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Locomotor circumvention strategies in response to static pedestrians in a virtual and physical environment

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ABSTRACT

Background: Circumvention of pedestrians is an essential requirement of community ambulation and can be challenging to reproduce in laboratory or clinical settings. Virtual reality (VR) is a powerful tool that allows investigations, assessments or training of such tasks under ecological but controlled conditions. The extent to which current VR technologies can elicit responses similar to those observed in the physical world, however, remains to be determined.

Research questions: (1) To what extent does the circumvention of static pedestrians in VR differ from that observed in the physical environment (PE)? and; (2) To what extent does the inter-trial variability of obstacle circumvention outcomes differ in VR vs. the PE?

Methods: Healthy young participants (n = 13) were assessed while walking and avoiding a collision with an interferer that stood either at 3.0 and 3.5 m from the participant's starting position (experimental trials) or that exited to the side (catch trials). The task was performed in the PE and VE, in a random order. A female collaborator acted as interferer in the PE and her kinematics was used to create the avatar used in the VE.

Results: Compared to the PE, the circumvention of a static pedestrian in VR was characterized by larger obstacle clearances and slower walking speeds. Characteristics of circumvention strategy such as the preferred side of circumvention, response to obstacle position and pattern of speed adaptation were similar between VR and the PE. Inter-trial variability for the different outcomes were also similar between the two environments.

Significance: Differences in obstacle clearance and speed indicate the use of "safer" circumvention strategies in VR. However, the patterns of locomotor adaptation that were largely similar between the two environments which suggests that VR is a valuable tool to study, assess and possibly train complex locomotor tasks such as obstacle avoidance.

1. Introduction

Obstacle circumvention is essential for a safe and independent ambulation in community settings [1]. It requires one to assess and update information of self-motion in relation to objects and other people that may obstruct the travel path. This information is primarily obtained by the visual system through the use of several depth perception visual cues and by measuring changes in one's gaze-movement angle (i.e. bearing angle [2]). In the presence of obstacles, pedestrians estimate the point in time when a collision would occur [2] and coordinate adjustments of walking trajectory and speed to ensure obstacle clearance [3].

The distance maintained from the obstacle during its circumvention is thought to reflect the safety margin deemed necessary by the pedestrian to successfully avoid an obstacle [4]. Studies have shown that while this clearance remains constant in response to factors such as walking speeds [5,6], it is enlarged under conditions of increased cognitive load (e.g. dual tasking [7]) and in the presence of sensory distractors (e.g. auditory sounds [8]). Recent studies further suggest that the nature of the obstacle also influences obstacle circumvention. For instance, larger clearances were observed when pedestrians crossed an aperture delimited by two confederates as opposed to two poles [9]. A study from our laboratory further showed that young adults use smaller obstacle clearances when avoiding moving pedestrians vs. cylinder in a virtual environment (VE [10]).

Replicating experimentally obstacle circumvention strategies in response to human obstacles in research and clinical setting can be challenging. Fortunately, the appropriate conditions can be reproduced

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in controlled, safe and ecological environments using virtual reality (VR). However, as VR simulations are not yet capable of delivering simulations that accurately embody all sensory systems, the extent to which they evoke natural motor responses can be disputed [11]. Distance reports are consistently underestimated in VEs [12,13] and field of view (FOV) restrictions, as often experienced when using helmet mounted displays (HMDs), have been shown to induce slower walking speeds [13,14] and a higher reliance on head movements to visually scan the environment [12]. In fact, studies which examined obstacle circumvention in response to static virtual cylinders or boxes reported the use of "safer" avoidance strategies, with subjects adopting larger obstacle clearances and slower walking speeds in the VE compared to the PE [5,15,16]. Although to a smaller extent, these differences were also observed as participants circumvented animate (another person) and inanimate (box) static obstacles while walking in a VE projected with a CAVE system [16]. Whether such findings would also be extended to the circumvention of a static pedestrian while immersed in a low-cost HMD-based VR system, which allow the user to move freely over a larger volume, remains to be determined.

