Framework of Virtual Reality Based Training System for Improving Stability and Gait of Lower Limb Prosthetic Users

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Abstract

Prosthetic legs are needed by individuals with a lower limb amputee to improve their quality of life. However, the current designs have several limitations that requires substantial training for adaptation to improve posture and gait. As an emerging technology, virtual reality (VR) provides prospective capability for such rehabilitation training. This study aimed to propose a framework of VR-based training system for improving stability and gait of prosthetic users, focused on lower limb prosthetic and transfemoral or above-knee amputations. Previous studies have demonstrated the ability of VR to improve both stability and gait. However, the training system used seems to diverse. Based on an extensive literature study, we concluded that the VR-based training system should consider the following three subsystems: technology, content, and feedback. Each sub-system has its alternative combinations. Finally, this study proposes a framework that can be used to test the system efficacy and overall acceptance of the VR-based system.

Keywords
Virtual Reality, Training, Limb Prosthetic, Stability, Gait, and Ergonomics.

1. Introduction
Prosthetic legs are needed by people with lower limb amputees to improve their welfare (Maia et al. 2015). With the loss of their body parts, lower limb amputees have difficulty in walking and moving that will affect their daily activities. In Indonesia, to ensure the welfare of people with disabilities, the government stipulates a minimum quota for disabled workers in companies (Undang-Undang No 8 Tahun 2016). However, the implementation of this regulations has not been going well (Shaleh 2018, Susiana 2019). This is because of the difficulty in adapting workplace designs that are suitable for various disabilities.

The use of prosthetic legs is designed to increase user's functionality to have a normal activity according to their desired functional level (Chui et al. 2020). To meet the function, design of prosthetic should consider many factors such as the anatomy of the users, gait biomechanics, quality material, etc. However, this will be costly, and no wonder that the existing design of prosthetic leg still cause several problems (Andrysek et al. 2020, Brandt et al. 2019, Crea et al. 2017, Esquenazi 2014, Kline et al. 2020, Sheehan et al. 2016, Sturk et al. 2019).

Previous studies have reported common problems associated with the use of prosthetic legs, including gait disturbances and impaired stability. Gait abnormalities have been reported among prosthetic leg users (Andrysek et al. 2020, Brandt et al. 2019, Crea et al. 2017, Esquenazi 2014, Kline et al. 2020). Gait disturbances include knee flexion and hip abduction (Andrysek et al. 2020, Esquenazi 2014) as well as asymmetrical gait cycle between prosthetic and sound leg (Andrysek et al. 2020, Brandt et al. 2019, Crea et al. 2017, Esquenazi 2014, Kline et al. 2020). In normal people, the biological sensors present in the human anatomy interact with the environment and make humans able to walk stably. The loss of these sensors in prosthetic foot users results in gait disturbances (Keri et al. 2018). In additions, the lack of biological sensors also results in impaired stability experienced by prosthetic foot users (Fung and Perez 2011, Keri et al. 2018, Sheehan et al. 2016, Sturk et al. 2019). Their stability decreases with fatigue developed after long walks (Wong et al. 2015, Yeung et al. 2012, Yeung et al. 2013). Decreased stability has been associated with a higher risk of falls in prosthetic foot users (Sturk et al. 2019). The number of falling tendencies experienced by prosthetic users reached 52.4%, which was higher than general elderly populations perceived to have frequent falls (Miller et al. 2001).

It has been known that design is among the main solutions to overcome gait abnormalities and to reduce instability of using prosthetic legs (Andrysek et al. 2020, Brandt et al. 2019, Hafner and Askew 2015, Kadhim et al. 2020, Moradi et al. 2020, De Pauw et al. 2020, Segal et al. 2006). However, previous research suggested that in addition to design, adaptation may also have important role to improve gait and stability. In a study conducted by Segal et al. (2006), the failure of prosthetic design to produce dynamic and postural stability was suspected to be caused by a lack of user adaptation.

