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ORIGINAL ARTICLE

Evaluating virtual reality locomotion interfaces on collision avoidance task with a virtual character

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Abstract

We have evaluated four locomotion interfaces, namely natural walking (NW), omnidirectional treadmill (OT), walk-in-place (WiP), and joystick (JS). In this within-group study, an avoidance movement task with a virtual character was performed by all participants for each examined interface. Our study considers that natural walking is the most realistic method for navigating in a virtual environment and explores the differences across the examined locomotion interfaces by collecting avoidance movement measurements (clearance distance, trajectory length, and trajectory curvature) and self-reported subjective ratings (simulation sickness, usefulness, satisfaction, ease of use, and task load). The results suggest that, despite the fact that the avoidance movement measurements of the WiP, JS, and NW interfaces share similarities, they, more often than not, differ from the measurements of the OT interface, which makes the OT interface unable to provide precise avoidance movement data for our participants. Moreover, the OT interface was rated lower by participants in terms of learning, usability, efficacy, satisfaction, physical demand, and effort. Our study shows that NW, OT, WiP, and JS as locomotion interfaces present several benefits and drawbacks concerning their application in avoidance movement behavior tasks with a virtual character.

Keywords Virtual reality · Locomotion interfaces · Avoidance movement · Natural walking · Omnidirectional treadmill · Walk-in-place · Joystick

1 Introduction

Performing locomotion in virtual environments is challenging. Firstly, the virtual environment is most likely bigger in size compared to the real environment in which the user is located. Secondly, mismatches between the virtual and real-world obstacles are quite evident, which makes it difficult for a user to move around without colliding with real-world obstacles [67]. To overcome these issues, locomotion interfaces that allow virtual reality users to navigate large virtual environments more efficiently have been developed over the past few years. In particular, though interfaces such as joysticks and techniques such as teleportation [21] allow users to navigate virtual environments, the self-motion experience of the user is limited [87]. Thus, interfaces such as the omnidirectional treadmill [25,43] and techniques such as redirected walking [84,97] and walk-in-place [104,108] enable users to experience walking in a virtual environment in a natural or near-natural way while also overcoming the limits of physical space.

We compare the capacity of omnidirectional treadmill (OT), walk-in-place (WiP), and joystick (JS) to provide avoidance movement data close to those obtained during natural walking (NW). Figure 1 depicts the four locomotion interfaces that were compared in this paper. For this study, we have considered prior work that has indicated that locomotion in virtual environments is a fundamental activity and that NW is considered to be the most realistic interface for walking in a virtual environment [108]. Therefore, we have adopted NW as our baseline interface, and we examine whether the OT, WiP, and JS interfaces can provide results close to those of NW.

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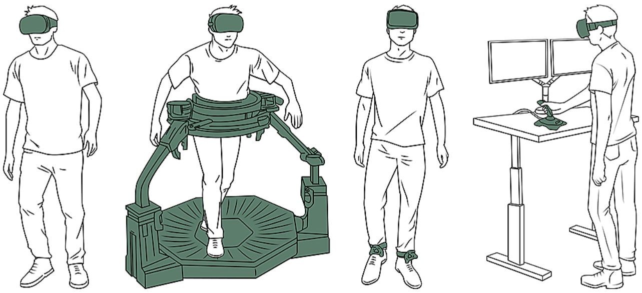

Fig. 1 Four locomotion interfaces evaluated in this study. From left to right: natural walking, omnidirectional treadmill, walk-in-place, joystick

In this study, participants were asked to perform a collision avoidance task [29,68,75,91] with a virtual character that was standing at the midpoint between the starting and the ending positions, which is a common task that is performed by virtual reality users when experiencing virtual reality scenario or playing games. We collected avoidance movement measurements (clearance distance, trajectory length, and trajectory curvature) and self-reported ratings (simulation sickness, usefulness, satisfaction, ease of use, and task load) in order to evaluate the examined locomotion interfaces. To recapitulate, our study's objectives were to investigate (1) whether avoidance movement differences exist across the four examined locomotion interfaces and (2) whether potential variations across the self-reported ratings of the locomotion interfaces could provide additional insights into user experience. In particular, our study attempts to answer the following research questions:

- **RQ1** How do OT, WiP, and JS compare to NW when participants perform an avoidance movement maneuver with a virtual character?
- **RQ2** How do participants evaluate their user experience across the examined interfaces?

The remainder of this paper is organized as follows: Sect. 2 discusses related work; Sect. 3 presents the methodology; Sect. 4 presents the results, which are discussed in Sect. 5; and Sect. 6 presents the conclusions and potential future research directions.

2 Related work

This section presents a brief overview of work related to this paper.

2.1 Locomotion in virtual environment

Typically, when people become immersed in virtual environments, they do not merely observe them, but they also become engaged by navigating and interacting in them through the use of a locomotion interface. For this purpose, a number of different interfaces and techniques have been developed over the past few years that provide users with the ability to navigate virtual environments [3,65,66,84,85,87,88,90,97,98,100,117,120]. Considerable work also evaluates the potentials of locomotion interfaces for providing navigation in virtual environments that are typically larger than the tracked space while maintaining spatial awareness [36,49,57,70,86,101,118,121]. Depending on the virtual reality experience and platform that is used to immerse users in a virtual environment, specific locomotion interfaces are deemed either as less or more appropriate [33]. As such, a developer might need to choose between using JSs, OTs, and force sensors [82,96,117].

Although considerable effort has been made to develop locomotion interfaces that stimulate all of the sensory channels involved in locomotion in a realistic manner, this has not been yet fully achieved. Currently, the user's NW motion is considered to be the most realistic interface available for such tasks [108] since NW in virtual environments produces the much needed adequate proprioceptive and vestibular cues similar to walking in the real environment [51–53]. Compared with other locomotion interfaces, the NW is credited with better memory and cognition attributes [100,120], better feeling of presence and immersion [108], and superior performance in search tasks [88].

Much of the more recent navigation work has focused on engaging the user in physical movement as it seems to result in better spatial awareness of the virtual environments when compared with other interfaces [36,49,101,111,118]. There are locomotion techniques which have been developed in order to maximize the reachable space in the virtual environment when physical movement is required. Among the most well-known techniques are the WiP [95,105] and redirected walking [54,72,84,97,99]. Redirected walking is classified within the NW interface [108].

