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Influence of user posture and virtual exercise on impression of locomotion during VR observation

Justine Saint-Aubert, Mélanie Cogné, Isabelle Bonan, Yoann Launey, and Anatole Lécuyer

Abstract—A seated user watching his avatar walking in Virtual Reality (VR) and imagining being walking may have an impression of walking. In this paper, we show that such impression can be extended to other postures and other locomotion exercises. We present two user studies in which participants worn a VR headset and observed a first-person avatar realizing virtual exercises. In the first experiment, the avatar walked and participants (n=36) tested the simulation in 3 different postures (standing, sitting and Fowler's posture). In the second experiment, other participants (n=18) were sitting and observed the avatar walking, jogging or stepping over virtual obstacles. We evaluated the impression of locomotion by measuring the impression of walking (respectively jogging or stepping) and embodiment in both experiments. The results show that participants had the impression of locomotion in either sitting, standing and Fowler's posture. The Fowler's posture however significantly decreased both the level of embodiment and the impression of locomotion. Moreover the sitting posture seems to decrease the sense of agency compare to standing posture. Results also show that the majority of the participants elicited an impression of locomotion during walking, jogging and stepping virtual exercises. The embodiment was not influenced by the type of virtual exercise. Overall, our results suggest that an impression of locomotion can be elicited in different users' postures and during different virtual locomotion exercises. They provide valuable insight for numerous VR applications in which the user observes a self-avatar moving, such as gait rehabilitation, training, video games, etc.

Index Terms—Action observation, Locomotion, Posture, Virtual Exercise, Embodiment

1 Introduction

Action observation therapy plays an important role in gait rehabilitation (see a review by [54]) and was developed on the basis that the same neurons fire when a person performs an action, as well as when he/she observes a similar action performed by another person (e.g. [18], [64], [65]). During such therapy, participants stay still and observe different locomotion exercises (walking, running, crossing obstacles, etc [50]) to practice motor tasks. Action observation is often used as in extension of physical therapy but sometimes as a therapy on its own, especially when participants are too weak and/or unable to move [54].

Video screen has been used for a long time to display the action in rehabilitation but there are growing appeals for the use of immersive Virtual Reality (iVR) systems since they provide more visual cues than traditional screen and could enhance the action observation training [13]. However little is known about the conditions under which iVR systems could be used for gait training exercises, notably on the influence of users' postures or of the type of virtual exercise on the impression of performing the action.

Two types of visual feedback could contribute to impression of walking in iVR: external motion of the environment [58] and avatar motion related to the sense of embodiment (ownership, self-location, and agency) [31]. Kokkinara et al. studied these factors during observation of a virtual walk in iVR [33]. In their experiment, healthy participants wore a VR headset and were in a seated position, with only head movements allowed. They observed an avatar in a first-person perspective walking for 4 minutes and reported that they felt like they were walking and had a sense of embodiment towards the avatar. In our paper, we propose to extend this work to other postures and virtual exercises for further use in rehabilitation.

The influence of the user's posture on the impression of walking remains an open question. Keeping a seated posture is sometimes complicated for participants who are tired and the weight of the VR headset may make the position even more difficult to hold. A Fowler's posture (supine position with inclining backrest) for example, is more appropriate [61] but it could affect the impression of walking. Conversely, some participants are able to remain in a standing posture and this could increase the impression of walking. Kruijff et al. for instance showed that between standing leaning control and sitting joystick control, the impression of walking was better in standing posture [34]. This improvement could be due to the difference in control or could be the result of posture and suggests that the influence of posture on the impression of walking should be further examined.

The impact of the type of virtual exercise is also unclear. An important part of physical training involves presenting different stages of difficulty such as walking, running, or crossing obstacles (e.g. [50]), and recent efforts have been made to extend the evaluation of walking exercise to jogging exercise. For example, Burin et al. evaluated healthy participants for the effects of an iVR exercise combining walking and running and participants reported having the sensation of walking [9]. Kruijiff et al. also demonstrated that with simple joystick control, participants can feel like they are running in iVR [34]. These works suggest that it

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may be possible to modulate the difficulty of the walking exercise, however the jogging exercise has not been studied individually and/or during action observation, and other virtual exercises such as crossing obstacles have to our knowledge never been tested.

Therefore, in this paper, we evaluated the influence of user posture and of virtual exercises such as walking, jogging and stepping over obstacles on the impression of walking (resp. jogging and stepping over obstacles). Two experiments were conducted with healthy participants. In the first experiment, participants (n=36) observed a first-person avatar walking while in 3 different postures: standing, sitting, or Fowler's posture (Fig. 1). Each participant tested all postures and estimated their impression of walking and embodiment in post-hoc questionnaires. Our evaluation outcomes show that an impression of walking can well be triggered in all three postures. It also demonstrates that the type of posture can influence the IoL as the impression of walking and ownership were found significantly lower in the Fowler's posture, and agency was potentially stronger in standing posture than in sitting and Fowler's posture. In a second experiment, other participants (n=18) were seated and observed a first-person avatar walking, jogging, or stepping over obstacles (Fig. 2). Each participant tested all the exercises and estimated their impression of walking (resp. jogging and stepping) and embodiment in post-hoc questionnaires. The results show that the majority of participants had the impression of walking, jogging or stepping over obstacles. Some participants had difficulty to elicit an impression of jogging. Our findings also indicate that the type of exercise does not significantly affect the embodiment.

Overall, the study contributes to providing valuable insights for the design of future gait rehabilitation exercises. It shows that the iVR system could be used in Flower's posture, although sitting and standing posture should be preferred. Furthermore, it suggests that the difficulty of the walking exercises could well be modulated with jogging and stepping exercises. However, some users can have difficulty to get an impression of jogging. These results are not only valuable for rehabilitation and can be interesting for many other applications, for instance in the context of video-games, during cinematic or play-time with limited body movements from the users.

The remainder of this paper is organized as follows: the related works are discussed in Section 2. Section 3 presents the experimental setup used in both experiments. Section 4 is focused on the first experiment, which investigates the influence of posture on the impression of waking. Section 5 describes the second experiment investigating the influence of virtual exercises on the impression of walking, jogging and stepping over obstacles. The paper ends with a general discussion and perspectives.

Fig. 1. The 3 postures evaluated in Experiment I. (Top left) The sitting, (Top right) the standing and (Bottom) the Fowler's posture.

2 Related Work

In the reminder of this paper, we propose to encompass the notions of impression of walking, of jogging and of stepping over obstacles under the expression "Impression of Locomotion" (IoL). This section presents previous works related to IoL. In a first part, we present the different factors that seem to influence IoL in iVR. In a second and third part, we explore how the posture or the type of virtual exercise may affect these factors.

2.1 Factors influencing the Impression of Locomotion

Previous works suggest that several factors can influence the IoL : vection, sense of embodiment, and other cognitive processes such as memory, motivation and intention.

Vection is an impression of self-motion [24], [58] caused by apparent movements of the virtual environment called optical flow [52]. Vection is related to visual motion in the horizontal and sagittal planes, but not exclusively, and the point-of-view oscillation that reproduces head sway can be simulated in the frontal plane in order to increase IoL [6], [35], [49].

The virtual embodiement, related to the avatar, also seems to contribute to IoL. Kilteni et al. decompose the virtual embodiment into three components: the sense of self-location, the sense of body ownership, and the sense of agency [31]. The self-location is concerned with the fact that "one feels self-located inside a physical body", the sense of agency is the sense that "I am the one who causes or generates an action" and the sense of body ownership corresponds to the self-attribution of a body [20], [31], [37]. The presence of an avatar seems to increase the embodiment if viewed from a first-person perspective [21], [23], [33], [55].