To accelerate adaptation in using prosthetic leg, training has been noted to be helpful. Training for prosthetic users can be done by walking on the ground (overground training) or using a treadmill. In contrast to overground training, training using a treadmill does not require a large place (Gates et al. 2012). Treadmills has a better preference in training since it is easier to observe how to walk and reduce the risk of falling (Gates et al. 2012). Moreover, by using a treadmill, walking speed can be easily regulated and can be used as an intervention factor in training (Sinitski et al. 2015).

Although training on a treadmill has many advantages over conventional overground training, walking on a treadmill for prosthetic leg users has some disadvantages. Treadmills have a different surface compared to the ground which will affect the way to walk (Gates et al. 2012). Training using both overground and treadmill must be done repetitively, and both are considered boring (Papegaaij et al. 2017). To answer this shortcoming, one alternative solution that can improve the performance of prosthetic leg training is the use of virtual reality (VR). VR is able to make users enter into a virtual environment and feel the virtual environment designed as is real (Chittaro and Buttussi 2015, Stevens and Kincaid 2015). Previous studies also stated that training with VR provides experience and fun (Horsak et al. 2020, Kramer et al. 2014, Lee et al. 2016). With these advantages, it is hoped that trainees motivation on training using walking on a treadmill will increase so that they are willing to participate in all training sessions.

The main objective of this study was to investigate the use of virtual reality-based training for users in amputees, especially transfemoral or above-knee amputations. Based on this investigation, this study proposed a framework of VR based training and evaluation methods to improve their posture, stability, and gait.

2. Methods

This research was carried out by conducting an extensive literature study to obtain a comprehensive mapping of the current state of the art of VR for training for prosthetic users. The previous studies were traced using the three search engines, Google Scholar; ScienceDirect; and Scopus with the main keywords "virtual reality", "lower limb prosthesis", "prosthetic leg", or "training". Of the three search engines used, 9 studies related to the scope of the research were obtained. These studies were involving a total of 174 participants. Further analysis was conducted to map the existing knowledge in terms characteristics, factors and training sub-system that may affect overall system effectiveness. Results of this mapping was then used as the basis for developing an analytical framework for the use of VR to improve the stability and gait of prosthetic foot users.

3. Results

3.1 Literature study results

The summary of previous research obtained from the literature study can be seen in Table 1.

Table 1. Mapping of the previous studies

No	Reference	Type of Study	Participants	Objective	Intervention	VR Technology	Activity	Result
1	(Andrysek et al. 2012)	Experiment	6 (children and adolescent transfemoral amputee)	To examine the safety, feasibility, and balance performance effects videogame system.	Two videogames involving weight shifting in standing were each played at home	Wii fit Video game	Game	Balance training at home using video games is perfect for children and adults with lower limb amputation. Interventions can be performed safely.
2	(Darter and Wilken 2011)	Case study	1 (transfemoral amputee)	To describe the effects of the training in a person with a transfemoral amputation.	Treadmill walking with real-time visual feedback on full-body gait kinematics, a walking path through a forested area	CAREN	Walking	The training produced improved frontal-plane hip, pelvis, and trunk motion during overground walking.
3	(Kruger 2011)	Experiment	11 (bilateral & lateral, transfemoral and transtibial amputee)	To determine the feasibility of using the CAREN for gait training, in individuals with lower limb amputations.	Participants walking on two scenarios: the continuous road and the road with overhead target	CAREN	Walking	All participants were found to increase their self-selected velocities; progression appears to be individua
4	(Miller et al. 2012)	Case study	2 (transfemoral amputee)	To describe the effects of a balance training program utilizing the Nintendo Wii™ Fit balance board and body- weight supported gait training	Training video games, including tilt table, skiing, tightrope walk, etc.	Wii fit Video game	Game	Participants demonstrated improvement in dynamic balance, balance confidence, economy of movement, and gait.
5	(Sheehan et al. 2016)	Case study	1 (transfemoral amputee)	describes walking function and mediolateral stability outcomes of an individual with a unilateral transfemoral amputation following a perturbation-based gait training intervention	Participants walk in an unstable virtual environment where the VE angle changes in two ways: pitching & rolling the surface	CAREN	Walking	There are improvements in function and stability. These benefits were retained at least 5 weeks after the final training session.

