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Walk on Hands: Can Vibrations in the Hands Support Walking Experience in Virtual Reality?

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***Abstract*—Previous works have shown that vibrations under the feet can significantly enhance the walking experience in Virtual Reality (VR). However, such approaches often require specialized hardware. Therefore, in this paper, we study if vibrations in the hands could represent a simple and cost-effective alternative to improve the walking experience in VR. We conducted a user study comparing vibrations displayed in the hands, vibrations under the feet, and no vibration in a VR passive walking simulation during which participants were seated and embodied a first-person avatar. We compared the different conditions regarding: the sensation of walking, avatar embodiment, cybersickness, and comfort. Interestingly, our results show that vibrations in the hands significantly increase the sensation of walking and embodiment compared to no vibration. Moreover, no significant difference is observed between vibrations under the feet and in the hands concerning the sensation of walking. Still, embodiment is higher with vibrations under the feet. No significant differences in cybersickness or comfort were observed between vibrations displays. Overall, our results promote using vibrations in the hands as a cost-effective and suitable alternative to vibrations under the feet in VR applications for which the walking sensation is prominent, leveraging for instance vibrations embedded in VR controllers.**

***Index Terms*—Haptic interfaces, Vibrations, Walking sensation, Embodiment, Virtual reality**

I. Introduction

Many Virtual Reality (VR) applications involve virtual walking, such as virtual tourism, rehabilitation, and gaming. However, natural walking in VR is often impractical due to physical space constraints and user fatigue [1]. To address this, alternative locomotion techniques allow users to control movement while seated, such as arm swinging [2], head bobbing [3], or button inputs [4]. Even passively observing a virtual walk can induce a sensation of walking through action observation [5]. However, these methods are far from rendering compelling walking sensations by their own.

Different haptic feedback under the feet have been tested to enhance virtual walking, including modulation of friction [6]–[8], vertical actuation [9]–[11], inflatable soles [12], [13], force feedback [14] and airflow [15], [16]. Vibrations represent a cheap and easy to implement alternative to these feedback and have proved to enhance the sensation of walking [17]–[22] so, for the remainder, we will focus on them.

Users can also embody a first-person avatar [23]. Observing this virtual body in motion can enhance both embodiment and the sensation of walking [21]. If observing a virtual walk in a seated position may reduce embodiment [24], vibrations have been shown to improve it [25]. It has also been found that they can mitigate cybersickness, a common issue in VR caused by mismatched visual and vestibular cues [26].

Fig. 1. This paper investigates the use of vibrations in the hands to augment walking experience in VR. When a virtual foot touches the ground, vibrations are displayed in the corresponding hand (left or right).

As it naturally aligns with the biomechanics of walking, most prior works have focused on delivering vibrations under the feet [17]–[22], [25]. However, foot-based solutions require specialized wearable interfaces [19] or platforms [17], [21], [25], limiting their accessibility. Previous works also spotted that some users are disturbed by vibrotactile feedback under the feet [19], [25]. Some users, in particular in rehabilitation, may also suffer from reduced tactile sensitivity on the feet (e.g, [27], [28]). Other approaches use vibrations to simulate muscle activation [29] or integrate them into VR headsets [26], but these solutions can be intrusive.

In this study, we propose an alternative solution to enhance the walking experience in VR for seated users who observe a passive walk: display vibrations in the hands when the virtual feet touch the ground (see Fig. 1). Since commercial VR controllers already provide vibrotactile feedback, this approach would require no additional hardware. Delivering haptic feed-

