Effect of vibrations on impression of walking and embodiment with first- and third-person avatar

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

Abstract—We investigate how underfoot vibrotactile feedback can be used to increase the impression of walking and embodiment of static users represented by a first- or third-person avatar. We designed a multi-sensory setup involving avatar displayed on an HMD, and a set of vibrotactile effects displayed at every footstep. In a first study (N = 44), we compared the impression of walking in 3 vibrotactile conditions : 1) with a "constant" vibrotactile rendering reproducing simple contact information, 2) with a more sophisticated "phase-based" vibrotactile rendering the successive contacts of a walking cycle and 3) without vibrotactile feedback. The results show that overall both constant and phase-based rendering significantly improve the impression of walking in first and third-person perspective. Interestingly, the more realistic phase-based rendering seems to increase significantly the impression of walking in the third-person condition, but not in the first-person condition. In a second study (N=28), we evaluated the embodiment towards first- and third-person avatar while receiving no vibrotactile feedback or by receiving vibrotactile feedback. The results show that vibrotactile feedback improves embodiment in both perspectives of the avatar. Taken together, our results support the use of vibrotactile feedback when users observe first- and third-person avatar. They also suggest that constant and phase-based rendering could be used with first-person avatar and support the use of phase-based rendering with third-person avatar. They provide valuable insight for stimulations in any VR applications in which the impression of walking is prominent such as for virtual visits, walking rehabilitation, video games, etc.

Index Terms—Vibrotactile feedback, Impression of walking, Embodiment, Avatar, Virtual Reality, Action observation

1 Introduction

In Virtual Reality (VR) applications, users are increasingly represented by a full-body avatar, viewed either from a "first-person perspective" (1PP), i.e., the user's point of view and the avatar's point of view are co-located (e.g. [1]), or from a "third-person perspective" (3PP), i.e., the avatar is typically located in front of the user, viewed from behind (e.g. [2]). Both perspectives can be used to observe the avatar walking, depending on the purpose and constraints of the VR application.

Even though the users remained static, they can have an impression of walking (IoW) and a sense of embodiment, the feeling of being inside (self-location), controlling (agency), and having a virtual body (ownership) [3], towards a walking avatar [4], [5]. In previous work, Kokkinara and al. [4] studied the virtual walk in seated participants wearing VR headsets. Participants observed avatar walking from 1PP and 3PP, and the results showed that they had an IoW and a sense of agency for both viewpoints.

The IoW of static users can be enhanced by adding vibrotactile feedback under their feet to simulate foot/ground interactions when users are not represented by an avatar (e.g [6], [7]) or represented by a 3PP avatar on a screen [8]. Matsuda et al. [9] investigated the effect of vibrotactile feedback with avatar observed from 1PP or 3PP in immersive VR and compared synchronous and asynchronous visual/vibrotactile feedback. They found an enhancement of the IoW with synchronous feedback and showed that the presence of an avatar, whether seen from 1PP or 3PP, is important to enhance this impression. However, they did not make comparison between simulation with and without vibrotactile feedback. This paper explores the interest of adding vibrotactile feedback to immersive VR simulation in order to enhance the IoW with 1PP or 3PP avatar.

In addition, little is known about the effect of vibrotactile rendering on the IoW. When the avatar walks, users can observe the movements of their feet corresponding to different gait phases [10] (Fig. 1). A simple representation would consist in generating vibrations on the whole foot when it is in contact with the ground, without taking into account the pressure zones (constant rendering). A more complex representation, based on the knowledge of human locomotion, would generate the vibrations according to the pressure zones on the foot produced during the gait phases [11] (phase-based rendering). The latter representation has been used by the majority of studies in the past (e.g. [8], [9], [12], [13], [14], etc), assuming that it would lead to a better IoW. Yet, the interest of using phase-based rendering rather than constant rendering has not been empirically demonstrated.

When talking about an avatar, another important dimension concerns the sense of embodiment. Previous work found a positive influence of vibrotactile feedback on the sense of presence [9], [15], [16] but the effect on embodiment during a virtual walk has not been explored.