Table 2. Mapping of the previous studies (cont.)

No	Reference	Type of Study	Participants	Objective	Intervention	VR Technology	Activity	Result
6	(Sturk et al. 2018)	Experiment	10 (transfemoral amputee), 10 able bodied	Explore gait differences between K3- and K4-level transfemoral amputation across different surface conditions.	Walking in various surface condition	CAREN	Walking	Using the VR system, it can be observed that there are differences in the way people with K3 and K4 amputees walk.
7	(Sturk et al. 2019)	Experiment	10 (transfemoral amputee, 10 able bodied)	Describe and quantify how people with transfemoral amputations (TFA) maintain stable gait over a variety of surfaces;	Walking in various surface condition	CAREN	Walking	This research provides a comprehensive analysis of the different adaptations made by people without amputations compared to people with transfemoral amputations
8	(Horsak et al. 2020)	Experiment	49 (normal people)	developed a fully immersive VR based balance-control exergame	Participants had to pop soap bubbles with their hands during an exergame using VR	VR HMD	Game	The exergame is applicable in terms of usability and user experience
9	(Tao et al. 2020)	Experiment	64 (transfemoral & transtibial)	Examine usage of an in-home exergame, compared to control, unsupervised after supervised training by older persons with lower-limb amputation	Supervised vs unsupervised	Wii fit	Game	Unsupervised exercise duration remained consistent with supervised, but frequency was reduced. Social and clinical

3.2. VR-based training sub-system

Based on the literature study obtained, a VR-based training system can be composed of several main sub-systems. The combination of these subsystems has resulted in variations the VR training system used in previous studies. The subsystems include VR technology, content, and feedback.

1. VR Technology

Virtual environments can be presented using various types of technology or hardware, including the use of desktop-based VR, immersive VR, 3D-based games, building informational modeling (BIM) based, and augmented reality (Wang et al. 2018). From the nine previous study related to the scope of this research, six of them used immersive VR system, including the Computer Assisted Rehabilitation Environment (CAREN) (Darter and Wilken 2011, Kruger 2011, Sheehan et al. 2016, Sturk et al. 2018, Sturk et al. 2019) and Head Mounted Display (HMD) (Horsak et al. 2020). Three other studies have utilized Wii Fit Video Game that classified as 3D game-based VR (Andrysek et al. 2012, Miller et al. 2012, Tao et al. 2020). Using CAREN, the image of a virtual environment is projected on a concave dome-shaped surface. The user will experience the feel of entering and moving in the artificial environment by seeing the movement of the visual stimuli on the dome. In contrast to VR HMD, visual stimuli are provided using a display that is attached directly to the user's head and isolates the user from the visual stimulus in the real world. Both VR Caves such as CAREN and VR HMD have a high ability to immerse users in a virtual environment so that they are classified as immersive VR, as shown in Figure 1. On another hand, the Wii Fit video game is a video game console produced by Nintendo that is widely used for gaming, exercise, and rehabilitation. Although the visual stimulus is only given using a screen that displays a 3D model of a virtual environment, the feeling of entering the game experienced by the user makes this device classified as VR.

(a) (b)

Figure 1. Two type of technology that need to be evaluated
(a) CAREN system (Sheehan et al. 2016) and (b) VR HMD

2. Content or Simulated Activity

In general, the simulated activities for the rehabilitation of prosthetic foot users, especially for the transfemoral amputee, can be grouped into two types: walking tasks and game playing tasks. Sturk et al (2018, 2019) used a real task, a walking task to observe the gait cycle characteristics of prosthetic foot users. Furthermore, Darter and Wiken (2011), Kruger (2011), and Sheehan et al. (2016) used VR to simulate walking tasks with various challenges which were later found to be able to produce improvements in gait and stability. However, studies using games as an exercise activity have also found to give positive results in balance and gait improvement (Andrysek et al. 2012, Miller et al. 2012). The use of games as a training activity has a "stimulating", "enjoyment", and "energizing" score and a good user experience (Horsak et al. 2020).

