Virtual Reality
https://doi.org/10.1007/s10055-023-00750-x

ORIGINAL ARTICLE

Seamless-walk: natural and comfortable virtual reality locomotion method with a high-resolution tactile sensor

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Received: 14 June 2022 / Accepted: 4 January 2023

Abstract

Efficient locomotion methods have been proposed to compensate for the limited space in real-world environments, and such methods offer users more immersive and natural experiences in relatively large virtual environments. The foot-based locomotion method is one of the best options for implementing natural locomotion using foot movement as an input. However, existing foot-based locomotion methods force users to wear equipment or take a video of the user's body. These actions can cause discomfort, unnatural feelings, or privacy problems. Thus, we propose a Seamless-walk system that can seamlessly translate a real-world gait action to locomotion signals using a high-resolution tactile carpet sensor without requiring wearable equipment. The proposed method captures and analyzes high-resolution footprint information using a machine learning technique and calculates the user's movement direction and speed in a real-time manner. In addition, the modular structure of Seamless-walk enables scalable installation of a tactile sensing platform at reasonable cost. Human tests ($n = 80$) confirmed that the proposed Seamless-walk system's technical advantage increases usability. A 3D virtual world exploration game experiment revealed that the proposed method significantly increases comfort and overall naturalness. Additionally, The proposed method has no negative effects on exploration suitability, task load, simulator sickness, or the game experience.

Keywords Virtual reality · Interaction paradigms · Human computer interaction · Human-centered computing

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Published online: 17 January 2023

1 Introduction

Virtual reality (VR) allows us to experience interesting new spaces through virtual environments (VE). However, VEs are generally much larger than the corresponding real-world play area; thus, space-efficient VR locomotion methods have been widely investigated to realize effective exploration of huge VEs. This research area has received increasing attention in recent years. Hence, more than 100 studies have attempted to implement VR locomotion systems to develop natural, efficient, or realistic applications in limited space (Di Luca et al. 2021; Al Zayer et al. 2018). Natural VR locomotion in limited space is one of the greatest challenges in VR research (Mandal 2013; Pai and Kunze 2017). Here, natural VR locomotion methods are those methods that use natural human gait movements as locomotion input (e.g., arm swinging, head bobbing, and leg moving) (Al Zayer et al. 2018). These methods have the advantage of being intuitive and easy to use. However, to enable the natural locomotion method in the strict sense, several conditions must be satisfied: (1) the system should use similar features of human movement as input; (2) the system should freely adjust the angle and speed of locomotion; and (3) the system should enable simultaneous locomotion and interaction, e.g., searching and grasping (Templeman et al. 1999).

In recent studies, foot-based locomotion methods have been widely studied to satisfy the naturalness of movement conditions. Using foot movement as the input of VR locomotion has several advantages over hand-based methods in VR locomotion scenarios. First, foot-based locomotion methods are the most intuitive and natural way to implement human locomotion in VR. Humans use their feet to move in the real-world; therefore, foot movement is one of the most direct signals of human locomotion. Second, foot-based methods enable comfortable multitasking. During foot-based locomotion, users can easily interact with objects using their hands or explore the VE using head rotating (von Willich et al. 2020). As a result, numerous techniques have been applied to implement the foot-based method, e.g., user movement tracking sensors, input controllers, and vision systems (Velloso et al. 2015). These methods capture human foot movement, and then translate the captured foot movement into VR locomotion signals.

Although these foot-based locomotion methods offer many advantages, however, they also introduce several limitations. Typically, such methods force users to wear equipment on the user's body (e.g., shoes or a strap) to track foot movement. This can cause discomfort since the attached sensor constrains the user's body or disturb the smooth movement (Cherni et al. 2020). Additionally, some foot-based locomotion methods have other disadvantages: cumbersome size, noncontinuous speed/angle adjustment, and privacy problems from the vision system. Hence, a more general locomotion method that can be utilized under various environmental conditions is required.

Therefore, in this paper, we propose a Seamless-walk system to realize comfortable, natural, and pleasant VR locomotion experiences. This method enables comfortable and natural movements by introducing high-resolution tactile sensing carpets and machine learning techniques. Through a tactile sensing carpet, the Seamless-walk system collects real-time high-resolution foot-floor tactile interaction information. Then, using machine learning, it extracts the user's movement information from multiple footprints. Finally, it translates the user's movement information, e.g., walking direction and speed, to VR input that corresponds with the game character's movement direction and speed.

Our contributions are summarized as follows. First, we implement a Seamless-walk system that only uses natural foot-floor interaction. Therefore, natural and comfortable locomotion experiences are realized without body constraints or sensor size issues. Furthermore, this advantage enables free head or hand movement by separating "walking direction"from head or hand movement. Additionally, our method does not need to care about a breach of privacy, unlike camera-based methods. Second, we implement a continuous direction and speed adjustment algorithm using a machine learning technique. This algorithm captures the direction and speed changes in detail. Therefore, users can freely walk, turn, or run in the VR space using the proposed method. Third, we implement Seamless-walk platform in a scalable and modular manner. Each 60 cm × 60 cm intelligent carpet (less than USD $25) can be freely assembled as wide as the user wants. In addition, the carpet sensors are easy to roll up and store when not in use. Finally, in a user evaluation with 80 participants, we compared the proposed Seamless-walk system to existing foot-based locomotion methods. The results indicate that the proposed Seamless-walk system is natural and comfortable foot-based locomotion while not adversely affecting the overall VR experience.

2 Related work

Foot-based locomotion is one of the most intuitive approaches to implement natural movement in VR. Therefore, numerous studies have investigated ways to implement foot-based locomotion methods, e.g., mediated sensing methods using a foot controller or intrinsic/extrinsic methods using user movement analysis (Velloso et al. 2015). The mediated sensing method typically employs a foot controller, e.g., a pedal (Balakrishnan et al. 1999) or a foot mouse (Springer and Siebes 1996). These methods could capture the user's foot movement directly by mechanical devices such as pushing or stepping. Thus, they can map the user's movement directly to the virtual character's action. However, these mechanical devices may need adaptation time to be familiar with the controller.

The intrinsic sensing method can overcome the limitations of foot controllers by understanding natural human movement. This method employs a foot-attached sensor to measure foot movements, e.g., insole (Ohnishi et al. 2018), shoe (Reinhardt et al. 2019), strap (Sato et al. 2021), and treadmill (Cakmak and Hager 2014) type pressure or acceleration sensors. Various approaches have been explored, from simply recognizing locomotion velocity by acceleration changing to extracting velocity and direction together by multimodal sensor input. In addition, with recent advancements in machine learning, some studies could extract human movement information using learning systems with action classification (Zhang et al. 2020). Such methods attempt to interpret the human's natural movement. Therefore, they can reduce the time required to learn 'how to use the sensor', and also facilitate natural movement. However, with such methods, the users must maintain contact with a sensor or wear a sensor device (Elvitigala et al. 2021) to conduct continuous movement tracking. Thus, the size of the attached sensor must be adjusted according to each user's body size, which can cause inconvenience. In addition, the sensors may limit freedom of the movement.