In addition, studies performed in the PE have described stereotypical walking trajectory adaptations both during goal directed locomotion [17] and obstacle circumvention [18]. However, since these adaptations largely depend on spatial information acquired through vision [11], it is unclear whether locomotion in VE exhibits similar variability when compared to the PE. Also, while variability of locomotor performance in VEs was examined before, existing reports were largely limited to spatiotemporal distance factors as outcomes reflecting gait stability during steady gait [19,20] and information about obstacle circumvention is lacking. Lastly, studies that compared obstacle circumvention in HMD-based VEs and PEs were conducted more than a decade ago and recent developments of virtual reality technologies now allows for higher quality graphics, enhanced real-time rendering, as well as HMDs with larger FOV and lighter weight, which highlights the importance of revisiting this topic.

This study was carried out as part of a larger project where obstacle circumvention strategies in response to human obstacles, either stationary or in motion, were examined in the VE and PE. In this specific study, we estimated the extent to which the circumvention of a static human obstacle differed in the VE vs. PE in healthy young adults. We further examined the inter-trial variability of obstacle circumvention outcomes in both environments. We hypothesized that due to a combination of perceptual and cognitive factors associated with performing the task in a VE, participants would maintain larger obstacle clearances and adopt slower walking speeds in the VE, which in sum is characterized as a "safer" circumvention strategy. It was further hypothesized that obstacle circumvention outcomes would display a larger inter-trial variability in the VE as compared to the PE.

2. Methods

2.1. Participants

Characteristics of participants are presented in Table 1. The experiment was approved by the ethics committee of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIRR) and all participants gave their informed written consent.

2.2. Instrumental set up and procedures

Data collection took place at the Virtual Reality and Mobility Lab of the Jewish Rehabilitation Hospital. Participants were first questioned about the frequency at which they used videogames or other simulators (daily, weekly, monthly, yearly or never). They were then assessed while walking overground and circumventing a female interferer in the PE and in a VE, in a random order. The testing area of 28 m^2 area allowed for free overground ambulation. A target (30 cm blue sphere)

Table 1
Subjects characteristics.

	Female	Male
	8 (62%)	5 (38%)
	Mean	**SD.**
Age (years)	25.23	2.71
Height (m)	1.71	0.12
Mass (kg)	70.6	13
Comfortable walking speed (m/s)	1.49	0.22
Maximum walking speed (m/s)	2.19	0.24

	Left + +	Left +	Both equally	Right +	Right + +
Handedness*	–	1	–	6	6

was placed in the far space (8.5 m) and the female interferer (same throughout the entire study) was located on the midline (0°) and facing the participant. Participants were instructed to walk to the target while avoiding a collision with the interferer, as necessary (Fig. 1A). In the two *experimental* conditions of interest, the interferer remained static at either at 3 m or 3.5 m location. These conditions were presented in a random order and interspersed with *catch* and *control trials. In catch trials*, the interferer would start moving and exiting the area to the right or left as soon as the participant reached 0.5 m of forward displacement. In *control trials*, the participant walked toward the target without the presence of the interferer. The catch trials were used to add uncertainty about the need or not to implement an avoidance strategy and the control trials were used in the off-line analysis to determine the participants' unobstructed walking trajectory. The conditions were randomized in 20 consecutive trials: 8 experimental trials (4 static trials at each obstacle position), 8 catch trials (interferer exiting to the sides) and 4 control trials (no interferer). No practice trials were given, however, data collection for this experiment took place on the same day and after another experiment that measured obstacle circumvention in response to moving interferers in the PE and VE. Therefore, all participants had previously undergone a VR experience. The interferer used in the present study was also part of the previous experiment which involved three different interferers [21].