Besides the NW and other commercial interfaces, more specialized hardware has also been used to provide a more active, near-natural locomotion experience to users, compared to, e.g., a joystick, which provides a passive experience. One of the most popular of such specialized hardware is the so-called virtual reality omnidirectional treadmill [25,43,93], which is designed to provide a semi-NW capability to users. Other specialized interfaces include the use of ball bearings, which create a low-friction concave surface so that the users can walk without any actual displacement [38,102], the use of robotic tiles [44], the use of a human-size hamster ball [63], and the use of a stepper machine [62]. The main disadvantage of most of these devices is their size and cost.

Several previously published papers have evaluated different aspects of locomotion techniques and interfaces. The results of most studies indicated that NW techniques outperform semi- or non-natural techniques when it comes to sense of presence [108] or user preferences [11]. Moreover, when evaluating locomotion interfaces, it has been found that, compared to real walking, teleportation provides faster navigation and increases the loss of orientation compared to a JS controller [30]. Additionally, instant teleportation is correlated with decreased spatial orientation [6,10,21], and as users need time to orientate themselves in their new surroundings, instant teleportation potentially leads to disorientation, which can break the feeling of presence [30,89,108] when compared to other locomotion interfaces.

Furthermore, it has been found [79] that users travel shorter distances, make fewer wrong turns, point to hidden targets more accurately and more quickly, and are able to place and label targets on maps more precisely when using redirected walking compared to using WiP or a JS controller. On the same note, redirected walking techniques have been found [13] to affect cognitive demands, which in turn may have an influence on spatial tasks when compared to real walking. Calandra et al. [14] found that the use of an OT requires more effort by participants compared to WiP, and Nabiyouni et al. [71] found that when participants performed locomotion by using Virtusphere (an OT-like interface), their speed was significantly slower and less accurate than when performing NW or when using a JS. According to the mentioned research, despite the number of interfaces and techniques out there and the number of evaluations that have been conducted, there are plenty of unexplored factors regarding locomotion interfaces and how users interact with them which require further investigation. Lastly, since considerable research has examined locomotion interfaces, to explore additional prior work, please read the survey papers written by Carsoso and Perrotta [15], Zayer et al. [1], and Boletsis [8].

2.2 Human interactions during locomotion

Interaction during locomotive tasks has been a topic of interest for the research community. Over the past few years, numerous studies have explored behavioral patterns [58] such as side-by-side [80] or face-to-face walking [26] with another walker or virtual character, group formations [46,81,103], and collision avoidance [68]. In particular, the collision avoidance task has been a topic of extensive research as it has shown to be an important source of useful information. Previously conducted studies have also explored the information that walkers need to process and consider during a collision avoidance task [24], the way that walkers adapt their motion [78] or circumvent [109], and the way walkers move in a dynamic environment [112,113]. Other prior work has focused on avoidance behavior with passive moving obstacles, such as a moving mannequin [7,18,32]. Among others, when avoiding a moving mannequin, these studies have detected (1) adjustments in heading and walking speed [18], and (2) correlations between the adaptation of the walker's movement and the crossing angle and walking speed conditions [39].

Moreover, Bönsch et al. [9] studied collaborative collision avoidance tasks and found that participants had anticipated collaborative collision avoidance when interacting with a virtual character; however, participants were also willing to independently change their paths in the virtual environments. Sanz et al. [91] studied avoidance behavior in NW scenarios; the walking motion of participants was compared across various scenarios in which they were instructed to avoid real and virtual static obstacles as well as humanlike and inanimate objects. The results indicated that participants performed distinctly different locomotive behaviors when encountering real versus virtual obstacles as well as anthropomorphic versus inanimate objects. Silva et al. [94] compared collision avoidance behaviors of participants and virtual characters and found that participants implemented different avoidance strategies while walking and circumventing virtual human characters compared to non-human obstacles in a virtual environment.

To evaluate the interaction of participants with virtual characters [60], proxemics [32,34,91] and interpersonal distance [5,26,42] between a participant and virtual characters have been used quite efficiently in the past. Among other things, research on interpersonal distance, equilibrium theory [4], and/or personal space (the immediate space surrounding a person) requirements have already identified two findings: First, proxemics can gain objective insights into the social presence perceived by the human user [4], and second, the characters appearance in terms of body shape [41], gazing [68,113], and expressed emotions [92] have an effect on the participants' behavior.

Several studies have found that characteristics such as the gender and height of a walker influence the way in which humans perform an avoidance movement [110]. One study has shown that walkers accurately estimate the future risk of a collision since they react only when required and they solve the collision avoidance task with anticipation [76]. Additionally, although adaptations are performed collaboratively, they are role-dependent [75]. In this paper, our intention is not to expand our knowledge on human–virtual character interactions during locomotion, but rather, to benefit from the previously conducted studies on collision avoidance between humans and virtual characters. We therefore aim at studying similar situations in the context of interaction between participants and a virtual character to understand how participants performed their avoidance behavior when using the four examined locomotion interfaces.

2.3 Evaluating human locomotion

Researchers have proposed a number of different techniques to understand and analyze the behavior of human locomotion. Some of the criteria used include completion time, distance traveled [19,20], number of collisions [56], precision of the followed path [83], shape of the trajectory [2], distance metrics between trajectories [12,29,96], distance error [45], and empirical observations of trajectory visualizations [120]. Fink et al. [29] also proposed a set of various metrics, which includes the followed path's mean radius of curvature, the distance between the origin and the target indicated by a straight line, and the distance between the path and the obstacles participants were instructed to avoid. Whitton et al. [116] have proposed the use of a trajectory-based principal component analysis to compare virtual reality locomotion interfaces. Various other methods that have incorporated components of the gait cycle such as stride length, stride velocity, and step width and its variability have also been used to understand and compare walking motion [37,96]. Cirio et al. [19] have proposed the use of trajectographical criteria that take into account shape, performance, and kinematic features. These trajectographical criteria can then be used to compare human motion performed in virtual and real environments. The current study is utilizing three avoidance movement behavior features (clearance distance, length of the trajectory, and curvature) in order to analyze and further understand the participants' avoidance behavior. This is so because these features provide a great deal of significant information regarding avoidance movement behavior when encountering a virtual character.

3 Materials and methods

The following sections describe the methodological details of the project.