3. Feedback

Feedback is an important factor in training, including lower limb prosthetic training. Feedback provides information about current conditions and helps trainees to develop a strategy to produce good balance and gait (Papegaaij et al. 2017). Feedback can be given while the training session is running or after the training session ends. While traditional training relies on trainers to provide performance feedback, using VR and a treadmill, real-time data on gait and stability indicators can be collected and given feedback on a poor and good performance by the user. Darter and Wilken (2011) provides performance feedback in the form of body balance parameters that are shown in real-time. Even though, no specific explanations were provided in other studies in term of feedback given, but with VR systems, the main feedback that can be received is movement feedback, while for game-based simulations, there are scores that can be shown (Horsak et al. 2020, Miller et al. 2012, Tao et al. 2020). From the literature study, it was found that all VR systems used in previous studies related to transfemoral prosthetic leg training were visual feedback. It is not known in detail regarding the use of other sensory modes as a channel to provide performance feedback.

4. A Proposed Research Framework

Previous studies suggested there are various designs of VR systems that can be used to improve stability and walking gait of prosthetic foot users. However, their efficacy is not known, and no data can be compared. Each study seems to focus only on one VR system in terms of one specific goal (Andrysek et al. 2012, Darter and Wilken 2011, Horsak et al. 2020, Kruger 2011, Miller et al. 2012, Sheehan et al. 2016, Tao et al. 2020). It is hoped that the VR system will not only provide good results in increasing stability and gait but also provide a good experience. To evaluate user experience, a holistic concept by Sauer et al. (2020) called Interaction Experience (IX) can be used. IX is a concept that integrating three big concept, usability, user experience, and accessibility, that widely used in ergonomic as primary concept to evaluate the performance of a designs, products, or services. The system that needed to be evaluated and the IX dimensions that needed to be measured can be seen in the Figure 2.

