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Freehand-Steering Locomotion Techniques for Immersive Virtual Environments: A Comparative Evaluation

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ABSTRACT

Virtual reality has achieved significant popularity in recent years, and allowing users to move freely within an immersive virtual world has become an important factor critical to realize. The user's interactions are generally designed to increase the perceived realism, but the locomotion techniques and how these affect the user's task performance still represent an open issue, much discussed in the literature. In this article, we evaluate the efficiency and effectiveness of, and user preferences relating to, freehand locomotion techniques designed for an immersive virtual environment performed through hand gestures tracked by a sensor placed in the egocentric position and experienced through a head-mounted display. Three freehand locomotion techniques have been implemented and compared with each other, and with a baseline technique based on a controller, through qualitative and quantitative measures. An extensive user study conducted with 60 subjects shows that the proposed methods have a performance comparable to the use of the controller, further revealing the users' preference for decoupling the locomotion in sub-tasks, even if this means renouncing precision and adapting the interaction to the possibilities of the tracker sensor.

1. Introduction

Over the last few years, Virtual Reality (VR) has experienced a significant revival thanks to the availability of low-cost hardware, which has transformed VR from a laboratory technique into a widely accessible technology. This new era has significantly affected the potential applications of VR, together with the ways users experience and use it (Sun et al., 2015). VR has found application in several contexts, such as medicine (Moro et al., 2017), education (Capece et al., 2019), and data visualization (Capece et al., 2018; Romano et al., 2019).

In relation to Human–Computer Interaction (HCI), these new possibilities have influenced research in the field, leading to the realization of new interaction metaphors, designs, and tools (Boletsis et al., 2017).

In this context, VR locomotion, which is an essential interaction component enabling the user to travel in a virtual environment (VE), has been conditioned by the technological revival of VR (Bozgeyikli et al., 2016). As a result, various existing virtual locomotion techniques have been updated, and new ones have been developed and studied, aiming to offer a "natural," user-friendly and efficient way of traveling in a VE (Christou et al., 2016; Frommel et al., 2017; Nabiyouni et al., 2015). A plethora of literature articles for locomotion in VR describes a great number of theoretical models and classifications developed to try to establish a common background for VR locomotion techniques (D. A. Bowman et al., 2004; Boletsis, 2017; Boletsis & Cedergren, 2019; Al Zayer et al., 2020). For instance, teleportation and walking-based approaches are today widely used VR locomotion techniques, integrated in commercial VR systems (Bozgeyikli et al., 2016; Bruder & Steinicke, 2014; Loup & Loup-Escande, 2019). At the same time, while locomotion solutions based on classic input devices have lost attractiveness because they are guilty of breaking the illusion of interacting with the virtual world directly, and the explicit walking gesture most of the time proves to be excessive or unnecessary, gesture-based locomotion techniques have become more robust and user-friendly (G. Caggianese et al., 2015; Ferracani et al., 2016). Following this thread, researchers have begun to investigate gesture-based interaction with VR content by using contactless motion-sensing devices, although still considering device-based approaches as a benchmark in terms of performance and ease of use (G. Caggianese et al., 2016, 2019). These devices, such as Microsoft's Kinect (Microsoft Kinect, 2010) and Leap Motion (Buckwald & Holz, 2010), track the body and hands in the physical space, enabling developers to design invisible interfaces. In this way, freehand techniques allowing a deeper immersion in the VE have begun to be more widely used. However, these techniques are challenging to design and optimize, the main problem being the choice of a gesture that easily adapts to all users. Additionally, fatigue can affect the user, especially when the gesture needs to be reproduced continuously to perform the movement.

This article presents an empirical evaluation study of three steering freehand-based locomotion techniques compared with each other and with a controller-based approach. Well-known approaches in the literature, classified as gaze-directed steering and hand-directed steering, have been implemented to be used with a head-mounted display (HMD) and a tracking sensor placed in the egocentric position. The goal has been to evaluate the efficiency, effectiveness, and user preferences in continuously controlling the virtual locomotion direction by using the different techniques. At the same time, other related factors have been investigated, such as the influence of the sensor field of view (FOV) on the use of the proposed techniques together with the relation between the performance and the interaction decoupling in sub-tasks, such as direction selection, and input conditions to control the movement. This article aims to contribute to such research by documenting the interaction aspects of these new VR locomotion techniques and by producing data that can be further used by researchers and developers to formulate conceptual works and to guide the design of new or updated VR locomotion techniques.

The remainder of this article is structured as follows: Section 2 presents related work; Section 3 describes the VR locomotion techniques that will be compared and empirically evaluated; Section 4 describes the comparative, empirical study, presenting the methodology employed and its results; Section 5 discusses the study's results and its overall research implications; finally, Section 6 provides a general discussion and concludes the article.

2. Related work

Increasing the sense of immersion perceived by the user is one of the main goals in VR research. As defined by D. A. Bowman et al. (1998) allowing the user to control her/his viewpoint motion in a three-dimensional environment represents a crucial element in the establishment of a sense of immersion or presence. New approaches based on the user's body movements have gradually replaced approaches based on the use of classic input devices, such as a keyboard, mouse, or joystick, as soon as tracking systems had been found to be more mature and less expensive. The literature reports many different solutions relating to the realization of VR locomotion interfaces (Boletsis, 2017) ranging from real-walking solutions, in which the user walks inside a small space (Borrego et al., 2016) or in-place (Langbehn et al., 2015; Tregillus & Folmer, 2016), to more specific solutions, in which the user travels inside a VE by using a stool chair orientation and leads (Kitson et al., 2017).

The various approaches present in the literature are generally organized into *walking-based, steering-based, selection-based*, and *manipulation-based* techniques (J. J. LaViola et al., 2017; Jerald, 2015). Among these approaches, we focused our attention on the steering-based ones, whose key feature is the continuous control of the direction performed through different techniques. Such techniques are further divided into two main categories: *Spatial Steering Techniques* and *Physical Steering Techniques* (J. J. LaViola et al., 2017). While the physical steering approaches prove to be limited to specific scenarios because they are based on specialized devices that vary according to the steering task performed (Brogan et al., 1998; Brooks, 1999), the spatial steering techniques are controlled by using body gestures that are properly mapped to control the virtual direction. J. J. LaViola et al. (2017) classify spatial steering techniques into four categories according to the part of the body used to control the steering: *(i) gaze-directed steering, (ii) hand-directed steering, (iii) lean-directed steering*, and *(iv) torso-directed steering*. The gaze-directed solutions allow the user to travel where she/he is looking, and, for this reason, eye-tracking should be provided (Stellmach & Dachselt, 2012). However, few applications track the movement of the user's eye, instead generally using the orientation of the user's head (Cardoso, 2016; Choe et al., 2019; Ruddle & Lessels, 2009; Suma et al., 2009). Christou et al. (2016) propose a comparison between two locomotion techniques in a way-finding task immersed in a CAVE (Cruz-Neira et al., 1993) emphasizing that during the traveling, the gaze-directed solutions limit the user in her/his looking around. Concerning the hand-directed steering, a significant work is that proposed by Zhang et al. (2017), which presents a locomotion method controlled by using double-hand gestures. In particular, the left palm is used to control the movement (forward or backward) while the right thumb controls the turning (left or right). In comparison with the joystick-based technique, the proposed solution shows a high level of user satisfaction, a low level of perceived fatigue, and an ease of learning and using, improving the immersion feeling and reducing the reported sickness. A proliferation of different solutions can be noted in the lean-directed steering category. In fact, the simplicity of this approach has produced techniques that differ in terms of the part of the body involved and in the choice of the tracking system (De Haan et al., 2008; J. J. LaViola et al., 2001; Kitson et al., 2015). An example proposed by Carrozzino et al. (2014), presents a foot controller device to travel through a VE by interpreting the natural motion of leaning toward the desired object as the travel direction. Few works support torso-directed steering due to the greater number of sensors required to track the user's torso movements and map them to a travel direction. Guy et al. (2015) proposed an exciting work, which provides a traveling technique based on a tracking of the shoulder or hip rotations to travel in the virtual scene. Such a type of steering technique has often been compared with other approaches belonging to the other categories, generally performing worse in terms of both thinking and travel time (D. A. Bowman et al., 1999, 1998; Suma et al., 2010).

Over the last few years, many studies have been performed in order to investigate the performances of these techniques and user preference. Most of the time, these studies have compared approaches belonging to different categories (Beattie & Morrison, 2019; Erra et al., 2019). For instance, Bozgeyikli et al. (2016) proposed a new locomotion technique called Point & Teleport and compared it with two other locomotion techniques: walk-in-place and the joystick. The study emphasized in the use of the new approach a reduction in motion sickness due to the absence of any visible translation in the virtual world. In another study, Slater et al. (1995) suggested that the walking-in-place methods may enhance the participant's sense of presence, but also that they turn out to be disadvantageous with respect to the efficiency of travel. Langbehn et al. (2018) analyzed the effect of three different locomotion techniques, joystick-based, teleportation, and redirected walking, on the user's cognitive map through an indoor VE. The results showed that the redirected walking technique and the teleporting solution were preferred to the joystick-based technique, which has been verified to be responsible for an increase in the perception of motion sickness. In a study conducted by Ferracani et al. (2016), gesture-based approaches performed using different sensor cameras were compared in terms of effectiveness and perceived naturalness. The interaction based on the use of the index finger proved to be a more intuitive, less tiring, and more precise solution.

Compared to the other studies present in the literature, this work proposes an evaluation of steering-based techniques realized using the same off-the-shelf and low-cost hardware. In more detail, the comparison involved freehand and uni-manual approaches implemented to realize user-friendly locomotion interfaces based on the user's hand gestures and head movements. To the best of our knowledge, this is the first study that compares similar solutions in terms of the hardware employed and constraints imposed, using a controller-based approach as a benchmark, and that investigates how the FOV management and the possibility of a decoupling of the locomotion interaction in direction selection and locomotion control influence technique performances and user preferences.

3. The freehand-steering locomotion techniques proposed

Four spatial steering locomotion techniques, *Palm* 3.2, *Index* 3.3, *Gaze* 3.4, and *Controller* 3.5, were realized, inspired by the seminal work of Mine (1995). The proposed techniques were developed as uni-manual approaches differing from each other in terms of the gesture used to control the locomotion steering and the input conditions required to start and stop the movement.

Palm, Index, and Gaze are based on gesture recognition by using a sensor placed in an egocentric position on top of an HMD to realize a freehand interface using metaphors designed for the general public (Valli, 2008). In contrast, the Controller technique follows the common habit of users when interacting with systems, operating by means of a hand-held-device. The use of a gesture-controlled interface presents the advantage of not requiring additional hardware. However, the interface has to cope with the limited FOV of the tracking sensors. Moreover, the interaction area moves in accordance with the user's head, since the sensor is anchored to the HMD. More details on the apparatus are presented in subsection 4.3.

According to the taxonomy published in the work of D. A. Bowman et al. (1997), a traveling task is presented as composed of three sub-tasks: *direction (target) selection, velocity (acceleration) selection*, and *input conditions*. In the proposed approaches, among the different solutions, the direction selection is performed by mapping different hand movements to control the locomotion steering. The ray-casting technique (Mine, 1995; Stoakley et al., 1995) is used to show the user the visual feedback of the locomotion direction through a red ray going out from the hand or the controller into the VE and a cursor indicating the corresponding position on the virtual terrain. To make the technique easy to learn and use during the experiments, we did not consider the sub-task of velocity selection, maintaining such a feature constant during the traveling. We defined specific gestures to initiate, continue, and terminate the motion in all the proposed approaches. Finally, an activation gesture was realized to activate/deactivate the locomotion modality, allowing the user to execute different tasks in the VE.

In the following subsections, we will first describe the activation gesture and then the design detail of the four locomotion techniques.