3.1 Participants

For this within-group study, we conducted an *a priori* power analysis to determine the appropriate sample size using the G*Power software [22]. The calculation was based on 95% power, a medium-effect size of .25 [27], four groups with four repeated measures, a repeated measures correlation of .50, a non-sphericity correction of $\epsilon = .60$, and $\alpha = .05$. The analysis resulted in a recommended sample size of 52 participants. We recruited 64 undergraduate and graduate students from our university. The participants were recruited through posters on campus, e-mails throughout the departments of the university, and in-class announcements. Participants provided informed consent in accordance with the Institutional Review Board of the Purdue University. No direct reward was given for participation. Of the sample, 21 were female and 43 were male. Moreover, 7 of the participants were experiencing virtual reality for first time, and all participants were experiencing virtual reality locomotion through the use of a treadmill for first time. Students' ages ranged from 18 to 32, with a mean of 22.11 (SD = 2.57). Also, students' height ranged from 158 to 202 cm, with a mean of 173.17 (SD = 13.94).

3.2 Study conditions

We evaluated the avoidance movement behavior and the participants experiences when using the examined four locomotion interfaces (see Fig. 1). For this study, the following four locomotion interfaces were chosen:

- *Natural walking (NW)* The participants were asked to wear a head-mounted display and walk in the virtual environment while avoiding the virtual character. During the NW, the participants were able to physically walk in the real world from one point to another (translational movement) by therefore affecting their movement in the virtual environment.
- *Omnidirectional treadmill (OT)* The Virtuix VR Omni treadmill was used to provide a near-NW experience for the participants. The participants were asked to stand onto the OT to perform the walking motion. Sensors were attached to the participants' feet to capture their movement; and the Unity package of Virtuix VR Omni was used to interpret the user's sequence of movements in a virtual environment.
- *Walk-in-Place (WiP)* The HTC Vive trackers were attached to the participants' feet. The WiP method developed by Wendt et al. [115] was implemented to allow our participants to move in the virtual environment by performing walking-related foot movements. In this condition, the participants were instructed to swing their legs up and down periodically in the perpendicular direction.
- *Joystick (JS)* The participants used the Logitech Extreme 3D Pro JS to control the movement and perform the avoidance task in the virtual environment. Participants were able to control the x- (right/left) and z-axis (forward/backward) position of the camera in the virtual environment; therefore, they were able to perform the avoidance task. The rotation of the camera was controlled by the rotation of the participants' head that was provided by the tracking devices embedded in the head-mounted display. The rotation of the head did not change the heading direction of the participants in the virtual environment. The participants were just able to rotate their head to observe the environment.

We decided that the participants should not be able to control the walking speed in the OT, WiP, and JS interfaces because (1) we did not want to include an additional factor to our experiment and (2) we realized that if we had included walking speed during OT, WiP, and JS, the participants would have to choose between walking and running. Nevertheless, during the NW interface, participants could opt for multiple levels between walking and running. We also realized during a pre-evaluation process that giving participants the ability to control the speed of movement might not have been fair for the OT interface since these participants would have to exert more energy to increase their virtual environment speed as opposed to the JS interface, which required only the press of a button. Thus, it was deemed that the only regular walking speed that should be used during the OT, WiP, and JS interfaces would be the one as specified by the U.S. Manual of Uniform Traffic Control Devices [28], which defines the normal walking speed of humans as an estimated 1.2 m/s. This speed was also assigned to the developed locomotion controller. It should also be mentioned that for the OT, WiP, and JS we did not have a calibration phase in which participants could have chosen the parameters of the locomotion controller. Instead, we used a linear rate control to translate the input state to motion in the virtual environment. Finally, we set the camera height to be the same for all participants and for all examined interfaces. Specifically, the camera height was set to be 170 cm, similar to the eye height of the virtual character. The chosen height was close to the average adult male height [23] in Northern Europe and North America. We considered all these factors as key aspects, as they helped us standardize the experimental conditions.

This study only explored a small number of experimental conditions. However, we could have included more. For example, the inclusion of teleportation could have been interesting; however, the teleportation would provide completely different trajectories (straight lines between chosen points). Moreover, in teleportation, the camera does not necessarily follow a path. Instead, the camera is teleported instantly to reduce cybersickness. This will make the comparison unfair since in all other cases the camera is controlled through some sort of user activity. Moreover, a redirected walking technique could have also been evaluated. However, we decided to not evaluate it since it lies under the "natural walking," which is a locomotion interface that is already evaluated in our study. We think that the inclusion of a redirected walking technique would have been unfair for the other three interfaces given that all three other interfaces (OT, WiP, and JS) can be implemented with various alternatives (e.g., WiP with hand swing and not foot swing).

In this study, NW is considered as ground truth because it is known to be the most realistic interface. It would have been interesting to compare it against real avoidance movements (e.g., walking in a real environment without a virtual reality headset) under similar configurations. Although this could have been an interesting addition to our project, we were more interested in understanding the avoidance movement behavior in virtual reality and not in a real environment. Moreover, in a real-world setting with a real human standing in a midpoint between a start and goal position, this might have impacted our participants completely differently compared to a virtual human. This would have also introduced additional differences since in the real-world setting the appearance of the human might have not matched with that of the virtual character as well as the movement of the real human might have been completely different in each trial. The advantage of conducting such a study only in virtual reality is that all participants exposed to the exact same stimulus.

3.3 Experimental environment, application, and implementation

The study was conducted in the Virtual Reality Lab at Purdue University. A simple virtual environment (see Fig. 2) was designed in 3ds Max and was imported to a Unity game engine to approximate the size of the Virtual Reality Lab. The exact same 3D model was used for the rest of the examined locomotion interfaces. A white and black indicator (circle) informed the participants of the starting (white indicator) and target (black indicator) positions. The participants had to avoid a virtual character placed at the midway point. To provide the participants with enough space and time to avoid the virtual character located midway, we chose a distance of 7 meters between the starting and target positions based on assessments from a previous study [68].

For this study, we used the HTC Vive Pro head-mounted display for projecting the virtual reality content. The HTC Vive wireless adapter was also used to transmit the visual

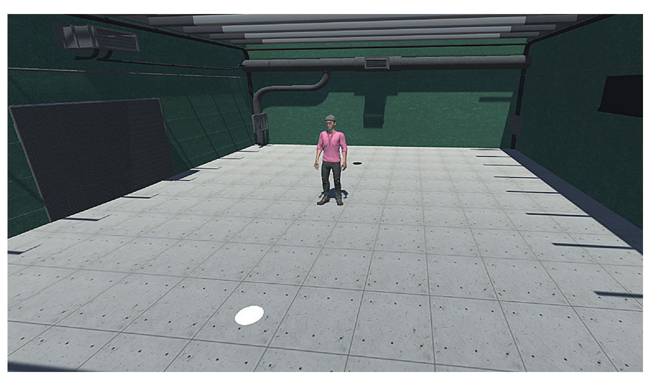

Fig. 2 Virtual environment that was designed to immerse participants in the virtual reality scene in the study. The white and black indicators (circles) informed the participants of the starting (white indicator) and target (black indicator) positions. The virtual character that should be avoided was placed at the midpoint between those two indicators

Fig. 3 Virtual character used in this study

content to the user during all examined interfaces, thereby eliminating any negative interference with human movement behavior that the cable of the head-mounted display might have produced when participants performed their avoidance movement task. Note that according to the HTC Vive, the wireless transmitter offers a near-zero latency. The Dell Alienware Aurora R7 desktop computers (Intel Core i7 CPU, 32GB Memory, NVIDIA GeForce RTX 2080) were used to run the application for all examined interfaces.