In this paper, we compare the IoW and embodiment elicited in users observing 1PP or 3PP avatar and receiving vibrotactile feedback under the feet. Two user studies were conducted with a device integrating two vibrotactile actuators under each foot. In a first experiment, the IoW was

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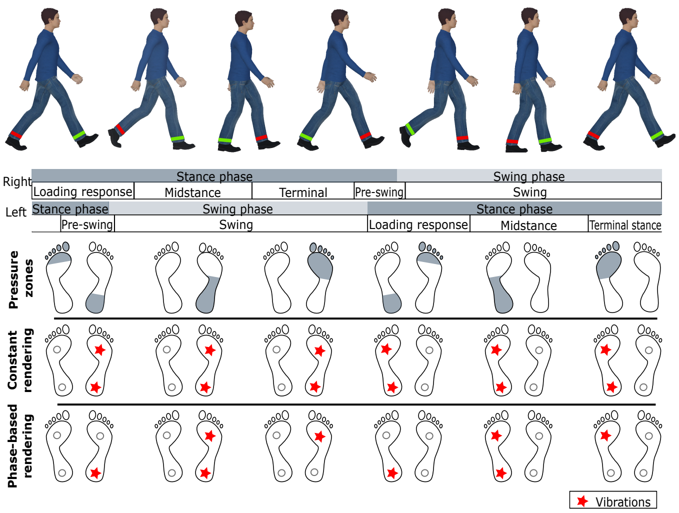

Fig. 1. The gait cycle with the different pressure zones on the feet and the two rendering techniques: constant and phase-based rendering.

explored on simulations integrating vibrotactile feedback with constant rendering, vibrotactile feedback with phase-based rendering, or no vibrotactile feedback. In a second experiment, the IoW and sense of embodiment with and without vibrotactile feedback were evaluated. The contributions of this paper are:

1) The comparison of no vibrotactile versus vibrotactile feedback for the IoW with users represented by 1PP or 3PP avatar.
2) The comparison of phase-based and constant rendering for the IoW with users represented by 1PP or 3PP avatar.
3) The comparison of no vibrotactile versus vibrotactile feedback for embodiment towards 1PP or 3PP avatar.

The remainder of this paper is organized as follows : Sec. 2 provides an overview of previous work related to vibrotactile feedback dedicated to VR locomotion. The first user study on the IoW is described in Sec.3 and the second study on the sense of embodiment is presented in Sec. 4. The paper concludes with a general discussion in Sec. 5 and a conclusion in Sec. 6.

2 Related Work

This section covers research related to underfoot vibrotactile feedback and their influences on the impression of walking and embodiment. The influence of vibrotactile feedback and rendering are examined in a first part. A second part describes research related to the role on the sense of embodiment. Finally, a third part discusses the possible effect of visual perspectives on vibrotactile integration.

2.1 Influence of vibrotactile feedback on IoW

2.1.1 Vibrotactile versus no vibrotactile feedback

Researchers have compared simulations with and without vibrotactile feedback, investigating the IoW in static VR users. Past studies showed that the combination of visiotactile feedback improved IoW compared to simulation with only visual feedback, when user are not represented by an avatar [6], [12], [17]. For example, Terziman et al. [6] used vibrating tiles under user feet to display vibrotactile cues and showed that the impression of walking is enhanced compared to simulation without vibrotactile feedback. Along the same lines, Turchet et al. showed that a device consisting of two tactors (small vibrotactile actuators) could improve the walking realism of static VR users that are not represented by avatar [8]. They also explored the interest of vibrotactile feedback with 3PP avatars represented on a screen and found similar results. Research has also explored the interest of transmitting vibrotactile feedback with immersive 1PP or 3PP avatar. Matsuda et al. [9] compared simulations with synchronized or asynchronized visual/vibrotactile feedback and found an enhacement of IoW with synchronized feedback. However, they did not make comparisons with simulation without vibrotactile feedback, which makes it difficult to interpret the need for vibrotactile feedback. Freiwald et al. [15] investigated the interest of vibrotactile feedback with active users embodied in 1PP avatar. Their results showed that, compared to simulation without vibrotactile stimuli, the IoW was enhanced with vibrotactile stimulation. This study seems to indicate that vibrotactile feedback would have a positive outcome on IoW but as users were active, they got proprioceptive feedback on the action which could have influenced their judgements. A first objective of this paper was then to compare the IoW with and without vibrotactile feedback of static users observing an avatar in VR.

2.1.2 Phase-based versus contact rendering

While we presented the studies that compared the IoW with or without vibrotactile feedback, other studies were interested in evaluating the influence of vibrotactile rendering itself, i.e. the type of vibrotactile feedback transmitted to the users. For example, Kitzaki et al. [14] and Matsuda et al. [9] demonstrated the importance of temporal congruence between vibrotactile and visual feedback. Dobricki et al. [18] showed that separate signals on each feet were needed to induce bipedal IoW. In this paper, we are interested in assessing the necessity to simulate gait phases. A gait cycle is divided into the stance phase (foot/ground contact) and the swing phase (no foot/ground contact) (Fig. 1). The stance phase is further divided into four sub-phases [10] (loading response, midstance, terminal stance and pre-swing) that are partially or completely reproduced during phase-based rendering. The simulation of loading response and terminal stance has been often used in past studies (e.g [8], [9], [14], [19], etc) but other system have been explored. For example Kruijff et al. [12] proposed system composed of 8 tactors and able to simulate all gait phases.