3.1. Activation gesture for the locomotion mode

Concerning the locomotion approaches the activation gesture was also designed to be executed with one hand, but in a different way for the freehand-based and controller-based techniques. For the freehand-based techniques, the user is required to place her/his hand with the palm facing upward and then closing the hand into a fist as shown in Figure 1. As feedback, the color of the synthetic hand changes from light gray to dark blue. In contrast, in the controller-based technique, the activation is achieved by squeezing the controller, precisely by using the Grip button placed on the side of the hand-grip. In this case, also, the mesh color of the virtual controller changes from black to dark blue (see Figure 1). The activation gesture was designed to be executed with either hand indifferently, meaning that the hand used to perform the activation gesture indicates the hand that the user wants to use to control the locomotion, usually her/his dominant hand.

3.2. Palm-steering technique

Palm steering is a freehand-steering technique that allows the user to specify the traveling direction through her/his palm orientation. The sub-tasks composing the palm-steering technique are implemented as follows:

- The direction selection is performed by the user holding her/his hand open in the FOV of the sensor. The outgoing vector from the palm tracked is then used to define the traveling direction. Moreover, visual feedback is shown, a red ray advancing from the palm down to the ground where a placeholder is visualized (see Figure 2).
- The locomotion is performed at a constant speed. Velocity selection is not allowed.
- The input conditions to determine when to start or stop the traveling are implemented through the grab gesture executed with the same hand as that used to control the traveling direction. This means that both direction and input conditions are coupled and controlled using the same hand. By closing her/his hand, the user expresses her/his intention to start moving, continuing until she/he reopens her/his hand. Moreover, two more input

Figure 1. The activation procedures for the freehand-based and controller-based techniques. The color of the virtual hand and the controller changes from gray to blue to indicate that activation has taken place.

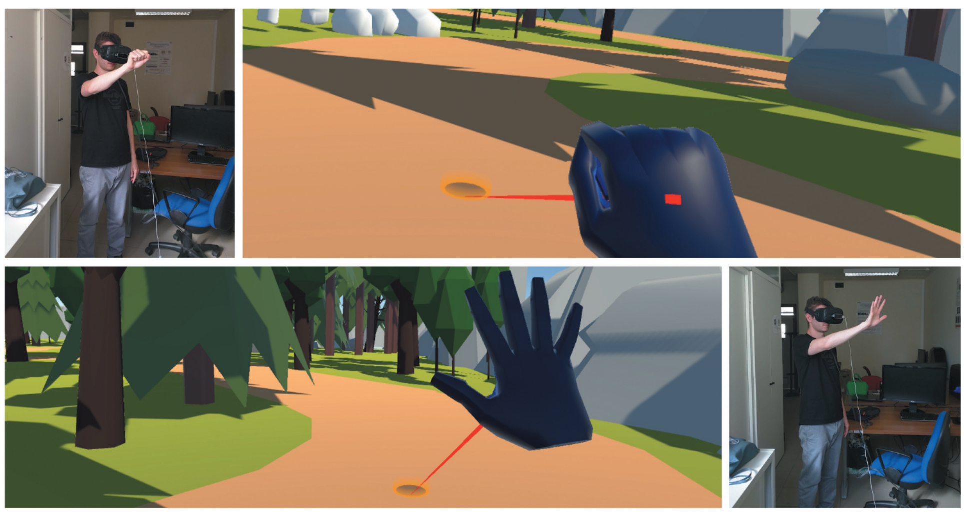

Figure 2. A user engaged in traveling in a VE with the palm-steering approach. The upper section of the figure shows the user starting the locomotion by closing her/his tracked hand. Differently, in the lower section of the figure, the user stops the movement by opening her/his hand.

conditions are considered and interpreted as involuntary stop and start conditions. A failure of the hand tracking (hand out of the tracking area) during the movement stops the traveling. When the user's hand performing the grab gesture is back in the FOV of the sensor, the traveling restarts.

This technique gives the user the ability to move in all directions, even walking backward and sideways without rotating the head. It provides that the choice of direction and when to move are controlled with the same hand. The implementation decouples the traveling direction from the user's looking direction meaning that the user can look around during the locomotion. However, since the sensor is anchored to the HMD, an excessive head rotation can lead to a hand tracking miss caused by the fact that the hand is no longer in the interaction area of the sensor.

3.3. *Index-steering technique*

The proposed index solution is a "crosshairs" mode-directed steering technique (Mine, 1995) in which the user controls her/his traveling through a gesture commonly used in every-day life (Del Bimbo et al., 2017). The sub-tasks composing the index-steering technique are implemented as follows:

- The direction selection is defined by the user placing her/his hand in the FOV of the sensor with only the index finger raised. The traveling direction is defined by the vector that moves from the user's head through the index fingertip (the crosshair) and then into the VE. The user needs to place the index fingertip so that it visually lies on top of the place that she/he wishes to reach. The visual feedback of the traveling direction is then displayed as a red ray advancing from the virtual index fingertip down onto the VE terrain where a placeholder indicates the position to reach (see Figure 3).

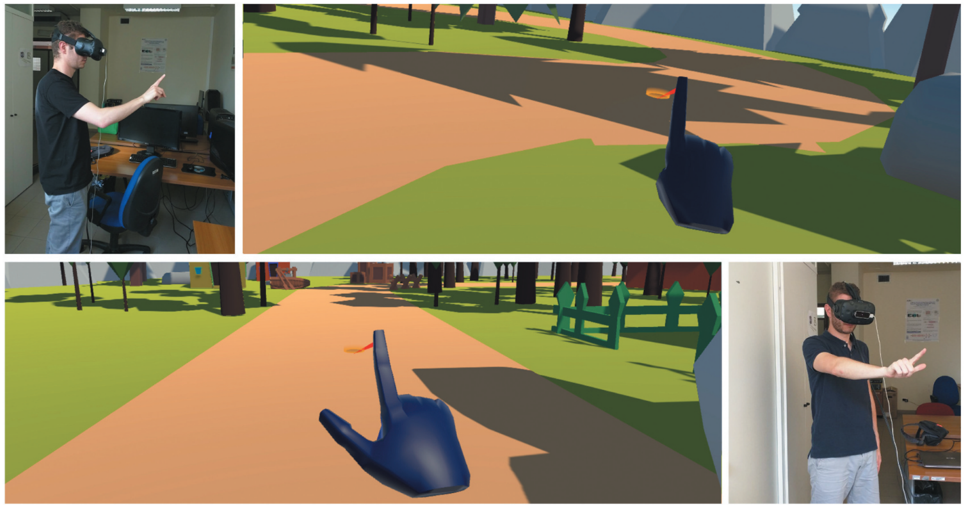

Figure 3. A user engaged in traveling in a VE with the index-steering approach. The upper section of the figure shows the user moving in the VE with his thumb closed on his middle finger. In the lower section of the figure, the user has stopped the movement by opening her/his thumb.

- The locomotion is performed at a constant speed. Velocity selection is not allowed.
- The input conditions to determine when to start or stop the traveling are implemented by tracking the thumb poses of the same hand as that used to define the traveling direction. To start moving, the user needs to close her/his thumb toward her/his middle finger and reopen it to stop the movement. Two more input conditions are considered. If the user moves her/his hand which is in control of the movement out of the FOV of the sensor during the traveling, the movement is stopped. When the user brings her/his hand back within the FOV of the sensor with her/his index finger raised and thumb closed on the middle finger, the traveling restarts.

Differently from the previous technique, due to the egocentric position of the sensor and the way the traveling direction is determined, the user cannot move in all directions without rotating her/his head. For instance, to move sideways, she/he needs to turn her/his head, bring the VE elements placed in that direction into her/his point of view and then overlap them with her/his index fingertip. However, as in the previous approach, the user is free to look around during the movement provided that her/his hand remains in the FOV of the sensor. This approach overcomes some of the difficulties that can be encountered with a pointing technique by proposing an approach similar to the use of a mouse in a desktop application. The user can choose a direction by maintaining a more comfortable hand pose that does not require her/his wrist to be excessively flexed, and that proves to be more easily tracked by the sensor since her/his palm cannot occlude her/his fingers.

3.4. Gaze-steering technique

In the Gaze approach, the user travels by choosing the direction with her/his gaze (Mine, 1995). The sub-tasks composing the gaze-steering technique are implemented as follows:

- The direction selection is defined by using the gaze direction of the user which is estimated by using the position and orientation of the HMD. In this case, to avoid introducing visual elements that could cause discomfort to the user, the direction chosen is displayed by using only the placeholder where the forward vector of the HMD intersects the virtual terrain.
- There is no velocity selection. The movement is performed at a constant speed.
- The input conditions to start and stop the movement are realized as in the Palm-steering technique. To move, the user needs TO assume the grab gesture (see Figure 4). The movement stops when her/his hand is open. In this way, the management of the input conditions proves to be decoupled from that of the direction selection. Finally, if during the movement the user allows her/his hand in the grab pose to fall out of the FOV of the sensor, the traveling is interrupted, but if afterward, the user brings it back; still, in grab pose, the navigation restarts.

The main advantage of this approach is the user's ease and speed of learning because her/his head is tracked from the HMD device so that the direction control proves to be very intuitive, especially in relation to the 2D horizontal plane motion (J. J. LaViola et al., 2017). Moreover, another advantage would be that the sub-tasks of direction selection and input conditions are decoupled, probably making the technique more comfortable to use. On the other hand, the main limitation of this approach is the constraint imposed on the user to look constantly in the traveling direction. Moreover, since the start and stop inputs are performed by using her/his hand, the user is required to maintain a coordination between her/his head and hand movements.

3.5. Controller-steering technique

Finally, the controller-steering technique allows the user's movement through the use of a controller. The sub-tasks

Figure 4. A user engaged in traveling in a VE with the gaze-steering approach by keeping her/his hand closed in a fist. The direction is obtained from the HMD orientation and shown as a placeholder on the terrain. To stop traveling, the user has to open her/his hand, as in the palm-steering approach.

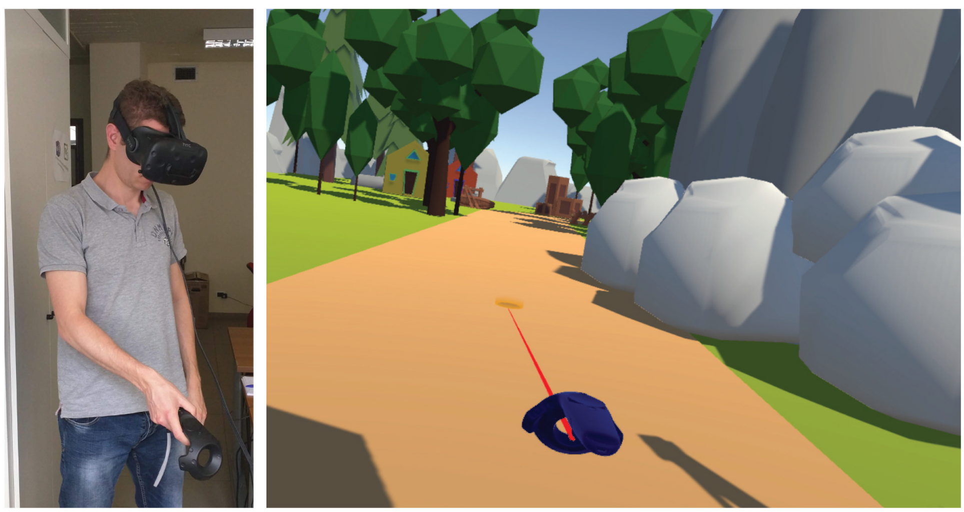

Figure 5. A user engaged in traveling in a VE with the controller-steering approach. The direction is defined by using the orientation of the controller. The traveling is allowed by holding down the trigger button and interrupted by releasing it.

composing the controller-steering technique are implemented as follows:

- The direction selection is defined by pointing with the controller into the VE. A ray advancing from the controller and a placeholder visualized in the intersection between the ray and terrain are used as visual feedback (see Figure 5).
- Velocity selection is not allowed. The user moves at a constant speed.
- The input conditions to start and stop the movement are implemented by exploiting the trigger button of the controller. To start moving, the user has to press the trigger button and then release it to stop. As a result, the direction selection and start/stop conditions are coupled and controlled using the same hand.