The virtual character (see Fig. 3) used in the study and the idle motion sequence were downloaded from Adobe Mixamo. The virtual character was assigned an idle (passive) motion. No gazing (`LookAt`) of the virtual character at the body of the participant was implemented; instead, the face of the virtual character was animated based only on the assigned idle motion. We decided that the character the participants were asked to avoid should be of male gender. We could have included additional virtual character of the opposite gender; however, since the scope of this particular study was to evaluate the avoidance movement behavior of participants based on four locomotion interfaces and not the gender of the virtual character, we limited our study and used only a male virtual character. Moreover, we also considered prior work that has found that the gaze of a virtual character affects the avoidance movement behavior of participants in virtual environments as well as that self-avatars affect avoidance movement behavior [68] and self-perception [50] in virtual environments. We therefore avoided assigning participants with a self-avatar as (1) we wanted to capture a collision avoidance reaction without the effects of an avatar, and (2) we did not want to confuse the participants with the lower body movement of a self-avatar, which most likely will not be identical to participants' lower body movement during using the OP and WiP interfaces. Finally, we did not change the height of the characters according to the height of the participants. All the above were considered as key aspects that helped us standardize the experimental conditions.

3.4 Measurements

Objective measurements (avoidance movement behavior data) and subjective ratings (questionnaire responses) were collected to evaluate the examined locomotion interfaces. The following subsections describe the measurements and ratings in detail.

3.4.1 Movement measurements

On the basis of previously published papers on avoidance movement behavior [68,69], we extracted three movement measurements from the captured trajectory, which provided spatial information about the participants' movement behavior [16]. As the extracted trajectories from the full-body motion of the participants were filtered into one hundred equidistant points [68], the measurements were based on those filtered points. The trajectories of our participants under the NW condition were captured using an HTC Vive tracker. The avoidance movement measurements were as follows:

- *Clearance* The clearance distance is the shortest distance between the participant and the virtual character found during the avoidance task. The clearance was measured in meters.
- *Trajectory Length* The length of the extracted root trajectory between the starting and ending point (goal position). The length was measured in meters.
- *Average Trajectory Curvature* The relative mean curvature of the trajectory compared to a reference trajectory. The criterion is the ratio between the evaluated trajectory curvature and the reference trajectory curvature. The curvature in each sample is computed as shown in [29].

3.4.2 Subjective measurements

For each locomotion interface, participants were asked to fill in a questionnaire, which measured (1) the simulation sickness, using the simulation sickness questionnaire (SSQ) [48]; (2) the learning, usability, efficacy, and satisfaction using the usefulness, satisfaction, and ease of use (USE) questionnaire [59]; and (3) the physical and mental effort using the NASA task load index (NASA-TLX) [35] questionnaire. The SSQ questionnaire was used to understand the changes to the simulation sickness across the examined locomotion interfaces, the USE questionnaire was used to evaluate the user experience of the participants through measuring the learning, usability, efficacy, and satisfaction of participants for each of the examined locomotion interfaces, and finally the NASA-TLX questionnaire was used to evaluate the physical and mental effort needed by participants when using each of the examined locomotion interfaces. For all questionnaires, a 7-point Likert scale was used to capture participants' responses.

3.5 Procedure

After scheduling the day and time that suited their schedule, the participants arrived at the laboratory space to participate in the experiment. At that time, the experimenter briefly informed participants about the project, and participants were given a consent form that was approved by the University's Institutional Review Board (IRB), which they were asked to read and sign. After signing the provided consent form, participants were asked to complete a demographics questionnaire. After the demographic questionnaire was completed, the Latin squares ordering method [47] was used to provide us the sequence that the participant will experience each of the locomotion interfaces; this method was used to ensure a balance of first-order carryover (residual) effects across all examined interfaces.

For each interface, the experimenter helped the participants to put on the necessary equipment. Once everything was set, a test scene, which was a virtual environment free from objects and obstacles, was provided to the participants to help them understand how each interface worked. This test scene interaction lasted no more than two minutes for each locomotion interface. For the OT interface, in addition to the two-minute exploration process, a five-minute calibration also took place.

After the participants were familiarized with the virtual reality locomotion interfaces, they were told that once the application began, they would be placed in a virtual environment different from the one they had just experienced and that a virtual character would appear in the midway point between their start position and the target position. The participants were instructed that the only task they had to perform was to avoid that virtual character and reach the target position. No other description about the interface, the environment, and the virtual character was provided. When participants finished the two trials, they were asked to remove the equipment they were wearing and were invited to follow the researcher to the location where the next interface would be tested. There was no specific break set for each participant. Instead, the time needed to adapt from one interface to the other was used as a mini break between the interfaces of the study. However, the participants were aware that they could request for an additional break if needed.

The participants were also informed about the structure of the experiment. Specifically, they were told that the experimenter would inform them when the collision avoidance segment of each examined interface of the study was concluded, and that after this segment was completed they would be asked to complete a questionnaire that would be handed to them. The appearance of the virtual character to which each participant would be exposed was not mentioned. Participants only saw the appearance of the character once the first trial had begun. Although participants were aware of the interface they were experiencing, they were not informed about the sequence in which they would experience each interface. Participants were also instructed to avoid the virtual character and reach the target position and to perform this process two times, similar to Olivier et al. [74]. Moreover, participants were not instructed on which side (left or right) they should bypass the virtual character. The total duration of the whole procedure lasted no more than 60 minutes.

4 Results

This section presents the results obtained from the study. The normality assumption of the objective measurements and subjective ratings were evaluated with the with Shapiro–Wilk tests at the 5% level and graphically using Q–Q plots of the residuals. The individual differences were assessed using a post hoc Bonferroni corrected estimates if the ANOVA was deemed significant. A $p < .05$ value was judged as statistically significant.