The interest of phase-based rendering over more simple vibrotactile rendering had been explored only in the study by Terziman et al. [6]. They compared IoW based on whether a single (heel strike) or two contacts (heel and toe strike) were simulated and showed that the single contact was preferred, suggesting that phase-based rendering is not necessary. Yet, they used vibrotactile tiles [20] to transmit the vibrotactile signals, so that the vibrations corresponding to each contact were not spatially separated. Participants may have had difficulty interpreting the simulation of two contacts in this condition. In addition, the simulation did not involve an avatar while with avatar representation, users have a visual feedback of the feet realizing gait phases and could find phase-based rendering more suitable.In this paper, we propose to compare IoW and embodiment with phase-based rendering and with simpler signal based on contact/no-contact rendering, referred to in this paper as ”constant rendering”.

2.2 Influence of vibrotactile feedback on embodiment

To our knowledge, no study have compared the sense of embodiment of static users observing an avatar walking in VR with and without vibrotactile feedback. Previous work investigated the influence of vibrotactile feedback on presence. A work by Soave et al. [16] showed that vibrotactile feedback displayed on a chair enhance the sense of presence while observing a virtual walk. Matsuda et al. [9] as well as Freiwald et al. [15] investigated vibrotactile underfoot feedback with avatar and also found a positive effect on the sense of presence. However, the sense of embodiment had not been measured. Previous work on the rubber hand illusion showed that vibrotactile feedback has a positive impact on ownership/embodiment [21]. In order to test this hypothesis during navigation, we propose to evaluate the embodiment induced in static users observing 1PP or 3PP avatar walking in VR.

2.3 Influence of visual perspective

Visual perspective is an important factor influencing user experience in VR. In an experiment where users could modulate the level of control, perspective, and appearance of their avatar, users tended to prioritize perspective and control over appearance [22]. In situations where the user remains static, perspective might then matter even more. In what follows, we discuss how visual perspectives can influence the user experience and how the integration of vibrotactile feedback can possibly differ between these perspectives.

Previous work suggests that visual perspectives could affect the IoW and the sense of embodiment [2], [4]. Kokkinara et al. [4] compared IoW and agency when viewing avatar from 1PP or 3PP. Their results suggest that IoW and agency are induced in both cases but are significantly higher in 1PP. Similar results on embodiment were found by Gorisse et al. [2] with active users walking with 3PP or 1PP avatar. We may wonder what would be the influence of adding vibrotactile feedback to the simulation with static users. Matsuda et al. [9] investigated IoW both perspectives and did not find significant difference but they they did not compare vibrotactile simulations with simulations without vibrotactile feedback. However, Medeiros et al. [23] compared 1PP versus 3PP avatar with different degrees of realism during walking simulation. Their results showed that 3PP and 1PP can induce similar level of embodiment if the avatar is coupled with realistic representation. vibrotactile feedback that correspond to a realistic representation could then have a greater effect in 3PP. This paper intends to verify these assumptions.

3 Exp. I : Influence on IoW

3.1 General overview

We conducted a first user study to compare the influence of vibrotactile feedback on the IoW when a user observes an avatar from 1PP and 3PP. We investigated 3 vibrotactile renderings : no vibrotactile rendering, constant vibrotactile rendering (simple contact/no contact informations) and phase-based rendering (representing gait phases) while the avatar performed a natural walk based on gait phases. Based on the observations highlighted in the related work section, we had several hypotheses regarding the outcome of this experiment :

- (H1) : vibrotactile feedback increase IoW with 1PP and 3PP avatars compared to simulation without vibrotactile feedback.
- (H2) : Phase-based rendering increase IoW with 1PP and 3PP avatars compared to simulation with constant vibrotactile rendering.
- (H3) : vibrotactile feedback has a greater effect on IoW with 3PP avatars than with 1PP avatars.

The procedure of the experiment I was approved by the Ethics Committee of the University Hospital of Rennes. 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 to testing. The experiment was run during pandemic crisis and experimenter and participants respected the sanitary measures in place at the time.