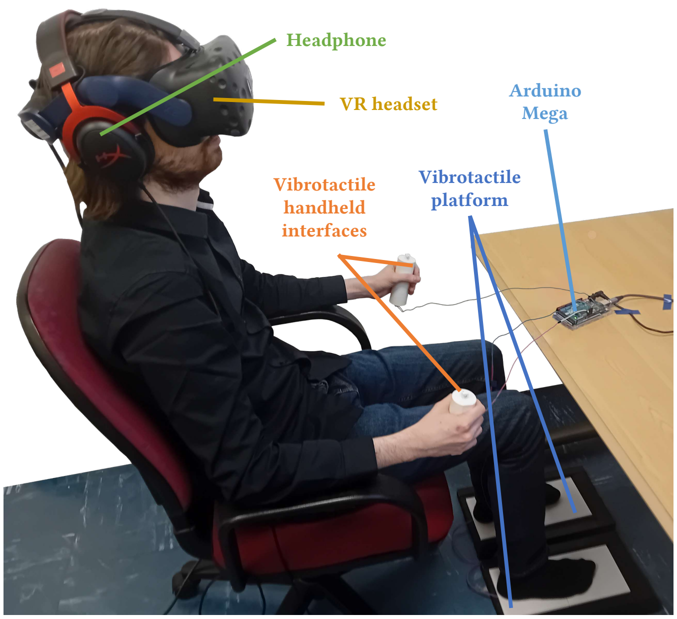

Fig. 2. Overview of the experimental set-up. A user is sitting on a chair with handheld vibrotactile interfaces in his hands and feet on vibrotactile platforms. He wears a VR headset and headphones to receive visual and audio stimuli from the simulation. An Arduino Mega commands the vibrations.

back to a different body part than the one performing the action is known as remapping. During manipulation task, it has been shown effective to deliver perception information at a different location than the contact point [30]. Tactile stimulation on the head has been linked to embodiment of hand movements [31], [32]. In the following, we conducted a user study to evaluate if vibrations displayed in the hands can enhance the walking experience of seated users by improving walking sensation, embodiment, and reducing cybersickness. We also compare this method to state-of-the-art foot-based vibrations to assess its effectiveness. The results indicate that:

- Vibrations in the hands augment the sensation of walking and the embodiment (response sub-component) compared to no haptic feedback.
- The impression of walking was not found significantly different between vibrations in the hands and under the feet but the latter augment the embodiment (multisensory sub-component).
- Comfort and cybersickness were not found significantly different between the conditions with vibrations.

II. User study

A. Objective and hypotheses

This user study aims to evaluate if vibrations in the hands can enhance the sensation of walking, the embodiment, the comfort during walking simulations in VR and how they affect cybersickness. We propose to compare vibrations displayed in the hands synchronously with a virtual walk to no haptic feedback. We formulate the following hypotheses:

- **[HW1]**: the sensation of walking is higher with vibrations in the hands than without vibration.

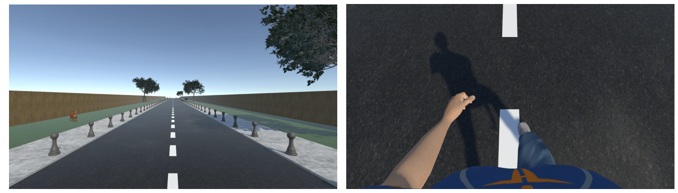

Fig. 3. Participants walk on a road in Virtual Reality (Left) and embody a first-person walking avatar (Right).

- **[HE1]**: the embodiment is higher with vibrations in the hands than without vibration.

It also aims to compare vibrations in the hands with vibrations under the feet. Because of the remapping of the feedback in the hands, we formulate the following hypotheses:

- **[HW2]**: the sensation of walking is higher with vibrations under the feet than with vibrations in the hands.
- **[HE2]**: the embodiment is higher with vibrations under the feet than with vibrations in the hands.

We also wonder if the remapping of the haptic feedback from the feet to the hands could improve users comfort:

- **[HC]**: the comfort is higher with vibrations in the hands than with vibrations under the feet.

Finally, vibrations can sometimes mitigate cybersickness and we hypothesized the same outcome when displayed in the hands:

- **[HS]**: the cybersickness is lower with vibrations in the hands than without vibration.