4.1 Avoidance movement behavior

A one-way analysis of variance (ANOVA) was conducted to analyze the obtained data, using the four locomotion interfaces as independent variables and the avoidance movement behavior measurements as dependent variables. Figure 4 illustrates the average trajectories performed by the participants for each locomotion interface. Descriptive statistics are provided in Table 1. Note that for the avoidance movement data the two trials were averaged for each interface per participant.

Regarding the **clearance measurement**, we found significant results across the examined interfaces [$\Lambda = .148$, $F(3, 61) = 117.165$, $p < .001$, $\eta_p^2 = .628$]. Pairwise comparisons indicated that the mean clearance for the JS interface was significantly lower than that for the NW, WiP, and OT interfaces, all at the $p < .001$ level. Moreover, we found that the mean clearance of the NW and WiP interfaces was significantly lower than that for the OT interface, both at the $p < .001$ level. No significant difference was found between NW and WiP.

The **length** measurement also gave significant results across the examined interfaces [$\Lambda = .115$, $F(3, 61) = 156.661$, $p < .001$, $\eta_p^2 = .885$]. The pairwise comparison showed that the mean length for the JS interface was significantly lower than that for the NW, WiP, and OT interfaces, all at the $p < .001$ level. We also found that the mean length for the NW interface was significantly lower than that for the OT interface at the $p < .001$ level and for the WiP interface at the $p < .005$ level. Finally, we found that the mean length for the WiP interface was significantly lower than that for the OT interface at the $p < .002$ level.

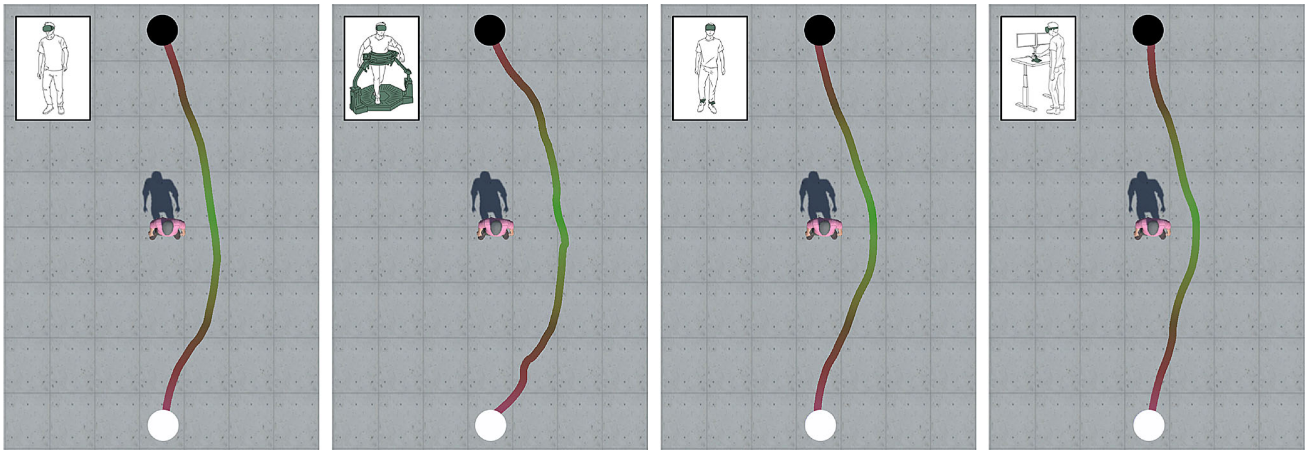

Fig. 4 Average trajectories of each of the examined interfaces. The gradient color on the trajectory denotes the distance between the participants and the virtual character. Green denotes the closest and red the furthest. The white indicator informed the participants of the starting position and the black indicator informed the participants of the target position. From left to right: NW, OT, WiP, and JS. As side notes, (1) left-sided trajectories were mirrored for visualization purposes, (2) $> 80\%$ of the participants performed a right-sided avoidance maneuver, and (3) $> 95\%$ of the participants decided to perform the avoidance maneuver using the same side in both trials

Table 1 Avoidance movement measurements across the examined locomotion interfaces

Measurement	Condition	Mean	SD	Min	Max	Results
Clearance	NW	.84	.13	.62	1.04	JS < (NW = WiP) < OT
	OT	1.26	.16	1.03	1.54	
	WiP	.88	.12	.67	1.09	
	JS	.65	.07	.52	.77	
Length	NW	8.32	.37	7.48	9.12	JS < NW < WiP < OT
	OT	9.62	.71	8.36	11.04	
	WiP	8.64	.62	7.50	9.94	
	JS	7.60	.25	7.20	8.02	
Curvature	NW	.9	.13	.75	1.26	(NW, WiP) = JS < OT
	OT	1.09	.20	.82	1.66	
	WiP	.99	.17	.77	1.49	
	JS	.94	.16	.66	1.29	

NW natural walking, *OT* omnidirectional treadmill, *WiP* walk-in-place, *JS* joystick

The **curvature** measurement also provided significant results [$\Lambda = .562$, $F(3, 61) = 15.835$, $p < .001$, $\eta_p^2 = .438$]. Pairwise comparisons indicated that mean curvature for the OT interface was significantly higher than that for the NW interface at the $p < .001$ level, the WiP interface at the $p < .004$ level, and the JS interface at the $p < .001$ level. Moreover, the mean curvature of the WiP interface was significantly higher than that for the NW at the $p < .01$ level. No significant difference was found across the NW and JS, and the WiP and JS interfaces.

4.2 Self-reported ratings

We collected self-reported ratings to further evaluate the locomotion interfaces used in this study. A one-way repeated measures ANOVA was performed to analyze the obtained data by using the experimental interfaces as independent variables and the self-reported ratings as dependent variables.