Extrinsic sensing systems can reduce the limitations of intrinsic sensing methods. Extrinsic sensing systems can capture the user's movement from a distance by motion trackers or cameras. However, it still cannot eliminate the bodily inconvenience of wearable devices. Motion tracker based methods still require small trackers to be placed on the user's body, such as the chest or leg (Feasel et al. 2008). Camera-based methods do not require any tracker to be placed on the user's body (Wilson et al. 2014; Bruno et al. 2017). However, such methods cannot adjust locomotion direction continuously if they use only a single camera (Kim et al. 2021). In addition, extrinsic sensing systems require a wide area to set up a vision system to capture the entire human body without blind spots (Velloso et al. 2015), and privacy concerns cannot be ignored (Luo et al. 2021; Zhao et al. 2018).

Through the above interaction methods, diverse foot-based VR locomotion methods, such as teleport, leaning, gesture, and walking-in-place (WIP) approaches, have been implemented. Among them, WIP methods compose one of the biggest categories of VR foot-based locomotion methods. WIP uses in-place walking as a locomotion input signal. WIP is well applied in a VE, and it is the closest way of reflecting people's natural movement (Al Zayer et al. 2018). Therefore, it has been continuously studied from a basic sensor-attached-based type to a vision-based type. Sensor-attached-based WIP implementation focuses on analyzing foot acceleration or foot pressure. In the beginning, simple virtual treadmill-type sensors have been mainly used (Slater et al. 1994, 1995; Choi and Ricci 1997). However, in recent studies, various forms of foot-attaching sensors have been developed to track feet accurately with comfort. Still, treadmill-type sensors are widely used for the WIP method (Cakmak and Hager 2014; Avila and Bailey 2014). These methods could get more accurate speed and direction information from omnidirectional treadmill sensors. This sensor could get human walking direction (from the waistband) and speed (from the foot sensor) directly; however, it needs a huge and heavy setup. The other methods tend to reduce the sensor size to provide a more comfortable WIP experience. These methods attempt to translate sensory output (mainly inertial measurement unit (IMU) sensors or pressure sensors) to locomotion input through computational processing (Lee et al. 2018; Zhang et al. 2020; Tregillus and Folmer 2016). Vision-based models focus on analyzing human walking motion using cameras (Wilson et al. 2014; Feasel et al. 2008; Kim et al. 2021; Kim and Xiong 2021). These approaches try to capture human body pose from recorded videos. Through this, the camera-based locomotion methods translate the walking pose to VR locomotion direction and speed.

Consequently, various WIP methods are implemented using mediated or intrinsic/extrinsic systems; all locomotion methods have their advantages and disadvantages. However, not many VR locomotion studies have been conducted using a pressure sensor mat, although it has several advantages: It is an extrinsic tracking system that does not require attaching sensors to the body; This is also an intrinsic method that captures continuous human movement via tactile sensing between the foot and the floor. Therefore, it can capture movement in detail without constraining the user's body while also reducing privacy issues (Srinivasan et al. 2005). One of the earliest studies used a self-produced locomotion interface that contained a few pressure sensors and a turntable platform (Bouguila et al. 2003, 2004). This invented locomotion system enables people to easily explore VE without an additional sensor attachment by tracking human foot pressure and rotating with floor sensors (Bouguila et al. 2003). Through developed hardware systems, a similar study has been reproduced with commercial products, such as the Wii balance board (Williams et al. 2011; Harris et al. 2014). These studies implement WIP and the leaning-based method to explore VE. However, all these methods used only a few pressure sensors; hence, they cannot capture the whole pressure of the foot. To collect a more substantial pressure reading from human movement, some studies have used more high-density pressure sensors (Bouguila et al. 2004; Carrozzino et al. 2014). These

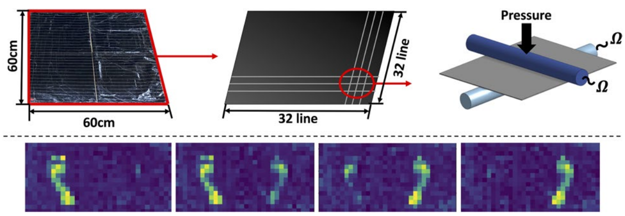

Fig. 1 High-resolution sensing carpet. Top: Each sensing carpet tile is 60 cm × 60 cm in size with n array of 32 × 32 sensors. Each sensor is located at the intersection of the orthogonally aligned electrodes, which converts the force stimulus to an electrical signal. The high-resolution sensing array captures the real-time pressure imprints of human movement. Bottom: Foot-interaction imprints from the sensing carpet obtained while a user is walking

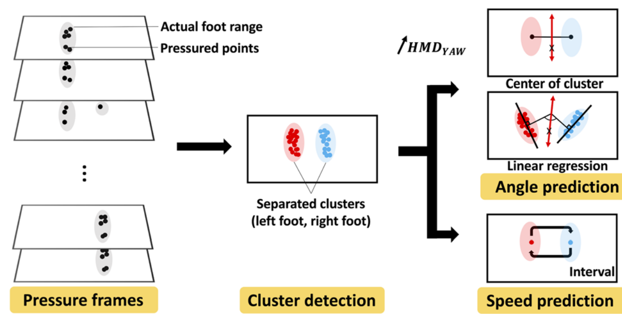

Fig. 2 Illustration of the walking angle and speed calculation. First, multiple consecutive images (e.g, 14 Frames in this study) are used as input to a machine learning model that extracts strong pressure points from the area stepped upon. Second, the model finds two clusters from the collected pressured points (representing the left and right feet) using K-means clustering. Finally, the angle and speed are estimated according to the two clusters

studies attempted the use of detailed foot pressure as locomotion input. Since the higher density of pressure sensors was invented and their usage was studied (Luo et al. 2021), it is expected that more sensitive and proper WIP methods with high-dimensional pressure sensors could be invented.

In this flow, our study attempted to make a more advanced WIP-type VR locomotion method with a high-resolution tactile sensor and machine learning. Our Seamless-walk system enables VR locomotion using a high-resolution pressure-sensitive floor sensor that eliminates body constraints and privacy issues while providing comfortable and natural feeling.

3 Proposed seamless-walk method

In this section, we describe the functionality of the tactile sensor carpet and work and how the algorithm translates tactile foot pressure input to locomotion signals.