B. Simulation

During the experiment, the participants are seated, and wear headphones and a Vive Pro 2 headset, tracked by a SteamVR 2.0 base in front of them (see Fig. 2). The participants can move the head and the view in the virtual environment is mapped to the same orientation. They observe a $4min$ long walking simulation in the middle of a road (see Fig. 3), designed using Unity 2022.3.10f1, while embodying a first-person avatar. On the sides of the road, some trees, bushes, cats and ducks appear occasionally, breaking the monotony of the environment pattern. The participants embody avatars generated using MakeHuman and walking at $1m/s$, using a walking animation from Mixamo. They experiment head bobbing, computed from that of the animation, but attenuated by 50% to reduce the potential cybersickness they could feel. Ambient sounds (wind, bird) and footstep sounds are displayed to the participants. The overall simulation works at $110fps$.

C. Haptic feedback

This section describes the haptic interfaces delivering vibrations to the participants' hands and feet during the experiment.

1) Haptic interfaces: Handheld interfaces are designed to display vibrations in the participants' hands (see Fig. 4). Commercial VR controllers embedded vibrators but cannot be used in the experiment because it would be complex to display vibrations under the feet with it, so to compare the two

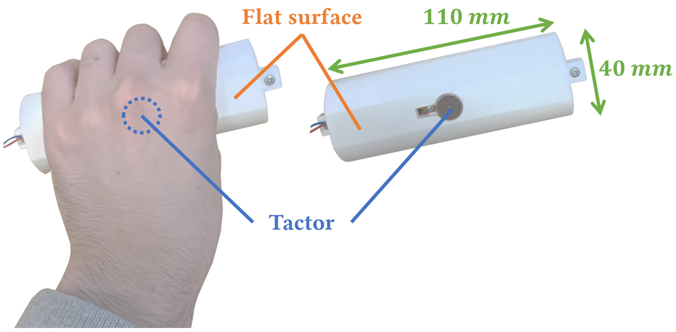

Fig. 4. The haptic handle (Right) displays vibrations in a participant's hand (here the left hand) (Left). During the experiment, participants hold an handle in each hand.

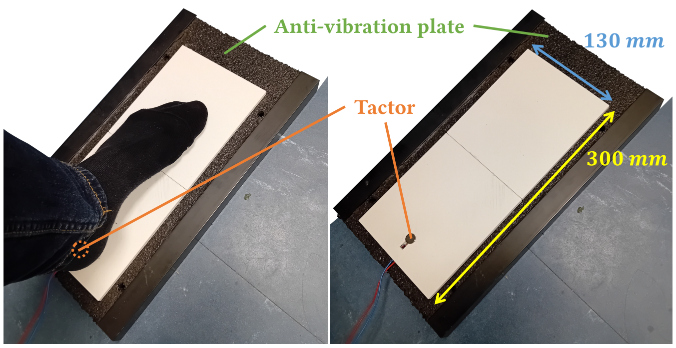

Fig. 5. The haptic platform (Right) displays vibrations on a participant's foot (Left). During the experiment, participants rest both feet on different platforms.

interfaces. Handles take the form of $110mm$ long cylinders of diameter $40mm$ with $16mm$ width flat surfaces over their entire length. They have a hollow structure, with a wall thickness of $6mm$. All the pieces are 3D printed in PLA, with a grid inside pattern that fills them at 15%. The vibrations are displayed using tactors *VPM2* of diameter $12mm$, thickness $3mm$, powered at $3V$ by an Arduino Mega, and generating 1G vibrations at $70Hz$. This frequency is chosen for being within the sensing limitations of human hands [33]. For each handle, a tactor is included at the center of the flat surface to ease contact with the skin, around the top of the third metacarpal.