This approach, as for the palm-steering technique, allows movement in all directions without the need to rotate the head. The use of a controller could impact on user's comfort, since it does not require the user to assume different hand poses. Moreover, the controller is always within the tracking area, freeing the user from keeping her/his hand within the FOV of the sensor while moving her/his head. Finally, the tactile feedback can reduce the gap between the perceived body movement and what is displayed on the screen (Skopp et al., 2014).

4. User study

For a comprehensive evaluation of the opportunity provided by the use of freehand interactions for locomotion in VR, we conducted an in-lab experiment comparing all the proposed techniques in the performance of the same task in the same VE. Moreover, the approaches have been evaluated, considering both quantitative and qualitative measurements.

4.1. Objectives and hypotheses

We wanted to measure the usability by assessing the efficiency and effectiveness of, and user satisfaction (Frøkjær et al., 2000) relating to, different freehand locomotion techniques compared with each other and with a baseline technique which uses controllers. According to several studies in which the efficiency and effectiveness have been evaluated in relation to navigation in VEs (Christou & Aristidou, 2017; Sayers, 2004), and following the ISO broad definition of usability (ISO9241–11, 1998), our efficiency measure focused on the task completion time while the effectiveness measure focused on the error rates and the quality of the solution, which was defined through the number of interruptions and the number of missed hand trackings. The aforementioned objective metrics, efficiency, and effectiveness, in this study were used as indicators of performance, i.e., a measure of the outcome of the user's interaction. Moreover, to complete the analysis of usability, we considered subjective metrics to explore the perceived motion sickness, emotion, usability, physical, and cognitive demands and preference.

In the main comparison between the freehand approaches and the controller-based solution, we hypothesized an equivalent level of performance. We believed that the improved accuracy of the tracking device combined with the naturalness of the gestures chosen for the implementation could mitigate the difficulty in using the freehand approaches. On one hand, the freehand solutions require the users to actively engage their body to complete a task by holding their hand in mid-air in front of the sensor, and to have a good head-hand coordination. On the other, the controller represents a well-known solution in which the remote can be held in a more comfortable position, e.g., at a user's side, returning tactile feedback that gives the user a familiar feeling, like that of holding a tool.

These considerations led us to formulate the following hypothesis:

H1: We expect no significant difference in terms of performance in traveling in a VE using the freehand-based locomotion techniques as compared to the controller-based locomotion technique.

Moreover, we were interested in investigating the interaction between the user's performance and the implementation choice of decoupling the control of direction selection and the input conditions. We hypothesized that in the freehand techniques the possibility of separately controlling the traveling direction and the start/stop conditions should result in a better performance. A user who is engaged in an interaction that requires her/him to assume an arm position which is not comfortable could find it advantageous to perform different traveling sub-tasks by using different body parts, as in the gaze-steering approach. Accordingly, we formulated the following hypothesis:

H2: We presume that the decoupling of the direction selection and input conditions to control the movement in relation to the freehand-based techniques will allow the users to obtain a better performance.

We also aimed to verify if the decoupling of the steering and input conditions could influence the frequency of the missed trackings of the user's hand. The number of missed hand trackings verified during the interaction represents the main issue in relation to the inside-out pose estimation method chosen to implement the freehand approaches and performed by placing the tracking devices on the user in an egocentric position. The user is required to perform the gestures in front of the sensor by managing her/his hand movements and avoiding bringing her/his hand out of its FOV. Concerning this last consideration, with a similar line of reasoning as that which led to the previous hypothesis, we believed that the possibility of performing the start/stop management decoupled from the traveling direction selection would require the user to follow the head movement in a way that would prove to be less prone to tracking mistakes than when the same traveling sub-tasks are coupled and controlled with the same hand. This prompted us to formulate the following final hypothesis:

H3: We suppose that the decoupling of the direction selection and input conditions to control the movement in relation to the freehand-based techniques will result in a lower number of tracking errors caused by an unconscious shifting of the user's hand in control outside the FOV of the sensor.

Finally, in relation to the qualitative evaluation of the proposed approaches, a set of task-level questionnaires was chosen from among those most commonly used in the literature. Our goal was to evaluate, through subjective metrics, the opinions of the subjects who participated in the study, particularly *(i)* their perceptions *(ii)* the perceived usability and *(iii)* their general experience of each approach. The overall aims were to determine if the freehand approaches were preferred to the use of the controller and to identify, among the freehand techniques, which one was preferred.

In order to evaluate the participant's feelings in using the proposed techniques, we exploited the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) used to ascertain any perceived nausea, oculomotor disorders, or disorientation possibly caused by the use of the techniques, and the Self-Assessment Manikin (SAM) (Bradley & Lang, 1994), which was chosen because it allows an assessment of the emotional state perceived during the use of the techniques through the use of pictorial assessment rather than verbal expression.

Concerning the perceived usability we decided to use the System Usability Scale (SUS) (Brooke, 1996) because it provides a rapid evaluation of the examined techniques and a useful score that simplifies a comparison with other approaches.

The user experience of the subjects who took part in the study was evaluated through the Single Ease Question (SEQ) questionnaire (Sauro & Dumas, 2009), which allows an evaluation of the perceived difficulty in performing the task, and the NASA-task load index (NASA-TLX) questionnaire (Hart & Staveland, 1988), in its short version Raw-TLX (Hart, 2006), which allows a measurement of the perceived workload after the use of any specific technique.

4.2. Participants

The study involved 60 unpaid volunteers (47 males and 13 females) recruited from the students of the University of Basilicata. Their ages ranged from 19 to 32 years old ($M \simeq 23$, $sd \simeq 3$). Almost all the participants were right-handed with only four left-handed. Finally, considering the answers of the participants to a pre-exposure questionnaire structured as a 5-point Likert scale in which 1 is "never" and 5 is "very frequently" it is possible to say that 30% of the participants declared that they had already had experience with a VR system while only 15% reported having practiced with a touchless interface (scores between 3 and 5 were considered as indicating a positive answer).

4.3. Apparatus

The PC used for the user study was a VR Ready computer, running a 64 bit Windows 10, with an Intel Core i5-7400 8GB and a Nvidia Geforce GTX 1060.

The freehand interactions were realized through the Leap Motion sensor that works by using two infrared cameras arranged so that their FOV intersects three infrared (IR) light-emitting diodes (LEDs) positioned alternately to the cameras. This device is able to detect and trace the user's hands and fingers with a high degree of accuracy and tracking frequency by reporting their positions and movements. The device can perform short-distance tracking (about 25 to 600 mm), with 150 degrees as the FOV. Thanks to its low weight, it can be mounted in front of an HMD to track the user's hand actions from an egocentric point of view.

The HTC VIVE HMD was used. It is characterized by OLED panels for each eye with 1080 × 1200 as the resolution. Each panel has a refresh rate of 90 Hz and 110 degrees as a FOV. The HMD has rotational and positional tracking on 6 degrees of freedom, in order to effectively manage the tracking of the user, through the Vive's base station called the Lighthouse (Suznjevic et al., 2017). The Lighthouse is a positional tracking system based on infrared tracking sensors allowing a configuration of the real world user space through a room-scale method (Peer & Ponto, 2017). The controllers supplied by HTC were two wireless ergonomic controllers that could be easily handled by a user with one hand. These controllers were fully tracked in the three-dimensional space allowing a stable indirect tracking of the user's hand movements in a room-scale environment. Moreover, the controllers also included accelerometers so that the hand tracking was the result of a fusion of the positional and tracking data.

The VE together with the locomotion techniques was developed by using the Unity game engine. The techniques were developed through C# together with Steam VR SDK (version 2.0) and Orion SDK for the Vive Controllers and Leap Motion, respectively.

The apparatus rendered the VR scenario at the maximum resolution of the HMD (2160 × 1200) at about 70 fps in the controller configuration, and at 45 fps in that of the Leap Motion.

4.4. Experimental task

The task proposed to the participants consisted in following a predefined path from a start to an end, the goal, in an immersive VE. Figure 6 shows the path, which was characterized by 22 bends to force a redirection of the locomotion and different path widths (a maximum width of 6 m and a minimum width of 1.5 m) to introduce different levels of difficulty in staying on the track. Following the entire path required the user to move for about 343 m, with, considering the shape of the track, a possible optimal path of 325 m. Since the proposed techniques do not allow any control of the velocity, the subjects moved along the path at a constant speed of 3.5 m per second.

The VE proposed to the user was realized using a set of free Unity assets for the terrain model and the other components visible in the scene. In detail, many elements were placed around the path to reproduce a village setting. These elements, which acted as distractors, were mostly static; with only a few of them characterized by simple animations, e.g., the waving of a flag.

4.5. Procedure

The user study was performed by organizing the subjects into 6 groups of 10 individuals. The study was conducted on one group at a time, following four main steps: *(i)* explanation of the procedure and presentation of the techniques, *(ii)* administration of the background questionnaire *(iii)* training, and

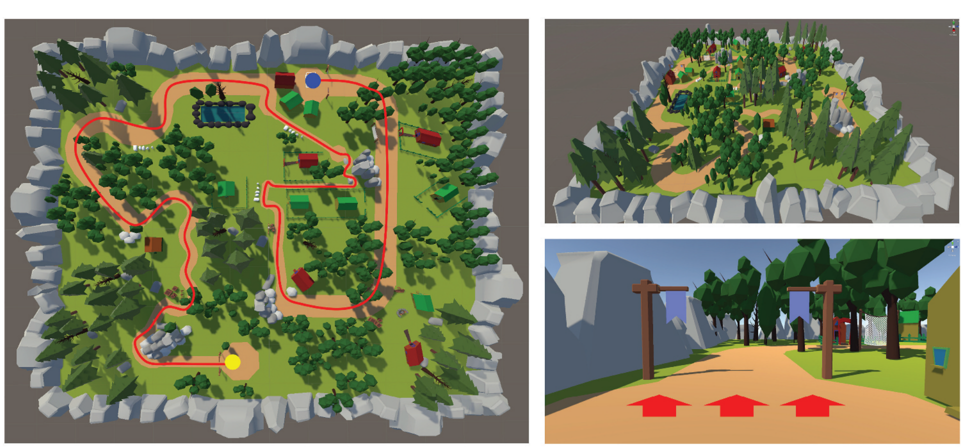

Figure 6. The left image shows the predefined path proposed to the subjects during the experimentation highlighted with a red line. The yellow point represents the start, while the blue point indicates the end. The lower right image shows the start flag and the upper right image shows an isometric view of the scene.

(iv) task execution and administration of the task-level questionnaires.

In the first step, a facilitator explained to the entire group of volunteers, in about 15 minutes, the procedure, presented a video of the four techniques, showing the interaction modalities for each of them, and demonstrated how the Leap Motion sensor works by highlighting its sensing range limitations.

Next, in the second step, a background questionnaire was administered to the participants, requesting information about their age, gender, and dominant hand, and asking them about their previous experiences with VR, touchless interfaces, and video games. Additionally, general questions were included to ascertain the current status of any physical disorders which could be intensified by the simulation. None of the participants had to be excluded from the study because she/he was considered an "unhealthy" subject. The completion of the questionnaire, together with the answering of a few questions, required a total time of 2 minutes and was performed by all subjects at the same time.

Afterward, in the third step, the participants were given the freedom to practice one at a time with the locomotion techniques in a VE different from the one used for the experimental task. The subjects practiced each technique for about 3 minutes.