4.2.1 Simulation sickness

Regarding the simulation sickness, which is based on the **SSQ** questionnaire, we found significant effects across the examined interfaces [$\Lambda = .246$, $F(3, 61) = 62.290$, $p < .001$, $\eta_p^2 = .754$]. Pairwise comparisons indicated that the mean score for the JS interface was significantly higher than that for the three other interfaces, namely the WiP interface at the $p < .001$ level, the OT interface at the $p < .001$ level, and the NW interface at the $p < .001$ level. Moreover, the mean SSQ score of the WiP interface was significantly

Table 2 Descriptive statistics of SSQ

Measurement	Condition	Mean	SD	Min	Max	Results
SSQ	NW	2.03	.52	1.19	2.81	(NW = OT) < WiP < JS
	OT	2.06	.49	1.13	2.88	
	WiP	2.57	.74	1.31	3.94	
	JS	3.64	.88	1.75	5.19	

NW natural walking, *OT* omnidirectional treadmill, *WiP* walk-in-place, *JS* joystick

Table 3 Descriptive statistics of USE questionnaire

Measurement	Condition	Mean	SD	Min	Max	Results
Learning	NW	5.27	.62	3.00	6.00	OT < WiP < (NW = HS)
	OT	3.63	1.24	1.50	6.00	
	WiP	4.30	1.24	1.50	6.00	
	JS	5.20	.44	4.05	6.00	
Usability	NW	5.37	.52	4.50	7.00	OT < (NW = WiP = JS)
	OT	3.45	1.06	1.50	5.50	
	WiP	5.30	.52	4.50	7.00	
	JS	5.34	.53	4.50	7.00	
Efficacy	NW	4.80	.67	3.50	6.00	OT < (NW = WiP = JS)
	OT	3.41	.76	2.00	5.00	
	WiP	4.77	.9	3.00	7.00	
	JS	4.95	.96	3.00	7.00	
Satisfaction	NW	4.20	.92	2.50	6.00	OT < (NW = WiP = JS)
	OT	3.29	1.34	1.00	5.50	
	WiP	4.48	.71	3.00	6.00	
	JS	4.34	.81	3.00	6.00	

NW natural walking, *OT* omnidirectional treadmill, *WiP* walk-in-place, *JS* joystick

higher than that for the three other interfaces, namely the OT interface at the $p < .001$ level, and the NW interface at the $p < .001$ level. No significant results were found between NW and OT. The descriptive statistics of the SSQ results are provided in Table 2.

4.2.2 Usefulness, satisfaction, and ease of use

We compare the usefulness, satisfaction, and ease of use across the examined locomotion interfaces. The descriptive statistics of the USE questionnaire are provided in Table 3.

The **learning** segment of the USE questionnaire indicated significant effects across the examined interfaces [$\Lambda = .388$, $F(3, 61) = 32.138$, $p < .001$, $\eta_p^2 = .612$]. Pairwise comparisons showed that participants rated the OT interface significantly lower than the NW interface at the $p < .001$ level, lower than the JS interface at the $p < .001$ level, and lower than the WiP interface at the $p < .001$ level. Moreover, our participants rated the WiP significantly lower than the NW interface at the $p < .001$ level and lower than the JS interface at the $p < .001$ level. No significant results were found between NW and JS.

The **usability** ratings also showed some effects across the examined interfaces [$\Lambda = .239$, $F(3, 61) = 64.616$, $p < .001$, $\eta_p^2 = .761$]. Pairwise comparisons indicated that participants rated the OT interface significantly lower than the NW interface at the $p < .001$ level, lower than the JS interface at the $p < .001$ level, and lower than the WiP interface at the $p < .001$ level. No significant results were found across NW, WiP, and JS.

By analyzing the **efficacy** rating, once again we found significant effects across the examined interfaces [$\Lambda = .383$, $F(3, 61) = 32.760$, $p < .001$, $\eta_p^2 = .617$]. Pairwise comparisons indicated that participants rated the OT interface significantly lower than the NW interface at the $p < .001$ level, lower than the JS interface at the $p < .001$ level, and lower than the WiP interface at the $p < .001$ level. No significant results were found across NW, WiP, and JS.

Similarly, regarding **satisfaction** ratings, we found significant effects across the examined interfaces [$\Lambda = .610$, $F(3, 61) = 13.018$, $p < .001$, $\eta_p^2 = .390$]. Pairwise comparisons indicated that the mean score of the OT interface was significantly lower than that for the NW interface at the $p < .001$ level, lower than the JS interface at the $p < .001$

Table 4 Descriptive statistics of NASA-TLX

Measurement	Condition	Mean	SD	Min	Max	Results
Mental demand	NW	2.88	1.65	1.00	6.00	NW = OT = WiP = JS
	OT	3.38	1.63	1.00	6.00	
	WiP	3.42	1.73	1.00	6.00	
	JS	3.33	1.37	1.00	5.00	
Physical demand	NW	3.13	1.40	1.00	5.00	JS < (NW = WiP) < OT
	OT	5.03	1.31	3.00	7.00	
	WiP	3.22	1.76	1.00	6.00	
	JS	2.30	1.06	1.00	4.00	
Temporal Demand	NW	2.38	1.11	1.00	4.00	NW = OT = WiP = JS
	OT	2.63	1.35	1.00	7.00	
	WiP	2.53	1.22	1.00	6.00	
	JS	2.42	1.22	1.00	4.00	
Performance	NW	5.19	1.51	3.00	7.00	NW = OT = WiP = JS
	OT	4.89	1.49	3.00	7.00	
	WiP	5.03	1.44	3.00	7.00	
	JS	5.02	1.39	3.00	7.00	
Effort	NW	1.92	.82	1.00	4.00	(NW = OT = WiP) < OT
	OT	3.63	1.73	1.00	6.00	
	WiP	2.08	.82	1.00	3.00	
	JS	2.03	1.02	1.00	4.00	
Frustration level	NW	4.17	1.48	2.00	6.00	NW = OT = WiP = JS
	OT	4.16	2.12	1.00	7.00	
	WiP	4.19	1.28	2.00	6.00	
	JS	3.78	1.17	2.00	6.00	

NW natural walking, *OT* omnidirectional treadmill, *WiP* walk-in-place, *JS* joystick

level, and lower than the WiP interface at the $p < .001$ level. No significant results were found across NW, WiP, and JS.

4.2.3 Task load

The collected **NASA-TLX** data was analyzed to investigate the effort exerted and performance of participants. The descriptive statistics of the NASA-TLX questionnaire are provided in Table 4.

By analyzing the self-reported rating, we were unable to find significant effects across the examined locomotion interfaces for **mental demand** [$\Lambda = .505$, $F(3, 61) = 2.143$, $p = .104$, $\eta_p^2 = .295$], **temporal demand** [$\Lambda = .476$, $F(3, 61) = .491$, $p = .690$, $\eta_p^2 = .124$], **performance** [$\Lambda = .583$, $F(3, 61) = .358$, $p = .784$, $\eta_p^2 = .317$], and **frustration level** [$\Lambda = .424$, $F(3, 61) = 1.663$, $p = .184$, $\eta_p^2 = .276$].

However, we found significant differences in the levels of physical demand across the examined locomotion interfaces [$\Lambda = .263$, $F(3, 61) = 57.031$, $p < .001$, $\eta_p^2 = .737$]. Pairwise comparisons showed that the physical demand required during the OT interface is significantly higher than that for the WiP interface at the $p < .001$ level, higher than the NW interface at the $p < .001$ level, and higher than the JS interface at the $p < .001$ level. The results also revealed that the JC interface required significantly less physical demand than that for the NW interface at $p < .01$ level, and less than the WiP interface at the $p < .01$ level. No significant results were found between NW and WiP.