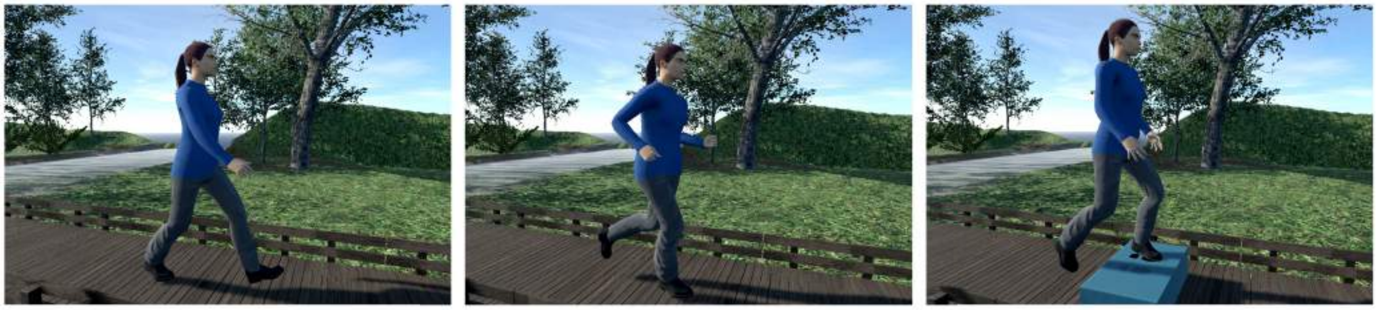

Fig. 2. The locomotion exercises investigated in Experiment II. From left to right : walking, jogging and stepping over obstacles.

Finally, Matsuda et al. compared walking simulations with and without an avatar, and showed that IoL was increased by the virtual body representation [41].

Other cognitive factors may influence the IoL such as the memory of the observed action that seems essential since action comprehension could result from the mapping of an observed action to motor representations of that action [19]. Motivation could also be involved, especially in the context of rehabilitation [26]. Finally, the intention/prediction to perform the exercise also seems important since when participants know they have to do something, they will tend to take credit for it even if they did not actually do it themselves [12], [76].

2.2 Influence of the body posture on the IoL

User's real posture can differ from the avatar's posture in the virtual world and such postural mismatch may potentially affect the IoL through the sense of self-location. Postural mismatch (the virtual and real bodies are in a different configuration) is different from spatial mismatch (the virtual and real bodies are delocated) however, it seems that postural mismatch could lead to a feeling of spatial mismatch as some users locate themselves in the head and others in the torso [1].

The posture could also have an impact on the ownership as shown in some studies that investigated the rubber hand illusion [7]. In this illusion, participants see a rubber hand being stroked with a paintbrush while their own hand is hidden and stroked synchronously, and the situation leads participants to feel that the fake hand is their own. Studies have shown that this effect is sensitive to the postural compatibility between the real and rubber hands: a sense of ownership occurs for small discrepancies [14] but decreases for large discrepancies [2], [17], [74]. Although these results are for the hand only, similar conclusions have been drawn for the whole body [38], [66], [71] . A full-body illusion can be generated using a procedure similar to the rubber hand illusion [38] but the process is somewhat different because vestibular feedback is involved. Vestibular feedback informs in particular on the position of the head in relation to gravity [3], [11], [47] and many studies have suggested that it has a critical role for embodiment (see [36] for a review and [57] for more recent findings). Full-body mismatch appears to produce similar results to hand mismatch: ownership is elicited when the user and avatar are in a different location [38], [40] or posture [66], however tilting the user's body relative to the avatar seems to decrease ownership [71].

Some works suggest that body posture can influence vection [25], [73], [77]. Tovee et al. found that the onset latency of vection was reduced in the standing posture compared to the supine posture [73]. Finally, differences in vection magnitude were found between supine and sitting posture by Guterman et al. [25]. Vection also involves many cognitive factors (see a review by [62]) that can vary depending on the posture. For example, Yound et al. showed that when users were exposed to information suggesting that they were stationary, such as feet touching a ground surface, vection was altered [77]. However, the influence of body posture on vection is not straightforward since other works did not find difference due to posture. Oman et al. found no difference in term of onset latency of vection between standing posture and the supine posture [46] and Tovee and al. found no difference in vection magnitude between supine and sitting posture [73]. McManus et al. recently suggested that the vection is related to the strength of visual reorientation and that the posture has no direct influence [42]. The question is then still open.

Posture could influence other cognitive mechanisms involved in IoL. For example, memory retrieval may be affected [60], [63] since having the same body position in which the experience was acquired facilitates access to that part of the memory [16]. Posture can also influence the motivational process. Price et al. recorded left frontal cortical activity related to motivation in different postures and their results indicated that tilting backward caused participants to have less activity compared to upright posture, indicating greater motivation in sitting and standing postures than in supine postures [59].

Finally, some postures could generate cybersickness. Cybersickness occurs when the movements of the simulation and the movements of the user are desynchronized, and leads to unpleasant symptoms such as nausea or headaches [15]. Although it does not directly impact IoL, cybersickness should be avoided in any VR simulation. The supine posture appears to be the most likely to generate cybersickness since misalignment between the real and virtual vertical axis was found to increase cybersickness [72]. Marengo et al. found that people who were sensitive to cybersickness while seated were even more sensitive to cybersickness while lying down, even if they were experienced VR users [39]. Standing posture also seems to generate cybersickness since it does not allow postural stability [15], [43].

All these observations tend to indicate that an IoL could be elicited in different postures. However given that many factors are involved and that cybersickness could be generated in some postures, empirical work seems necessary to clarify the exact influence of body posture on IoL.

2.3 Influence of the type of exercise on the IoL

Various exercises have been tested in the context of gait rehabilitation (see a review by [54]) and for example, Park et al. evaluated a program with different stages: walking on straight and curved paths, walking on even and uneven surfaces, crossing obstacles and walking with functional tasks [51]. This program, as well as other programs, generally yielded positive results, but few involved VR displays and they were not directly interested in assessing the IoL.

Some studies have investigated the IoL during different exercises, but in a multimodal context. Terziman et al. showed that reproducing foot/ground contact through auditory cues and vibrations transmitted under the feet increases the IoL during walking [70]. Similarly, Turchet et al. reported that such feedback could improve the realism of a running simulation [75]. While these studies inform us that an IoL can be achieved with multimodal feedback, the contribution of visual feedback alone remains unknown.

Exercises can influence vection because they generate different optic flows. The direction of the optic flow seems to be important as it has been reported that vection is stronger during vertical (up-down) movement than during horizontal (right-left) movement [29], [67]. In the same vein, Kokkinara et al. evaluated the IoL during the VR observation of an avatar going up a hill [33] and reported that the IoL could have been increased by the slope. In addition to direction, navigational speed could also impact vection as Brandt et al. revealed that the velocity perceived is linearly related to its physical speed [8].

The type of exercise could also affect the embodiment through the sense of ownership. For example, a study by Bergstrom et al. showed that uncomfortable body position of the avatar resulted in less subjective ownership therefore the type of avatar movements seems to play a role [4]. In other studies, authors suggest that subjective body ownership is related to participants' heart rate, which appears to change with exercise. Burin et al. showed that participants' heart rate increased with effort when observing an exercise split between walking and running [9]. Along the same line, Kokkinara et al. found that observers' heart rates increased when the avatar climbed a hill [33]. While further work is still needed, these studies suggest that the type of exercise might influence the virtual body ownership.

Finally, the type of exercise can have a direct impact on other cognitive factors related to IoL, such as the intention/prediction. For Kannape et al. "one has to be able to predict the immediate consequences of one's movements and confirm these predictions against the actual sensory feedback received from the environment to successfully control one's movements" [28]. In the same idea, other authors argue that walking corresponds to action observation since it involves cyclic and highly automatic movements [33]. The type of task can also influence memory retrieval. For example it has been reported that action observation seems to be more effective when the movement has been learned in the past by the observer [10].

Overall, these observations suggest that different locomotion exercises could elicit an IoL. The positive influence of vertical movement on IoL seems to indicate that an impression of crossing over obstacles is achievable. And because an impression of running was reported in the context of multimodal feedback, the observation of a jogging exercise might also elicit an IoL. Empirical work is needed to confirm such hypotheses.

3 Experimental Method

We conducted two user studies to evaluate the influence of the user posture (Sec. 4) and of the type of virtual exercise (Sec. 5) on the IoL. The procedure was compliant with the MR004 reference methodology and was approved by the Ethics Committee of the University Hospital of Rennes, France, on March 17th, 2021. The experiments were carried out in accordance with the approved guidelines. An information letter was provided to the participants including: the aims of the study, the protocol and the risks involved. All the participants gave written informed consent prior testing.