A 12-camera Vicon motion capture system (Vicon-512™, UK) recorded full-body kinematics at 120 Hz from 40 passive reflective markers (Pug-In-gait model). In the VE, participants wore an HTC Vive™ HMD to enable the visualization of the virtual scene. The HTC Vive™ allows a diagonal FOV of 145 degrees and weights 0.5 kg. Both in the PE and VE, participants further wore an HTC Vive™ motion controller on their lower back to track in real-time the crossing of the 0.5 m threshold that determined the onset of interferer movement during catch trials. Data from the HMD and controller were fed into the Unreal™ 4.12.5 gaming engine which controlled the VE and trigger signal for interferer movement. Additional information about the tracking systems and calibration procedure can be found in our previous work [21].

2.3. Physical environment task

In the physical environment task, the female collaborator wore 13 passive reflective makers that were located on the clavicle and bilaterally on the acromion, lateral epicondyle, heel, second toe, as well as the distal end of the ulna and radius (i.e. wrist). At the start of each trial, the interferer received instructions through a television screen, placed behind the participant's starting position. The instructions informed the interferer about her initial position and task condition for the current trial. Note that the interferer adopted the wanted initial position (3 m or 3.5 m) as the participants had their eyes close. In the catch trials, the background switched from a black to a white background after the participant reached 0.5 m of forward displacement,

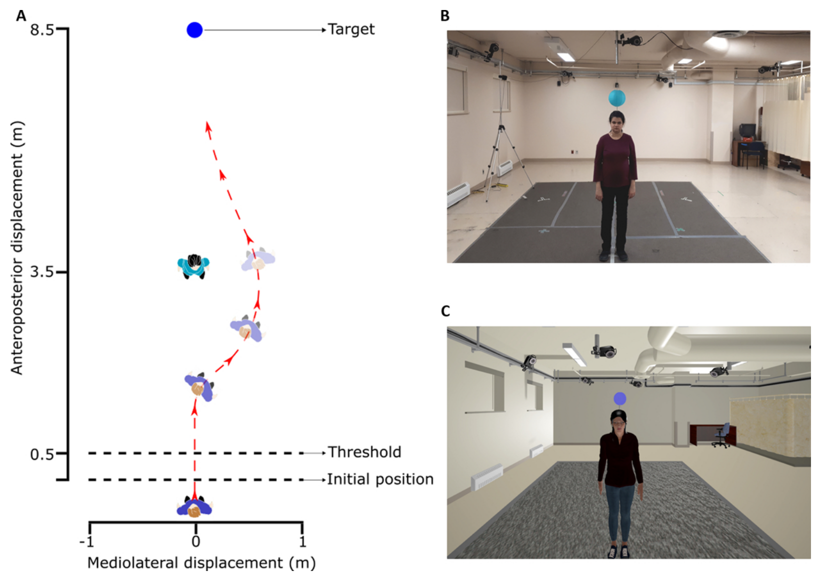

Fig. 1. Schematic representation of the experiment from a bird's eye view (A). Environments as viewed by the participant from the start position in the PE (B) and in the VE, as displayed in the HTC VIVE™ (C).

prompting the interferer to start exiting the volume toward the indicated side.

2.4. Virtual environment task

The VE was built in Autodesk® Maya LT™ and replicated the dimensions and features of the real-life laboratory in which the participants performed the PE task (Fig. 1B and C). In addition, an avatar was created (Autodesk® Maya LT™) using the pre-recorded kinematics from the female collaborator and placed in the virtual scene. The position and behavior of the interferer was controlled in Unreal™.

At the start of each trial, a "Get ready" sign appeared for 1s in the HMD, superimposed on the VE, followed by a "beep" sound that signaled the start of the trial. In collision free trials, a "stop" sign would be displayed upon reaching 5 m of forward displacement. In case the participant collided with the virtual interferer, a "collision" sign would be displayed in the HMD and the trial would stop. Upon completing the present and our previous VR experiment [21], participants responded to two questionnaires assessing sickness from the simulation (Simulator Sickness Questionnaire – SSQ [22]) and the feeling of presence within the VE (Igroup Presence Questionnaire – IPQ [23]).

