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Improving Walking Performance in Prosthetic Leg Users: The Role of Virtual Reality and Audio Feedback

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Abstract. Virtual reality (VR) has emerged as a promising technology for enhancing the rehabilitation process and improving the life quality for lower limb prosthetic user. The integration of audio within VR environments can significantly impact the performance of lower limb prosthetic user, improve their gait patterns, enhance balance control, and avoid user from falling. This research paper investigates the effectiveness of VR and audio stimuli in improving gait in amputees wearing prosthetic legs. A VR-based training system is developed, utilizing a head-mounted display (HMD) and audio cues synchronized with footsteps or slowed down. Thirteen transfemoral prosthetic leg users participate in the study, assessing the impact on gait parameters. Participants were asked to walk in 3 conditions: without audio (WA), with audio (A), and slow tempo audio (SA). Results demonstrate significant enhancements in step length, stride length, and step time, achieving balance between the prosthetic and normal limbs. The integration of audio stimuli proves advantageous in enhancing walking performance and addressing asymmetries. The findings suggest that VR with slow-tempo audio cues holds promise for improving rehabilitation outcomes for prosthetic leg users. Future research should focus on optimizing training methods and exploring full potential of audio-integrated VR for gait rehabilitation in amputees.

1 Introduction and Objectives

The use of prosthetic legs by amputees often leads to gait disturbances, indicating that merely designing a good prosthetic leg is insufficient to address this problem. [1]–[3]. To minimize gait disturbances and facilitate adaptation, amputees require accelerated training, which has been shown to enhance proprioceptive sensors crucial for walking activities [4]. Treadmill exercise is a widely employed method for lower limb amputee rehabilitation. It allows users to cover long distances without requiring extensive training spaces, reduces falling risks, and facilitates gait observation [5], [6]. In addition, walking speed which is one of the challenges of walking for prosthetic foot users can also be adjusted easily and becomes an aspect to be trained [7]. However, disparities between treadmill and overground

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walking surfaces can result in unfamiliarity and impact walking patterns [8]. Additionally, the repetitive nature of prosthetic leg training can be monotonous, potentially diminishing motivation [9]. Thus, there is a need to develop innovative training methods that simulate overground walking conditions and provide an enjoyable experience for trainees.

One promising technology for prosthetic foot training is Virtual Reality (VR), which immerses users in virtual environments [10]. This presence can make the virtual environment in VR feel real. VR has been demonstrated to make training sessions engaging [11]-[13], improve proprioceptive training through instability simulations, and aid in establishing body balance [14]. Among VR systems, the Computer Assisted Rehabilitation Environment (CAREN) has been utilized for prosthetic leg training. [5], [15]-[18]. CAREN projects virtual environments on a dome-shaped screen and incorporates a treadmill capable of simulating various surfaces and movements. Studies have shown that walking on CAREN is comparable to walking on the ground [5].

This study focuses on the development of a VR system to enhance the rehabilitation process for prosthetic foot users, particularly in improving their walking patterns. The selection of visual display technology is one aspect of the development, with VR Head Mounted Display (HMD) chosen for its immersive nature. However, concerns arise regarding the complete isolation of users from their visual surroundings when performing treadmill exercises using VR HMD. This makes the user unable to see the movement of the treadmill and potentially endangers them. One solution that can be used is the use of audio stimuli. In addition to being able to give a signal to the user regarding the speed of the treadmill, the use of audio treadmill walking is known to be able to speed up the walk [19].

The use of audio in the design, besides being expected to reduce the risk of falling, is also expected to improve the walking performance of prosthetic users. The walking speed of prosthetic foot users is relatively low [20] so it is expected that with the use of audio, the walking speed can increase. In addition, previous research on people with cerebral palsy showed that Rhythmic Auditory Stimulation (RAS) can improve walking abilities, especially velocity, stride length, and cadence [21]. The use of RAS is also known to increase stride length in people with Parkinson's , reduce index asymmetry of stance and stride times in stroke sufferers [22], and affect stride width in normal people [23].

This study aims to evaluate the impact of audio integrated with a VR-based training system on prosthetic walking performance. Specifically, the study investigates the influence of audio tempo on spatio-temporal gait parameters such as cadence, gait speed, stride length, and step length. Previous studies have demonstrated that matching the audio tempo with the user's walking speed can enhance these parameters [21], [24]. In another study, an audio tempo was evaluated which was slower than the user's walking speed. In Parkinson's sufferers, it is known that an audio stimulus that is slowed down by 15% of the initial walking speed can result in a greater stride length [25]. However, the same results were not found in studies involving stroke sufferers, where the use of a slower tempo was not able to produce an increase in stride length [26].