3.1 General overview

In both experiments, participants observed an avatar. They were seated, standing, or in Fowler's posture and wore a VR headset that provided visual and auditory feedback. The VR headset was tracked so that the view was updated to match the participants' head orientation. The virtual environment was a wooden pontoon surrounded by a forest with some hills, trees, flowers, and rivers visible along the way (Fig. 3).

Fig. 3. The virtual environment used in the experiments: a straight pontoon surrounded by a forest.

Participants were represented in the virtual scene by a life-size anthropomorphic avatar. A set of 2 genders, 3 heights, 3 weights, 3 skin colors were available and the association that most resembled the participant was chosen by the experimenter (see Fig. 4 for the two most commonly used avatars). The avatar's head was co-located with the participants' head so that they were viewing the avatar from a first-person perspective. The light came from behind, so that the avatar's shadow was clearly visible on the ground in front (Fig. 4 bottom).

At the beginning of the simulation, the avatar stood on the pontoon and started walking, running or stepping

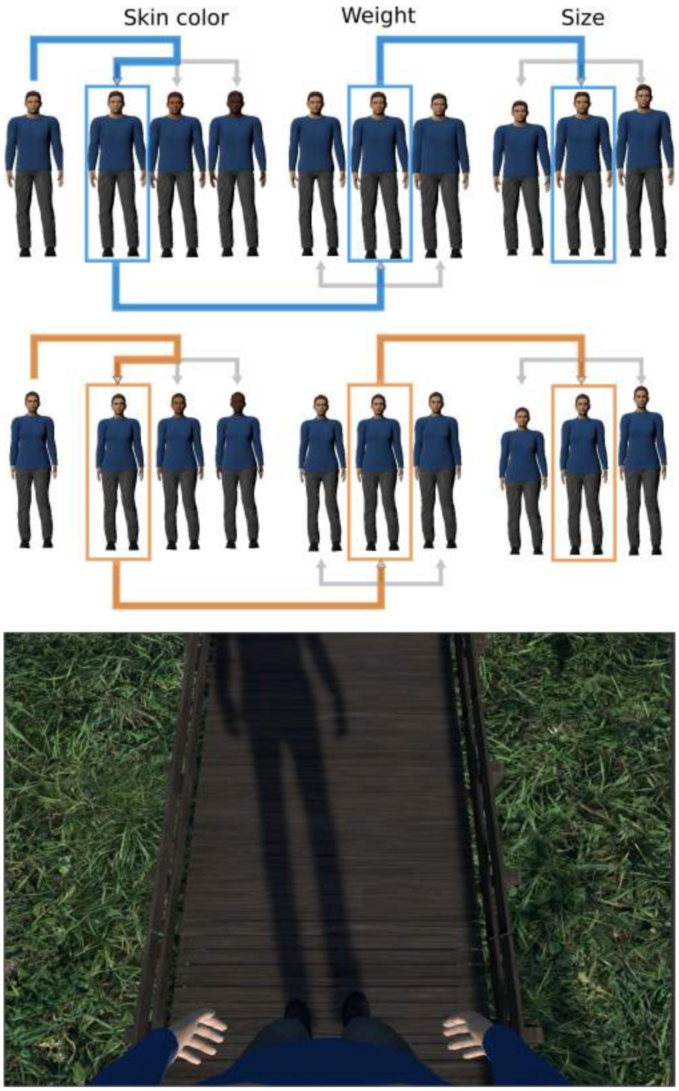

Fig. 4. Examples of some avatars available for men (Top) and women (Middle). The customization sequences the most used in the experiments is highlighted. (Bottom) First-person view of the scene.

over obstacles after three seconds. The optic flow of the environment and, head oscillations and movements of the avatar were simulated. The sound of the avatar's footsteps was also displayed as well as ambient sounds (wind in the trees, birds, river). A simulation lasted four minutes and then the avatar stopped.

Participants were informed at the beginning of the experiment that they will see the avatar walking, jogging or stepping over obstacles and that they they will be able to observe its movements and the movements of the environment by moving their heads freely. They were asked to "try to imagine that you are walking (jogging or stepping over obstacles)". Priming participants is likely to be done in application such as rehabilitation.

3.2 VR set-up

The virtual environment was implemented in *Unity3d* (Version 2019.3.11f1) and ran at a frequency of 90 Hz. The VR headset used was an *HTC Vive Pro* (2880 x 1600 pixels) that includes internal head tracking and audio. Its 3D position was tracked by two external light houses located in front of the participant and was integrated into Unity using the *SteamVR* plugin. The system was calibrated for each participant using the *SteamVR* configuration.

The avatars were created with the software *MakeHuman*. Their movements were simulated using animations from *Mixamo*. A mask was applied to the head, which was controlled by the participants. An inverse kinematics solution between the head and the trunk was used (*Final-IK* plugin).

3.3 Real postures

Participants could hold different postures (see Fig. 1):

- Sitting : Participants sat in a chair with their backs straight and supported on the backrest. Their knees were bent at 90°and their feet were touching the floor. Their arms were relaxed in the air.
- Standing : Participants stood with their arms relaxed at their sides. No support was used to stabilize the body.
- Fowler : Participants were lying on a bed with their knees straight. Their trunks were tilted at 45 °from the vertical and their arms were positioned along the body. A cushion was placed behind their heads so that the back of the VR headset would not disturb them. We chose to not test the completely horizontal posture (supine posture) because we found in a pilot experiment that it induced cybersickness and because the VR headset was uncomfortable to wear in this posture. This outcome is consistent with recent findings by Tian et al. [72] showing that cybersickness in the supine posture may occur if, as in our simulation, the virtual coordinate system contradicts the real-world coordinate.

Participants kept their shoes on during the experiments, however high heels were not accepted in order not to bias postural stability in standing posture. In order for participants to have the same view of the virtual environment in Fowler's posture as in standing and sitting posture, the virtual scene was tilted so that the axis of the pontoon matches the axis of the head (see visual reorientation illusion [27]). It was applied manually, case by case, at the beginning of the simulation.

3.4 Virtual locomotion exercises

Participants could observe different virtual exercises (see Fig. 5 for more details):

- Walking : The avatar walked at a constant pace of 1 m/s (3.6 km/h). Leg movements, arm swing and torso movements were simulated.
- Jogging : The avatar ran at a constant pace of 2.8 m/s (10 km/h). The leg movements, arm swing and torso movements were simulated. The legs did not rise much, which was more consistent with a jogging movement than a running movement.
- Stepping over obstacles : The avatar walked until he/she encountered obstacles that consisted of 20 cm high cubes. The avatar would step on the obstacle with one leg, then the second leg before stepping back on the second leg and then on the first. The leading leg alternated between right and left and was indicated

by a footprint on the obstacle. The distance between obstacles was randomized but predefined so that it was the same for all participants. In total, the avatar crossed 18 obstacles during a simulation.

4 Exp. I: Influence of user's posture on IoL

4.1 Aim of the experiment and hypotheses

This experiment aimed to determine whether static users in a sitting, standing, or Fowler posture could feel like they were walking during action observation in iVR. To this end, participants tested the 3 postures (in a counterbalanced order) and rated their IoL in a questionnaire.

We had several hypotheses about the results of this experiment. First, we expected that the visual dominance would be sufficient to elicit an IoL in any posture. Moreover, in the standing posture, even though participants had to maintain upright, the posture was closer to that of the avatar. Finally in the Fowler's posture, real and virtual axis were not consistent. Therefore we expected that:

- (H1) : Participants would have IoL in every posture.
- (H2): The IoL would be stronger in standing posture.
- (H3) : The IoL would be weaker in Fowler's posture.