The foot interfaces (see Fig. 5) are designed to closely resemble the handheld ones to minimize bias from vibration propagation. Each interface consists of two plates measuring $300mm$ by $130mm$ and is 6 mm thick. Each plate includes a tactor, similar to those used in the handheld interfaces. The tactors are positioned 30 mm from the back edge of the plates, allowing participants to place them under their heels, which is where the feet make initial contact with the ground while walking. Additionally, the plates are placed on anti-vibration tiles to limit the transmission of vibrations to the ground.

2) Integration in the VR environment: The haptic feedback was integrated into the simulation using serial communication with the Arduino Mega, operating at $9600baud$. Constant feedback patterns have proved to elicit a similar sensation of

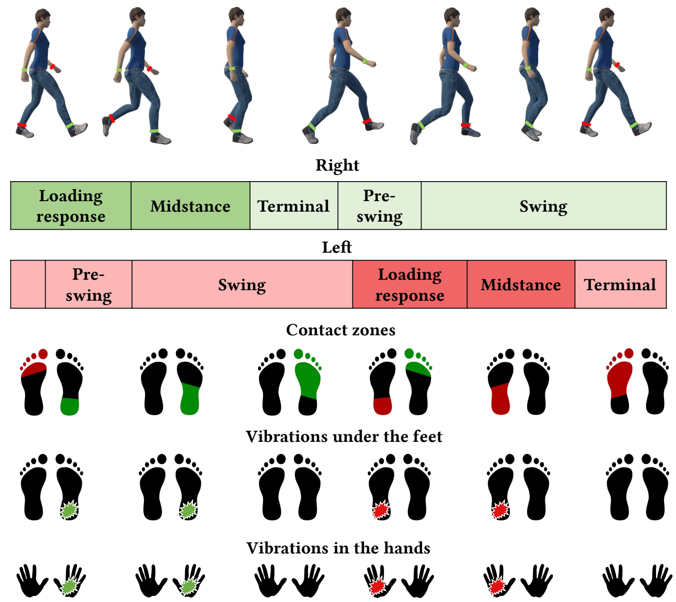

Fig. 6. Activation of the vibrations under the feet and in the hands according to the virtual walking gait. Vibrations are triggered when the virtual heels (left and right) touch the ground. This coincides with the loading response and midstance phases of the walk.

walking than phase-based pattern [25] so we use this pattern for vibrations under the feet, but restrict it to the contact of the heel with the ground (loading response and midstance phases on Fig. 6) to keep the foot feedback coherent with the position of the tactors. The same pattern was chosen for the hands. Interestingly, this feedback also coincides with the movement of the arm from the back to the front of the avatar (see Fig. 6).

D. Participants and procedure

A total of 24 participants took part in the experiment (7 females, 16 males, 1 other; 6 aged 18-24, 18 aged 25-34; 5 reported being left-handed, 19 right-handed; 15 using VR weekly or daily, 6 using haptic interfaces weekly or daily).

The study protocol conforms to the Declaration of Helsinki and the Nuremberg Code. The participants are first informed that they will experiment three virtual walks with different haptic conditions. The order of the conditions is counterbalanced between participants using a Latin square method. The participants are instructed to sit on a chair and to keep their heel over the feet tactors, their knee forming a right angle, the handheld interfaces in their hands, with the tactor on the top area of the third metacarpal and the arm relying on the arm rest of the chair, in all the conditions (see Fig. 2). They keep their socks during the experiment and were instructed to imagine performing the movement they experiment in VR.