2.5. Data analysis

Kinematic data of the participants and the interferer were labeled in Vicon-512 Workstation (Vicon Motion Systems, UK) and the participants center of mass (CoM) trajectory was calculated using the full body marker set and anthropometric data. Subsequently, all recorded data (Vicon and Unreal) were exported to MATLAB® (MathWorks, USA) for further analysis. Kinematic data was then filtered using a 4th order low pass Butterworth filter with a cutoff frequency of 10 Hz.

Circumvention strategies were characterized based on the following variables. *Minimum distance* (smallest distance between the participant's and the interferer's manubrium of the sternum), *full body minimum distance* (smallest distance computed in 3D space amongst all possible pairs of body landmarks for the participant and interferer) and *maximum lateral deviation* (largest value of mediolateral displacement). These outcomes were calculated in a time interval that started at 0.5 m of forward displacement and ended at obstacle crossing. The *onset of circumvention was calculated as* the time index of the first point where CoM lateral velocity was greater than the average plus 2 standard deviations of the values observed in control trials (without any obstacle), as further detailed *previous work* [21]. Inter-trial variability was calculated for each of these outcomes and each participant using standard deviations and coefficients of variation.

2.6. Statistical analysis

A generalized estimated equation model (GEE) was used for the individual analysis of each outcome. The model included 2 within-subject factors, namely the environment (PE vs. VE) and the obstacle position (3 m or 3.5 m). Significant interactions were further elaborated using simple effects with a priori identified pairwise comparisons followed by Tukey post hoc tests. Inter-trial variability outcomes were compared across environments and obstacle position using the Friedman's test for dependable samples. All statistical analyses were performed using SAS v.9.4 and the level of significance was set to $p < 0.05$.

3. Results

No collisions were observed in either environment. The average total score in the SSQ was of 13.81 ± 8.69 at the end of the experiment. Additionally, participants reported a strong feeling of spatial presence and of being present in the virtual scene, with an average of 4.92 and 5.15 in the respective components of the IPQ. Frequency of video games or simulator amongst participants was once a year ($n = 6$), once a month ($n = 5$), weekly ($n = 1$) or daily ($n = 1$).

Walking trajectories from one representative participant are displayed in Fig. 2. It can be observed that walking trajectories between environments are similar, with no difference in the preferred side of circumvention. Trajectories in the VE, however, did show greater deviations from a straight path.

The GEE analysis revealed a significant main effect of environment for minimum distance (χ^2 (1,207) = 8.00, $p = 0.005$), full body minimum distance (χ^2 (1,207) = 8.03, $p = 0.005$), and maximum deviation (χ^2 (1,207) = 9, $p = 0.003$), with larger values being observed for these three outcomes in the VE vs. PE (range of difference = 0.10 to 0.12 m) (see Fig. 3). For these outcomes, there were no significant effects due to obstacle position ($p = 0.98$, $p = 0.24$ and $p = 0.7$, respectively for minimum distance, full body minimum distance and maximum deviation) and no significant interaction effects ($p = 0.4$, $p = 0.25$ and $p = 0.67$). The distance from the obstacle at onset of trajectory deviation remained similar between the VE and PE (χ^2

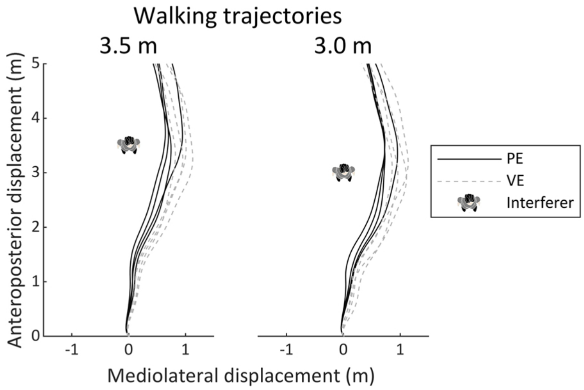

Fig. 2. The figure displays all trajectory traces from one representative participant when circumventing an interferer located at 3.5 m and 3 m from the participant's start position in the PE (plain line) and VE (dotted line).