4.2 Participants

A sample of 36 healthy volunteers (9 men; mean age: 37.5 years; standard deviation: 9.7 years; minimum: 23 years; maximum: 57 years) participated in the experiment. They were recruited through public information in the rehabilitation department of the University Hospital of Rennes and were all hospital staff. They were not compensated for their participation and did not report any visual impairment or physical problems that might have affected the experiment. Overall, 80% of participants reported never using VR technology, 14% used it sometimes, and 6% used it often. Moreover, 39% were not sensitive to motion sickness, 44% sometimes, and 17% often.

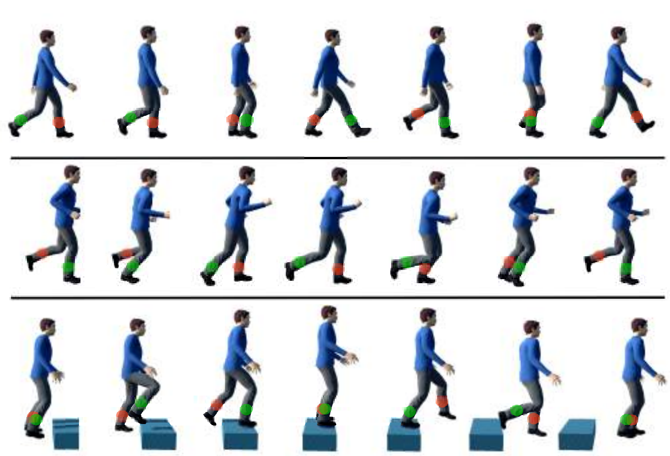

Fig. 5. The 3 exercises evaluated in Experiment II with detailed movements over time. From top to bottom: walking, jogging, and stepping over obstacles. Red dots are placed on the left leg and green dots on the right leg to help understand the movement.

4.3 Data collected

At the end of each simulation, participants completed a questionnaire that included the standardized Gonzales et al. questionnaire on embodiment (12 questions) [22] and a question on the overall impression of walking [33] "During the experiment, I felt like I was walking." Participants also answered questions to evaluate cybersickness based on the SSQ questionnaire (9 questions) [32] and a question on the impression of slope: "During the experiment, I felt like on a sloping ground" to check if the rotational shift in the Fowler's posture was correctly implemented.

For all the questions except for the SSQ questionnaire, participants answered on a 7-point Likert-scale ranging from "strongly disagree (1)" to "strongly agree (7)". Questions on the embodiment were regrouped following the method proposed by Gonzales and al. to provide individual scores for ownership, agency and self-location. For the SSQ questionnaire, participants answered on a 4-point Likert scale ranging from "not at all (0)" to "severe (3)". Scores were converted using the method proposed by Kim and al. to obtained a cybersickness score from 0 to 100.

4.4 Results

The participants' responses are presented in Fig. 6.

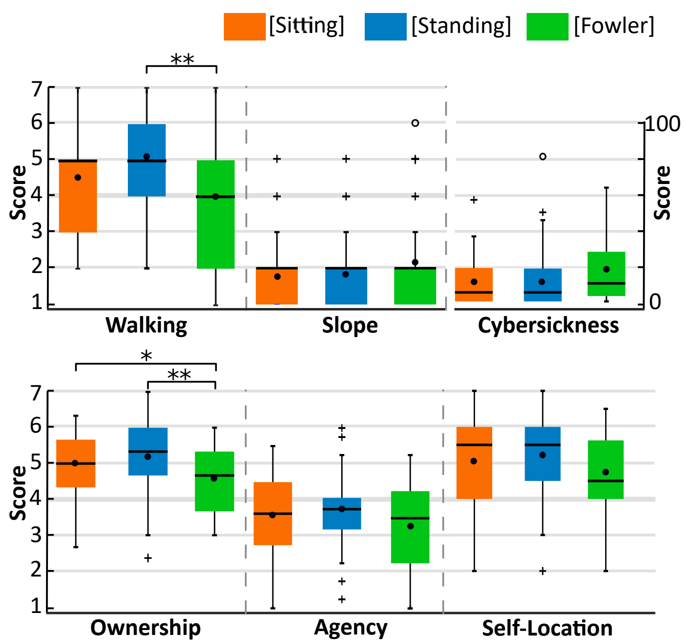

Fig. 6. Results for Experiment I : Participant's responses assessing their impression of walking, embodiment, impression of slope surface and impression of cybersickness in the 3 different postures.

First, we examined the results for each posture individually. The abbreviation "*m*" represents the median, "*25th*" the 25th percentile and "*75th*" 75th percentile related to the variability of the score across all participants. The impressions were qualified as very poor (m < 2), poor (m ≥ 2 and < 3), somewhat poor (m $>= 3$ and < 4), average (m $= 4$), somewhat good (m ≥ 4 and < 5), good (m ≥ 5 and < 6), excellent (m ≥ 6 and < 7) :

- In **sitting posture**, participants had a good impression of walking (m = *5.0*; *25th* = *3.0*; *75th* = *5.0*). For the embodiment, the impression of self-location was good (*m = 5.5; 25th = 4.0; 75th = 6.0*), the ownership was good (*m = 5; 25th = 4.3; 75th = 5.7*) and the agency was somewhat poor (*m = 3.6; 25th = 2.8; 75th = 4.3*).

- In **standing posture**, participants had a good impression of walking (*m = 5.0; 25th = 4.0; 75th = 6.0*). The impression of self-location was good (*m = 5.5; 25th = 4.6; 75th = 6.0*), the ownership was good (*m = 5.3; 25th = 4.8; 75th = 6.0*) and the agency was somewhat poor (*m = 3.7; 25th = 3.1; 75th = 4.0*).
- In **Fowler's posture**, participants had an average impression of walking with higher variability than for others responses (*m = 4.0; 25th = 2.0; 75th = 5.0*). The impression of self-location was somewhat good (*m = 4.5; 25th = 4.0; 75th = 5.5*), the ownership was somewhat good (*m = 4.6; 25th = 3.8; 75th = 5.0*) and the agency was somewhat poor (*m = 3.5; 25th = 2.2; 75th = 4.1*).

For all the postures, the cybersickness was low (*SQPV score* ≤ 20) and participants had a very poor to poor impression of slope ($m <= 2$).

We then compared the ranking between the three different postures. A non-parametric analysis was performed using the Friedman test because the normality assumption was not met for some data. If a significant effect was found, a post-hoc analysis via the Nemenyi procedure was performed to check the significance of the pairwise comparisons. We found a significant effect of posture on impression of walking (p=0.001). Standing posture was significantly better rated than Fowler's posture (p=0.002). We also found a significant effect on the impression of ownership ($p<0.001$). Both sitting and standing postures were rated significantly higher than Fowler's posture (p=0.012 and $p<0.001$, respectively). Posture had no significant effect on the impression of self-location, agency, slope and cybersickness. We also tested whether the order of appearance of posture affected the results and found no significant effect.

4.5 Additional analysis

Questionnaires measuring embodiment are still subject to debate and while we have used the questionnaire proposed by Gonzalez et al. to assess the sense of embodiment, the authors have recently proposed a refined version of this questionnaire [53] that was simply not available at the time of our experiment. In order to complete our analysis, we re-analyzed the embodiment answers a posteriori following the directives of the new version (see Fig. 7). Using questions available in the original questionnaire, it was possible to partly compute the ownership (R10, R13 and R12 in the new version [53]) and to fully compute the agency (R3 and R13 in the new version).

We compared the ranking between the postures using the same procedure than before. We found a significant effect of the posture on the ownership ($p<0.001$) with standing posture rated higher than Fowler's posture (p=0.001). We also found a significant effect of the posture on the agency ($p<0.001$) with the standig posture rated higher than sitting posture (p=0.012) and than Fowler's posture ($p<0.001$).

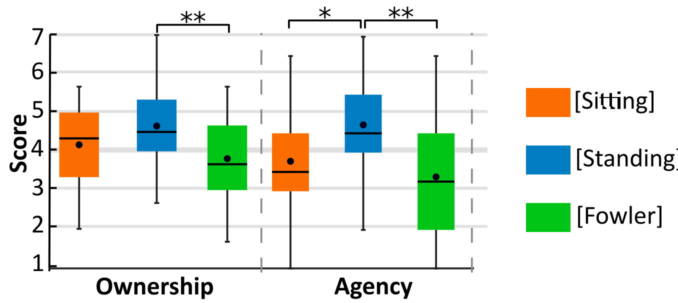

Fig. 7. Results of experiment 1 re-analyzed with the new version of the questionnaire of Peck and al. [53]. Only the agency and ownership results that differ from the old version of the questionnaire are shown.