Next, all the subjects performed the task. Following the same order as in the previous step, the volunteers performed the locomotion task, as presented in the previous section 4.4, using each of the four techniques one at a time in about 2 minutes. Each volunteer used a different ordering of the locomotion techniques, based on a Latin square. The participants were required to perform the traveling task as quickly and accurately as possible, trying not to "walk" off the marked path. During the task execution, no restrictions or constraints were imposed on the subjects, who were free to move in the VE in any way they thought best to achieve the goal. Each time a subject traveled off the path, no specific visual feedback or verbal indication by the facilitator was used to correct the direction. Finally, after the use of each technique, the facilitator administered to the subjects a set of task-level questionnaires to evaluate their perceived motion sickness and general emotions, and the perceived usability of the technique and difficulty in performing the task. Completion of the questionnaires required a total time of about 5 minutes. The execution of consecutive tasks performed by using different locomotion techniques required an equivalent time duration to that needed for the members of the group to execute the task. This meant that all subjects had to have performed the first task with their first technique before moving on to the second task to be accomplished with the second approach. The order of volunteers always remained the same to maintain a constant break time between consecutive tasks, which was of about 20 minutes.

Therefore, the total time for the execution of the user study can be summarized as follows:

- Procedure explanation and technique presentation – about 15 minutes.
- Completion of background questionnaire – about 2 minutes.
- Training, 3 minutes per technique – about 12 minutes.
- Task execution, task-level questionnaires, and break between consecutive tasks, repeated four times, once for each technique – about 27 minutes subdivided as follows.
  - task execution – about 2 minutes.
  - completion of task-level questionnaires – about 5 minutes.
  - break to allow all group subjects to perform the task – about 20 minutes.

4.6. Design

We performed a within-subject design with 1 four-level factor; the four described locomotion techniques. The performance was measured in terms of *execution time, errors made in following the path, the number of times the locomotion was interrupted*, and *the number of times the hand tracking was missed* with repeated measurements on all the four levels of the within-subject factor.

In detail, the execution time represents the time needed to achieve the goal. The path errors were calculated by considering the number of frames in which the subject was walking outside of the predefined path. In this way, the number of frames spent outside the path represents an indirect measure of the difficulty of traveling along the path with the specific technique used. However, less straightforward measures for usability characterize the last two dependent variables. The number of interruptions, namely the number of times the subject needed to stop the movement to correct the direction of locomotion, is useful to understand the usability of the proposed technique considering that an effective approach allows the user to control at the same time the orientation and input conditions to start and stop the traveling. The last measure, the number of times the hand tracking is missed, is related to the three approaches that exploit the hand-tracking sensor. This variable measures the number of times the sensor loses the tracking of the user's hand because it moves out of the FOV of the sensor during the locomotion. In our opinion, this measure is useful to highlight the difficulties that the subjects experience in managing the sensor FOV and therefore in performing the task. Regarding the last measure, it is important to note that, although the navigation is interrupted if the user's hand is no longer tracked, this interruption is not counted as a voluntary traveling interruption.

In summary, the dependent variables collected were the execution time (*ET*), the number of frames traveled off the path, namely errors (*E*), the number of traveling interruptions (*I*), and the number of missed trackings (*MT*). The locomotion techniques were counterbalanced using a balanced Latin square and, excluding the training, the amount of trials was 240 (60 participants x 4 locomotion techniques).

5. Results and discussion

5.1. Quantitative evaluation

Since the distribution of the data collected did not meet the requirements for normality, we decided to assess the hypotheses by using the non-parametric Friedman's ANOVA test. Table 1 shows the descriptive statistics of the dependent variables collected during the user study. In the following subsections, the results of the analysis of the validity of our hypotheses are presented.

Table 1. Descriptive statistics of the collected dependent variables execution time (ET), number of frames traveled off the path, namely errors (E), number of traveling interruptions (I), and number of missed trackings (MT).

		M	Mdn	sd	Min	Max	Interquartile Range
ET	Palm	103.19	100.84	7.48	92.49	123.82	10.37
	Index	105.81	98.73	20.13	34.42	176.58	13.57
	Gaze	103.79	100.33	11.33	88.65	135.49	12.57
	Controller	101.84	99.00	10.08	86.99	141.19	9.43
E	Palm	128.77	31.50	253.25	0	1158.00	86.00
	Index	127.77	39.50	233.73	0	1521.00	176.00
	Gaze	208.12	119.50	253.07	0	1200.00	253.00
	Controller	119.63	53.00	192.31	0	1032.00	174.00
I	Palm	4.53	3.00	5.000	0	19.00	6.00
	Index	3.88	2.00	5.069	0	22.00	6.00
	Gaze	5.52	3.00	6.307	0	27.00	8.00
	Controller	10.00	6.50	11.68	0	66.00	15.00
MT	Palm	62.30	11.50	98.50	0	527.00	108.00
	Index	59.37	0	206.14	0	1401.00	42.00
	Gaze	100.55	50.00	131.19	0	534.00	108.00
	Controller	–	–	–	–	–	–

5.1.1. Hypothesis H1

Concerning the hypothesis H1 we compared the mean ranks for the dependent variables ET, E, and I. As we expected, the execution time did not significantly change over the different interaction modalities, $\chi^2(3) = 5.5$, $p > .05$ (Figure 7). However, the Friedman χ^2 statistic proved to be significant for both the variables E, $\chi^2(3) = 21.2$, $p < .01$ and I, $\chi^2(3) = 24.7$, $p < .01$, meaning that the interaction modality significantly affects both the number of errors and of traveling interruptions made during the locomotion.

Given this significant initial analysis, Wilcoxon tests were used to follow-up this finding in which the performances achieved with the freehand-based techniques were compared with the technique that uses the controller. A Bonferroni correction was applied, and thus all effects were reported at a .0167 level of significance. The comparison revealed that the number of errors committed by the subjects using the proposed techniques was always higher than the number of errors committed when using the Controller approach (Figure 8 box (a)).

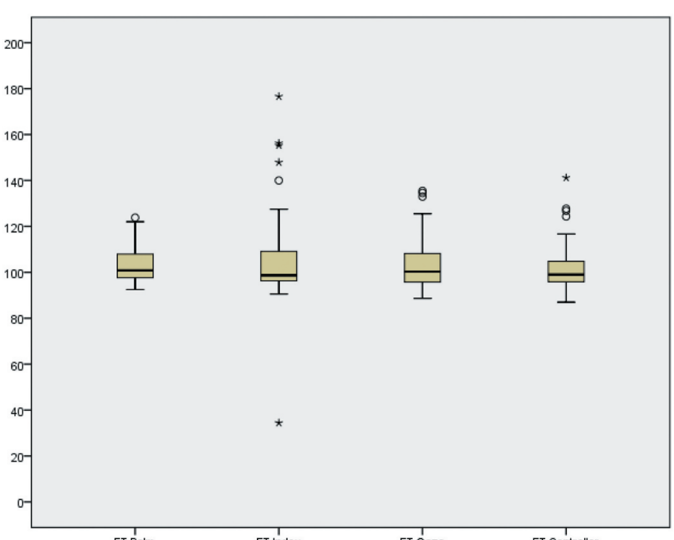

Figure 7. Summary representation of the ET distribution. The comparison performed over the different interaction modalities does not highlight any significant variation in the execution time.

From the analysis performed, in the comparison between Controller and Palm, it appeared that the number of errors performed did not significantly vary: Controller ($Mdn = 53.0$) and Palm ($Mdn = 31.50$), $T = 638.50$, $p > .05$, $r = -.06$. Similarly, the number of errors was not significantly different also when comparing Controller ($Mdn = 53.0$) with Index ($Mdn = 39.50$), $T = 674.50$, $p > .05$, $r = -.01$. Differently, in the last comparison between Controller and Gaze, the number of errors was significantly higher with Gaze ($Mdn = 119.50$) than with Controller ($Mdn = 53.0$), $T = 463.00$, $p < .05$, $r = -.28$. Therefore, as a result of this significant result in the comparison Controller-Gaze, we can conclude (based on the fact that positive ranks were used) that there was a significant decline in the number of errors committed in changing the technique from Gaze to Controller ($z = -3.039$, $p < .05$).

Moreover, the post hoc analysis related to the number of traveling interruptions performed during the locomotion highlighted a significant increase by moving from freehand interactions to the technique that uses the controller (Figure 9 box (a)). The follow-up test revealed that the number of interruptions was significantly higher with Controller ($Mdn = 6.5$) than with Palm ($Mdn = 3.0$), $T = 320.00$, $p < .001$, $r = -.36$. The same effect was also observed in the comparison with the Index ($Mdn = 2.0$), $T = 229.00$, $p < .001$, $r = -.41$, and Gaze ($Mdn = 3.0$), $T = 398.00$, $p < .05$, $r = -.27$, approaches. Therefore, from all the

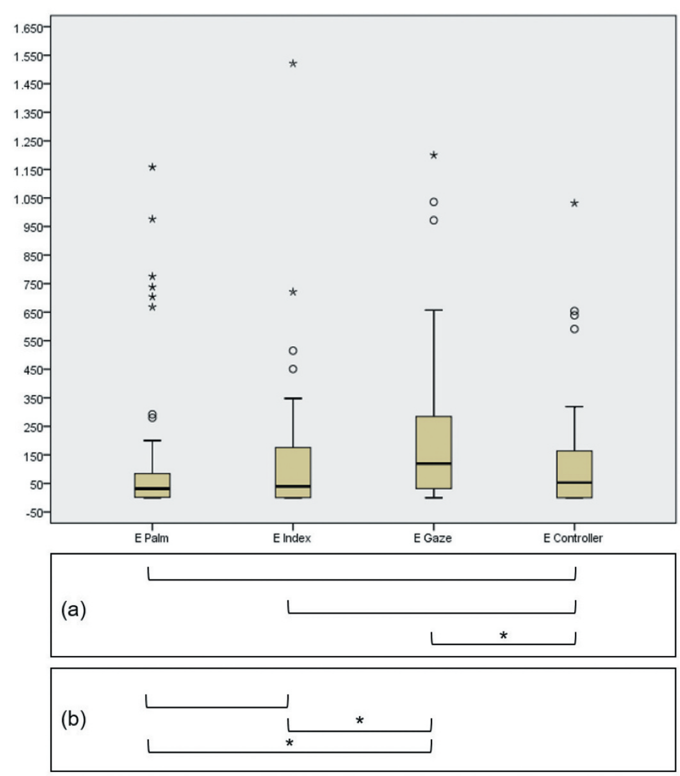

Figure 8. Summary representation of the E distribution. Box (a) shows the comparisons between the freehand techniques and the controller-based technique, pointing out, with an asterisk, when the number of errors significantly varies by moving between two different approaches. Box (b) shows the results of the performed comparison performed with only the freehand approaches, pointing out the significant effects identified.

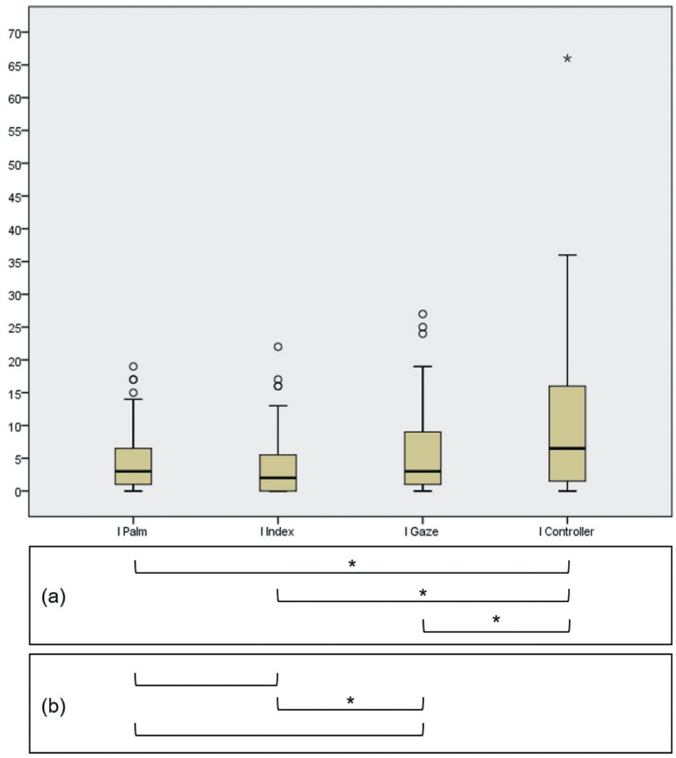

Figure 9. Summary representation of the I distribution. Box (a) shows the comparison between the freehand techniques and the controller-based solution highlighting, with an asterisk, when the number of interruptions significantly varies by moving between two different approaches. Box (b) shows the results of the comparison performed among only the freehand-based approaches, highlighting the significant effects identified.

comparisons we can conclude (based on the fact that negative ranks were used) that there was a significant increase in the number of interruptions in changing the technique from Palm ($z = -3.905$, $p < .001$), Index ($z = -4.540$, $p < .001$), or Gaze ($z = -2.972$, $p < .05$) to Controller.