The objectives of this study are twofold: to analyze the effect of sound rhythm as audio stimuli in a VR system on the gait of lower limb prosthetic users and to provide recommendations concerning the use of audio stimuli in designing training for lower limb prosthetic user rehabilitation.

2 Methods

2.1 Participants

This research was conducted by involving 13 prosthetic leg users. All participants were men who used a transfemoral prosthetic leg, resulting from an accidental amputation. Participants have an age range of 20-50 years with an average age of 38.46 years (st.dev 7.4 years). There were 8 participants who had their right leg amputated and 5 participants who had their left leg amputated. Participants have experience using prosthetic legs, with at least 2 years experience.

2.2 VR-based Training System Development

The first step in this study was VR-based training system development. The training system was developed at the Work Engineering and Ergonomics Laboratory of the Bandung Institute of Technology (ITB). This system simulates running conditions on a straight track shown in the visualization using the Oculus Quest 2 Head Mounted Display (HMD). The walking simulation was carried out on a modified Kettler Ecorun R3 treadmill by adding handrails and body harnesses to keep participants safe. This system is also integrated with Kinect V.2.0 motion capture which is placed 1.5 m in front of the participant to detect foot movements. While the participant is walking, spatiotemporal data is processed and used to synchronize the movement of the virtual environment. The virtual environment will move according to the heel strike detected by Kinect.

The developed training system is capable of simulating several running conditions, by varying the visual slope, audio settings, and resistance. Visual slope is used to simulate walking conditions on flat, downhill and uphill tracks. The audio that can be simulated is the sound of footsteps, with a tempo that can be adjusted by inputting the resulting sound interval in seconds. Obstacles are given in the form of stones that appear randomly on the running track.

2.3 Design

The research protocol was approved by the ITB Research Ethics Committee which evaluates research protocols involving humans. All participants had signed an informed consent before being involved in the research and were allowed to stop their involvement in the research at any time.

There are four stages in this study, namely preparation, training, equipment setup, and experimentation. At the preparatory stage, participants were explained experimental procedures, filled in participant data, signed informed consent, and measured participants' body dimensions as input anthropometric data in the motion capture system. Next, participants will take part in a training session to familiarize themselves with walking using VR and a treadmill. The training session was carried out until the participants stated that they were used to using VR and walking on the treadmill. Also at this stage, participants were asked to determine the desired treadmill speed. Determining the speed according to the user's preference is intended to produce a natural gait according to the user's ability and prevent the user from falling due to an inappropriate walking speed. Participants were given 10 minutes of rest to recover before starting the equipment setup and experimentation. Next, the equipment was set up, 39 reflective markers were installed on the participant's body to detect the participant's movement with the Vicon Motion Capture. In the preparation stage, measurements of normal walking conditions were also carried out for 20 seconds. The step time data from normal walking conditions obtained from the Kinect are then used to determine the interval of a given footstep audio stimulus.

At the experimental stage, participants were asked to walk on a straight, horizontal track without obstacles in 3 conditions given in random order. The conditions given are running without audio (WA), with audio (A), and audio slowed down (SA). In the condition with audio, the audio interval given is the same as the average step time obtained in the initial running condition measurement, whereas in the slowed tempo audio condition, the audio interval given is 15% slower than the step time [27]. Each condition is executed for 20 seconds. The user's movement data while walking is measured using the Vicon Motion Capture System. Movement data from Vicon is then processed with the help of Vicon Nexus to obtain spatio-temporal data for the three running conditions. The spatio-temporal data for the three conditions were then compared with the help of the SPSS statistic 25 to find out whether there were significant differences between the audio conditions. Not all data recorded within 20 seconds is used because each participant has a different number of gait cycles. To obtain relatively stable gait data, only 20 gait cycles per condition per participant were processed and compared statistically. A visual display of the running simulation and data collection process can be seen in Figure 1 and Figure 2.

Fig. 1. A visual display of walking simulation on a VR-based prosthetic gait training system

Fig. 2. Data Collection

3 Results

3.1 Comparison of Prosthetic and Intact limb

The normality test was carried out on spatiotemporal data, namely step length, stride length, step width, step time, and stride time of 13 participants for the normal and prosthetic sides of the foot. Based on the Kolmogorov Smirnov test, it was concluded that most of the data did not meet the normal distribution ($p<0.05$) so that comparisons of the normal and prosthetic legs were continued using the Wilcoxon Sign Ranked Test. The average data and standard deviation and their visualization in graphs can be seen in Table 1 and Figure 3.