3.1 High resolution tactile sensor

The Seamless-walk platform comprises of four separate carpet tiles, each of which is 60 cm × 60 cm size and contains an array of 32 × 32 sensors (Fig. 1). Each sensing carpet tile is constructed by orthogonally aligning electrodes on each side of the commercial piezoresistive films. Each sensor is located at the intersection of the orthogonally aligned electrodes and can measure pressure up to 14 kPa through the change of resistance (Luo et al. 2021). The high spatial resolution of the sensing matrices (1.8 cm between each electrode) allows the sensing carpet to capture the human footprint in great detail. Figure 1 shows example foot-interaction imprints obtained while a user walked on the tactile sensing carpet. In addition, the tactile sensing carpet platform is easy to install and expand because it is based on a modular construction design. The sensing carpet enables measurement at a 17-Hz frame rate during VR games. In addition, detection can be performed stably even when soft foam, e.g., a yoga mat (thickness: 1 cm), is placed over the sensor to increase comfort.

3.2 Speed and angle prediction

The high-resolution tactile sensing carpet can capture the detailed foot pressure imprints in real-time as the user performs diverse actions. To predict the direction and speed of the user's movement, we employ a K-means clustering method to track an individual user's left and right feet as clusters. From these clusters, we extract the body direction and foot intervals to calculate the angle and speed (Fig. 2). Followings are more detail information about this speed and angle estimating sequences.

Footprint images obtained from a high-resolution tactile sensor are used as the input. The number of input image frames has been determined to ensure that both feet could be included in the input data (in our case, 14 frames in 0.87 s; Seamless-walk capture 17 frames in a second). By referring to the most preferred gait cycle of adults (around 0.52 s/step) (Schmitz et al. 2009), Seamless-walk successfully capture both feet information within enough time ($0.87s > 0.52s \times 1.5$).

Then, the coordinates of strongly pressed sensors are collected from each input. The strongly pressed points correspond to a high pressured (generated by foot) location that cannot be generated by general noise. Assuming that noise is generated by a probability with normal distribution, we set the pressured locations as points which are less likely noise with 99.8% of probability (three times the standard deviation; 3σ). The collected pressure points are divided into two clusters using K-means clustering ($k = 2$), and each group represents the location of each of the user's feet.

To find the movement direction, the clusters and a head-mounted display (HMD) yaw value (HMD_{yaw}) are used. Here, we first define the directional slope (*DS*) from the cluster information to determine the direction the human body is facing. We use two complementary methods to produce the *DS*.

The first method considers the cluster centers. Here, the *DS* is obtained by drawing a line perpendicular to the straight line connecting the center point of each cluster (i.e., a foot) using Eq. (1) (the negative reciprocal of the each foot connecting line slope), where $C1_x - C2_x$ is the *x*-coordinate difference between clusters 1 and 2, and $C1_y - C2_y$ is the *y*-coordinate difference between clusters 1 and 2. The slope *DS* represents the user's body direction (forward or backward), because it is perpendicular to the line connecting both feet.

$$\mathrm{DS} = -\frac{C1_x - C2_x}{C1_y - C2_y} \tag{1}$$

The second method uses linear regression to obtain the direction of the body. Here, for each cluster, the linear regression is applied to identify the longest side of the cluster, i.e., the direction of the foot. The *DS* is then obtained by averaging the directions of both feet. This method has higher accuracy than the first method, especially when the user's feet are positioned diagonally. However, this method tends to fail when the user is running, typically using only the smaller front area of the foot. As a result, sensor struggles to infer the direction of the feet from the shapes of the clusters. Thus, we validated the prediction of this method by checking the length of feet. If the length of the feet is less than a threshold *T* (15 cm; half of usual foot size), the prediction is considered invalid. We integrated both methods as follows. The second method is used when it is valid; otherwise, the first method is used to identify the *DS*.

We then calculate the user's movement direction according to *DS* and HMD_{yaw}. The user's moving angle is calculated by taking an arctangent to the direction slope. Note that the arctangent can only represent values between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$; thus, it is possible that the angle rotated 180 degrees is the actual angle of movement. Therefore, by referring to HMD_{yaw} value, we can select the direction of movement that is close to the direction of the person's gaze. Here, we assume that the user's head generally does not rotate more than 90°. The algorithm that produces the angle of movement is described in Algorithm 1.

Algorithm 1 Pseudocode of algorithm to predict direction

Input:
pressure images from tactile sensor, $Pressure$
foot length threshold, T
yaw of head-mounted display, HMD_{yaw}
Output: moving direction of the user, D
$G1, G2 =$ get two clusters from $Pressure$
$S1 =$ slope 1 from linear regression using $G1$
$L1 =$ length of a foot along $S1$
$S2 =$ slope 2 from linear regression using $G2$
$L2 =$ length of a foot along $S2$
if $L1 > T$ and $L2 > T$ **then**
  $DS = (S1 + S2)/2$
else
  $C1 =$ center of $G1$
  $C2 =$ center of $G2$
  $DS = -(C1_x - C2_x)/(C1_y - C2_y)$
end if
if $|\arctan(DS) - HMD_{yaw}| \leq 90$ **then**
  $D = \arctan(DS)$
else
  $D = \arctan(DS) - 180$
end if

To obtain the movement speed when each frame updates, a speed estimator is employed to determine whether the current maximum pressure point is included in the same cluster as the previous maximum pressure point. When the cluster to which the maximum pressure point belongs changes, it is considered that a single step has progressed and the speed is calculated.

Algorithm 2 Pseudocode of algorithm to predict speed

Input: pressure images from tactile sensor, $Pressure$
Output: speed of the user, S
$I_u =$ under bound interval (slowest)
$I_c =$ calculated interval from $Pressure$
if $I_c > I_u$ **then**
  $S = 0$
else
  $S = (I_u - I_c) \times speedFactor$
end if

In Algorithm 2, I_u denotes the under bound step interval, which is the slowest walk interval, and I_c denotes the current step interval. If the interval of the step is greater than I_u, the speed is treated as 0; otherwise, the speed is adjusted linearly according to the length of the step interval. In addition, *speedFactor* denotes the standard speed factor (1 m/s in our case). When there are two pressured points in the distinct cluster for specific continuous frames (eight frames in our case), the subject is considered to be standing still, and speed is set to 0. Note that we use the average of the last five obtained speeds as the final speed to stabilize movement.

3.3 Algorithm validity

To evaluate the validity of our algorithm for VR locomotion, we conducted a sensor accuracy test. In the test, angle prediction accuracy, speed prediction accuracy, and foot recognition accuracy were conducted. For the test, 20000 frames of walking data were collected through five separated angles ($-90°, -45°, 0°, 45°, 90°$) and eight distinguished speeds (100, 110, 120, 130, 140, 150, 160 , and 170 steps per minute (SPM)). Participants were requested to collect 200 frames of walking data for each of the 40 pairs of conditions (5 levels of angle × 8 levels of speed). The participants performed an in-place walk on the Seamless-walk platform while maintaining direction and step speed. We provided direction guidelines to the participants by drawing guidelines on the floor. We also provided step speed guidelines by metronome sound. To get clearer data, we only used central 100 frames of data while removing the beginning and ending data. Five participants were recruited for data collection (21–31 years; mean (M) = 25; standard deviation (SD) = 3.81). Three of the participants were male, and two were female. The height range of the participants was 161–177 cm (M = 169.4; SD = 6.50), the weight range was 49–75 kg (M = 64.8; SD = 9.91)), and the foot size range was 235–270 mm (M = 256.0; SD = 14.57).