The results achieved show that the compared techniques prove to be equivalent in terms of efficiency but not in terms of effectiveness. Although all the techniques allowed the subjects to conclude the task in approximately the same time, the number of errors and interruptions made proved to be significantly different between the freehand interactions and the controller-based solution leading us to reject hypothesis H1.

Concerning the execution time, observing the behavior of the subjects, we realized that some of them were more concerned about not making traveling errors than completing the task as quickly as possible, causing a series of anomalous values in the detected time at the high end of the distribution. Instead, the absence of traveling constraints and the lack of any feedback on errors made, combined with the timed task were the cause of path cuttings that led to anomalous detected times at the low end of the distribution (see the outliers in Figure 7). During the execution of the task, almost all subjects tried to travel as few meters as possible, often making errors in executing the bends of the path. In this way, the errors proved to be distributed along the entire path, which allowed the subjects to gain a few seconds in the final time. To explore these values in more in detail, it is important to consider that the task could be performed, following the optimal path of 325 m at the constant velocity of 3.5 m per second, in about 92.85 seconds. Since the number of both I and MT can only contribute to the increase in the execution time, the anomalous execution time at the low end of the distribution can be attributed to the number of errors (E) made, which could correspond to shortcuts made along the path. Nevertheless, from our observations of the execution of the tasks, it seemed that the shortcuts taken by the subjects were always due to a difficulty in controlling the proposed technique or to a perceived disorientation that led the participant to miss some small part of the path. Moreover, in order to have a measure of the minimum time necessary to perform the task correctly, the times recorded with the different techniques with the minimum number of E, I, and MT proved to be: Palm, 98.01 seconds (E = 0, I = 0, MT = 0), Index, 96.32 seconds (E = 0, I = 0, MT = 0), Gaze, 99.39 seconds (E = 0, I = 4, MT = 3), and Controller, 99.53 seconds (E = 0, I = 0, MT = 0). The ET values shown in 1 do not take into account any time gained or lost due to errors made. Considering the minimum values, if these are increased by the possible time gained, the total time exceeds the threshold value of 92.85 seconds. Among these data, the minimum ET corresponding to the Index technique, 34.42 seconds, although increased by the time gained through the errors made, remains below the threshold of 92.85 seconds. From our observations of the task execution, it seemed that the subject, even though making a small number of traveling interruptions (I = 4), also experienced many difficulties in orienting herself along the path with the Index technique. The estimated shortcut of 18 m (E = 234) reveals that the subject completely skipped a part of the path without even noticing.

On the other hand, the number of errors and interruption made is inversely proportional to each other, revealing a surprisingly high number of interruptions committed with the Controller technique. The explanation of this result was identified by observing the subject's behaviors in performing the locomotion task. The Controller techniques, thanks to the tactile feedback, inspired more confidence in the subjects, who began to perform a rapid interruption of the locomotion in order to execute a turn. On average, the subjects deliberately avoided controlling the direction while performing the movement, preferring to stop the movement, modify the direction, and then restart the movement. This behavior mainly occurred where the path width was smaller. It did not affect the total execution time resulting in the subjects making fewer errors. As revealed by the anomalous values reported in Figure 9, some subjects overused this behavior (navigation interspersed with interruptions) with also the free-hand approaches, revealing a difficulty in performing both the locomotion sub-tasks at the same time.

On the contrary, all the techniques based on the leap motion sensor revealed a number of interruptions that was significantly lower than the number performed with the Controller. Moreover, the number of errors committed with the freehand techniques is comparable to that when Controller is used only in the case of Palm and Index but not for Gaze, which proves to be worse. Indeed, while Palm and Index reveal a lower number of interruptions, they show a number of errors that are similar to that produced with the Controller. Regarding the errors made, the subjects complained about a loss of control, especially where the path was narrow. At these points, we observed that many users had problems correctly managing the locomotion direction. This difficulty proved to be widespread in relation to all techniques but was more marked in respect of the freehand approaches. However, in our opinion, most of the anomalous detected errors at the high end of the distribution (see the outliers in Figure 8) were caused by the lack of any errors feedback given to the subjects during the task execution. The presence of such feedback might have increased the subjects' level of attention, so limiting the number of errors made.

5.1.2. Hypothesis H2

To test hypothesis H2, we performed an additional post hoc comparison among only the freehand-based approaches to identify any significant effect of the implementation choice of decoupling the control of direction selection and input condition on the subjects' performances. The dependent variables considered were E and I. However, due to the lack of any significant initial analysis obtained with the Friedman's ANOVA, no post hoc test for ET was performed.

The results showed a significant increase in E in the transition from the Index ($Mdn = 39.50$) to Gaze ($Mdn = 119.50$) technique, $T = 414.50$, $p = .001$, $r = -.30$, and, in the same way, in the transition from Palm ($Mdn = 31.50$) to Gaze ($Mdn = 119.50$), $T = 450.0$, $p < .05$, $r = -.27$. However, there was no significant variation in E in the transition from Palm ($Mdn = 31.50$) to Index ($Mdn = 39.50$). Therefore, we can conclude, based on the fact that negative ranks were used, that there was a significant increase in the number of errors made when the subjects switched to use the Gaze technique (Index to Gaze, $z = -3.273$, $p = .001$ and Palm to Gaze, $z = -3.140$, $p < .05$) (Figure 8 box (b)).

As regards the number of interruptions, there was a significant effect in the transition from the Index ($Mdn = 2.0$) to Gaze ($Mdn = 3.0$) technique, $T = 373.00$, $p < .05$, $r = -.25$. In fact, as a result of this comparison, we can conclude, based on the fact that negative ranks were used, that there was a significant increase in the number of interruptions in changing technique from Index to Gaze ($z = -2.728$, $p < .05$) (Figure 9 box (b)).

In accordance with the above results, we can assert that the decoupling of direction selection and locomotion control does not improve the user performances in terms of path errors committed and interruptions performed and, therefore, hypothesis H2 has proved to be false and has been rejected.

The Gaze technique, while undergoing more interruptions than Palm and Index, is not able to correct the direction of locomotion properly, so proving to be no better than the other two techniques in terms of the number of errors committed. The subjects obtained better performances if both the controls of direction selection and input conditions were coupled and controlled by the same hand.

Observing the user's behavior during the task execution, we noticed that, as with the Controller solution, the Gaze technique prompted the subjects to perform a high number of interruptions. Considering that no recommendation had been made to the subjects regarding the number of possible interruptions, we observed that this behavior was caused by the modality of selecting the traveling direction. The direction selection, performed when using Gaze, often forced the volunteers to redirect their gaze downward. This situation worsened at the narrowest and most tortuous points of the path, where the users were forced to look right at their feet. The need to adopt this gaze orientation to select the direction made the subjects lose an overview of the path, forcing them to interrupt the movement before choosing a new direction. Moreover, many users also complained, in the situations just described, about a perceived excessive navigation speed, which had increased the need to interrupt the navigation but, more importantly, had made it very difficult to navigate without making errors.

5.1.3. Hypothesis H3

Finally, to determine whether the hypothesis H3 should be supported or rejected, an additional post hoc analysis was performed to highlight any significant effects induced by the technique on the subjects' performance measured in terms of difficulties encountered with the hand tracking. The dependent variable considered was MT by virtue of comparisons among the three approaches based on the use of the tracking sensor. The analysis showed a significant effect on the variable MT only in the transition from Index ($Mdn = 2.0$) to Gaze ($Mdn = 3.0$), $T = 302.50$, $p < .001$, $r = -.32$.

In conclusion, based on the fact that negative ranks were used, we can observe that there was a significant increase in the number of missed hand trackings in changing techniques from Index to Gaze ($z = -3.520$, $p < .001$) (Figure 10).

Contrary to what we had hypothesized in H3, the analysis evidenced that the possibility to perform direction selection decoupled from the input condition was more prone to result

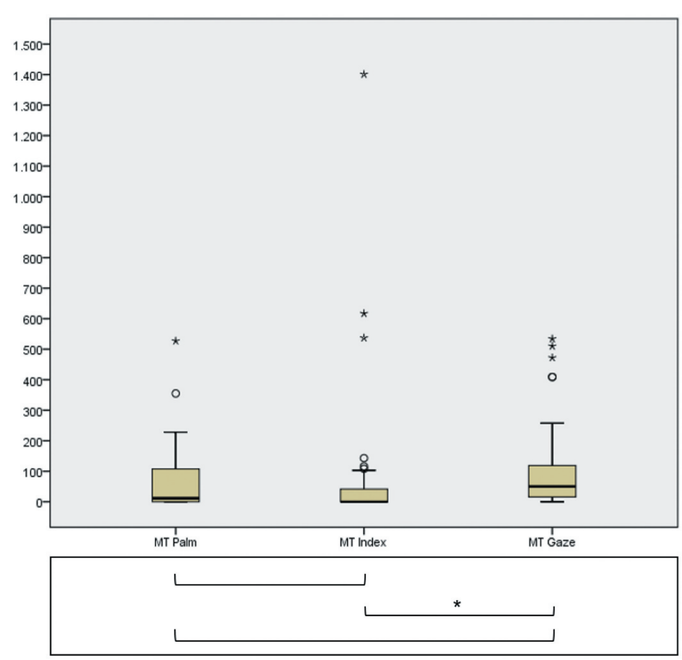

Figure 10. Summary representation of the MT distribution. The box shows the comparisons performed between the freehand-proposed techniques highlighting, with an asterisk, when the number of missed hand trackings varied significantly by moving between the different approaches.

in tracking mistakes than when the two sub-tasks were coupled. This finding led us to reject hypothesis H3. Observing the task sessions, we realized that the subjects, when using the Gaze approach, which is the one that decouples the locomotion sub-task, had many difficulties holding their hand in the sensor FOV. The continuing gaze reorientation, used to redirect the locomotion, was not always performed together with the movement of the hand. Additionally, this lack of coordination between head and hand was not helped by the path used in the task. In fact, at the points of the path where minimal steering was required, the lack of coordination was compensated for by the sensor's FOV. On the contrary, when the path became more challenging, requiring a more decisive change of direction, the lack of coordination turned into a tracking mistake. Moreover, as mentioned above, when the volunteers were forced to redirect their gaze downward, we observed some subjects having great difficulty in using the sensor because, each time their gaze was redirected downward, their hand shifted outside the FOV of the sensor (errors represented as outliers of Gaze approach in Figure 10).

On the other hand, the techniques that couple the locomotion sub-task (Palm and Index) facilitated the management of the sensor FOV because the choice of direction already forced the user to pay attention to the fact that the sensor had correctly traced her/his hand. On average, Index performed better than Palm, but the subjects' behavior using Palm was more homogeneous due to the fact that the traveling redirection did not require wide hand movements. Instead, Index required the subject to perform wider hand movements for the direction selection, which in some cases led to a very high number of tracking errors (represented as outliers of the Index approach in Figure 10).

5.2. Qualitative evaluation

5.2.1. Evaluation of user perceptions

5.2.1.1. Simulation sickness evaluation. To quantify the extent of any simulation sickness due to the proposed approaches with respect to the use of the controllers, we administered to the subjects the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) consisting of 16 questions concerning the same number of symptoms. For each question, the participant was asked about their current experience and symptoms, using a 4-point Likert scale ranging from "none," indicating the absence of any perception of that symptom (level 0) to "severe," meaning, on the contrary, a traumatic presence (level 3). The participants were asked to complete the SSQ after each task. As described in the procedure description 4.5, the participants were given a 20 minute break between consecutive tasks to minimize the effect of any motion sickness from the previous task execution impacting on the performance of the following task.