Our data analysis also indicated a significant difference in the levels of effort across the examined locomotion interfaces [$\Lambda = .566$, $F(3, 61) = 15.597$, $p < .001$, $\eta_p^2 = .434$]. Pairwise comparisons showed that the physical effort required during the OT interface is significantly higher than that for the WiP interface at the $p < .001$ level, higher than the NW interface at the $p < .001$ level, and higher than the JS interface at the $p < .001$ level. No significant results were found across NW, OT, and WiP.

5 Discussion

In this study, two goals were set: (1) to assess the differences in performing a collision avoidance maneuver when encountering a virtual character across the examined four locomotion interfaces (NW, OT, WiP, and JS) and (2) to subjectively evaluate the locomotion interfaces based on participants' feedback. The subsections below discuss our findings.

5.1 Avoidance movement behavior

Our analysis of the obtained data revealed some significant results concerning the way that our participants performed collision avoidance tasks across the examined locomotion interfaces (**RQ1**). Our results indicated that all movement behavior measurements of the OT interface were significantly different compared to the rest of the examined locomotion interfaces. Moreover, some similarities were found across NW, WiP, and JS for all of the examined measurements. Although we were expecting significant results between the examined locomotion interfaces, we found these results interesting because they indicated that participant avoidance movement behavior in a virtual environment relates closely to the interface being used to perform the avoidance movement maneuver.

Specifically, in terms of the clearance measurement, no significant results were found between NW and WiP when participants were exposed to the virtual character. Moreover, when the participants avoided the virtual character using the OT interface, the clearance distance was significantly higher than any other interface. We also found a significant difference between NW/WiP and JS, which was unexpected. We interpret these findings as follows: When participants were asked to avoid a virtual character with an interface that is considered to provide a natural (NW) or semi-natural walking (WiP) experience, the proprioceptive and vestibular cues of participants were triggered [17,31], which led to an increased level of walking realism in the virtual environment [64]. This increased level of walking realism made our participants more aware of their bodies since it seems that such activities result in an improved spatial awareness of the environment [117,119]. This spatial awareness encouraged our participants to keep a greater clearance distance when avoiding the virtual character using NW or WiP compared to JS.

In terms of the length of the trajectory, our results show that there are distinct differences across all examined interfaces. On the one hand, the participants avoided the virtual character by following shorter trajectories when using the JS compared to NW interface. This result suggests that when the participants are given a short locomotive task, a shorter path length can yield a lower conformity to trajectories resulted from natural walking, since it has been found that path dimension significantly affects user performance [10]. Another possible cause of the shorter path followed when using the JS interfaces is related to the optical flow, which has been found to affect visual guidance during locomotion [114]; thus, we interpret this difference as our participants being able to focus on and lock the target more easily when using the JS interface since they were not being affected by the movement of their body. Therefore, this generated slightly different trajectories, indicating that the trajectories are highly dependent upon the input device being used and the task/activity being performed. On the other hand, our participants avoided the virtual character by following longer trajectories when using the WiP and OT interfaces. According to previous studies, participants who are exposed to a WiP interface turned more often and navigated more sequentially [106], which caused the loss of orientation [30]. Something similar has been found when using OT, since turning is a complex task to perform in such interfaces and such complexity results in reorientations [73,77].

Our last avoidance movement measurement is the curvature of the captured path. First, we found that the curvature of NW, WiP, and JS behave similarly. However, according to our results, the curvature of OT was significantly higher compared to the other three interfaces. For us, this result was an expected one. Specifically, we were expecting that the results provided by the OT interfaces would be motions with more exaggerated trajectories. The OT interface was the one that our participants had never experienced before, and was based on the NASA-TLX data, which is also discussed later. The participants required a higher physical demand and effort, leading to less focused manipulations [40,61] and less precision. By using this interface multiple times, it could be possible for our participants to overcome the issue and provide more accurate trajectories.

A close examination of the collected data revealed two additional observations. First, we found that for NW, WiP, and JS, the clearance distance lay inside the participant's personal space according to the proxemics model [34], which has also been found in previously conducted studies concerning the avoidance movement of participants with a virtual character [91]. However, for the OT, the clearance distance lay outside the participant's personal space and inside the social space. Second, by observing the collected data, we found that in the NW, WiP, and JS interfaces, the minimum distance between the participants' position and the position of the character occurred when participants were behind the virtual character, similar to previous findings [5]; however, this did not apply to the OT interface. Specifically, we observed that during the OT interface, the closest distance between the participants and the virtual character was when the participants were in front.

Given the results obtained from this study, on the one hand it can be said that when participants are exposed to either the WiP or the JS interface, such locomotion interfaces are able to provide movement behavior similar to NW, but with some differences. On the other hand, our results show that the OT should not be considered the best possible option for understanding the avoidance movement of participants since the captured avoidance movement of the participants tends to be exaggerated (e.g., the participants followed longer paths, and the clearance distance and curvature were much higher compared to the rest of the interfaces). It can be said that interfaces that provide a natural (NW) or near-natural (WiP) walking experience or interfaces that provide precise control (JS) could be considered among potential interfaces for conducting studies that examine collision avoidance with a virtual character. However, additional experimentation is needed to further understand the actual precision of such interfaces and to determine how they differ compared to NW. After all, we should keep in mind that the strategies used by participants to perform a locomotive task in a virtual environment could be significant to the interface, environment, and task, but also dependent on the sophistication of the participants [10].

5.2 Self-reported ratings

In addition to the objective measurements, we also collected subjective self-reported ratings to further evaluate the examined locomotion interfaces (**RQ2**). The collected SSQ data concerning motion sickness revealed that participants rated the JS interface higher than the other interfaces. This result reveals that near-walking interfaces such as OT and WiP affect the proprioceptive and vestibular cues of the participants in a way that could be considered close enough to the way that these cues are affected when exposed to NW [107]. Thus, it could be said that more active locomotion interfaces reduce simulation sickness when compared to a passive interface such as the JS [55].