3.2 Experimental setup

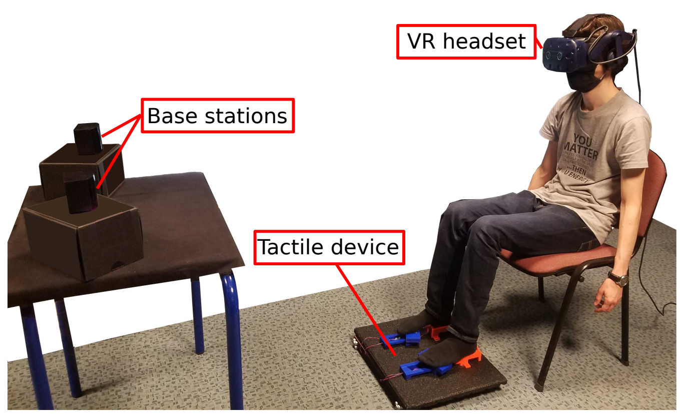

Fig. 2. Overview of the experimental setup.

Participants were seated in a chair and watched an avatar walk while receiving different vibrotactile stimuli under their feet (Fig. 2). A VR headset (HTC Vive Pro (2880 x 1600 pixels)) provided visual to the participants and was tracked so that the view was updated to match the orientation of their heads. Its 3D position was tracked by two external light houses located in front of the participant and was integrated in Unity using the *SteamVR plugin*. The system was calibrated for each participant using the *SteamVR* configuration. Participants' feet were placed on a vibrotactile device, with shoes removed. Pink noise was transmitted through headphones embedded in the VR headset to mask external noises. Step sound was not rendered.

The virtual environment was implemented in *Unity3d* (Version 2019.3.11f1) and ran at a frequency of 90 Hz. It consisted of a straight path along a beach with some coconut trees, sand castles, beach towels, etc. visible along the way (Fig. 3). The floor of the path was kept neutral so that the feeling of contact was not influenced by a specific material.

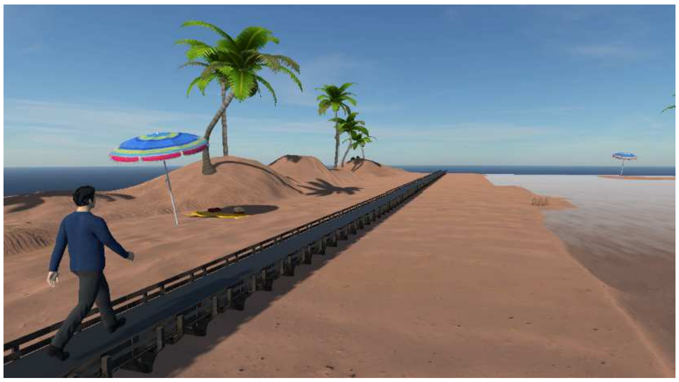

Fig. 3. The virtual scene is a path along a beach.

The avatars were life-sized and created using *MakeHuman*[1]. Two models were used to match the gender of the participants, each featuring a skeleton with 39 joints. Their movements were simulated by a walking animation from *Mixamo* [2] corresponding to a forward walk at $1m/s$ (3.6 km/h). The participant saw leg movements, pelvic movements, and arm swaying but a mask was applied to the animation at the head level which was controlled by the VR headset. The head bobbing (lateral and up and down movements) [24] and leaning forward motions were directly simulated from the walking animation of the avatar. It was damped by a factor 2 to prevent participants from being sick because of the oscillations. In order to link the movements of the head with the movements of the body in a natural way, inverse kinematic was computed with the animation tool *FinalIk*.

3.3 Vibrotactile feedback

Vibrotactile feedback was delivered by tactors. In previous studies, tactors were usually inserted into a foam sole, but such a system is difficult to adapt to each participant. We therefore created a new system inspired by the Brannock device to measure feet size (Fig. 4).

The device consisted of two coin tactors : a tactor T1 located below the heel level and a tactor T2 located at the front of the sole level. These locations correspond to the points of highest pressure during a gait cycle [25]. Sliders and stop edges facilitate the positioning of the tactors under the foot on the platform. The tactors were fixed in foam pads to limit vibration propagation and the different parts of the device were separated by an anti-vibration surface. "The foam pad were small (2cm square) and thin (3mm) so as not to deform under the feet of the participants.

1. www.makehumancommunity.org/
2. www.mixamo.com/

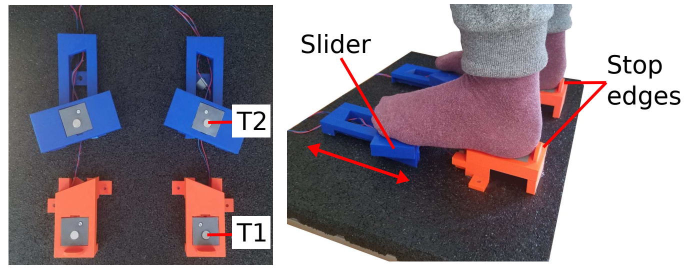

Fig. 4. vibrotactile device adjustable for different foot sizes and including 2 tactors under each foot.