In accordance with the work of Kennedy et al. (1993), the symptoms considered were grouped to identify four representative scores. *Nausea* (**N**: general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping), *Oculomotor* (**O**: general discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating and blurred vision) and *Disorientation* (**D**: difficulty focusing, nausea, fullness of head, blurred vision, dizziness, and vertigo). These three specific subscores are combined to give a *Total Score* (**TS**) that represents the overall severity of any cybersickness experienced by the participants.

As expected, all the proposed approaches revealed the occurrence of symptoms associated with cybersickness caused by a sensory mismatch or a conflict between the vestibular and visual senses (LaViola, 2000). Figure 11 shows the average results organized according to the four SSQ indexes mapped against the four techniques considered in this study. In accordance with the categorization of symptoms presented by Stanney et al. (1997) almost all the scores are in the ranges 10–15 and 15–20, indicating a level of symptoms perceived at the end of tasks that ranges from significant to concerning.

Exploring the scores in more detail, the N value falls for almost all the techniques within the range 10–15, meaning that the severity of the perceived symptoms is significant. The same score for the Controller approach falls within the lower range (5–10), meaning that the severity of the perceived symptoms was considered minimal by the subjects. The perceived symptoms clustered for the O score lead to a level of oculomotor disorders classifiable within the significant range 10–15 in the case of Controller and Gaze and within the problematic range 15–20 for both the Index and Palm approaches. Regarding the D score, the symptoms are classifiable as a concern for almost all the techniques, falling within the range 15–20. With the Palm technique, this score exceeded the value of 20, meaning that it was considered by the subjects as a bad simulation.

In a comparison between the freehand solutions and the controller-based approach, the latter, while presenting a significant level of symptoms, reveals a slightly lower score for all the indexes N, O, and D than the freehand techniques. Moreover, the symptoms related to the N score using the Controller were considered minimal by the subjects, while the same score related to the other techniques falls within a higher range. This result can be explained by considering

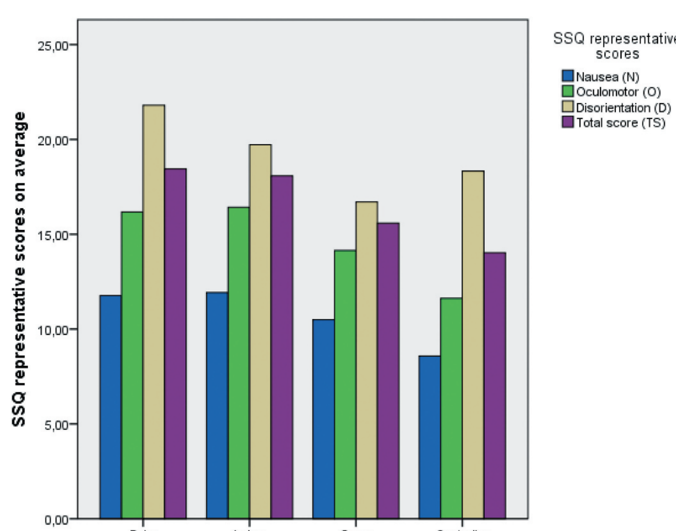

Figure 11. SSQ representative average scores collected after each task performed using each of the proposed techniques.

the factors known to impact on the likelihood of users developing symptoms. One of these is related to the level of control perceived by users during the execution of a task. In Kolasinski (1995) it was reported that simulations without a good control on the motion through the VE were more prone to cause cybersickness symptoms. Considering the specific conditions of the present study, such as the task proposed and the implementation of the locomotion techniques, the Controller technique, which generally involved a high number of interruptions when used by the subjects, allowed them to perceive a good control of the motion and consequently a less severe level of sickness. However, it is important to notice that among all the indexes only in a single case does one of the proposed techniques perform better than Controller, namely the disorientation score obtained with the Gaze technique. The better score of Gaze could be explained by considering that the subjects, in comparison with the other approaches, proved to be less distracted by the movements of the virtual hand or virtual controller used to control the locomotion. They needed to stay focused on the point toward which they intended to move, causing a reduction in the extent of the symptoms assignable to disorientation.

Comparing the freehand approaches, the technique that exploits gaze to redirect the locomotion proves to have the best evaluation, collecting on average the lowest score in all representative categories. The level of N for all the three techniques falls within the lower band of the range 10–15, so situated in the minimum significant level of the classification in relation to the perceived symptom. The scores collected to classify oculomotor disorders (O) showed a significant presence (range 10–15) for Gaze and a possible concern in relation to the other two techniques (range 15–20). The disorientation score (D) provides the highest, and therefore the worst, value, classified as not acceptable (>20) for Palm and as a concern in the other two approaches. Among the freehand approaches, the homogeneous results revealed for the N index may be explained by considering that for 43% of the participants the experimentation was their first ever experience with a VR system. Nevertheless, the values of both the O and D indexes reveal a difficulty in using freehand-based techniques, a difficulty most highlighted in relation to the Palm technique as it has proven to be the one most difficult to control. The O index highlights the disturbance of visual processing during the simulation (a difficulty focusing and blurred vision) and the symptoms caused by that disturbance (headache, eyestrain, and fatigue), and the D value emphasizes the perceived feeling of dizziness and a difficulty in focusing on the elements of the scene.

Finally, Figure 12 shows the distribution of TS values for all the proposed techniques. The TS values confirm the aforementioned considerations, Controller ($M = 14.02$, $Mdn = 7.48$ and $sd = 16.02$) and Gaze ($M = 15.58$, $Mdn = 7.48$ and $sd = 17.24$) prove to be the techniques less prone to produce cybersickness symptoms. Moreover, among the freehand approaches, Gaze performs better than Index ($M = 18.08$, $Mdn = 7.48$ and $sd = 24.46$) and both of these techniques are preferred to Palm ($M = 18.45$, $Mdn = 13.09$ and $sd = 20.21$). The anomalous detected scores at the high end of the distribution (see the outliers in Figure 12) were caused by a high perception of the symptoms grouped in the assessment of disorientation occurring in a limited number of subjects who were undergoing their first experience with a VR system.

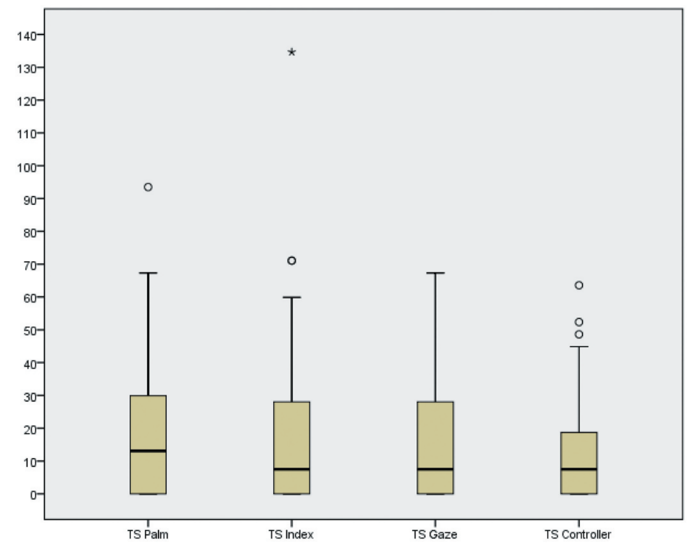

Figure 12. TS score distribution after each trial performed using each of the proposed techniques.

5.2.1.2. Self-assessment manikin scale.

The Self-Assessment Manikin (SAM) (Bradley & Lang, 1994) questionnaire represents a non-verbal method for a quick assessment of the *pleasure, arousal*, and *dominance* associated with a person's emotional reaction to an event. The questionnaire proposes a question for each emotional dimension, organized using a 5-point Likert scale, to which the subject responds by choosing the image corresponding to her/his emotional state.

Figure 13 shows the three sets of images proposed to the subjects during the experimental procedure; however, the verbal expressions presented in the image did not appear during the test. For the emotional dimension of pleasure, the ratings range from a happy smiling manikin to an unhappy frowning one. This dimension describes the positive or negative feelings caused by an event and, on this scale, anger, and anxiety are supposed to have a negative valence; on the contrary, joy is supposed to have a positive valence. For the arousal dimension, the set of images ranges from an excited wide-eyed figure to a relaxed sleepy one. Arousal describes the physiological and psychological condition of a person which is describable as perceived vigilance. Finally, for the dominance dimension, the collection of pictures describes how far a person feels in control of a situation. The pictures range from a small individual who feels a lack of control to a large person who is dominant and in control of the situation.

The participants completed the SAM questionnaire shortly after the end of each task and were asked to report their emotions in using the locomotion techniques. The scoring of the SAM questionnaire was performed by assessing the pleasure, arousal, and dominance associated with each

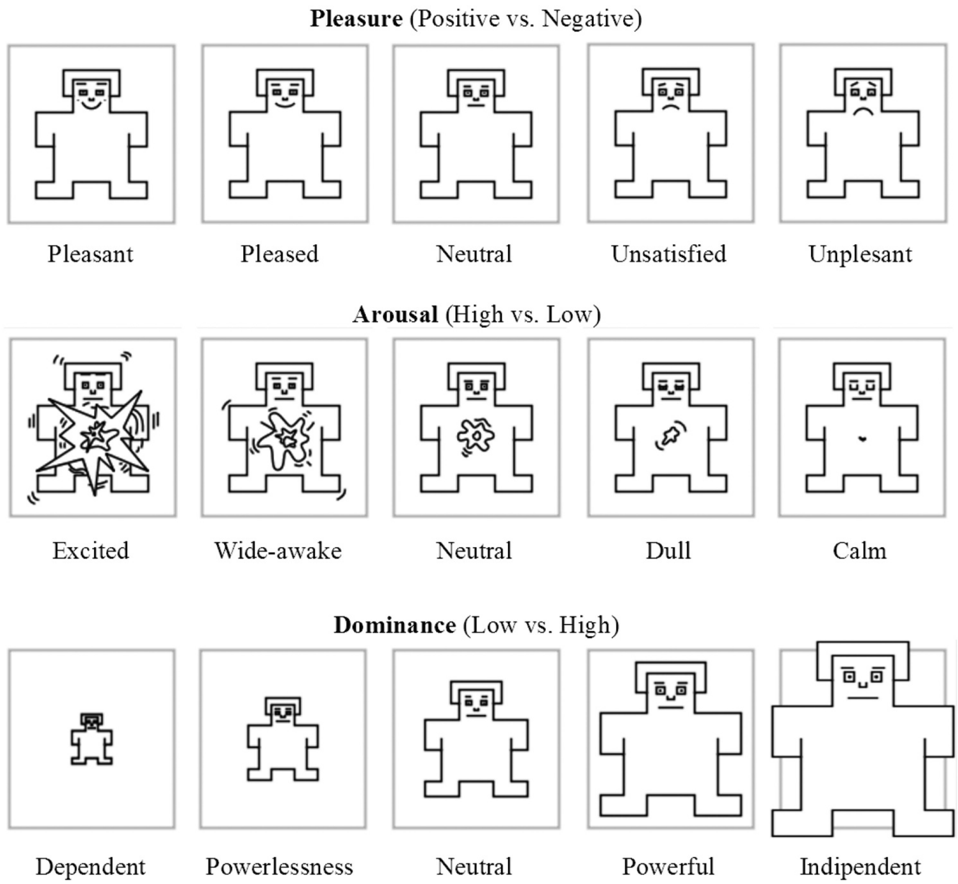

Figure 13. An elaborated version of the manikins of the 5-point scale SAM Test proposed by Bradley and Lang (1994). The figure aims to highlight the meaning of the pictures on each scale. However, the verbal expressions did not appear in the version presented during the experimental procedure.

picture, as reported in Figure 13. The responses of the participants have been transformed from the 1–5 point scale into a dimensional space of $[-1, 1]$ allowing us to evaluate how much the emotional state of the participants varied from the neutral state of zero.