5 Exp. II : Influence of exercise on IoL

5.1 Aim of the experiment and hypotheses

This experiment aimed to assess the IoL in walking, jogging or stepping over obstacles exercises. To this end, seated participants who did not participate to Experiment I observed the three exercises in a counterbalanced order and judged their IoL in a questionnaire.

We expected that jogging would lead to similar results as walking, and that stepping would produce a clear change in the vertical optic flow of the environment during ascent/descent. However, we hypothesized that the magnitude of IoL would depend on the exercise. The discrepancy between virtual and real motion is larger for jogging simulation than for walking simulation and stepping over obstacles is not a cyclic action. Therefore we expected that :

- (H4) : An IoL would well be triggered during jogging and stepping exercises.
- (H5) : The IoL would be lower during jogging than during walking exercise.
- (H6) : The IoL would be lower during stepping than during walking and jogging exercises.

5.1.1 Participants

A sample of 18 healthy volunteers (14 women; mean age: 42.7 years; standard deviation: 10.0 years; mininum: 25 years; maximum: 60 years) participated in the experiment. They were different from the participants involved in Experiment I. They were recruited through public information in the rehabilitation department of the University Hospital of Rennes and were all members of the hospital staff. They were not compensated for their participation and did not report any visual impairment or physical problems that might have affected the experiment. All participants reported never having used VR technology. Moreover, 50% were not sensitive to motion sickness, 33.3% sometimes, and 16.7% often.

5.2 Data collected

At the end of each task, participants completed the same questionnaire than in experiment I : the questions on embodiment and cybersickness were the same but the questions on the slope was removed. The question on the global impression of locomotion "During the experiment, I had the impression of walking" was completed with two other questions : "During the experiment, I had the impression of jogging" and "During the experiment, I had the impression of stepping over obstacles". These 3 questions were all presented, no matter the task, and participants had to answer on 7-point Likert-scales ranging from "strongly disagree (1)" to "strongly agree (7)".

5.3 Results

Participants' responses are presented in Fig. 8.

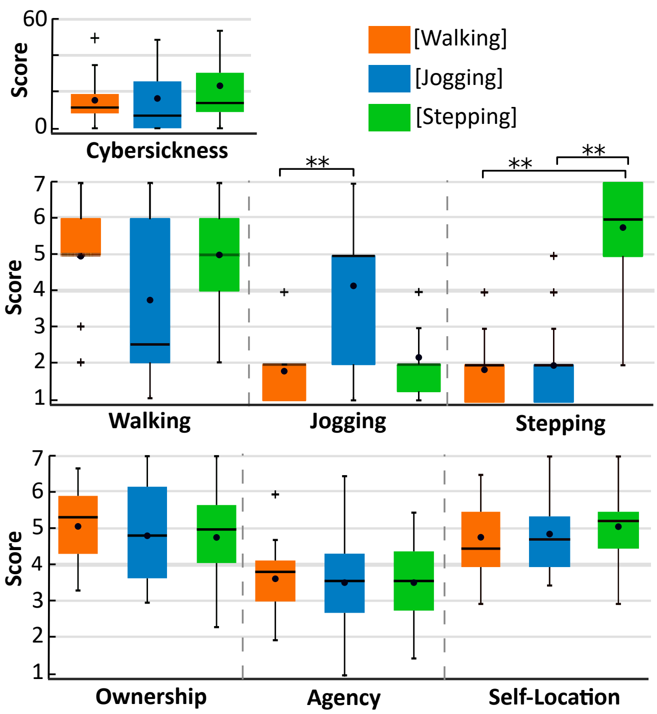

Fig. 8. Results for Experiment II : Participant's responses assessing their impression of walking, jogging, stepping, embodiment and cybersickness in the 3 exercises.

We first examined the results of each task individually. The impressions were qualified from "very poor" to "excellent following the same procedure than in Sec. 4.4 :

- During **walking exercise**, participants had a good impression of walking (*m = 5.0*; *25th = 5.0*; *75th = 6.0*), a poor impression of jogging (*m = 2.0*; *25th = 1.0*; *75th = 2.0*) and a a poor impression of stepping over obstacles (*m = 2.0*; *25th = 1.0*; *75th = 2.0*). Concerning the embodiment, the ownership was judged as good (*m = 5.3*; *25th = 4.3*; *75th = 5.9*, the agency as somewhat poor (*m = 3.9*; *25th = 3.0*; *75th = 4.0*) and the self-location as somewhat good (*m = 4.5*; *25th = 4.0*; *75th = 5.3*).
- During **jogging exercise**, participants had a good impression of jogging but with high variability (*m = 5.0*; *25th = 2.0*; *75th = 5.0*). They also had a poor impression of walking but with high variability (*m = 2.5*; *25th = 2.0*; *75th = 6.0*) and a poor impression of stepping over obstacles (*m = 2.0*; *25th = 1.0*; *75th = 2.0*). For the embodiment, the ownership was judged as somewhat good (*m = 4.8*; *25th = 3.8*; *75th = 6.0*), the agency as was somewhat poor (*m = 3.6*; *25th = 2.8*; *75th = 4.1*) and the self-location as somewhat good (*m = 4.8*; *25th = 4.0*; *75th = 5.2*).
- During **stepping exercise**, participants had a good impression of walking (*m = 5.0*; *25th = 4.0*; *75th = 5.0*), a poor impression of jogging (*m = 2.0*; *25th = 1.3*; *75th = 2.0*) and an excellent impression of stepping over obstacles (*m = 6.0*; *25th = 5.0*; *75th = 7.0*). Concerning the embodiment, the ownership was good (*m = 5.0*; *25th = 4.0*; *75th = 5.5*), the agency was somewhat poor (*m = 3.6*; *25th = 2.8*; *75th = 4.1*) and the self-location was good ((*m = 5.3*; *25th = 4.5*; *75th = 5.4*).

The cybersickness remained low (*SQPV score* ≤ 20) during all the tasks.

We then compared the rating between the tasks using the same procedure as described in Sec. 4.4. We found a significant effect of the type of exercise on the impression of jogging ($p<0.001$) with jogging exercise significantly rated higher than walking exercise ($p=0.005$). We also found a significant effect on the impression of stepping over obstacles ($p<0.0001$) with stepping obstacles exercise significantly rated higher than walking exercise ($p=0.001$) and jogging exercise ($p=0.001$). The exercise had no significant effect on the impression of self-location, agency and cybersickness. We also compared the impression of walking during walking simulation with the impression of jogging during jogging simulation and the impression of stepping during stepping simulation (not directly visible on Fig. 4.4) and found a significant effect ($p=0.002$) with stepping exercises rated higher than jogging ($p=0.028$). We also tested if the order of appearance of the task would affect the results and found no significant effect.

5.4 Additional analysis

As in Sec. 4.5, we re-analyzed a posteriori, the ownership and agency answers for the new version of the questionnaire [53]. We found no significant effect of the type of exercise.

6 General discussion

6.1 Influence of the posture

The experiment I assessed the influence of posture on the IoL. As we expected, participants in sitting posture experienced an IoL and the embodiment appeared to contribute in part to this impression, with ownership/self-location scoring above average and agency just below. These results are consistent with those obtained by Kokkinara et al. when the avatar was viewed in first-person and head swaying was simulated [33].

The results showed that participants had good IoL in standing posture, partially supporting the hypothesis (H1). The overall impression of walking was rated above average, and embodiment scores were rated above average. The fact that participants had to maintain an upright posture while standing did not break the illusion. Krujiff and al. investigated standing leaning locomotion and found that users had an impression of self-motion [34]. Our result extends their finding to standing passive locomotion.