Consequently, the angle prediction average error was ±4.70° (SD = 4.90). Our algorithm successfully recognizes the user's body direction, as illustrated in Fig. 3). Furthermore, speed predicting could successfully map stepping speed to VR locomotion speed almost linearly (Fig. 3). We guess that this nonlinear speed adjustment could be induced because some participants could not make fit their SPM to guided metronome sound due to physical demand.

Additionally, we conducted statistical tests for the different angle and speed groups. Due to all groups having normally distributed data, we conducted the ANOVA and post-hoc Tukey tests. The test results show a significant difference in these angle and speed groups ($p = .000 < .01$, $p = .000 < .01$). Furthermore, the results of the post-hoc Tukey confirm that each pairwise within groups was significantly different. These results strongly indicate that the Seamless-walk platform could successfully capture angle and speed differences. Finally, to check foot recognition accuracy, we checked error input. Only 0.465% of the data failed to capture individual footsteps.

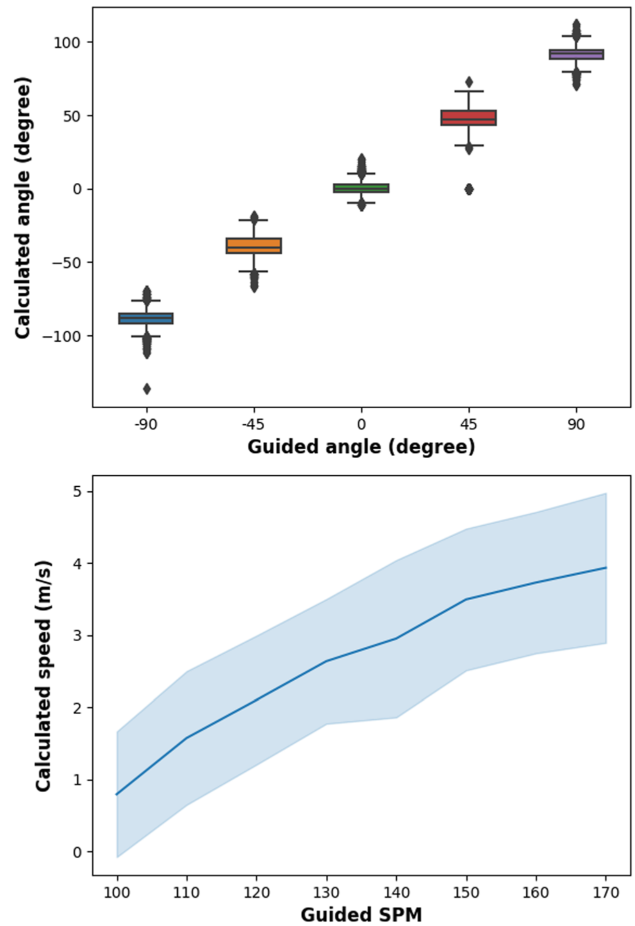

Fig. 3 Algorithm validity test result. Top: angle accuracy test result. Bottom: speed adjustment test result

4 Research questions

In the previous section, we described the technical advantages of the proposed Seamless-walk method. However, technical advantages do not guarantee user satisfaction; it is often more important how users feel and react to the product (Garrett 2010). Therefore, in this study, we considered the following research questions to analyze and test the proposed method's usability experimentally.

RQ1. Can the Seamless-walk system provide a comfortable and natural feeling?
RQ2.Can the Seamless-walk system be used by the general public?

To answer these research questions, we investigated the following research hypothesis (RH). In terms of RQ1, to prove a Seamless-walk's comfort and naturalness, we constructed discomfort questionnaires (DQ) and naturalness questionnaires (NQ), as shown in Table 1. The DQ contained general questions asking about body constraint and discomfort levels

Table 1 DQ and NQ for RQ1

Questions
Discomfort questions
DQ 1. I felt constrained
DQ 2. I was unable to move my body freely
DQ 3. I felt uncomfortable
Naturalness questions
NQ 1. The locomotion method was realistic
NQ 2. I felt like I was walking naturally as if I was walking in the real life
NQ 3. Walking in the game environment was similar to walking in the real life
NQ 4. I found the experience of walking in VR natural
NQ 5. I felt like I was in the real-world

(questions 1~3). The NQ investigated various aspects related to the naturalness of the locomotion method (questions 1~ 2), the naturalness of the VR experience (questions 3~4), and overall naturalness (question 5). Here, the participants were asked to rate each DQ and NQ item on a 10-point Likert scale (1 for "Not at all"and 10 for "Very Much"). We expected the proposed Seamless-walk system to receive the lowest discomfort score in the DQ (RH1) and the highest naturalness score in the NQ (RH2).

For RQ2, we wanted to determine whether the proposed Seamless-walk system can provide a solution to a wide range of users. Therefore, we investigated whether the Seamless-walk system has any negative effects on general performance, i.e., VE exploration suitability (RH3), task load (RH4), VR sickness (RH5), and game experience (RH6). Finally, we investigated user preference (RH7). Here, we assumed any significant negative effects on general performance or user preference would indicate that the proposed system may not be effective for a wide range of users. To answer each RH precisely, we obtained task load, game experience, and simulator sickness scores using previously published questionnaires, i.e., the NASA task load index (NASA-TLX) (Hart and Staveland 1988), a game experience questionnaire (GEQ) (IJsselsteijn et al. 2013), and a simulator sickness questionnaire (SSQ) (Kennedy et al. 1993), respectively. In addition, VE exploration suitability was measured by exploration score which was calculated from game log data. In addition, self-reports about method preference were collected after each game session.

5 Experiment

5.1 Comparison

To confirm our hypothesis, we set up three control groups for comparison. Each control group satisfied the following conditions: (1) Providing foot-based locomotion, as well as providing continuous adjustment of direction and speed just like Seamless-walk does; (2) To avoid similar comparisons, only the products with different characteristics have been chosen; (3) To fairly represent other foot-based locomotion methods, the prevailing locomotion methods and products were given priority. Thus, the following three control groups were selected for comparison (Fig. 4).

Foot mouse With a foot mouse, users use their feet to manipulate the movement of game characters. The foot mouse could change the VR character's speed and direction by foot tilting and rotating. The character speed changes linearly according to the tilt of the foot mouse. And the character rotates left or right according to the foot-mouse rotation direction.