Figure 14 shows the average values of the test subjects' self-assessed pleasure, arousal, and dominance for each technique. Notably, the average value of all three measures deviates from zero toward the side of the scale which represents a positive meaning. For the pleasure evaluation, the Controller technique achieves the best result, being the only value to exceed the score of 0.5 ($M = -0.64$ and $sd = 0.47$). On the contrary, the Palm approach shows the worst result ($M = -0.33$ and $sd = 0.49$). Between the extremes fall the other two techniques, among which Gaze ($M = -0.45$ and $sd = 0.49$) performs slightly better than Index ($M = -0.38$ and $sd = 0.52$). An analysis of the perceived arousal reveals that all the techniques hardly move from the neutral value, and indicates that the Gaze ($M = -0.17$ and $sd = 0.53$) approach performs better than Palm ($M = -0.15$ and $sd = 049$) and in turn better than both Controller ($M = -0.08$ and $sd = 0.62$) and Index ($M = -0.07$ and $sd = 0.50$). However, in our opinion, the subjects misunderstood the sense of the arousal scale, considering the left side as the negative evaluation. Indeed, with this consideration, the questionnaire reveals that Gaze and Palm induced in the subjects a higher state of anxiety. We

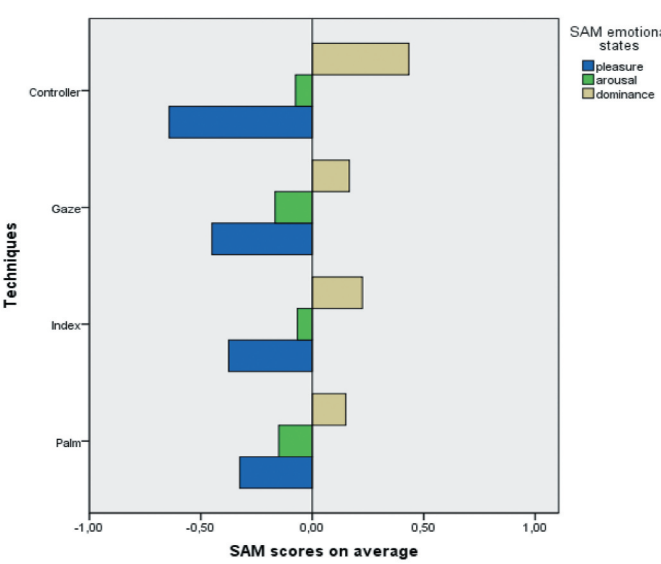

Figure 14. Average values of the subjects' self-assessed pleasure, arousal and dominance for each technique. The collected values have been transformed from the 1–5 point scale into a dimensional space of $[-1, 1]$ to enable a better evaluation of the variation from the neutral sate indicated by zero.

believe that this result was caused by the difficulty in managing the direction selection. In detail, with Palm, even small palm rotations can turn into unintentional changes of locomotion direction while, with Gaze, the frequent reorientation of the looking direction requires the subjects to pay a higher level of attention in order to avoid missing a hand tracking. Considering the perceived Dominance, the technique that proved to provide the subjects with a better control was Controller ($M = 0.43$ and $sd = 0.61$), followed by, in order, Index ($M = 0.23$ and $sd = 0.61$), Gaze ($M = 0.17$ and $sd = 0.56$), and Palm ($M = 0.15$ and $sd = 0.58$). This result confirms the opinion reported above (in Section 5), namely that the techniques that prove to be more complicated for the subjects are, at the same time, perceived to be less controllable.

In conclusion, the considerations just advanced are valid even if only the freehand techniques are taken into account. The Palm technique is considered to be the most difficult to control while the best is the one based on pointing, providing to be more similar to the approach with controllers. Among these techniques, Gaze is characterized by the highest score for pleasure justified by the fact that, for the completion of the proposed task, the subjects considered it more comfortable to move with the gaze direction rather than control the movement by using the hand. Indeed, holding the hand in the FOV of the sensor, even if only to start and stop the movement, induced in the subjects a state of anxiety which corresponds to that of the technique considered least pleasant, namely Palm. Finally, the emotional reaction relating to Index shows that it was considered more controllable than both Gaze and Palm even though slightly less pleasant to use than the latter ones for the reasons given above.

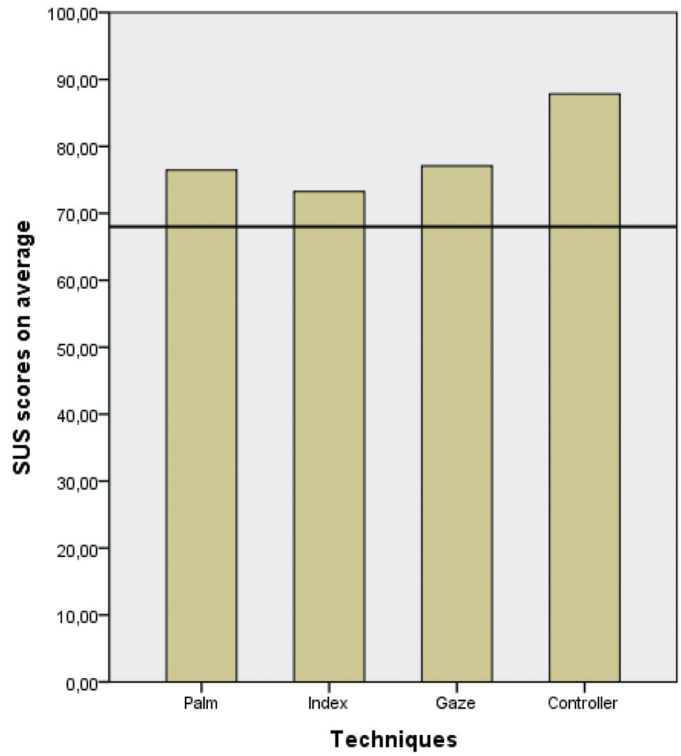

Figure 15. Average values of the SUS scores indicating the subjects' perceived usability of each technique. The threshold set at 68 shows that all the techniques achieved an evaluation above the average.

5.2.2. Usability evaluation

5.2.2.1. System Usability Scale. To measure the subjects' subjective perception of the usability of the proposed locomotion techniques, a 5-point Likert-scale questionnaire has been used. In detail, the participants were asked to complete the System Usability Scale (SUS) (Brooke, 1996, 2013) answering the questions using a scale from 1 (very low) to 5 (very high). The questionnaire is composed of 10 statements, and in order to avoid response biases, the items are organized with an alternation of positive and negative statements. The SUS allows you to obtain a rapid evaluation of the techniques with a score expressed as a single number which ranges from 0 to 100.

Figure 15 shows the results of the SUS questionnaire. Based on the research of Sauro (2011), who commented that a SUS score above 68 would be considered above average, we can observe that all the proposed approaches achieve a score higher than that threshold. Furthermore, in accordance with the research of Bangor et al. (2009) it is possible to classify the perceived usability of all the techniques by using an adjective. All the approaches studied prove to be above the "good" threshold set at the score of 71.4. The lowest score is obtained by Index (M = 73.25 and sd = 21.18), followed by Palm ($M = 76.46$ and $sd = 16.69$) and, slightly superior, Gaze ($M = 77.37$ and $sd = 14.37$). Finally, the solution based on the use of the controller achieves the best score ($M = 87.83$ and $sd = 11.54$), resulting in a classification between "excellent" and "best imaginable".

Among the freehand-based techniques, Gaze proves to be more usable due to the decoupling of the steering modalities and the interaction used to manage the start and stop of the locomotion. The unexpected result is that obtained by Palm, which scores better than Index. The reason for this rating may be found in the gesture chosen to start and stop locomotion in the Index technique. In fact, the weakness of this gesture is represented by the fact that the user, during locomotion, can occlude the position of her/his fingers with her/his hand, causing an involuntary release (interruption of the movement). We believe that this weakness, partially due to the position of the sensor and to the attitude of the user in performing the technique, conditioned the score by lowering the perceived usability.

5.2.3. User experience evaluation

5.2.3.1. Single ease question. At the end of each trial, the facilitator asked the subjects to complete a questionnaire in order to perform an evaluation of the perceived difficulty in using each technique. The questionnaire proposed was in the Single Ease Question (SEQ) format, with a rating scale ranging from 1 (very easy) to 7 (very difficult) (Sauro, 2012; Sauro & Dumas, 2009).

Figure 16 shows a higher perceived difficulty with respect to the freehand-based techniques, with Index obtaining the worst result ($M = 2.53$ and $sd = 1.76$) followed, in order, by Palm ($M = 2.38$ and $sd = 1.40$), and Gaze ($M = 2.28$ and $sd = 1.41$). In contrast, Controller was perceived as less difficult to use ($M = 1.42$ and $sd = 0.71$). However, since the scale ranges from 1 to 7, the average scores of the freehand-based approaches represent a good result in each case, highlighted by the fact that

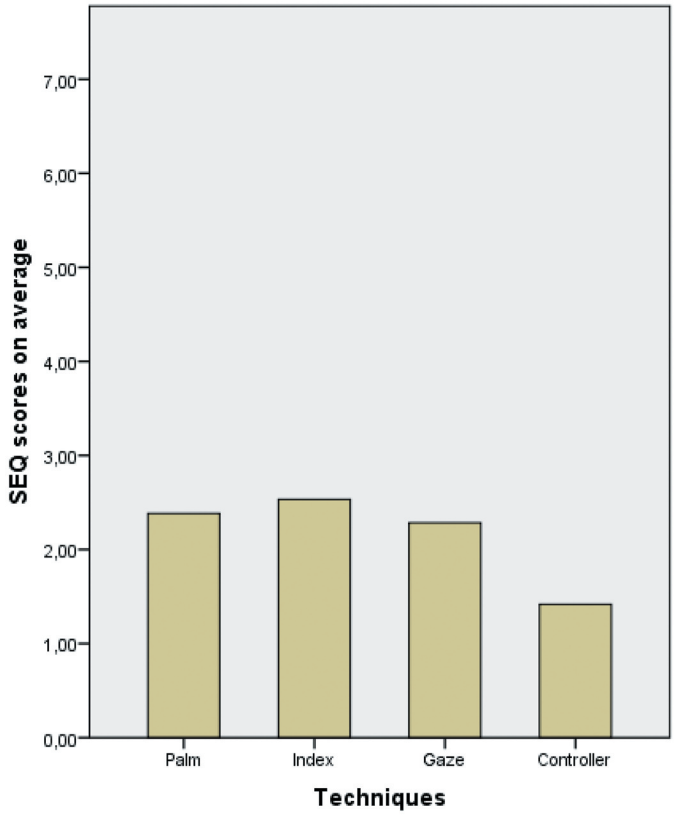

Figure 16. Average values of the SEQ scores indicating the subjects' perceived difficulty in performing the task with the techniques proposed. The rating scale ranges from 1 (very easy) to 7 (very difficult).

all the scores are very close to that achieved by Controller. These approaches, which are considered difficult in equal measure, pay for the presence of constraints, such as the user having to keep her/his hand in the sensor's FOV, and also for the fact that they must be used with greater care than Controller.

5.2.3.2. NASA-TLX. At the completion of the testing procedure, the subjects completed the NASA-TLX questionnaire (Hart & Staveland, 1988) to provide a subjective evaluation of the overall perceived workload. The NASA-TLX evaluation consists of a set of six rating scales measuring mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension is rated on a scale divided into 20 grades along a low-high continuum (poor-good for each performance item). In order to make the evaluation process more straightforward, the NASA-TLX was used in its short version that does not include the weighting process. This version is known as Raw-TLX (RTLX) (Hart, 2006), and in the literature, it has been compared to the original version proving to be a valid alternative (Bustamante & Spain, 2008).

Figure 17 shows the results of the RTLX questionnaire completed after each trial. It is worth noting that the average values of all the measured dimensions relating to all the proposed approaches fall within the positive sections of each scale, showing in each case a positive evaluation of the perceived workload in terms of each of its components.