The tactors had a diameter of 12 mm and were activated by an *Arduino Uno* board that delivered a constant signal generating 1 G vibrations at 70 Hz. This frequency corresponds to a rigid ground made of wood [26]. The *Arduino* card was coupled with *Unity* via serial communication at 38400 baud. Different vibrotactile signals were sent depending on the vibrotactile rendering evaluated. The gait phases corresponding to the walking of the avatar were spotted on the timeline of the animation and were used to trigger the vibrotactile signals when necessary.

3.4 Protocol

3.4.1 Method

At the beginning of the experiment, participants were instructed to try to imagine that they were the avatar and that they were actually walking. They were then informed that they would have to compare vibrotactile stimuli. As in the study of Turchet et al. [27], a two-alternative forced-choice method was employed to compare the vibrotactile stimulations in the experiment I. As comparison of vibrotactile feedback can be hard to achieve, the two-alternative forced-choice method allows to present multiple times the same comparisons to the participants and to increase the reliability of the answers.

Participants watched the avatar walk while receiving an initial vibrotactile simulation. Then the avatar would stop for 3 seconds and walk again with another vibrotactile feedback (see Sec. 3.4.3 for the walk duration). At the end of the second walk, the avatar stopped and the participants had to choose with which vibrotactile feedback they "had a better impression of walking". They answered orally with "1" or "2" depending on which part of the simulation they chose. Responses were recorded by the experimenter.

3.4.2 Vibrotactile levels

A total of 3 vibrotactile levels were compared :

- Constant vibrotactile rendering, representing simple contact/no contact informations. The 2 tactors (T1 and T2) were activated during loading response, midstance and terminal stance and deactivated during pre-swing and swing phase (Fig. 5 Top). The pre-swing was not simulated to match the activation time of phase-based rendering.
- Phase-based vibrotactile rendering, representing gait phases. The tactor T1 was activated during loading response and midstance while T2 was activated during midstance and terminal stance (Fig. 5 Bottom).

The pattern reproduced the contact during a real walk, as the ones studied by Gonzalez et al. [11]. In their study, there is no sensor at the front of the sole so the activation of T2 was defined depending on the high average of two adjacent sensors.

- Without vibrotactile rendering.

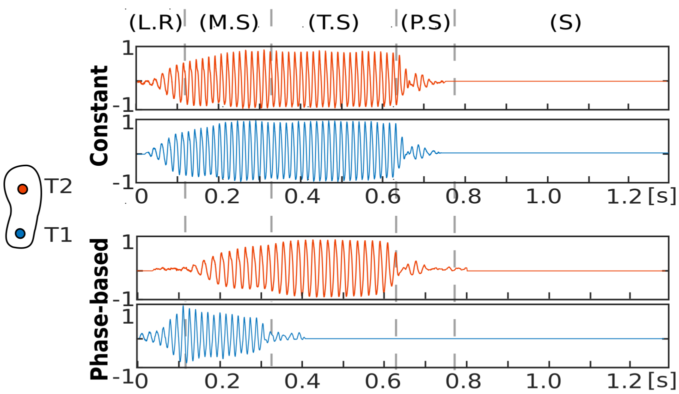

Fig. 5. Waveform of tactors signals captured with a sound recorder during constant and phase-based rendering.

3.4.3 *Avatar perspectives*

Participants observed the avatar either from 1PP or 3PP (Fig. 6). In 1PP, their head was co-located with the head of the avatar. In 3PP, they were at the same level as for 1PP but located 2 meters behind the avatar and could see its whole body when they looked ahead.

Fig. 6. From left to right : Male avatar observed from 1PP. Male and female avatar observed from 3PP.

The procedure was different depending on whether the avatar was observed from 1PP or 3PP. In the 1PP condition, the participant had to look at the avatar's feet for 10 seconds (to be aware of the avatar's movements) and then ahead for 10 seconds (as they are likely to do it during actual simulation), for each vibrotactile stimulus. If participants looked in the wrong direction, the avatar stopped until they looked in the correct direction. In the 3PP condition, participants had to observe ahead for 20 seconds.