(1,207) = 1.84, $p = 0.17$) but a main effect of obstacle position was observed (χ^2 (1,207) = 5.49, $p = 0.02$), due to larger onset distances being implemented for the obstacle located at 3.5 m vs. 3 m (difference = 0.17 m).

For the analysis of walking speed (Fig. 4), a main effect of environment was observed for minimum (χ^2 (1,207) = 10.44, $p = 0.0012$), average (χ^2 (1,207) = 11.19, $p = 0.0008$) and maximum walking speeds (χ^2 (1,207) = 11.19, $p = 0.0008$). Indeed, all three walking speed outcomes were consistently smaller by an average 0.17 m/s in the VE compared to the PE. Furthermore, a significant main effect of obstacle position (χ^2 (1,207) = 11.18, $p = 0.01$) was observed for maximum walking speed, with faster values observed when the obstacle was located at 3.5 m vs. 3 m (average difference = 0.03 m/s). There were no significant interaction effects due to environment and obstacle position for minimum ($p = 0.22$), average ($p = 0.43$) or maximum ($p = 0.7$) walking speed. The preferred side of circumvention,

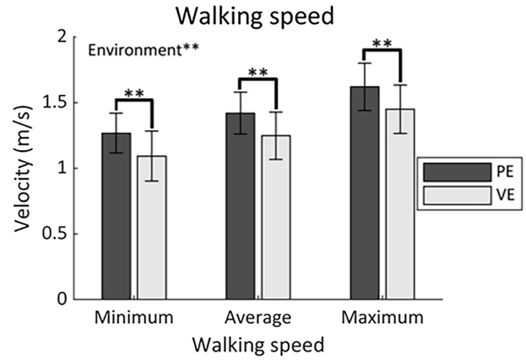

Fig. 4. Mean ± 1SD value of all participants for minimum, average and maximum walking speed. * $p < 0.05$. ** $p < 0.01$.