After each condition, they answered to the questions "During the experiment, I felt that I was walking.", based on [5], "During the experiment, the haptic feedback felt comfortable." and to Peck and Gonzalez-Franco's embodiment questionnaire [34] using 1-7 Likert scales. In addition, at the beginning of the experiment and after each condition, they are instructed

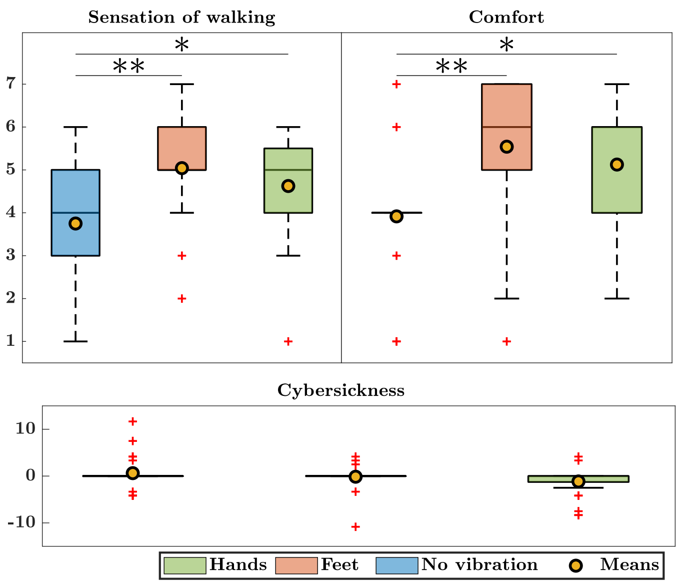

Fig. 7. Results for the sensation of walking, comfort and cybersickness in each condition ($*$ stands for $p < 0.05$ and $**$ for $p < 0.01$)

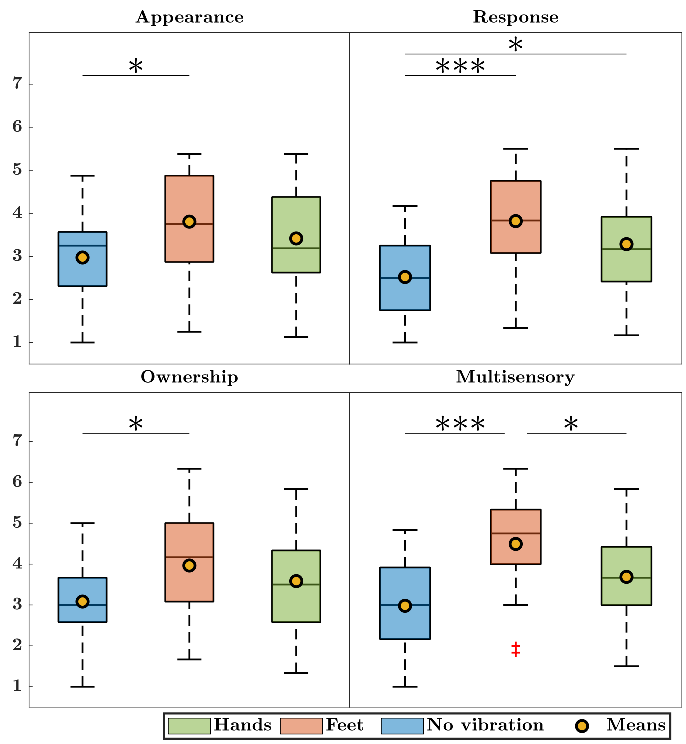

Fig. 8. Results for embodiment (appearance, response, ownership and multisensory) in each condition ($*$ stands for $p < 0.05$ and $***$ for $p < 0.001$)

to fill a VRSQ questionnaire [35] to evaluate the cybersickness (on a 0-100 scale). Additional comments from the participants are also recorded. After all the conditions, the participants are asked to rank each condition according to the sensation of walking, their comfort, and their overall preference.

III. Results

The results for the sensation of walking, comfort and cybersickness are presented in Fig. 7 and for the embodiment in Fig. 8 for each condition (no vibration, vibrations in the hands and vibrations under the feet). The embodiment is displayed for each sub-component (appearance, response, ownership, and multisensory) detailed in [34] to gather more information. Cybersickness is computed from the differences between the VRSQ results before and after each condition. Fig. 9 shows the rankings for the sensation of walking, comfort and preference. In the following, these results are analyzed. The independent variables are the 3-level within-subjects factor condition and the 3-level between-subjects factor group.