The results indicated that an IoL was somehow elicited in the Fowler's posture, confirming (H1). Participants rated their overall impression of walking as average and their ownership and self-localization as above average. The Fowler's posture was really different from the avatar's posture. Moreover self-location, ownership, and memory retrievals may have been impaired (see Sec. 2.2 for details) by this posture. Still, participants had an average IoL, demonstrating the strength of visual dominance over somesthetic/vestibular signals.

Scores for the impression of walking were still variable in the Fowler's posture, indicating that the illusion was not effective for all participants. We speculate that this could be explained by a different degree of visual field dependence between participants. Recently, Tegkun et al. investigated the full-body illusion in supine posture and found that participants who relied more on visual information (visual field dependent) perceived the illusion more strongly than other participants (non-visual field dependent) [66]. In our experiment, this could explain the variability in supine posture since vision and somesthetic/vestibular feedback were the most contradictory. We did not measure participants' visual field dependence, so further investigation is needed to validate this hypothesis.

No significant difference was found between sitting and standing postures in term of impression of walking, so hypothesis (H2) is rejected. We expected a difference to show up since Krujiff and al. showed that standing leaning locomotion enhanced self-motion sensations compared to seated joystick locomotion [34]. Along the same line, differences between seated leaning locomotion and standing stepping locomotion were found [44]. However, in both cases, users moved differently when sitting and standing. We believe that the type of control played an important role in their comparison and that in the case of action observation, the impression of walking is more similar in standing and sitting posture.

However, the standing posture could lead to a higher agency than the sitting posture. While we found no significant difference with the first version of the questionnaire, a significant difference showed up with the refined version. This first demonstrates the importance of the type of questionnaire and supports research efforts to design reliable versions. It then suggests that standing posture would be more appropriate than sitting posture during action observation of walking exercise. To confirm this outcome, it would be interesting to replicate our experiment using the full version of the refined questionnaire as well as others available questionnaires.

The experiment showed that Fowler's posture could influence the magnitude of IoL, supporting (H3). The impression of walking and sense of ownership were rated significantly lower in the Fowler's posture than in the sitting or standing posture. It seems that a large postural mismatch is required to observe a difference in IoL. Such decrease in ownership for large discrepancy is consistent with the conclusions drawn by other studies for the rubber hand illusion [2], [17], [74] and for full-body illusion [71]. In particular, Thur et al. demonstrated a decrease in ownership when the user's body was tilted in the frontal plane [71]. Our results extend this result by suggesting that ownership is also decreased when real and virtual bodies are co-located, when the body is tilted in the sagittal plane and when no tactile stimulation is involved.

We did not study the supine posture because of potential cybersickness, but we may wonder what its impact on IoL would have been. The visual and vestibular systems would have been more conflicted in the supine position than in the Fowler's posture, so we assume that ownership and IoL would have been lower in the supine position than in the Fowler's posture. However, the legs and trunk would have been aligned in the supine posture, as in the avatar posture. Thus, future research is needed to answer this question.

6.2 Influence of the type of exercise

The influence of the type of exercise on IoL was evaluated in Experiment II. A previous study showed that an IoL could be triggered during observation of a walking exercise [33] and our experiment confirmed this result. The mean scores for the impression of walking and embodiment in Experiment II were close to those in Experiment I under the same conditions, which confirms our findings. Moreover, the same results were observed for the stepping exercise which involved a large part of walking.

Our results indicated that participants had a very good impression of stepping over obstacles, partially supporting (H4). The overall impression of stepping was higher than the embodiment scores, leading us to believe that vection played an important role. This result would be consistent with research showing that vection is increased during vertical movement [29], [67] and correlates with comments provided by some participants at the end of the experiment who, after experiencing all three tasks, expressed that they "really felt like they were stepping over obstacles."

The impression of stepping over obstacles was rated significantly higher than the impression of jogging during the jogging exercise and we did not expect such results. Our hypothesis (H6) is rejected. Interestingly, the avatar's movements during the stepping exercise were not cyclic, unlike the walking and jogging movements. They were predictable because obstacles were visible on the pontoon and participants were informed that they would be stepping over obstacles at some point in the experiment. Thus, our results are consistent with Wegner et al.'s prediction of the importance of action priming [76] and suggest that other exercises could be performed as long as they are predictable. They also indicate that exercises that are predictable can, in some cases, be more effective than cyclic ones.

Participants had a good impression of jogging during the experiment, confirming (H4). But based on the variability in scores, it appears that some participants had difficulty distinguishing jogging from walking, supporting (H5). No significant difference in embodiment was found between walking and jogging so the vection may play a more important role. One explanation could be that vision is more sensitive to low temporal frequency optic flow and the vestibular system to high frequency stimulation [48]. Thus if some participants relied more on vestibular than on visual feedback, their impression of vection could have been altered during the jogging. Another explanation could be related to memory retrieval, and we speculate that individuals who are used to exercising might be more engaged in the jogging simulation. We asked participants about their daily activity and found that of the participants who had an above average impression of jogging, all performed at least two activities per week involving vection (walking, jogging, or biking). Among participants who did not feel like jogging, only 20% performed such activities. If physical activity does influence the impression of jogging, this could be a problem in some context. However, our experimental procedure does not allow us to properly test these hypotheses and further research would be needed to confirm this trend.

Interestingly, the agency does not seem to depend on the virtual exercise. Agency during action observation has only been studied for walking exercise [33] and our results show that the same level of agency can be achieved regardless of the complexity of the exercise.

While no significant difference was found in terms of ownership between the exercises, we expected that a difference would appear between walking and stepping. Indeed, Kokkinara et al. revealed an increase in participants' heart rate during hill climbing that they suspected to be related to an increase in ownership [33]. Our results did not seem to match their expectations, but the simulations were different: in our experiment, the avatar crossed an obstacle at a specific time and in their experiment, the avatar climbed continuously. So while we measured the overall ownership at the end of the task, it could have been increased only at the time of the actual stepping. To verify this, it would be interesting in the future to measure the heart rate of the participants to see if fluctuations exist during the exercise.

6.3 General considerations

Cybersickness was monitored during the experiments to ensure the reliability of other questionnaire responses. The SQPV scores highlighted that cybersickness remained quite low in all postures and exercises. During the simulations, the pace was constant and the movements were mainly longitudinal so the results tied well with previous studies showing that constant vection [5] and longitudinal movements [30], [68] limit cybersickness. Similarly, the impression of slope was controlled in Experiment I. The scores provided evidence that participants did not experience the ground as a slope and these results were important to ensure that the offset applied in the Fowler's posture was accurate enough to expose participants to the same visual conditions as in the other postures.

The experiments were designed to investigate the influence of posture and exercise separately. However, we may wonder if the posture would have a different influence on jogging and stepping exercise than on walking exercise. For example, previous work reported that the latency of onset of vection was shorter when patterns moved vertically than when they moved horizontally, but only when participants were seated, with no difference found when in supine posture [29]. Thus, Fowler's posture may affect the perception of stepping differently than sitting posture and further research is needed on this point.

6.4 Limitations and future works

In Experiment I, head movements in the Fowler's posture were constrained by the configuration and it was more difficult to turn the head in order to observe the avatar than in the other postures. We may wonder how this constraint can affect the IoL and especially the sense of ownership. It would be also interesting to explore the IoL with a mirror placed in front of the avatar [41], [56] or with eye tracking in addition to the existing head tracking in order to expand the field of view.

While we performed our analyses on healthy participants, the results could be different with patients. Some patients are tired and/or have not been physically active for a long time so we expect that they could struggle to have an IoL. It would be interesting to conduct the same study with patients in rehabilitation to confirm this assumption.

So far, sensory feedback was limited to vision in our study. Future research could explore the influence of multisensory stimulation on IoL, particularly of visuo-tactile feedback. For example, simulations replicating step contact with vibrations improved the impression of walking [69] and the impression of running [75] in static users. A study by Nordhal et al. also suggested that tactile stimulation could give the illusion of vertical movement [45]. Thus, it could be interesting to use tactile feedback to enhance the impression of walking, running, and stepping over obstacles. Studies on the rubber hand illusion and on the full body illusion have shown that tactile feedback contributes to the sense of ownership in different postures, and since our study showed that ownership was significantly reduced in Fowler's posture, adding tactile feedback could be valuable.