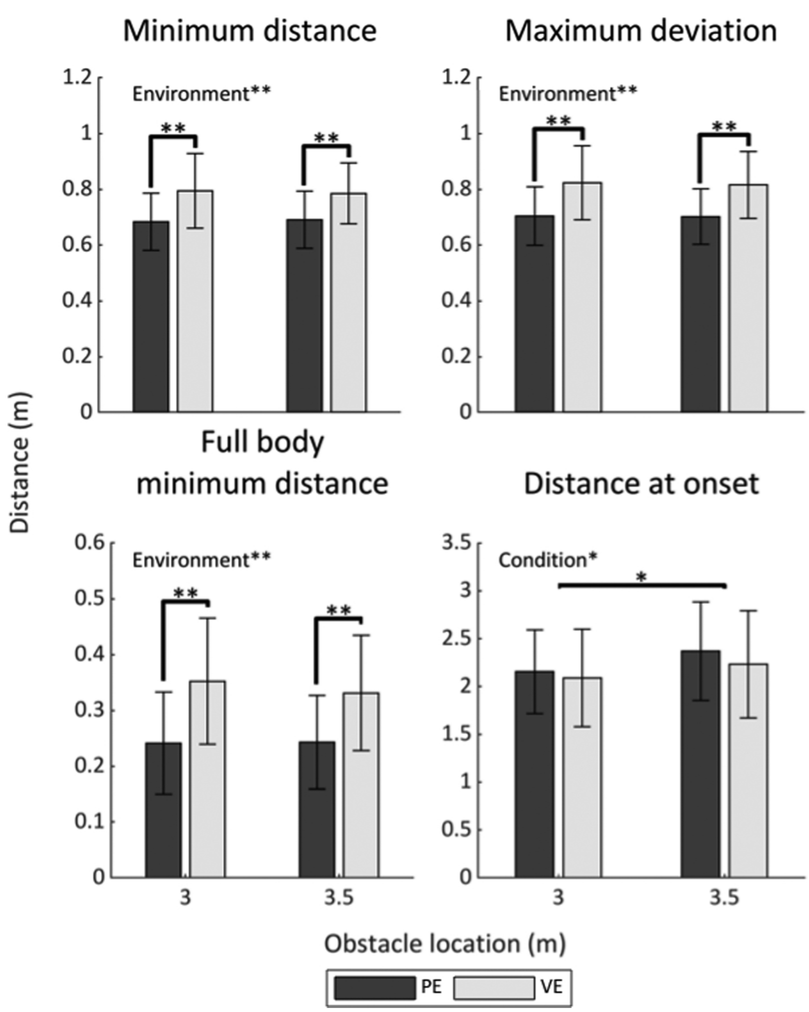

Fig. 3. Group mean ± 1SD value for minimum distance (left upper panel), full body minimum distance (left lower panel), maximum deviation (right upper panel) and distance from the obstacle at the onset of circumvention strategy (right lower panel). Statistically significant main and interaction effects are indicated, as applicable. Likewise, post-hoc comparisons that were statistically significant are also illustrated. * $p < 0.05$. ** $p < 0.01$.

Table 2
Inter-trial variability in obstacle circumvention outcomes as assessed by standard deviation values and coefficients of variation (in parenthesis) for each environment (physical vs. virtual) and each obstacle position (3.0 m vs. 3.5 m). Significant differences in coefficients of variation (* $p < 0.05$) were observed between the virtual and physical environment.

	Physical environment		Virtual environment	
	3.0 m	3.5 m	3.0 m	3.5 m
Minimum distance	0.07 (9.95)	0.06 (8.19)	0.08 (10.43)	0.06 (6.47)
Full body minimum distance	0.06 (26.02)	0.06 (23.1)	0.06 (18.01*)	0.05 (15.7*)
Maximum deviation	0.07 (10.17)	0.06 (8.2)	0.08 (9.24)	0.06 (7.08)
Onset distance	0.31 (13.78)	0.40 (16.96)	0.30 (14.91)	0.31 (13.9)
Average speed	0.05 (3.56)	0.05 (3.32)	0.06 (5.36)	0.06 (4.79)

where participants preferentially veered toward the right (57.97%), showed no significant effects due to environment ($p = 0.14$) or obstacle position ($p = 0.82$) and no interaction effect ($p = 0.71$).

Finally, the analysis of the average standard deviation and coefficient of variation for the different obstacle circumvention outcomes revealed significantly smaller ($p = 0.03$) coefficients of variation for full body minimum distance in the VE compared to the PE, both for the 3 m and 3.5 m obstacle conditions (Table 2). Other inter-trial variability outcomes showed no significant differences as a function of environment or condition. When considering the preferred side of circumvention, 7 out of 13 participants veered to the same side more than 80% of the trials while the remaining participants did not display a consistent behavior. Nevertheless, whether this pattern of preferred side of deviation exhibited large or small variability, the response was similar when comparing the VE and PE.

4. Discussion

To the best of your knowledge, this study is the first to quantify differences in circumvention strategies in response to a static pedestrian in a HMD-based VE vs. the PE. We found that participants adopted larger obstacle clearances and walked slower in the VE vs. the PE. Previous investigations of circumvention strategies in response to static obstacles in the VE have also observed larger clearances, both in terms of personal space [5] and minimum distance [15,16], as well as slower walking speeds [15,16]. Results of the present study are thus consistent with earlier observations, which are thought to reflect the use of “safer” or more “conservative” circumvention strategies in response to virtual obstacles [5,15,16]. The magnitude of differences between the two environments in the present study, however, were rather small, reaching 0.10 m–0.12 m for obstacle clearance outcomes and 0.17 m/s for walking speed. Interestingly, Fink et al. [15], who examined the circumvention of a static inanimate obstacle while wearing an HMD observed a similar difference in walking speed in the VE vs. PE (0.16 m/s), while differences in terms of minimum distance and maximum deviation (0.16 m) between the two environments was slightly larger than in the present study. Another study which examined the circumvention of both animate and inanimate objects using a CAVE system has described similar results, but differences were much smaller, with an increase in clearance of 0.06 m and reduction in walking speed of 0.04 m/s [16].