A. Scores for walking sensation, comfort and cybersickness

The normality assumption is tested for each component using the Shapiro-Wilk test and is not met for the sensation of walking, comfort, and cybersickness. An Aligned Rank Transform (ART) model was used before performing a two-way ANOVA test for the condition, group, and the interaction of group and condition. Post-hoc tests were performed using the Estimated Marginal Means method with Bonferroni correction. The analyzes for group, and the interaction of group and condition, are not significant for all variables, so only the results for condition are detailed below. Additionally, only the significant results are detailed for readability.

The analysis reveals a significant effect of the condition on the sensation of walking ($F_{2,63} = 5.62$, $p = 0.006$, $\eta_p^2 = 0.151$). Vibrations under the feet ($M = 5.04$, $SD = 1.04$) and in the hands ($M = 4.63$, $SD = 1.28$) elicit a significantly higher sensation of walking than the simulation without vibration ($M = 3.75$, $SD = 1.51$, $p = 0.007$ and $p = 0.041$ respectively). Similarly, a significant effect is also found for comfort ($F_{2,63} = 10.8$, $p < 0.001$, $\eta_p^2 = 0.255$). Vibrations under the feet ($M = 5.54$, $SD = 1.56$) and in the hands ($M = 5.13$, $SD = 1.57$) are rated significantly more comfortable than no vibration ($M = 3.92$, $SD = 1.18$, $p < 0.001$ and $p = 0.012$ respectively).

The difference of cybersickness between the beginning and the end of the experiment remained very low ($Max = 15$) and no significant difference is found between conditions.

B. Scores for embodiment

The normality assumption is met for all the sub-components of the embodiment, so an analysis is performed on these data using a two-way ANOVA test for condition, group, and their interaction. If a significant effect is found, a post-hoc analysis via the Tukey HSD procedure is performed to check the significance of the pairwise comparisons. The results are displayed on Fig. 8. The analyzes for the group and the interaction of the group and condition are not significant for all variables, so only the results for the condition are detailed below. Additionally, only the significant results are detailed.

The analysis reveals a significant effect of the condition on all the components of embodiment. Appearance ($F_{2,69} = 3.64$, $p = 0.031$, $R^2 = 0.095$) is significantly higher with vibrations

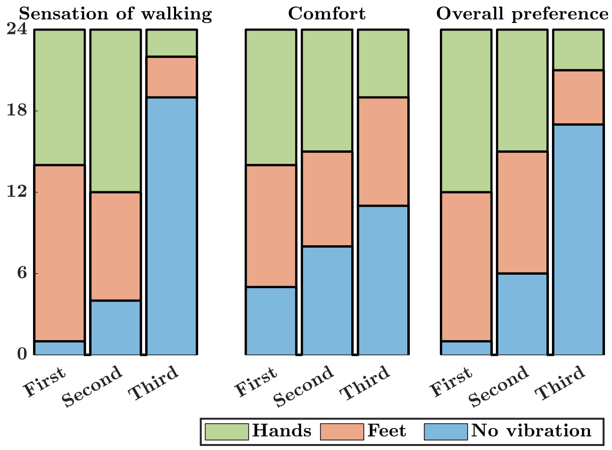

Fig. 9. Ranking of the conditions for the sensation of walking, comfort and preference.