Table 1. Comparison of spatiotemporal parameters between prosthetic and intact limb

Parameter	*P-Value Wilcoxon Sign Ranked Test*	Prosthetic limb	Intact limb
Step Length (m)	0,000*	0,49 ± 0,04	0,43 ± 0,04
Stride Length (m)	0,000*	0,83 ± 0,07	0,79 ± 0,05
Step Width (m)	0,796	0,10 ± 0,05	0,10 ± 0,06
Step Time (s)	0,000*	1,20 ± 0,13	1,03 ± 0,10
Stride Time (s)	0,572	2,24 ± 0,12	2,23 ± 0,13

Note: Values are expressed in mean ± standard deviation

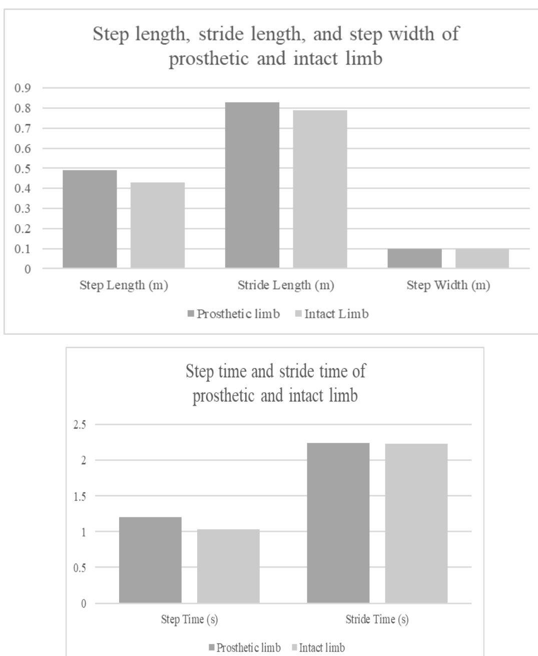

Fig. 3. Graph spatiotemporal parameters means between prosthetic and intact limb

From the mean comparison statistical test conducted using the Wilcoxon Sign Ranked Test, it can be seen that there is a significant difference in the parameters of step length, stride length, and step time between the prosthetic and intact limb with a significance value of 0.000. The step length and stride length of the prosthetic leg are longer than the normal foot, as well as the step time that appears.

3.2 Comparison of Gait in Treatment

The data normality test was carried out using the Kolmogorov-Smirnov which concluded that most of the spatiotemporal data in the three treatment conditions, namely without audio (WA), with audio (A), and slow audio (SA) were not normally distributed ($p < 0.05$). Thus, a comparison test between the three treatments was carried out using the Friedman test. The results of the Friedman test carried out and the average data and standard deviation for step length, stride length, step width, step time, and stride time can be seen in table 2 while the results of the Post-Hoc test can be seen in table 3.

Table 2. Comparison of spatiotemporal parameters between prosthetic and intact limb

Parameter	P-Value	Prosthetic Limb			P-Value	Intact Limb		
		WA	A	SA		WA	A	SA
Step Length (m)	0.000	0.49 ± 0.04	0.37 ± 0.03	0.37 ± 0.04	0.041	0.43 ± 0.04	0.45 ± 0.04	0.46 ± 0.04
Stride Length (m)	0.000	0.83 ± 0.07	0.83 ± 0.06	0.92 ± 0.09	0.001	0.79 ± 0.05	0.81 ± 0.04	0.89 ± 0.04
Step Width (m)	0.000	0.1 ± 0.05	0.13 ± 0.05	0.13 ± 0.05	0.000	0.1 ± 0.06	0.13 ± 0.05	0.14 ± 0.05
Step Time (s)	0.000	1.2 ± 0.13	0.96 ± 0.08	0.96 ± 0.09	0.000	1.03 ± 0.1	1.23 ± 0.08	1.27 ± 0.08
Stride Time (s)	0.019	2.24 ± 0.12	2.2 ± 0.1	2.23 ± 0.1	0.012	2.23 ± 0.13	2.2 ± 0.11	2.23 ± 0.11

Note: Values are expressed in mean ± standard deviation of the Without Audio (WA), With Audio (A), and Slow Audio (SA) conditions

Table 3. P-value post hoc test results using the Wilcoxon Signed Rank Test

Parameter	***Prosthetic Limb***			***Intact Limb***		
	WA-A	WA-SA	A-SA	WA-A	WA-SA	A-SA
Step Length (m)	0.000*	0.000*	0.865	0.231	0.016*	0.003*
Stride Length (m)	0.403	0.013*	0.000*	0.017*	0.000*	0.000*
Step Width (m)	0.000*	0.000*	0.064	0.000*	0.000*	0.181
Step Time (s)	0.000*	0.000*	0.289	0.000*	0.000*	0.000*
Stride Time (s)	0.107	0.430	0.045*	0.130	0.417	0.027*

Note: The table compares the conditions Without Audio-With Audio (WA-A), Without Audio-Slow Audio (WA-SA), and With Audio-Slow Audio (A-SA)

Friedman's test results show that there are significant differences in step length, stride length, step width, step time, and stride time with the difference in audio tempo given. This significant difference was found on both the prosthetic and normal feet ($p<0.05$). Further post-hoc tests using the Wilcoxon Signed Rank Test showed that significant differences between the two treatments were found in most of the treatments.