7 Conclusion

In this paper, we presented two user studies evaluating the Impression Of Locomotion (IoL) during observation of different exercises and for different user postures in VR. Two factors related to IoL were investigated: the impression of walking (or jogging or stepping) and the embodiment. The results first showed that action observation could well elicit IoL when the participant was sitting, standing, or in Fowler's posture. IoL and ownership were stronger in the standing and sitting postures and agency was stronger in standing posture, indicating that standing posture should be preferred if possible. The results also showed that IoL could be elicited during other exercises than walking. A strong IoL was elicited during stepping over obstacles exercise and the majority of the participants also had an IoL during jogging exercise. Some participants however struggle to elicit an IoL during this exercise. The type of exercise did not have a significant effect on the embodiment.

Overall, our results provide valuable insight for the development of iVR-based action observation therapy dedicated to gait rehabilitation. They could also benefit to numerous other VR applications involving self-avatar and locomotion sensations such as video-games, training simulations, virtual visits, etc.

References

[1] A. J. Alsmith and M. R. Longo. Where exactly am i? self-location judgements distribute between head and torso. *Consciousness and Cognition*, 24:70–74, 2014.

[2] E. L. Austen, S. Soto-Faraco, J. T. Enns, and A. Kingstone. Mislocalizations of touch to a fake hand. *Cognitive, Affective, & Behavioral Neuroscience*, 4(2):170–181, 2004.

[3] J. Barra and D. Pérennou. Le sens de verticalité est-il vestibulaire? *Neurophysiologie Clinique/Clinical Neurophysiology*, 43(3):197–204, 2013.

[4] I. Bergström, K. Kilteni, and M. Slater. First-person perspective virtual body posture influences stress: a virtual reality body ownership study. *PloS one*, 11(2):e0148060, 2016.

[5] F. Bonato, A. Bubka, S. Palmisano, D. Phillip, and G. Moreno. Vection change exacerbates simulator sickness in virtual environments. *Presence: Teleoperators and Virtual Environments*, 17(3):283–292, 2008.

[6] M. Bossard and D. R. Mestre. The relative contributions of various viewpoint oscillation frequencies to the perception of distance traveled. *Journal of vision*, 18(2):3–3, 2018.

[7] M. Botvinick and J. Cohen. Rubber hands feeltouch that eyes see. *Nature*, 391(6669):756–756, 1998.

[8] T. Brandt, J. Dichgans, and E. Koenig. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental brain research*, 16(5):476–491, 1973.

[9] D. Burin, Y. Liu, N. Yamaya, and R. Kawashima. Virtual training leads to physical, cognitive and neural benefits in healthy adults. *NeuroImage*, 222:117297, 2020.

[10] B. Calvo-Merino, D. E. Glaser, J. Grèzes, R. E. Passingham, and P. Haggard. Action observation and acquired motor skills: an fmri study with expert dancers. *Cerebral cortex*, 15(8):1243–1249, 2005.

[11] J. Carriot, P. DiZio, and V. Nougier. Vertical frames of reference and control of body orientation. *Neurophysiologie Clinique/Clinical Neurophysiology*, 38(6):423–437, 2008.

[12] V. Chambon, N. Sidarus, and P. Haggard. From action intentions to action effects: how does the sense of agency come about? *Frontiers in human neuroscience*, 8:320, 2014.

[13] J. W. Choi, B. H. Kim, S. Huh, and S. Jo. Observing actions through immersive virtual reality enhances motor imagery training. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 28(7):1614–1622, 2020.

[14] M. Costantini and P. Haggard. The rubber hand illusion: sensitivity and reference frame for body ownership. *Consciousness and cognition*, 16(2):229–240, 2007.

[15] S. Davis, K. Nesbitt, and E. Nalivaiko. A systematic review of cybersickness. In *Proceedings of the 2014 conference on interactive entertainment*, pages 1–9, 2014.

[16] K. Dijkstra, M. P. Kaschak, and R. A. Zwaan. Body posture facilitates retrieval of autobiographical memories. *Cognition*, 102(1):139–149, 2007.

[17] H. H. Ehrsson, C. Spence, and R. E. Passingham. That's my hand! activity in premotor cortex reflects feeling of ownership of a limb. *Science*, 305(5685):875–877, 2004.

[18] L. Fadiga, L. Fogassi, G. Pavesi, and G. Rizzolatti. Motor facilitation during action observation: a magnetic stimulation study. *Journal of neurophysiology*, 73(6):2608–2611, 1995.

[19] J. R. Flanagan and R. S. Johansson. Action plans used in action observation. *Nature*, 424(6950):769–771, 2003.

[20] S. Gallagher. Philosophical conceptions of the self: implications for cognitive science. *Trends in cognitive sciences*, 4(1):14–21, 2000.

[21] H. Galvan Debarba, S. Bovet, R. Salomon, O. Blanke, B. Herbelin, and R. Boulic. Characterizing first and third person viewpoints and their alternation for embodied interaction in virtual reality. *PloS one*, 12(12):e0190109, 2017.

[22] M. Gonzalez-Franco and T. C. Peck. Avatar embodiment. towards a standardized questionnaire. *Frontiers in Robotics and AI*, 5:74, 2018.

[23] G. Gorisse, O. Christmann, E. A. Amato, and S. Richir. First-and third-person perspectives in immersive virtual environments: Presence and performance analysis of embodied users. *Frontiers in Robotics and AI*, 4:33, 2017.

[24] R. Gurnsey, D. Fleet, and C. Potechin. Second-order motions contribute to vection. *Vision Research*, 38(18):2801–2816, 1998.

[25] P. S. Guterman, R. S. Allison, S. Palmisano, and J. E. Zacher. Influence of head orientation and viewpoint oscillation on linear vection. *Journal of Vestibular Research*, 22(2, 3):105–116, 2012.

[26] M. K. Holden. Virtual environments for motor rehabilitation. *Cyberpsychology & behavior*, 8(3):187–211, 2005.

[27] I. P. Howard and G. Hu. Visually induced reorientation illusions. *Perception*, 30(5):583–600, 2001.

[28] O. Kannape and O. Blanke. Agency, gait and self-consciousness. *International Journal of Psychophysiology*, 83(2):191–199, 2012.

[29] C. Kano. The perception of self-motion induced by peripheral visual information in sitting and supine postures. *Ecological Psychology*, 3(3):241–252, 1991.

[30] A. Kemeny, P. George, F. Mérienne, and F. Colombet. New vr navigation techniques to reduce cybersickness. *Electronic Imaging*, 2017(3):48–53, 2017.

[31] K. Kilteni, R. Groten, and M. Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.

[32] H. K. Kim, J. Park, Y. Choi, and M. Choe. Virtual reality sickness questionnaire (vrsq): Motion sickness measurement index in a virtual reality environment. *Applied ergonomics*, 69:66–73, 2018.

[33] E. Kokkinara, K. Kilteni, K. J. Blom, and M. Slater. First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Scientific reports*, 6(1):1–11, 2016.

[34] E. Kruijff, A. Marquardt, C. Trepkowski, R. W. Lindeman, A. Hinkenjann, J. Maiero, and B. E. Riecke. On your feet! enhancing vection in leaning-based interfaces through multisensory stimuli. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, pages 149–158, 2016.

[35] A. Lécuyer, J.-M. Burkhardt, J.-M. Henaff, and S. Donikian. Camera motions improve the sensation of walking in virtual environments. In *IEEE Virtual Reality Conference (VR 2006)*, pages 11–18. IEEE, 2006.

[36] B. Lenggenhager, C. Lopez, T. Metzinger, and J. M. Windt. Vestibular contributions to the sense of body, self, and others. *Open MIND*, 2015.

[37] B. Lenggenhager, M. Mouthon, and O. Blanke. Spatial aspects of bodily self-consciousness. *Consciousness and cognition*, 18(1):110–117, 2009.

[38] B. Lenggenhager, T. Tadi, T. Metzinger, and O. Blanke. Video ergo sum: manipulating bodily self-consciousness. *Science*, 317(5841):1096–1099, 2007.