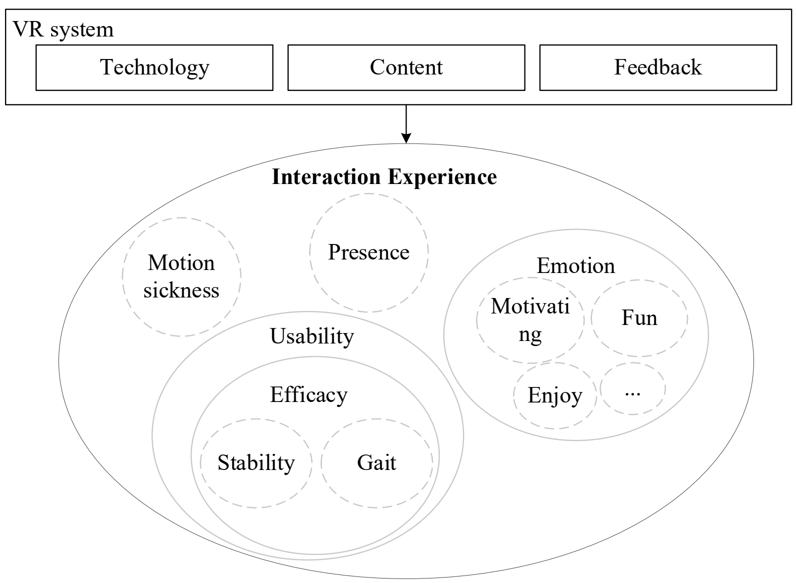

Figure 2. Interaction experience for VR system

4.1. Design of VR system

The development of VR-based training should be done by considering the above three subsystems. The first sub system to be evaluated is technology. Different technologies can give different effects to humans during the simulation. One of the differences that can arise with different types of VR is the level of presence (Stevens and Kincaid 2015). Presence is defined as the sense of being in the virtual world (Berkman and Akan 2019). From previous research, VR HMD uses a visual stimulus that completely covers the user from a real environmental stimulus (fully immersed) so that it is possible to have a higher level of presence. On the other hand, VR HMD has a higher potential for causing motion sickness due to vestibular disorders. Motion sickness is one of the most important challenges to consider in the development of VR systems (Lovreglio et al. 2018). This phenomenon appears in the form of symptoms such as nausea or vertigo experienced when using VR. Sickness when using VR arises because of a mismatch between the senses of sight (visual), vestibular senses, and somatosensory senses (Keshavarz 2016). Issues related to the emergence of motion sickness in VR have raised questions about the safety of using VR. For this reason, it is necessary to design a VR system with minimal sickness levels. In terms of technology selection, it is necessary to consider technology that has a high presence so that it can provide good training performance, but also produces low motion sickness. Previous research used three kinds of VR hardware, namely VR Cave (CAREN), VR HMD, and Wii as a

3D game-based VR. However, the technology from the Wii function as a game console can also be run by VR Cave and HMD, so if you want to evaluate it, the types of technology that need to be compared are VR Cave and HMD.

The second subsystem that needs to be determined is the content of the VR simulation. From previous research, it is known that the content used for prosthetic foot rehabilitation is walking activity and game activity. Determination of the simulated activity is important because different activity simulations can have different effects (Yazgan et al. 2019). Yazgan et al. (2019) have conducted a research on patients with multiple sclerosis (MS) by comparing two types of activities, gaming tasks and functional tasks to improve balance. Full games produced a higher balance based on the Berg Balance Scale (BBS) value. In addition, the trainees' quality of life when using game tasks was higher than functional tasks (Ferraz et al. 2017, Yazgan et al. 2019). Although user experience, such as the assessment of quality of life for game-based or exergame-based exercise, has been compared with functional training, the comparison is done for patients with multiple sclerosis (Yazgan et al. 2019) and Parkinson disease (Ferraz et al. 2017). The usability comparison of the two types of activities especially for lower limb prosthetic training has not been carried out. In VR development, it is necessary to compare usability between functional activities, namely walking tasks and gaming activities.

The next subsystem that needs to be considered is the stimulus that will be used to provide performance feedback. Nine previous studies used visual signals to provide information related to performance during training. In fact, by using VR, there are other stimuli that can also be utilized. In addition to visual feedback, VR can provide tactile and auditory feedback. The use of vibrotactile as performance feedback related to the symmetry of the temporal parameters of gait can improve gait symmetry (Crea et al. 2017). However, in other studies, it is known that with haptic devices, cognitive load increases and performance decreases (Erolin et al. 2016), giving haptic cues makes tasks more difficult and reduces task efficiency (Martinez et al. 2011). The installation of tactile feedback in overground training has also not succeeded in providing an increase in performance but does not result in an improvement in all participants (Yang et al. 2012). On the other hand, the audio signal given to VR is known to influence participants' perceptions regarding the fidelity of the visual display. However, it is not known whether the audio signal will be better than the tactile signal or if the visual feedback is sufficient for training users of the prosthetic foot. Determination of the stimulus mode will also determine how the level of presence of VR and the usability of the VR system as a whole.

VR development can be done by generating alternative VR systems which can be seen in Figure 3. There are 12 alternative VR systems that can be generated for further evaluation.