As suggested in our earlier work [21], a combination of perceptual and cognitive factors could explain differences observed between the VE and PE. In the VE, distances [24] and walking speeds [25] are underestimated, which may explain the larger obstacle clearances and slower walking speeds observed here. Such perceptual bias may be attributed, at least in part, to the HMD characteristics, including its mass and limited FOV [25,26]. In support of this hypothesis, our previous findings indicate that circumvention strategies while wearing an HMD that is heavier and has a smaller FOV [21], as in earlier studies [5,15], are characterized by larger clearances and slower walking speeds. Furthermore, systems that a free of such limitations (e.g. FOV restriction and weight) have observed even smaller differences between the VE and PE [16], supporting the suggestion that the impact of the VR system employed on perception is a factor that contributes to modulate the observed differences in the VE. Beyond perceptual factors, task novelty and a possible sense of threat in VR may have further added to the perceptual bias and contributed to the adoption of more cautious circumvention strategies.

Results also revealed that characteristics of circumvention strategy such as the preferred side of deviation, response to obstacle position (larger onset distance for the obstacle located further ahead) and pattern of speed adaptation (faster maximum walking speed for the obstacle located further ahead) were similar in the VE vs. PE. These findings, which aligns and adds to previous studies that showed a similar path curvature [15] and lateral asymmetry of personal space [5] in the PE and VE, suggest that key characteristics of circumvention strategies are preserved in VR simulations.

Finally, while smaller coefficients of variation for full body minimum distance were observed in the VE vs. PE, standard deviation values remained similar between the two environments. Thus, rather than reflecting an absolute reduction in inter-trial variability in the VE, these observations indicate the presence of a relative change in inter-trial variability that results from the larger full body minimum distances observed in the VE (i.e. denominator in coefficient of variation calculation). The variability observed in the present study was of small magnitude, alike that reported by others in the PE for goal-directed walking [17,27] and obstacle circumvention [18]. Performance variability can be viewed as a mean by which the motor control system can adapt to different task and environmental constraints [28,29], but also as a result of noise that alters the individuals' assessment of internal body state (e.g. body orientation) and external world (environment) and the resulting motor output [30]. While VR simulations may not fully and accurately replicate the sensory experience of the PE, our results suggest that healthy young participants, within immersive VR conditions as in the present study, can adequately estimate their internal body states in relation to the environment, leading to good predictive control [31] and hence contextually-adapted and reproducible circumvention strategies.

One limitation of this study pertains the generalizability of its results to other VR displays that may present different FOV and levels of immersion (2D vs. 3D), etc. Further research is also needed to determine the extent to which current results apply to other populations such as older adults and persons with perceptuo-motor impairments.

5. Conclusion

The present study has sought to examine and contrast circumvention strategies in response to a static pedestrian located at different positions in a VE vs. PE. Results showed that healthy young adults implement circumvention strategies in the VE that are comparable and as reproducible as those observed in the PE. The small differences in the magnitude of obstacle clearance and walking speed that were observed between the two environments, however, suggest the use of use of “safer” or more “conservative” circumvention strategies in the VE that may be attributed to perceptual and/or cognitive factors. Collectively, the results of this study support the use of VR to study, assess and possibly train complex locomotor tasks such as obstacle avoidance.

Conflict of interest statement

All authors declare that they have no conflicts of interest.

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