Leg strap sensor A leg strap sensor translates the user's leg acceleration change to the game character's speed. We used the Nintendo Switch joy-con controller and its leg strap as a leg strap sensor. The open-source joy-con unreal plugin has been used to translate the user's movement to the character's speed (supplementary 1). However, it cannot change the moving direction; therefore, we set the moving direction along the gaze direction.

Treadmill A treadmill sensor (Virtuix omni) translates the user's movement by feet and waist sensors. The treadmill sensor tracks the user's walking speed with foot-attached sensors and then translates it as the VR character's speed. The moving direction could be decided by the waist sensor rotation. These multiple sensors to manipulate the game character's movement.

All comparison controllers are set by following each controller manual. To ensure that the sensors were used and evaluated fairly, each sensor's maximum speed and speed change rate were set up equally.

Fig. 4 (Left to right) Foot mouse, treadmill, leg strap, and proposed Seamless-walk systems. Each picture demonstrates how each locomotion method is used

5.2 Implementing the VR game

The VR game used in this evaluation was a first-person shooter (FPS), as shown in Fig. 5a. In this game, the players are required to shoot as many enemies as possible while moving along mountain paths. However, the VE is dark, and enemies hide randomly near bushes. Thus, to avoid missing enemies, the players must carefully search for and shoot the enemies. The game scoring system was set to "exploration score,"which divides the total shooting score by the moving distance. This scoring system indicates how well the participants explored the VE with a given locomotion method. Therefore, the exploration score gets higher if participants shoot enemies without missing enemies while walking. On the other hand, if participants miss many enemies while walking, it leads to a lower exploration score.

The experimental VR games were implemented using Unreal Engine 4 with three-dimensional (3D) assets. The VE was 750 m^2 with 2.6 km of mountain road. In addition, we placed various trees and bushes along the side of the mountain road and configured 17 different monster-generating areas along the mountain road (Fig. 5b). In each monster-generating area, five monsters were generated randomly from among 10 potential spawn locations (Figure 5c).

5.3 Experimental setup

In this experimental evaluation, we used four high-resolution sensing carpets for the Seamless-walk system (total area: 120 $cm \times 120$ cm). For the VR equipment, we used an Oculus Quest 2 controller and HMD. For the leg strap system, we used a Nintendo Switch controller, which contains an inertial measurement unit. For the foot mouse system, we used the 3dRudder Foot Mouse, and for the treadmill system, we used the Virtuix Omni.

5.4 Participants

We recruited 80 participants (18–33 years; M = 22.35; SD = 3.41). Fifty-two of the participants were male, and 28 were female. The height range of the participants was 159–188 cm (M 170.9 cm; SD = 6.68 cm), the weight range was 46–110 kg (M = 67.02 kg; SD = 13.1 kg), and the

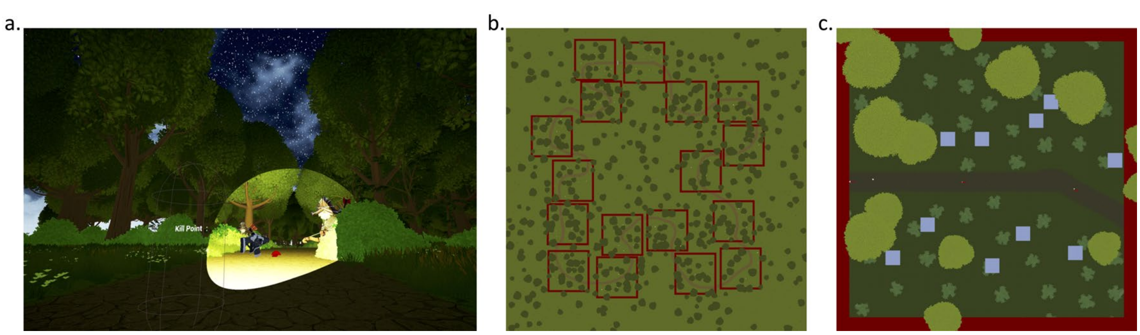

Fig. 5 **a** In-game view; **b** Top-down view of VE (red boxes are monster-generating areas); **c** an example of monsters spawning in the area (white boxes are monster spawn locations)

foot size range was 225–295 mm (M = 256.9 mm; SD = 19.5 mm).

To account for the learning effect, an experiment was designed between-subject tests. With counterblancing, participants were divdied into four groups. Each participant was assigned to a single locomotion method in consideration of the gender ratio, previous VR experience, and VR motion sickness level of the participants to ensure the same characteristics of each group (Table 2). Here, the score for previous VR experience was 1–5 (1 = no VR experience, 5 = more than 10 hours of VR experience). The score for motion sickness level was 1–5 (1 = no VR sickness, 5 = severe VR sickness). For participants that did not know their VR sickness level, we set each participant's sickness level to an average value of all other participants' VR sickness scores.

5.5 Procedure

In this experiment, we compared the foot mouse, omnidirectional treadmill, leg strap, and Seamless-walk systems. We conducted the experiment with 80 participants, and each participant used only one VR locomotion method. The experimental procedure is described as follows.

- *Participant groups* First, we asked the subjects to fill out a questionnaire about demographics, VR experience, and VR sickness history before participating in the experiment. We balanced the groups and assigned each participant to a group. Here, gender, VR experience, and VR sickness information were used to form the groups.
- *Introduction* After the participants arrived, we welcomed each participant and explained the purpose of the experiment, the experimental procedure, and what kind of information would be collected. We then informed the participants about the game's rules and goals, i.e., look around carefully and find monsters to shoot. The participants were asked to stay on the road during the gameplay because we wanted the game experiences to be as similar as possible. In case of severe motion sickness, the participants were instructed to stop playing as required.
- *Settings and experiment* We started the experiment by adjusting the sensor size (if required by a locomotion method) and positioning the sensor in a comfortable spot. After showing the participant how to move, change direction, and change speed with the assigned locomotion method, the participant was asked to familiarize themselves with the VR equipment and locomotion method for 2~3 minutes. After confirming the participant's readiness, we started the 10-minute main gameplay phase. Here, we recorded the shooting score and total movement distance.
- *Questionnaires and interviews* After the participants completed the main game experiment, they filled out the DQ, NQ, NASA-TLX, GEQ, and SSQ. In addition, we also received qualitative feedback in interviews. We asked the participants to provide personal feedback, including comments about the advantages and disadvantages of the experienced locomotion method. We also asked the participants to rate their satisfaction with the locomotion method on a scale from 1 to 10.

6 Results

We performed statistical analyses of the in-game data and survey results collected during the experimental stage. This experiment was conducted with four groups of participants, and the data were not distributed normally; thus, a nonparametric Kruskal-Wallis test was used to determine significant differences. Here, if significant differences were found at a significance level of $p < 0.05$, the differences were analyzed using a post-hoc Dunn's test pairwise between groups. All results are presented in Tables 3 and 4.