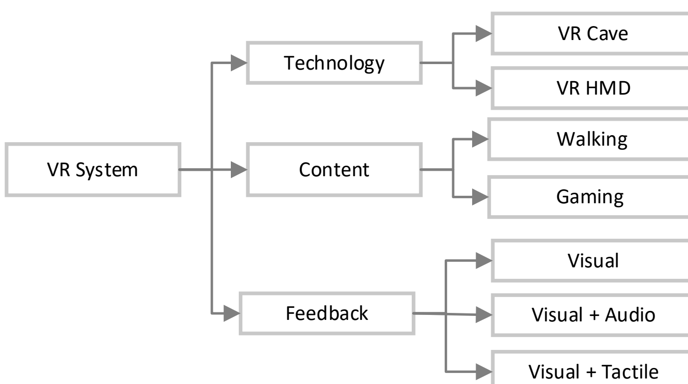

Figure 3. VR-based training system alternative

4.2. Evaluation Method of VR System

The main evaluation criteria should be the effectiveness of the VR system in achieving the main goal of training, namely improving stability and gait. Assessment of training efficacy is generally done by comparing gait and stability performance indicators before and after training. Gait performance and stability can be observed objectively using a force plate system. This system combines 3D motion capture with a force plate and can be used to collect gait cycle data with high sample rates (Sterigou 2020). Using the force plate system, various gait parameters can be measured such as temporal-spatial parameters (speed, stride length, stride time) (Darter dan Wilken, 2011, Sturk et al. 2018, Gates et al. 2012), hip, pelvis, trunk range of motion (Darter and Wilken, 2011, Sinitski et al. 2015) , as well as gait variability (standard deviation of speed, foot clearance, root-mean-square of medial-lateral trunk acceleration), step width variability (Sheehan et al. 2016, Sturk et al. 2018). This system can also assess stability based on margin of stability (MoS) parameters (Sheehan et al. 2016, Sturk et al. 2019) as well as the center of pressure shift, sway area, sway velocity (Horsak et al. 2020). In addition to using the force plate system, balance can also be measured using the Berg balance score (BBS) (Yazgan et al. 2019), , measuring the time it takes to stand up from a sitting and walking position (Time up and Go) (Wuest et al. 2014, Yazgan et al. 2019), as well as an assessment of the ability to walk for a certain duration of time (Ferraz et al. 2017, Yazgan et al. 2019). Using these various measurement tools, it can be seen whether the use of a VR system can improve gait and stability for prosthetic leg users or not.

There are three issues that needed to be observed to assess the overall user experience while using VR, including: presence, emotions, and motion sickness. VR presence can be measured subjectively using the Presence Questionnaire (PQ) (Berkman and Akan 2019). This questionnaire consists of 28 questions related to the degree of presence felt while using the simulator. Presence is easier to measure subjectively than objectively because of the subjective nature of the presence phenomenon itself (Berkman and Akan 2019). Emotions can be measured using the User Experience Questionnaire (UEQ) questionnaire (Horsak et al. 2020). The UEQ contains 26 questions that express the user's feelings when using the product. Motion sickness in virtual reality can be measured using the Virtual Reality Sickness Questionnaire (VRSQ). Objectively, motion sickness in VR can also be measured by looking at postural stability based on the body's center of pressure (COP) which can be obtained using a motion capture system (Arcioni et al. 2019). In addition, the increase in the dominance of the sympathetic nerves which can be seen from the measurement of heart rate variability can also be used as an indicator of the emergence of motion sickness in the use of VR (Malińska et al. 2015).. From this stage, it is hoped that the combination of VR subsystems that will provide the best experience will be obtained, those with high presence and usability values, and low motion sickness.

5. Conclusion

This research has identified nine previous studies that have used VR for stability and gait training for prosthetic leg users, especially for transfemoral or above-knee amputees. These studies have evaluated the success of VR systems as a medium in training. However, each study uses a different system, and their performance and efficacy cannot be compared. This study identified three subsystems that need to be further evaluated for system integration which are technology, content, and feedback subsystems. Based on these three combinations, a comprehensive evaluation can be done assess the ability of the VR system to improve stability and gait, as well as in terms of system evaluation design to obtain the best user experience by providing high presence and usefulness values with low motion sickness. From this framework, further research can be carried out to produce a VR system with the best interaction experience that can be utilized in stability and gait training for prosthetic foot users.

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