The overall score, calculated as the average of the six subscales measured during the questionnaire administration, reveals that the technique that is perceived as requiring a more significant workload is Palm ($M = 34.67$ and $sd = 17.82$) followed, in order, by Gaze ($M = 34.36$ and $sd = 17.50$), Index ($M = 31.72$ and $sd = 19.57$) and Controller ($M = 25.58$ and $sd = 14.55$).

A consideration of the individual subscales, shown in Table 2, reveals that the Palm technique obtains the highest score for "mental demand", "physical demand", "effort", and "frustration," while Gaze performs worse in terms of "temporal demand" and "subjective sensation of performance". In comparison to these, the Index solution achieves better ratings in all the six subscales, only performing worse than Controller. Table 2 also reports the frequency of the subjects' responses expressed in percentages with respect to four value thresholds $0-25$, $26-50$, $51-75$, and $76-100$ allowing a more detailed analysis of the performance of the freehand-based techniques.

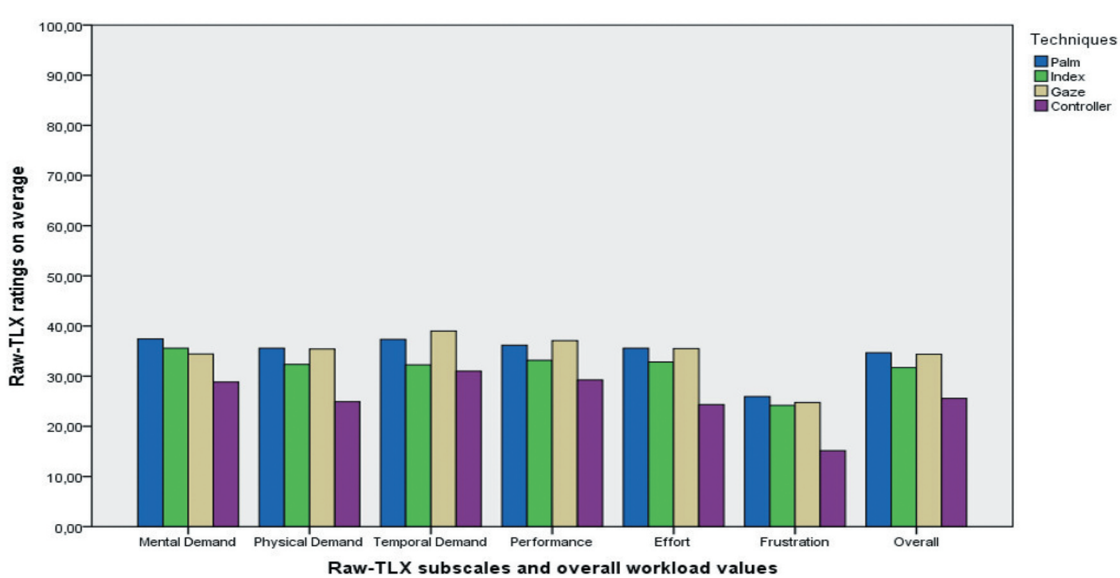

Figure 17. Average values of the RTLX subscales used to evaluate the overall perceived workload in performing the task for each of the proposed techniques. The overall score has been calculated by averaging the six subscales.

Table 2. Workload average values and sds, resulting from the RTLX questionnaires. The last four columns show the frequency of the subjects' responses expressed as a percentage.

		M	*sd*	0–25%	26–50%	51–75%	76–100%
Palm	Mental Demand	37.42	24.20	43.33	26.67	23.33	6.67
	Physical Demand	35.58	20.82	43.33	31.67	23.33	1.67
	Temporal Demand	37.33	20.95	30.00	50.00	16.67	3.33
	Performance	36.17	23.24	43.33	33.33	15.00	8.33
	Effort	35.58	22.88	46.67	28.33	21.67	3.33
	Frustration	25.92	22.09	68.33	18.33	10.00	3.33
Index	Mental Demand	35.58	22.38	46.67	25.00	25.00	3.33
	Physical Demand	32.33	21.36	46.67	33.33	15.00	5.00
	Temporal Demand	32.25	21.48	53.33	30.00	11.67	5.00
	Performance	33.17	26.44	55.00	20.00	16.67	8.33
	Effort	32.83	24.24	58.33	16.67	18.33	6.67
	Frustration	24.17	21.68	70.00	21.67	3.33	5.00
Gaze	Mental Demand	34.42	22.55	53.33	21.67	21.67	3.33
	Physical Demand	35.42	22.42	45.00	30.00	20.00	5.00
	Temporal Demand	39.00	22.76	36.67	36.67	21.67	5.00
	Performance	37.08	23.84	38.33	38.33	15.00	8.33
	Effort	35.50	21.83	45.00	31.67	21.67	1.67
	Frustration	24.75	19.18	70.00	20.00	8.33	1.67
Controller	Mental Demand	28.83	22.37	56.67	26.67	11.67	5.00
	Physical Demand	24.92	18.87	61.67	28.33	8.33	1.67
	Temporal Demand	31.00	21.81	53.33	26.67	15.00	5.00
	Performance	29.25	25.30	60.00	21.67	8.33	10.00
	Effort	24.33	17.62	63.33	26.67	10.00	0.00
	Frustration	15.17	11.87	86.67	11.67	1.67	0.00

Table 3. Summary of the results.

Results		
Quantitative evaluation	ET	• Controller achieved the fastest execution time.
		• Among the freehand techniques on average Palm and Gaze performed better than Index.
	E	• Controller proved to be the least prone to errors • Among the freehand approaches, Index was slightly better than Palm while Gaze was the worst.
	I	• Controller showed the highest number of interruptions. • Among the freehand solutions Index was the best followed by an equivalent performance of Palm and Gaze
	MT	• Among the freehand approaches, Index was the best closely followed by Palm and then by Gaze that proved to be the worst.
Qualitative evaluation	User Perceptions	• The SSQ showed that Controller and Gaze proved to be less prone to cybersickness symptoms because they provided the participants with a better perception of control. Index and Palm were the techniques perceived as the worst. • The SAM proved that right after Controller the participants enjoyed Gaze the most even if it caused a feeling of anxiety due to the continuous holding of the hand in the FOV of the sensor. Index was perceived as more controllable than Gaze and Palm although slightly less pleasant to use than Gaze.
	Usability	• The SUS determined that the Controller technique was the favorite. Among the freehand approaches, Gaze was perceived as slightly more usable than Palm and Index.
	User Experience	• The SEQ proved that Controller was experienced as the least difficult technique to use in performing the task. Next, Gaze was better than Palm and Index. • The NASA-TLX showed that the perceived workload was lower with the Controller followed by Index, Gaze, and finally, Palm, which proved to by the freehand technique that required the most physical effort.

The possibility of traveling in all directions by changing the palm orientation was judged negatively by most of the subjects. In fact, 30% of the subjects' rated the mental demand of this technique with a score between 51 and 100. For the same reason, almost 15 subjects considered this technique physically demanding (25%) and hard to accomplish (23.3%) assigning a score higher than the threshold score of 50. Consequently, at the completion of the task, 13.3% of the subjects admitted to feeling a level of frustration higher than 50. Gaze was identified as an approach that leads to rushing (scores higher than 50) by 26.7% of the subjects, resulting in a perceived performance that was rated by 23.3% of the participants as "poor". The reason may be found in the fact that most of the subjects performed the steering with this technique through an interruption of the locomotion, meaning that each time the subject first pointed at the desired position and then started to move. The Index approach shows its highest score in the subscale "mental demand," in respect of which 28.3% of the subjects scored the technique with a value higher than 50. This may be explained by considering the gesture used to control the movement, which seemed to distract the subject from the task execution.

6. General discussion

The experimental findings (see Table 3 for an overall summary of the results) revealed that the freehand techniques are able to guarantee performances, in terms of execution time, similar to those achieved with the controller. However, the same assessment cannot be made if the locomotion precision (i.e., errors made along the path) and perceived difficulties in executing the task (i.e., interruptions performed) are considered. The freehand approaches proved to be less precise and more prone to errors than the technique involving the use of a controller, especially when the direction selection and the locomotion control were decoupled. In contrast, the number of locomotion interruptions turned out to be higher with the method considered by the subjects more usable, and less physically and mentally tiring, namely the controller-based approach.

The user perception evaluation, in addition to revealing a user preference for the tactile feedback offered by the controller, also confirmed that the visual processing of a great amount of information increases the sense of nausea. Controlling the locomotion direction through head movements was preferred by the subjects and resulted in an increase in the perceived pleasure because of the absence of any need to verify continuously the orientation of the virtual hand. Conversely, pointing by using the hand was considered as improving the sense of control in the case of Index because the direction selection corresponds to a two-dimensional pointing system. The usability evaluation findings revealed a widely perceived difficulty in managing the hand position with respect to the sensor FOV when using the freehand approaches. Among such approaches, although the scores among the techniques did not vary greatly, the decoupling of the direction control and input conditions performed by Gaze was considered more usable and less physically demanding. However, the increased ease in use combined with the simple gesture required to control the locomotion led the subjects to use the Gaze technique in a different way than we had expected. Almost all the subjects performed the task proceeding in a straight line with continuous locomotion interruptions to correct the locomotion direction.

6.1. Limitations and future directions

The study reported in this article has certain limitations, which also need to be taken into account. A first limitation is related to the type of task proposed to the subjects, namely walking along a path characterized by different turns and an uneven width. The proposed techniques might have had very different performances if the task had not constrained the movement along a predefined path but had required the subjects, for instance, to travel freely in a building. We found that the use of a path was appropriate to the goal of the study since it allowed us to define indirectly the difficulty in using the techniques. The choice of this task was guided by the idea that the simpler technique is, the better it can be in performing this kind of task without traveling error and requiring only a limited number of interruptions. However, although we believe that the path selection has not undermined the comparison, we acknowledge the limitations of this assumption.

A second limitation concerns the apparatus used. Our goal was to investigate empirically how free-hand locomotion techniques perform in VR. To achieve this objective it was necessary to choose a pose estimation method. We considered the inside-out method, performed with a Leap Motion placed on the user, as appropriate for this purpose since it is widely used by the human–computer interaction community. However, the results achieved are conditioned by the characteristics of the sensor and by the position in which the sensor is placed on the user. While the apparatus used does not undermine the comparative evaluation of the proposed approaches, we acknowledge that it prevents us from inferring general principles about freehand locomotion solutions.

Finally, further research is needed to assess if locomotion by means of freehand approaches performs differently in other task scenarios and when more accurate tracking systems are used.

6.2. Conclusions

In this article, an evaluation study has been presented to investigate the possibility of using freehand techniques in addressing the locomotion problem in VR taking into account the interaction problems caused by the limitations of current hand-tracking sensors. Considering current tracking sensors, their frequent use in VR usually placed in an egocentric position, and their current limitations, three locomotion techniques based on freehand interaction and one based on the use of a controller have been realized. The design of the freehand-based approaches was differentiated in terms of the modalities of choosing the locomotion direction and controlling the input conditions to start and stop the movement. The techniques were quantitatively and qualitatively investigated by comparing the freehand approaches with each other and with the controller-based solution. Participants performed a locomotion task in which they were required to follow a predefined path in an immersive environment in the presence of distractors. The study collected data relating to measures of performance, such as efficiency (i.e., completion time) and effectiveness (i.e., performed errors, locomotion interruptions, and tracking errors), in addition to data relating to five measures to evaluate the user's perceptions: simulation sickness by means of the SSQ questionnaire, user emotional reaction by means of the SAM questionnaire, a user usability evaluation by means of the SUS questionnaire, a user experience evaluation by means of the SEQ questionnaire, and cognitive load assessment by means of the NASA-TLX questionnaire.

The study presented and the results collected may contribute to providing suggestions for researchers and interaction experts in relation to the design of effective and efficient locomotion techniques for immersive VR. In particular, we believe that the performance of the freehand techniques and the issues related to the tracking sensors will encourage further research in this area.

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