3.4.4 *Distribution*

The experiment had a mixed factorial design, with vibrotactile rendering as within-subject variable and perspective as between-subject variable. Perspective was chosen as a between-variable since participants would have been exposed to too many conditions (6 conditions : 3 vibrotactile levels x 2 perspectives) if they had tested both perspectives. It would also have been more complicated to explain the procedure to the participants with perspective as within-variable since procedure was a little bit different between 1PP avatar and 3PP avatar. A participant then met all the vibrotactile conditions but tested only one perspective condition. During the experiment, 24 comparisons were made by participants: no vibrotactile/constant rendering was presented 6 times, no vibrotactile/phase-based rendering 6 times and constant/phase-based rendering 12 times. The vibrotactile vs. no vibrotactile comparison was presented less often than the vibrotactile vs. vibrotactile comparison, because we thought the comparison was more obvious. The order of comparisons was random but the order of stimuli was evenly distributed, so for example constant rendering / no vibrotactile rendering was presented the same amount of time than no vibrotactile rendering / constant rendering. An example of sequence tested by one participant was [N/C, N/C, P/C, N/C, P/C, P/N, C/P, N/P, C/N, C/N, C/P, C/P, P/C, N/P, C/N, P/N, P/C, N/P, P/C, C/P, C/P, P/N, C/P, P/C] with "N" corresponding to no vibrotactile, "P" to phase-based and "C" to constant feedback. The overall experiment took around 20 minutes by participant.

3.5 Participants

A total of 44 participants took part in the experiment I. They had no knowledge of the purpose of the experiment. They were recruited among the medical staff of the University Hospital of Rennes. None of them reported any physical or cognitive issues that could have been detrimental to the experiment. Moreover, none of them reported having uncontrolled epilepsy. A number of 22 participants observed the avatar from 1PP (11 men; mean age: 30.1 years; standard deviation: 7.7 years). The others 22 participants observed the avatar from 3PP (11 men; mean age: 28.8 years; standard deviation: 7.1 years; minimum: 21 years; maximum: 50 years). There were no significant differences in age or gender between the participant groups.

3.6 Experimental results

The results of the experiment I are visible in Fig. 7.

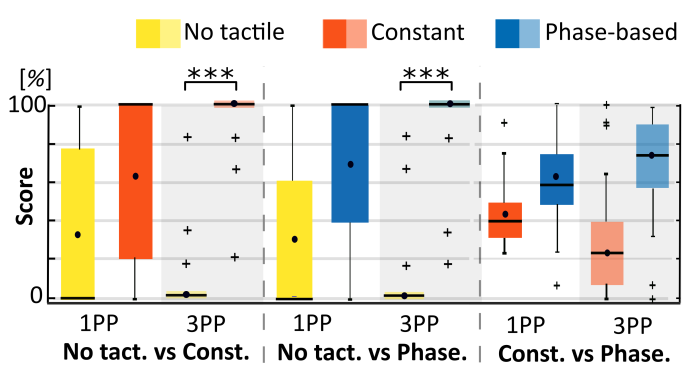

Fig. 7. Percentage of chosen answers for the IoW. The boxplots represent the medians and dispersions while the dots indicate the means.

Since the normality assumption was not met for some the data, we used linear mixed-effects models with random effects over the individuals to test for the effect of vibrotactile feedback and perspectives. We fitted the full model :

vibrotactile and perspective as main effects with interaction. We checked that the residuals of the models were approximately normally distributed. Post-hoc tests were performed using estimated marginal means method. In the following, the letter "e" indicate the estimate and "rand" the standard deviation of random effect.

Vibrotactile feedback had an effect on the model during constant versus no feedback comparison. The Iow with constant vibrotactile feedback was rated higher than without vibrotactile feedback ($p < 0.001, e = 83.3, rand = 0$) in 3PP and in 1PP ($p = 0.006, e = 33.2, rand = 13.6$). Perspective had a significant effect on the IoW. It was rated higher in 3PP than in 1PP during constant versus no vibrotactile comparison ($p = 0.01, e = 24.9$).

Vibrotactile feedback had an effect on the model during phase-based versus no feedback comparison. Phase-based feedback was rated higher than no feedback in 3PP ($p < 0.001, e = 84.9, rand = 0$) and in 1PP ($p = 0.002, e = 38.1, rand = 7.9$). Perspective had a significant effect on the IoW rated higher in 3PP than in 1PP ($p = 0.01, e = 24.9$).

Perspective also had no significant effect on IoW for constant versus phase-based rendering. IoW with phase-based vibrotactile feedback was higher than with constant vibrotactile feedback in 3PP ($p < 0.001, e = 34.0, rand = 4.5$). No significant effect was found in 1PP between constant and phase-based feedback.

4 Exp. II : Influence on embodiment

We conducted a second user study to get more information on the influence of vibrotactile feedback on impression of walking and to explore the impact on embodiment.