6.1 Discomfort and naturalness questions

In the discomfort aspect, the Seamless-walk system generally received a lower mean rank score (representing less discomfort) than the compared locomotion methods. As shown in Fig. 6, the median value of discomfort is also lower than other locomotion methods. In addition, significant differences were found for all discomfort questions (Table 4). For DQ1 ("I felt constrained"), the results differed significantly depending on the locomotion method ($H(3) = 11.224, p = .011$). The post-hoc Dunn's test revealed a significant difference between the treadmill and Seamless-walk systems.

Table 2 The gender ratio, mean of age, VR sickness level, and previous VR experience of each locomotion method

	Treadmill	Leg-strap	Footmouse	Seamless walk	Total
Number of males	13	13	13	13	52
Number of females	7	7	7	7	28
Mean of previous VR experience (*SD*)	2.55 (1.07)	2.50 (1.12)	2.65 (1.09)	2.60 (0.88)	2.58 (1.03)
Mean of VR sickness level (*SD*)	1.99 (0.60)	1.77 (0.84)	1.72 (0.48)	1.89 (0.50)	1.84 (0.63)
Mean of age (*SD*)	21.8 (2.70)	22.5 (3.88)	21.4 (2.95)	23.8 (3.46)	22.4 (3.41)

Table 3 Results of the Kruskal-Wallis test by locomotion method

Questions	Kruskal-Wallis H	df	Asymp. Sig.
Discomfort questions			
DQ 1. I felt constrained	11.224	3	0.011*
DQ 2. I was unable to move my body freely	8.143	3	0.043*
DQ 3. I felt uncomfortable	10.064	3	0.018*
Naturalness questions			
NQ 1. The locomotion method was realistic	0.287	3	0.962
NQ 2. I felt like I was walking naturally as if I was walking in the real life	6.111	3	0.106
NQ 3. Walking in the game environment was similar to walking in the real life	2.283	3	0.516
NQ 4. I found the experience of walking in VR natural	4.915	3	0.178
NQ 5. I felt like I was in the real-world	9.343	3	0.025*
Exploration score	6.035	3	0.110
NASA-TLX	2.521	3	0.471
SSQ	1.735	3	0.629
GEQ			
Competence	3.387	3	0.336
Immersion	3.192	3	0.363
Flow	1.950	3	0.583
Tension/annoyance	6.802	3	0.078
Challenge	2.463	3	0.482
Negative_affect	3.232	3	0.357
Positive_affect	4.616	3	0.202
User preference	3.623	3	0.305

*$p < 0.05$

Here, the Seamless-walk participants felt less constrained than the treadmill participants ($p = .0064 < .01$). A significant difference was also observed between the locomotion method groups for DQ2 ("I was unable to move my body freely") ($H(3) = 8.143, p = .043$). According to the post-hoc test, the Seamless-walk participants could move their body more freely than the foot mouse participants ($p = .030 < .05$). Finally, another significant difference was observed for DQ3 ("I felt uncomfortable") ($H(3) = 10.064, p = .018$), which was directly asking about their discomfort during the gameplay experience. These results revealed that the proposed Seamless-walk system is significantly more comfortable than the treadmill system ($p = .013 < .05$).

In terms of naturalness, there were no significant difference in NQ1~NQ4. Although it did not reach significance level, a slight difference was observed for NQ2 ($H(3) = 6.111, p = .106$). However, a significant difference was observed in terms of overall naturalness in NQ5 ($H(3) = 9.343, p = .025$). The post-hoc analysis revealed that the Seamless-walk, foot-mouse, and leg-strap systems are more natural than the treadmill system ($p = .037 < .05; p = .037 < .05; p = .037 < .05$).

6.2 Overall performance

No significant differences were observed between the locomotion method groups in the overall performance aspect (exploration score, NASA-TLX, SSQ, and GEQ). However, even it does not reach significance level, some weak evidence was observed in exploration scores ($H(3) = 6.035, p = 0.110$). Table 4 shows that the leg strap's exploration score is slightly less than that of the other locomotion methods.

6.3 Qualitative results

We conducted a short interview with each participant to obtain feedback about their preferences and the advantages and disadvantages of the experienced locomotion method. According to the interview results, the proposed Seamless-walk system received the highest user preference mean rank score (Table 4). However, it does not reach significance level ($H(3) = 3.623, p = 0.305$). The participants' overall advantage/disadvantage responses are given in Table 5.

Table 4 Mean ranks by locomotion method

Variable	Seamless-walk (S)	Foot-mouse (F)	Treadmill (T)	Leg-strap (L)	Significant difference
Discomfort questions					
DQ1	30.45	38.43	54.25	38.88	S < T**
DQ2	29.48	49.95	42.68	39.90	S < F*
DQ3	28.68	44.05	50.95	38.33	S < T*
Naturalness questions					
NQ1	42.83	39.53	39.43	40.23	–
NQ2	47.03	40.68	30.20	44.10	–
NQ3	41.58	42.50	33.92	44.00	–
NQ4	41.8	45.15	30.88	44.18	–
NQ5	44.83	46.18	26.93	44.08	S > T*, F > T*, L > T*
Exploration score	45.70	40.15	45.95	30.20	–
NASA-TLX	37.55	43.68	45.35	35.43	–
SSQ	39.45	37.73	46.33	38.50	–
GEQ					
Competence	41.95	39.35	33.75	46.95	-
Immersion	45.4	37.68	34.40	44.53	–
Flow	44.15	43.20	34.93	39.73	–
Tension/annoyance	37.90	41.43	50.53	32.15	–
Challenge	38.18	39.43	47.38	37.03	–
Negative affect	38.55	45.20	44.43	33.83	–
Positive affect	44.20	39.78	31.78	46.25	–
User preference	47.93	37.15	35.33	41.60	–

$^*p < 0.5$, $^{**}p < 0.1$

7 Discussion

Here, we answer our research questions by integrating the statistical results and interview results.

7.1 RQ1. Can the Seamless-walk system provide a comfortable and natural feeling?

Overall, the experimental results revealed that the proposed Seamless-walk system can provide a comfortable and natural feeling when moving in a VE.

For the discomfort questions (RH1), the proposed Seamless-walk system generally obtained a lower discomfort mean rank, and significant differences were observed compared to the foot-mouse and treadmill locomotion methods. In addition, in the qualitative feedback, some participants commented that the proposed Seamless-walk system was *"Comfortable because there was no physical restraint"* (P63), and one participated stated that they *"Felt free because I did not wear a sensor"* (P53). This indicates that the participants felt comfortable because the Seamless-walk does not require the user to wear sensor devices.