under the feet ($M = 3.81$, $SD = 1.15$) than without vibration ($M = 2.97$, $SD = 0.97$, $p = 0.024$). Response ($F_{2,69} = 9.86$, $p < 0.001$, $R^2 = 0.222$) is significantly higher with vibrations in the hands ($M = 3.28$, $SD = 1.07$) and under the feet ($M = 3.82$, $SD = 1.10$) than without vibration ($M = 2.52$, $SD = 0.863$, $p < 0.001$ and $p = 0.030$). Ownership ($F_{2,69} = 3.84$, $p = 0.026$, $R^2 = 0.100$) is significantly higher with vibrations under the feet ($M = 3.97$, $SD = 1.20$) than without vibration ($M = 3.08$, $SD = 0.910$, $p = 0.020$). Finally, multisensory ($F_{2,69} = 10.6$, $p < 0.001$, $R^2 = 0.236$) is significantly higher with vibrations under the feet ($M = 4.49$, $SD = 1.13$) than with those in the hands ($M = 3.69$, $SD = 1.24$, $p = 0.044$) and without vibration ($M = 2.98$, $SD = 1.03$, $p < 0.001$).

C. *Rankings for walking sensation, comfort and preference*

The normality assumption is not met for these data so a non-parametric analysis is performed using the Friedman test. If a significant effect is found, a post-hoc analysis via the Nemenyi procedure is performed to check the significance of the pairwise comparisons with Bonferroni correction.

A significant difference is found for the sensation of walking ($p < 0.001$, $Q = 20.3$). The vibrations under the feet and in the hands are ranked higher than the simulation without vibration for eliciting a sensation of walking ($p < 0.001$, $d = 1.18$ and $p = 0.001$, $d = 1.08$ respectively). Similarly, the overall preference presents similar significant results ($p < 0.001$, $Q = 16.1$). The vibrations under the feet and in the hands are significantly preferred to the simulation without vibration ($p = 0.003$, $d = 0.958$ and $p = 0.001$, $d = 1.04$ respectively). No significant difference is found for the rankings of comfort.

IV. Discussion

A. *Influence on the sensation of walking*

Participants evaluated the sensation of walking using Likert scales and rankings. Both results indicate that vibrations in the hands significantly enhanced the sensation of walking compared to the condition without vibration, supporting **[HW1]**. The sensation of walking in VR can then be improved with simple vibrations applied in the users' hands. In the future, commercial VR controllers could display such feedback.

The sensation of walking is higher for vibrations under the feet than without vibration, and this aligns with previous findings [17], [19], [21], [25]. Scores between vibrations in the hands and vibrations under the feet are not statistically different, so **[HW2]** is not supported. This suggests that vibrations in the hands are quite convincing, even when compared with vibrations under the feet.

We may wonder how participants interpreted the feedback they received in the hands. While we designed it to be the remapping of virtual-foot-ground interactions onto their hands, some participants had different interpretations. Specifically, five participants felt as though they were being pushed by the wind, three thought it represented the movement of their arms, and five felt as if they were using walking sticks. Interestingly, the timing of the vibrations coincides with the virtual arms moving from the back to the front of the avatar, as well as when the heel touches the ground (see Fig. 6). If the interpretations of "wind" and "arm movement" align coherently with the walking motion, the "walking sticks" interpretation should correlate with a different timing. The participants who perceived the feedback as related to walking sticks justified their interpretation by the fact they effectively held vertically a stick in each hand. These different interpretations may be explained by the haptic "uncanny valley" effect [36]: the incoherence between visual and haptic cues leads to a lesser realism of the simulation. Thus, the participants may have searched an explanation, yet different because of the absence of a clear visual cue producing the haptic feedback. These interpretations could explain the results between vibrations in the hands and no vibration, and why no significant difference shows up between vibrations in the hands and under the feet.

B. *Influence on the embodiment*

The embodiment was evaluated through four sub-components (appearance, response, ownership, and multisensory). The results indicate that response is significantly higher for vibrations in the hands than without vibration, so **[HE1]** is partially supported. The response comprises questions related to the effect of tactile feedback on the virtual body (e.g., "I felt that my own body could be affected by the virtual world", "It seemed as if the touch I felt was caused by the ground touching the virtual body"; see [34] for more details). The vibrations in the hands constitute a sensory response to an external event, so this result is coherent. The results show no significant difference between vibrations in the hands and no vibration for the multisensory sub-component. Still, it includes a question, "It seemed as if I felt the touch of the ground in the location where I saw the virtual body touched," which could have been impaired by the remapping technique.

