual pattern of motion in a particular direction, the observer perceives the motion as if it were in the opposite direction, which is called the vection effect [28]. In this study, the visual cortex of a person who can walk symmetrically with a prosthetic leg was filmed. Due to the vection effect, participants are expected to feel as if they are moving forward in a symmetrical rhythm. Previous studies have shown that the vection effect increases as the viewing angle of the visual stimulus increases [29]. In our study, the VR group wore HMDs and viewed images in a virtual space, while the tablet group watched the video on a tablet in front of them. It has been reported that there is a positive correlation between immersion and vection effect [30,31]. The VR group had a significantly greater sense of immersion than the tablet group, and there was a positive correlation between the sense of immersion and the rate of improvement in walking speed, suggesting that the vection effect was greater in the VR group, and the intervention in that group was the most effective compared to that in the other group.

The current challenges in the rehabilitation of LLAs are the fear of falling, psychological effects induced by pain, lack of prosthetic wearing duration, and lack of follow-up after discharge [32]. Studies have reported that the use of VR for rehabilitation leads to “enjoyment” and “motivation” [33,34]. These findings suggest that the application of VR to the rehabilitation of lower limb amputees may provide a positive psychological effect and promote an improvement of wearing duration. In addition, since VR is not affected by the environment, it is advantageous such that the patient can practice prosthetic walking at home after discharge.

In a situation where the acquisition of symmetric prosthetic walking in a short period is required, VR in combination with in-situ stepping in the parallel bars can be used because a large improvement in walking speed was obtained in a short period of time (5 min) in this study. Thus, in this study, we have presented the possibility that this method can be used as an introduction to gait rehabilitation for LLAs.

However, our study has some limitations. First, the participants were healthy adult men, and the intervention was performed using a simulated prosthetic gait. It is unclear whether the results of this study can be directly applied to individuals with lower limb amputation. Therefore, we believe that it is at least worthwhile to use it for the introduction of rehabilitation of LLAs, although it needs to be studied in the future in patients with LLAs to see if the same effect can be obtained in rehabilitation of LLAs. Second, the intervention time was only 5 min. Although we observed an improvement in walking speed even with a 5-min intervention, the optimal training duration is unclear. Third, only acute effects were observed. Since our results suggest only an acute improvement a long-term follow-up and examination of its sustained effects is necessary.

5. Conclusions

In this study, we investigated the effectiveness of VR-based simulated prosthetic gait practice for short-term acquisition of simulated prosthetic gait; the VR group showed an improvement in walking speed compared to the tablet and control groups. Furthermore, the VR group showed a higher immersion score during the intervention than that by the tablet group, and there was a correlation between the rate of improvement in walking speed and the immersion score. This indicates that the higher the immersion score, the shorter the walking time.

Therefore, our findings suggest that VR-based rehabilitation may be an effective way to introduce gait rehabilitation for LLAs. The results may help improve the quality of life of these individuals.

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Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

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