In contrast, the participants expressed discomfort with the other three methods. Although we did not observe a significant difference with the leg strap locomotion method, some participants commented that *"the strap became loose as I walked"* (P38), and *"it was uncomfortable because the strap slipped"* (P62). With these responses, we observe that the leg-strap method still cannot avoid attaching-type sensors issues (size adjustment) (Elvitigala et al. 2021). Additionally, seven participants responded that *"It was uncomfortable because the gaze direction and moving direction do not separate"*. It makes it difficult for the participants to look around their surroundings. However, four participants responded that the leg strap is comfortable. We believe this result could be obtained because the leg strap method extremely reduced the attaching area (only one strap) by sacrificing some functions (angle adjustment). For instance, the treadmill system that requires many sensors to be attached was significantly more uncomfortable than the Seamless-walk system. Additionally, the treadmill participants stated that *"It was uncomfortable because there were so many things to wear"* (P41), and *"I felt like I was trapped inside a barrel"* (P56). For the foot mouse system, participants also expressed discomfort, saying that *"it was uncomfortable because the foot controller pushed away"* (P61) and *"my foot slipped from the foot mouse as I play"* (P76). Even though the foot mouse system does not require wearing a sensor, the interaction between the foot and the controller

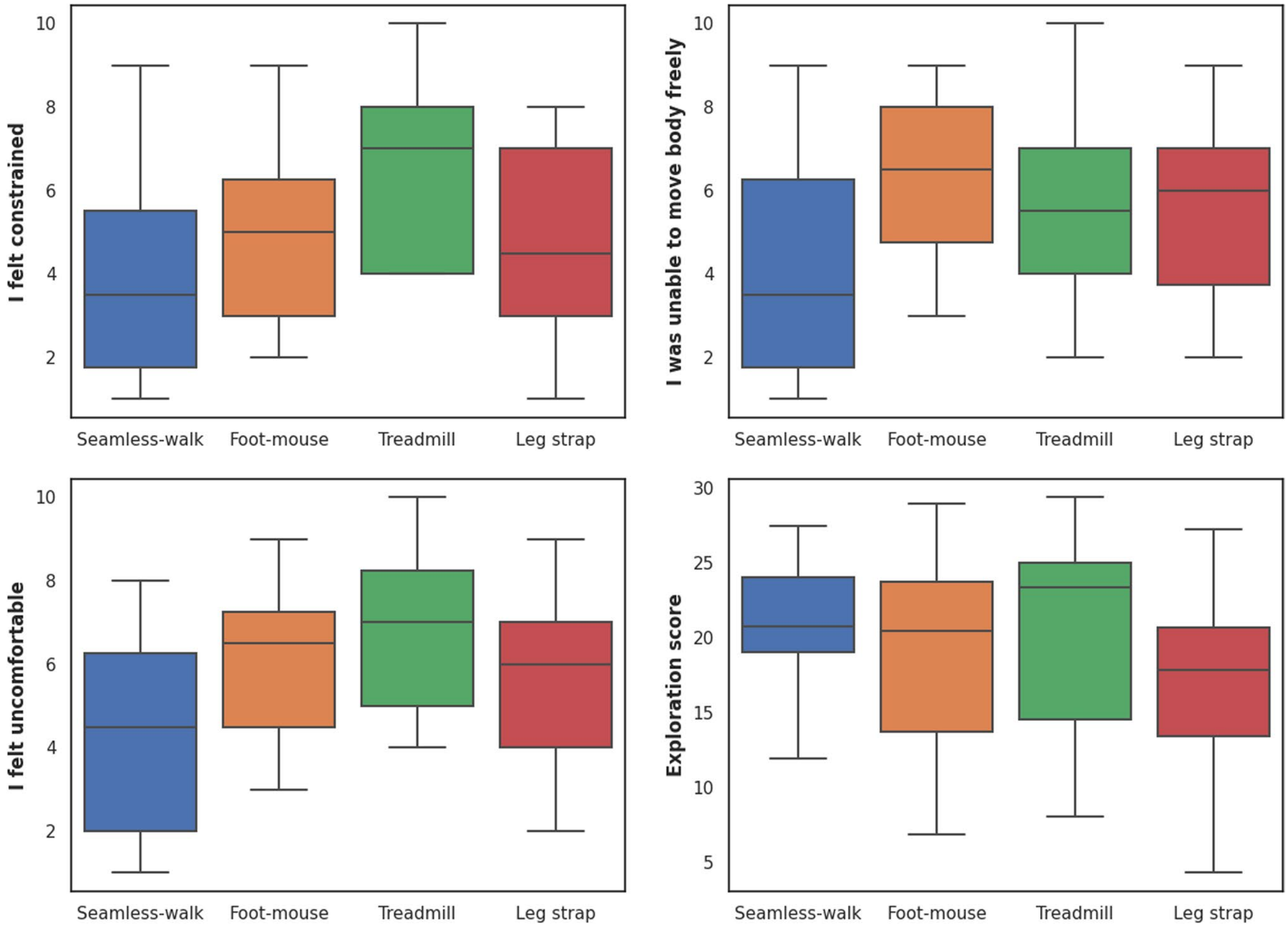

Fig. 6 Comparison of box plots on the discomfort questionnaires and exploration score

Table 5 Advantage/disadvantage responses and frequency from interviews (multiple responses were allowed)

Seamless-walk	Foot mouse	Treadmill	Leg strap
Advantages			
Comfort (5)	Low physical demand (4)	Naturalness (2)	Naturalness (5)
Immersion (3)	Fast response (3)	Easy to use (2)	Comfort (4)
Naturalness (3)	Easy to use (3)	Active (2)	Fun (2)
Disadvantages			
Small sensing mat (11)	Hard to control sensor (14)	Unnatural walking (9)	Moving gaze direction (7)
Go unintended direction (9)	Go unintended direction (5)	Physical demand (7)	Sensing error;drift (5)
Hard speed adjust (4)	Unnatural walk (4)	Too much constraint (4)	Slip strap (4)

resulted in discomfort, which was not observed with the proposed Seamless-walk system.

In terms of the naturalness aspect (RH2), the proposed Seamless-walk system does not significantly differ compared to other locomotion method's naturalness (NQ1 and NQ2) and the VR experience naturalness (NQ3 and NQ4). However, a significant difference was observed in terms of overall naturalness (NQ5) compared to the treadmill system. Some participants stated that *"It was nice that the movement was provided like a real walk"* (P20 and P23) and *"Walking was well applied to the game"* (P36). These responses support the observation that the proposed Seamless-walk system can provide a natural feeling. Interestingly, the foot mouse and leg strap methods also received some responses about their naturalness, and a significant difference was observed at NQ5. Those two locomotion methods also have "natural"characteristics: foot mouse could smoothly change speed and angle by foot; leg strap use walking motions as input of the game. However, these methods do not satisfy the naturalness requirement, which was discussed in a previous study (Templeman et al. 1999). Foot mouse employs ankle tilting as locomotion input, unlike human gait. Additionally, the leg strap method cannot adjust the moving direction itself; it cannot apply searching and moving simultaneously.