4.1 Method

The task, setup and protocol were similar to Experiment I. In order to get more information on the IoW and to evaluate the embodiment, we chose to expose participants to a single simulation per condition, followed by a questionnaire at the end of each condition. During a simulation, the avatar walked for 4 minutes and we investigated 2 vibrotactile renderings : no vibrotactile rendering and phase-based. Participants evaluated their embodiment answering to the questionnaire of Peck et al. (version of 2021, 16 questions) [28] and their IoW answering to "During the simulation, I felt that I was walking" based on [4]. They answered on 7-point Likert-scales ranging from "strongly disagree (1)" to "strongly agree (7)". Participants also answered questions to evaluate cyber-sickness based on the VRSQ questionnaire (9 questions) [29]. They answered on a 4-point scale ranging from "not at all (0)" to "severe (3)". Scores were converted using the method proposed by Kim and al. to obtained a cyber-sickness score from 0 to 100.

Based on the observations highlighted in the related work section, we had several hypotheses regarding the outcome of this experiment :

- (H4) : vibrotactile feedback increases the IoW with 1PP and 3PP avatars compared to simulation without vibrotactile feedback.
- (H5) : vibrotactile feedback increases embodiment with 1PP and 3PP avatars compared to simulation without vibrotactile feedback.
- (H6) : vibrotactile feedback has a greater effect on embodiment with 3PP avatars than with 1PP avatars.

The procedure was approved by the ethical committee of Inria Rennes and took 20 minutes per participant.

4.2 Participants

A total of 28 participants took part in the experiment II. They were different from participants of experiment I and were students from our research center. They were split in two groups where one group experienced the walking experiment in 1PP (N=14; 10 men; mean age: 24.7 years; std : 3.8 years) and the other group in 3PP (N=14; 9 men; mean age: 24.2 years; std: 3.9 years). The conditions with and without vibrotactile feedback were counterbalanced.

4.3 Experimental results

The results of experiment II are visible in Fig. 8. The same procedure than in Experiment I was used to analyze the data.

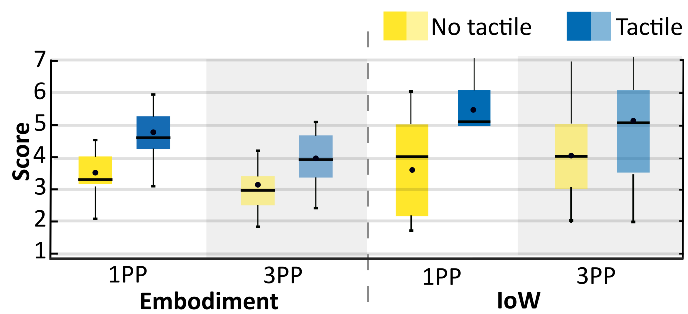

Fig. 8. Participant's responses assessing their embodiment and impression of walking. See Fig. 7 for details on the display.

Results showed that the embodiment with vibrotactile feedback was higher than without vibrotactile feedback in 1PP ($p < 0.001, e = 1.2, rand = 0.54$) and in 3PP ($p = 0.003, e = 0.81, rand = 0.59$). No significant effect of the perspective on the embodiment was found.

Results showed that IoW with vibrotactile feedback was higher than without vibrotactile feedback in 1PP ($p = 0.001, e = 1.7, rand = 0.6$). An effect of vibrotactile feedback was found in 3PP ($p = 0.049, e = 0.92, rand = 1.2$) but was not significant after applying Bonferroni correction. No significant effect of the perspective on IoW was found.

Vibrotactile feedback and perspective had no significant effect on cybersickness.

5 General Discussion

5.1 Influence of vibrotactile feedback on IoW

The influence of vibrotactile feedback on the impression of walking was investigated in Experiment I and II. The results of the Experiment I showed that the impression of walking was improved by adding vibrotactile feedback with a 1PP or 3PP avatar, supporting (H1) and (H4). The IoW measured in Experiment II seems to support these findings, even if their analyzes lack of statistical power to confirm them in 3PP. Our results in 3PP are consistent with the results reported by Turchet et al. [8] obtained with a display screen. Our study extend them to simulation involving immersive scenario with life-size avatars. For the 1PP avatar, a study by Matsuda et al. [9] focusing on temporality showed that IoW was enhanced by synchronous visuo-vibrotactile feedback compared to asynchronous feedback. Our studies show that the presence of vibrotactile feedback itself is important. Previous research has also shown that IoW was enhanced by vibrotactile feedback with a 1PP avatar embodied by active users [15]. We show that even without proprioceptive feedback, IoW is enhanced by vibrotactile feedback.

The results of Experiment I also indicate that vibrotactile rendering, whether constant or phase-based, increases the impression of walking in 1PP and 3PP. Phase-based rendering was significantly more efficient than constant rendering with the 3PP avatar, which partially confirms (H2). This type of rendering should therefore be preferred in VR simulations involving 3PP avatars. We found no significant difference between phase-based and constant rendering when the avatar was observed from 1PP. This result is consistent with Terziman et al. [6] who compared a simple and a more complex rendering technique and found no significant difference between the two. Their study was conducted without an avatar and our results suggest that even though users can observe the movements of a 1PP avatar, no significant difference emerged. Users seem to overlook inconsistencies between the avatar's movements (related to phase-based movements) and the constant vibrotactile rendering. Foot movements were perhaps easier to interpret from behind (in 3PP) than from above (in 1PP). Therefore, both types of rendering could be implemented with a 1PP avatar to improve the IoW.