[39] J. Marengo, P. Lopes, and R. Boulic. On the influence of the supine posture on simulation sickness in virtual reality. In *2019 IEEE Conference on Games (CoG)*, pages 1–8. IEEE, 2019.

[40] A. Maselli and M. Slater. Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. *Frontiers in human neuroscience*, 8:693, 2014.

[41] Y. Matsuda, J. Nakamura, T. Amemiya, Y. Ikei, and M. Kitazaki. Perception of walking self-body avatar enhances virtual-walking sensation. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 733–734. IEEE, 2020.

[42] M. McManus and L. R. Harris. When gravity is not where it should be: How perceived orientation affects visual self-motion processing. *Plos one*, 16(1):e0243381, 2021.

[43] O. Merhi, E. Faugloire, M. Flanagan, and T. A. Stoffregen. Motion sickness, console video games, and head-mounted displays. *Human factors*, 49(5):920–934, 2007.

[44] T. Nguyen-Vo, B. E. Riecke, W. Stuerzlinger, D.-M. Pham, and E. Kruijff. Naviboard and navichair: Limited translation combined with full rotation for efficient virtual locomotion. *IEEE transactions on visualization and computer graphics*, 27(1):165–177, 2019.

[45] R. Nordahl, N. C. Nilsson, L. Turchet, and S. Serafin. Vertical illusory self-motion through haptic stimulation of the feet. In *2012 IEEE VR Workshop on Perceptual Illusions in Virtual Environments*, pages 21–26. IEEE, 2012.

[46] C. M. Oman, I. P. Howard, T. Smith, A. C. Beall, A. Natapoff, J. E. Zacher, and H. L. Jenkin. The role of visual cues in microgravity spatial orientation. *The neurolab spacelab mission: neuroscience research in space*, pages 69–82, 2003.

[47] S. Palmisano, R. S. Allison, and F. Pekin. Accelerating self-motion displays produce more compelling vection in depth. *Perception*, 37(1):22–33, 2008.

[48] S. Palmisano, B. J. Gillam, and S. G. Blackburn. Global-perspective jitter improves vection in central vision. *Perception*, 29(1):57–67, 2000.

[49] S. Palmisano and B. E. Riecke. The search for instantaneous vection: An oscillating visual prime reduces vection onset latency. *PloS one*, 13(5):e0195886, 2018.

[50] H.-J. Park, D.-W. Oh, J.-D. Choi, J.-M. Kim, S.-Y. Kim, Y.-J. Cha, and S.-J. Jeon. Action observation training of community ambulation for improving walking ability of patients with post-stroke hemiparesis: a randomized controlled pilot trial. *Clinical rehabilitation*, 31(8):1078–1086, 2017.

[51] H.-R. Park, J.-M. Kim, M.-K. Lee, and D.-W. Oh. Clinical feasibility of action observation training for walking function of patients with post-stroke hemiparesis: a randomized controlled trial. *Clinical rehabilitation*, 28(8):794–803, 2014.

[52] A. E. Patla. Understanding the roles of vision in the control of human locomotion. *Gait & posture*, 5(1):54–69, 1997.

[53] T. C. Peck and M. Gonzalez-Franco. Avatar embodiment. a standardized questionnaire. *Frontiers in Virtual Reality*, 1:44, 2021.

[54] T.-H. Peng, J.-D. Zhu, C.-C. Chen, R.-Y. Tai, C.-Y. Lee, and Y.-W. Hsieh. Action observation therapy for improving arm function, walking ability, and daily activity performance after stroke: a systematic review and meta-analysis. *Clinical rehabilitation*, 33(8):1277–1285, 2019.

[55] V. I. Petkova, M. Khoshnevis, and H. H. Ehrsson. The perspective matters! multisensory integration in ego-centric reference frames determines full-body ownership. *Frontiers in psychology*, 2:35, 2011.

[56] C. Preston, B. J. Kuper-Smith, and H. H. Ehrsson. Owning the body in the mirror: The effect of visual perspective and mirror view on the full-body illusion. *Scientific reports*, 5(1):1–10, 2015.

[57] N. Preuss and H. H. Ehrsson. Full-body ownership illusion elicited by visuo-vestibular integration. *Journal of Experimental Psychology: Human Perception and Performance*, 45(2):209, 2019.

[58] F. H. Previc. The effects of dynamic visual stimulation on perception and motor control. *J Vestib Res*, 2(4):285–295, 1992.

[59] T. F. Price and E. Harmon-Jones. Approach motivational body postures lean toward left frontal brain activity. *Psychophysiology*, 48(5):718–722, 2011.

[60] G. Rand and S. Wapner. Postural status as a factor in memory. *Journal of Verbal Learning and Verbal Behavior*, 6(2):268–271, 1967.

[61] L. Rebenitsch and C. Owen. Review on cybersickness in applications and visual displays. *Virtual Reality*, 20(2):101–125, 2016.

[62] B. E. Riecke. Cognitive and higher-level contributions to illusory self-motion perception (" vection"): Does the possibility of actual motion affect vection?(spatio-temporal integration of multimodal sensations, symposium 2 at the 27th annual meeting). *The Japanese journal of psychonomic science*, 28(1):135–139, 2009.

[63] J. H. Riskind. Nonverbal expressions and the accessibility of life experience memories: A congruence hypothesis. *Social Cognition*, 2(1):62–86, 1983.

[64] G. Rizzolatti. The mirror neuron system and its function in humans. *Anatomy and embryology*, 210(5-6):419–421, 2005.

[65] P. Sale, M. G. Ceravolo, and M. Franceschini. Action observation therapy in the subacute phase promotes dexterity recovery in right-hemisphere stroke patients. *BioMed research international*, 2014, 2014.

[66] E. Tekgün and B. Erdeniz. Influence of vestibular signals on bodily self-consciousness: Different sensory weighting strategies based on visual dependency. *Consciousness and Cognition*, 91:103108, 2021.

[67] L. Telford and B. J. Frost. Factors affecting the onset and magnitude of linear vection. *Perception & psychophysics*, 53(6):682–692, 1993.

[68] L. Terenzi and P. Zaal. Rotational and translational velocity and acceleration thresholds for the onset of cybersickness in virtual reality. In *AIAA Scitech 2020 Forum*, page 0171, 2020.

[69] L. Terziman, M. Marchal, M. Emily, F. Multon, B. Arnaldi, and A. Lécuyer. Shake-your-head: Revisiting walking-in-place for desktop virtual reality. In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology*, pages 27–34, 2010.

[70] L. Terziman, M. Marchal, F. Multon, B. Arnaldi, and A. Lécuyer. The king-kong effects: Improving sensation of walking in vr with visual and tactile vibrations at each step. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 19–26. IEEE, 2012.

[71] C. Thür, M. Roel Lesur, C. J. Bockisch, C. Lopez, and B. Lenggenhager. The tilted self: visuo-graviceptive mismatch in the full-body illusion. *Frontiers in neurology*, 10:436, 2019.

[72] N. Tian, R. Clément, P. Lopes, and R. Boulic. On the effect of the vertical axis alignment on cybersickness and game experience in a supine posture. In *2020 IEEE Conference on Games (CoG)*, pages 359–366. IEEE, 2020.

[73] C. A. Tovee. *Adaptation to a linear vection stimulus in a virtual reality environment*. PhD thesis, Massachusetts Institute of Technology, 1999.

[74] M. Tsakiris and P. Haggard. The rubber hand illusion revisited: visuotactile integration and self-attribution. *Journal of Experimental Psychology: Human Perception and Performance*, 31(1):80, 2005.

[75] L. Turchet, P. Burelli, and S. Serafin. Haptic feedback for enhancing realism of walking simulations. *IEEE transactions on haptics*, 6(1):35–45, 2012.

[76] D. M. Wegner, B. Sparrow, and L. Winerman. Vicarious agency: experiencing control over the movements of others. *Journal of personality and social psychology*, 86(6):838, 2004.

[77] L. Young and M. Shelhamer. Microgravity enhances the relative contribution of visually-induced motion sensation. *Aviation, space, and environmental medicine*, 1990.

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