However, in the interview, nine participants reported that the proposed Seamless-walk system occasionally moved in an unintended direction when using the sensor. However, during the sensor accuracy test, no significant angle prediction or foot recognition errors were found. The problem may have been caused by the fact that the Seamless-walk system only recognizes body direction. A previous study that investigated body, head, and eye interactions while walking and turning concluded that head direction changes first and then the body direction follows after a slight delay (Imai et al. 2001). Thus, body direction may not align precisely with the intended direction when people turn. In addition, this effect may have been more severe in the VR scenario because it is difficult for the user to acquire effective spatial awareness and correct body perception while wearing the HMD (Costantini 2014). In addition, having the visual sense blocked by the HMD may reduce tactile perceptions which may worsen self-body perception (Tipper et al. 2001).

Nevertheless, the proposed Seamless-walk system obtained the highest preference score (RH7) and locomotion method naturalness (NQ1 and NQ2), even though the scores do not reach significance levels. In addition, even though unintended direction issues were observed, the exploration score obtained by the proposed system was very close to the highest mean ranks. Thus, the unintended direction issues did not seem to significantly reduce the overall game experience or the natural feeling of the proposed system. The participants" responses also support this opinion. Six participants who reported direction issues also reported that the proposed Seamless-walk system is natural, intuitive, or immersive (P17, P18, P35, P36, P45, and P73). In addition, one participant stated that *"Moving direction was confusing in the beginning, but I adapted quickly"* (P65).

7.2 RQ2. Can the Seamless-walk system be used by the general public?

Overall, the experimental results demonstrate that the proposed Seamless-walk system can provide better or similar usability than the compared locomotion methods in terms of preference, efficiency, game experience, task load, and VR sickness (RH3~7).

For the user preference aspect, the user preference mean rank score obtained by the proposed Seamless-walk was higher than that of the compared locomotion methods (RH7). Although, it does not reach significance level ($p = 0.305$), it is important because user preferences represent overall product satisfaction, and this result implies that the proposed Seamless-walk system could potentially replace other commercialized locomotion methods. Interestingly, this preference shows different results from the previous study which denote that the gaze directing WIP method is more preferred than the body directing one (Williams et al. 2013). This result represents that foot-based directing may be better than torso directing in the WIP technique.

In terms of VE exploration suitability, we cannot find any significant result for the exploration score ($H(3) = 6.035, p = .110$). Therefore, we could not say the Seamless-walk method is better than other locomotion methods, but it could be successfully adopted in VR games, as with the foot mouse and treadmill methods. Interestingly, with the exploration score shown in Fig. 6, Seamless-walk system shows a narrow inter-quartile range (IQR). This result also denotes that a wide range of users could use a Seamless-walk system similarly irrespective of their physical level or VR experience.

Relative to the game experience aspect (with GEQ), the proposed Seamless-walk system provides an experience that is similar to that of the compared locomotion methods (RH6). We found that Three participants reported that the proposed Seamless-walk system provided an immersive effect, while only one participant commented on the immersive effect of the treadmill system. The other two locomotion methods did not receive any participant comments regarding their immersive effect. Because of the lack of responses that resulted in non-significant differences, we suggest a more thorough analysis of immersion for future work.

The Seamless-walk system also demonstrated that there are no significant differences in terms of simulator sickness and task load (RH4 and RH5). By interpreting these results together with the DQ results, we consider that the proposed Seamless-walk system establishes comfort locomotion without causing VR sickness or increasing task load. Although there was no significant difference found in the NASA-TLX test, seven participants reported high physical demand on the treadmill method. This result can be supported by a previous study that shows the treadmill system exhibits undesired side effects, e.g., high physical demand (Cherni et al. 2020).

In summary, the experimental results indicate that the proposed Seamless-walk VR locomotion system is a comfortable and natural solution that can be used by a wide range of users. Additionally, for the preference and exploration scores, the proposed Seamless-walk system could replace the compared methods while not exhibiting negative effects. However, other methods still have their advantages: Foot mouse requires low physical demand and provides smooth reaction; the treadmill safely provides WIP with its body-supporting structure; the leg strap provides a portable, less-expensive, and comfort WIP method. Seamless-walk method is not "always the best" locomotion method. Users could make their choice along with their preferences and environment.

8 Limitation and future work

In this study, we only considered foot interactions to implement the Seamless-walk system. This method has numerous advantages; however, we observed a slight direction change mismatch problem. In addition, we did not consider gaze direction which may useful in terms of gait direction adjustment in VR locomotion systems (Imai et al. 2001). Thus, in future, it may be necessary to combine body direction and gaze direction information to improve the performance of the proposed system.

Another limitation of this study is that it only generates a locomotion signal. In VEs, users can perform a variety of movements, e.g., running, walking, sliding, and jumping (Zhang et al. 2020). Currently, the Seamless-walk system is only used for direction and speed changes during walking. Fortunately, a previous study attempted to classify human movement using high-resolution tactile sensors (Luo et al. 2021). In addition, another previous study investigated an effective 3D pose reconstruction method using high-resolution tactile sensors (Luo et al. 2021). Thus, in future, we plan to combine these functions into a single locomotion system tool to realize a more complete VR interaction method that includes locomotion, 3D user pose reconstruction, and user action classification using high-resolution tactile sensors.

9 Conclusion

In this paper, we have proposed a Seamless-walk VR locomotion system. We evaluated the proposed method experimentally in a user study, and the results confirmed that the proposed system has several advantages compared to existing foot-based locomotion methods. We found that the proposed Seamless-walk system was a significantly comfortable and natural locomotion method. Additionally, the experiment results confirm that the Seamless-walk system could be used by the general public, and there are no negative effects on the general performance of the system. The proposed Seamless-walk system is also low cost, light, easy to expand, and easy to carry.

However, this study does not only aim to develop a new VR interface but becomes more valuable as a step to break the barrier between the real and virtual worlds. Even with the advancements in extended reality and the increased number of related studies, the virtual and real worlds remain separate. Thus, we still need an interpreter who can translate real-world's signals into virtual worlds (and vice versa). As a positive step forward this translation, the proposed Seamless-walk system attempts to directly connect real-world gait actions to a virtual character's gait movement. Although this trial study represents a small step toward a complete digital twin, we believe that future studies will eventually complete a truly Seamless virtual world, and the proposed method represents an important component of this realization.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10055-023-00750-x.

Acknowledgements This work was supported by the GIST-MIT Research Collaboration grant funded by the GIST in 2022. This work was partly supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2021R1A4A1030075) and Institute of Information and communications Technology Planning and Evaluation (IITP) grant funded by the Korea government (MSIT) (2019-0-01842, Artificial Intelligence Graduate School Program (GIST)).

Data availability The datasets generated during the current study are available in the github repository, [https://github.com/jjyunho/Seamless_walk].

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

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