The data obtained from the USE questionnaire also indicated that it was much easier for the participants to learn how the NW and JS locomotion interfaces work than the OT and WiP ones. This was an expected result since the participants are exposed to NW and JS interfaces more often and are thus more familiar with them compared to OT and WiP, which our participants do not get exposed as frequently. In terms of usability, efficacy, and satisfaction, our participants indicated that (1) the OT was the least easy to use, (2) its output was not as expected, and (3) the participants were less satisfied with it compared to the other examined interfaces. Taken together, these findings are considered reasonable outcomes. As has been found in a previous study [14], the OT is a locomotion interface that requires more than the usual effort by the participants, and it does not output accurately enough the participants' movement intention.

Since we were unable to find significant differences on the mental demand, temporal demand, performance, and frustration levels, it can be said that all examined locomotion interfaces trigger similar some of the task load dimensions of participants, which means that there are certain task load dimensions that our participants are exposed to that are unrelated to the interface. However, the data collected by the NASA-TLX questionnaire has generated significant results for physical demand and effort; more specifically, both task load dimensions were rated higher by our participants when exposed to the OT interface compared to any other locomotion interface.

To interpret some of the findings obtained from the NASA-TLX questionnaire, we adopted the comments received from the participants at the end of the study. Specifically, for the NW, almost all participants mentioned that this interface was the most natural way for them to perform the given task. Moreover, many participants were quite enthusiastic when wearing the head-mounted display and the wireless adapter for transmitting visual content as they did not have to worry about cables lying on the ground. Notably, the wireless adapter offers near-zero latency and none of the participants complained about it. Moreover, several participants found it quite comfortable to wear the head-mounted display with the adapter attached and walk with it during the study.

The OT received the most negative comments. Specifically, the majority of participants mentioned that they were disappointed by the effort they had to put in. Many of them even said that this interface does not provide a walking in a virtual environment experience because there was no actual matching between the effort they put in using the OT and the amount of walking they experienced in the virtual environment. Moreover, a number of participants also told us that they felt like they were walking uphill instead of walking on a flat terrain. Two more participants expressed that initially they were excited when they realized they would be using an OT. However, their excitement was short lived once they started using it. Finally, two participants said that the OT locomotion interface has great potential, but its design requires multiple structural iterations before it can provide a near-natural walking experience. Thus, similar to the results of a previously conducted study, the NW techniques outperform semi- or non-natural techniques when it comes to user preferences [11]. Taken together, the results obtained from the data analyses and the participants' comments indicate that the OT used in this study might not be the optimal interface for conducting scientific studies concerning the avoidance movement of participants since the objective measurements obtained could not be considered accurate and the subjective data and comments received from our participants indicated a low level of satisfaction.

However, most of the comments received about the WiP locomotion interface were positive. Specifically, participants told us that even if they just swung their feet, which is not something they do when walking, this felt to be a more natural activity when compared to feet swinging performed during the OT interface. Other participants said that after learning how the interface worked, they were able to move whenever they needed without thinking or putting in much physical effort. Finally, some participants were confused about why the speed of their feet swinging did not correspond to the speed they were moving in the virtual environment. Having a constant speed imposed by the system had a negative effect on the presence in OT and WiP. Therefore, letting the participant choose their own speed would have improved the user experience with OT and WiP interfaces. Lastly, the few comments received about the JS locomotion interface indicated that this was the easiest interface to use and learn; the one that required less effort, and except for NW, the one they considered to be the most reliable means to perform a locomotive task in the virtual environment. From our viewpoint, these are expected comments since participants are familiar with such interfaces and they feel comfortable using them.

Concluding this section, we would like to clarify that various other OTs could be used to provide an immersive locomotive experience in a virtual environment. There are OTs with a completely different design and with different tracking functionalities and foot swing recognition methods. Therefore, the results we obtained for the OT interface could only apply to the particular OT device that was used for the purpose of this study and not any other commercial OTs.

5.3 Limitations

On a different note, our study has five limitations. First, for experimental purposes, this study explored a single human-like virtual character. We made this decision in order to evaluate the avoidance movement behavior of the participants based on the examined locomotion interfaces. To further understand the ability of such interfaces to capture an accurate avoidance movement, further experimentations that encounter various appearance intervals in between neutral (regular) and aversive/unpleasant (zombie) characters is needed. The second limitation is that an additional interface could be included. We chose to explore a foot swing WiP interface; however, we could have also included a hand swing interface. We chose only one WiP since we believed that both of these two interfaces would have yielded similar results. The third limitation is related to the size of the experimental room. We did not consider having a larger room where participants were required to turn and navigate around corners and other elements. Instead, we decided to ask participants to perform a short movement task since we wanted to explore whether and how such a short task could possibly affect the avoidance maneuver, and consequently understand whether and how the four different locomotion interfaces affect such simple action. The fourth and final limitation is the omission of a questionnaire exploring the naturalness/realism of the avoidance interaction. At the end of the study, we realized that such a questionnaire could have added more insights into participants' experiences. Last, our participants were mainly trained to use the OT for two minutes. We think that additional training might have helped our participants to better perform in OT. However, there are no published research and guidelines on how to deal with OT in experimental studies. Thus, we assumed that the calibration process along with the two extra minutes (training) could have been enough for our participants. However, we think that additional experimentation is needed toward understanding how much training is needed when using such an interface. Nonetheless, the mentioned limitations do not invalidate our findings on whether the examined locomotion interfaces provide precise participant avoidance movement behavior when encountering a virtual character.

6 Conclusions and future work

In this paper, we have evaluated four virtual reality locomotion interfaces in order to assess their differences when the participants were asked to perform an avoidance movement task with a virtual character. Although the examined locomotion interfaces and the virtual character that participants were instructed to avoid were restricted for experimental purposes, we deem that the results obtained from the chosen interfaces provide valuable information to the research community.

Apart from the mentioned limitations that are worth exploring in the near future, considerable investigation is needed concerning the movement behavior of people when using different locomotion interfaces. Besides the interaction task that was performed by our participants in this study, additional explorations such as movement behavior precision during path following, movement behavior in constrained and unconstrained environments, the evaluation of the examined interfaces but with walking virtual characters with a variety of headings and speeds, and other walking tasks such as sidestepping and stair stepping should also be explored. The examination of the advantages and disadvantages of different interfaces would provide insights to the research community regarding the precision of such interfaces and their ability to provide data to efficiently represent actual human activity, intention, and choices when interacting in virtual environments through movement-related tasks.

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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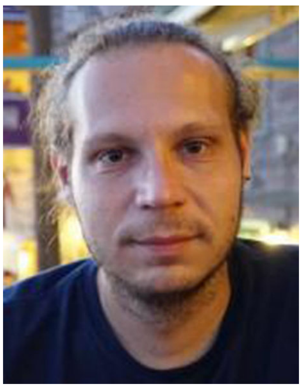

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