4 Discussion

The results of testing the difference between normal feet and prosthetic feet in 13 participants using Vicon motion capture system revealed significant differences in step length, stride length, and step time. Prosthetic foot users exhibited greater step length and stride length on the side of the prosthetic leg compared to the normal foot, consistent with findings from previous studies [28]–[30]. This phenomenon may be attributed to gait disturbances during the swing phase, where participants struggle to achieve sufficient clearance on the amputated leg side. As a compensatory mechanism, they adopt a circumduction gait pattern or form a semi-circular pattern while swinging the prosthetic leg. Possible factors contributing to this issue include an excessively long prosthetic leg or a narrow/loose prosthetic leg socket.

The longer step time observed in the prosthetic leg aligns with previous research findings [30]. This extended step time stems from the user's inability to maintain a prolonged stance phase on the prosthetic leg side, resulting in an imbalance with a shorter stance phase. Moreover, the swing time of the prosthetic leg is slower than that of the normal leg, further contributing to the longer step time. These asymmetries in step length, stride length, and step time have the potential to induce fatigue and musculoskeletal disorders in prosthetic leg users, necessitating intervention.

To address these issues, interventions should focus on optimizing prosthetic leg design, including the length of the leg and the fitting of the socket. Customizing these factors to individual users' needs can help achieve a more balanced gait pattern and reduce gait disturbances during the swing phase. Additionally, gait training programs should target improving symmetry and coordination between the prosthetic and normal legs, aiming to enhance overall gait performance and minimize the risk of fatigue and associated muscle disorders. Future research can explore the effectiveness of such interventions and identify other potential factors contributing to gait disturbances in prosthetic leg users.

The use of appropriate audio stimuli has the potential to address gait disturbances in prosthetic foot users, as evidenced by significant differences observed in step length, stride length, and step time parameters when using audio adjusted to footsteps or slowed down. This finding is consistent with previous studies [25], [31]. By providing audio cues that are tailored to footsteps or slowed down, a balance in gait parameters between the normal and prosthetic legs can be achieved. This is particularly important to address the longer step length of the prosthetic leg compared to the intact leg.

Regarding step length, the provision of audio and slowed down audio significantly reduced the step length of the prosthetic leg compared to the condition without audio. On the normal leg side, the use of slowed down audio significantly increased the step length. Comparing audio adjusted to footsteps with slowed down audio, the latter resulted in a significantly higher step length. This is beneficial in improving step asymmetry by shortening the step length of the prosthetic leg and extending the step length of the intact leg.

In terms of stride length, the use of slowed down audio significantly increased the stride length on the prosthetic leg side compared to the condition without audio. Comparing audio adjusted to footsteps with slowed down audio, the latter actually increased the stride length of the prosthetic leg. On the normal leg side, both audio and slowed down audio resulted in a higher stride length compared to the condition without audio, contributing to maintaining balance.

In the step time parameter, both audios adjusted to footsteps and slowed down audio reduced the step time on the prosthetic leg side and increased it on the normal leg side. This indicates a change in the user's walking strategy to match the audio cue, with faster movement of the prosthetic leg and slower movement of the normal leg. However, a longer step time was observed in the normal leg compared to the prosthetic leg, possibly due to the relatively short training time of 20 seconds per stimulus. Longer training durations and the inclusion of user rewards and motivation can enhance adaptation and improve running performance.

While the research findings are promising, there are several limitations to consider. The participants in the experimental session still relied on holding the handrail for stability during treadmill walking in the VR environment. This may have influenced their gait. However, efforts were made to minimize this factor through practice sessions and encouraging participants to gradually reduce reliance on the handrail. The duration and intensity of training were also suboptimal, with data collection limited to 20 seconds per treatment. A longer duration would allow for better adaptation and more robust impacts. Future research should consider longer and repeated training durations as a follow-up to this study.

5 Conclusion

In conclusion, in this study it is known that the use of audio in a VR-based prosthetic leg training system has great potential to have a positive impact on the user's gait. With the audio stimulus, the step length, stride length, step width, and step time on the normal foot side become larger. Meanwhile, the step length and step time on the prosthetic leg side becomes smaller with the audio stimulus to balance the gait of the normal leg side and the prosthetic leg side where in conditions without audio the step length, stride length, and step time of the prosthetic leg side is greater than the prosthetic leg side normal. Furthermore, the use of slowed audio can be considered to be a more challenging cue for the user so that it can provide a more significant change in performance.

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