In the experiment I, a number of participants preferred not to have vibrotactile rendering with the 1PP avatar. In the past, similar results have been found by Turchet et al. [8] and the authors argued that this could be due to the quality of the surface simulation. Interestingly, the phenomenon did not appear in our experiment for the 3PP avatar, so signal quality does not seem to be an issue. It also did not appear in Experiment II, but the test population was very different, with more VR users. One explanation could be that participants in Experiment I felt overwhelmed in 1PP. Some participants, at the end of the experiment, shared their feelings and mentioned that the vibrations were "too much to handle" for them. In 3PP, the avatar's movements were visible and potentially easier to interpret or the task was easier because participants did not have to look towards their legs. Another explanation could be that some participants experienced cyber-sickness effects with the 1PP avatar. We limited such an effect so as not to bias the results by reducing the walking speed, keeping the direction constant, and dampening the head swing. The same animation and settings were also used in [5] with participants novice in VR and they did not experience cyber-sickness so it seems unlikely that it was caused in the simulation but this should be investigated in a future study. As it stands, our results suggest that future applications should consider the possibility of not simulating vibrotactile feedback for 1PP avatar so as not to affect the IoW of some participants.

5.2 Influence of vibrotactile feedback on embodiment

The influence of vibrotactile feedback on embodiment was investigated in the Experiment II. The results show that vibrotactile feedback contributes to increasing the embodiment towards the 1PP and 3PP avatars during the virtual walk, supporting (H5). This is particularly important to ensure that users connect with their virtual avatar and are not solely influenced by vection - the movement of the surrounding environment - for their walking impression. Here, the results indicate that vibrotactile feedback simulating stepping is a way to increase the connection between the user and the avatar.

Previous work has evaluated embodiment toward 1PP and 3PP avatars [4], [5] when observing a virtual walk. Our results appear to be lower, especially for 1PP. The test population was different as well as the questionnaire used to assess embodiment. Other parameters of the simulation could have contributed to this effect. For example, we showed pink noise to the participants in order to isolate them from the outside world, especially from the tactors, whereas in the case of [5] the noise of footsteps was simulated. The results of Kokkinara et al. [4] also suggested that head bobbing could be detrimental to some components of embodiment while it was simulated in our experiments.

5.3 Influence of perspectives

Perspectives appear to influence the interpretation of vibrotactile rendering in Experiment I, supporting (H3). The IoW was rated higher with vibrotactile feedback in 3PP than in 1PP. Participants could rely more on vibrotactile rendering to increase the presence and/or the connection with the avatar. It would be interesting to conduct further research on this point.

In Experiment II, embodiment with vibrotactile feedback was not significantly higher in 1PP than in 3PP. This result does not seem to support (H6), that vibrotactile feedback could compensate for the lack of embodiment in 3PP in order to approximate embodiment in 1PP. This hypothesis was made because Medeiros et al. [23] compared a 1PP and 3PP avatar with different degrees of realism during a walking simulation and showed that 3PP and 1PP can induce a similar level of embodiment if the avatar is associated with a realistic representation. From our results, vibrotactile feedback does not seem to induce a similar effect. However, embodiment is not significantly higher in 1PP than in 3PP when it should be [4], maybe because perspective was a between subject factor in our study, while within factor could more appropriate to measure embodiment [30]. The comparison between embodiment in 1PP and 3PP should then be further explored in a dedicated study.

6 Conclusion

We investigated the influence of vibrotactile rendering without a foot on the impression of walking and embodiment elicited in static VR users represented by a 3PP or 1PP avatar. To this end, two user studies were conducted to evaluate the influence of vibrotactile rendering on the impression of walking and vibrotactile feedback on embodiment.

Overall, the results of these studies show that vibrotactile feedback increases the impression of walking and embodiment for 1PP and 3PP avatars in immersive VR. Phase-based feedback improved the impression of walking compared to constant feedback when the user observed a 3PP avatar, so it should be preferred in this case. No significant difference was found in first-person, indicating that simple constant vibrotactile rendering could be used.

In the future, it could be interesting to further investigate the use of vibrotactile feedback along with auditory feedback, such as footsteps, since they are beneficial to the IoW [8] or to study the influence of vibrotactile rendering on other aspects, such as participants' ability to assess self-motion velocities or distances traveled [12].

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