The results indicate that vibrations under the feet enhance significantly the embodiment compared to the condition without vibration. This correlates with previous findings [25]. Concerning the comparison with vibrations in the hands, a significant effect is found for the multisensory sub-component higher for vibrations under the feet, partially supporting **[HE2]**. In the same way as the comparison between vibrations in the hands and no vibration, this result could be explained by the remapping induced by our technique.

C. Influence on comfort and cybersickness

The comfort was evaluated by participants using Likert scales and rankings. Likert scores for vibrations in the hands and under the feet are quite high, indicating that both feedback are comfortable for the participants. The scores from the Likert scales are significantly higher when the participants feel vibrations. However, the rankings show no significant difference. One explanation for this difference could be the formulation of the Likert statement: "During the experiment, the haptic feedback felt comfortable". Participants have reached a quasi-consensus for a 4 (neither comfortable nor not comfortable) since no haptic feedback was displayed.

The results don't indicate a significant difference between vibrations in the hands and under the feet, so **[HC]** is not supported. These vibrations had the same intensity to avoid bias between the two. However, feet and hands perceive vibrations differently, and hands could be more sensitive. As we have applied the same vibrations to all participants, the results could have also been influenced by individual differences [37]–[39]. In their comments, three of them reported too high vibrations under the feet and six in the hands. In applications, vibrations could be tailored to increase user's comfort. Vibrators used in the experiment have amplitude and frequency correlated and have a small activation range, so it would require different actuators, like voice coil actuators.

The results show no significant difference in term of cybersickness between conditions, so **[HS]** is not supported. However, the walking simulation was designed to limit it to avoid bias (high frame rate, attenuated head bobbing, no accelerations, no turns). So, the cybersickness remained very low, preventing the comparison of the impact of the different conditions. In the future, it would be interesting to test the vibrations in a simulation that elicits cybersickness.

D. Overall preference

At the end of the experiment, the participants had to rank the conditions according to their preferences. The results suggest that the two conditions with vibrations were preferred to the condition without vibration. However, no significant difference shows up between vibrations under the feet and in the hands. This makes the vibrations in the hands a suitable alternative to vibrations under the feet for walking simulations in VR when no feet interface is available.

V. Perspectives and Future work

It would be interesting to further explore the hand remapping technique in the future. Some participants reported that they appreciate vibrations in the hands because they interpret it as an event other than footstep contact in the virtual scene. (e.g. wind, walking stick). Additional visual effects could support these interpretations [36] and potentially increase the walking experience, particularly the embodiment.

This study proves the effectiveness of vibrations displayed in the hands for the simulation of walking, but the remapping technique could be interesting for other actions (e.g., running, swimming). For swimming, vibrations in the hands could also be tested together with vibrations under the feet.

Participants observed the virtual walk during the experiment but it would be interesting to evaluate the influence of vibrations in the hands for different type of control [40]. For instance, when users use leg motions (e.g., walking-by-cycling [41]), their motions are closer to one of the avatars, and vibrations in their hands could affect the walking experience. On the contrary, for movements such as arm swinging [2], vibrations in the hands could positively impact the experience.

Previous works have proved that a greater embodiment reduces the error in distance estimation in VR [42]. This could serve as an additional metric to evaluate the interest of vibrations in the hands for a distance estimation while walking.

Usually, VR controllers are used to interact with different objects in the scene. During this experiment, we have only considered a walking experiment during which the user remains static. Although walking and object manipulation are not often simulated simultaneously, it would be interesting to investigate if the interaction with the scene while walking would impair the results of this paper.

Finally, while we focus on the simulation of rigid contact with vibrations, previous works show that vibrations displayed under the feet can simulate different ground material properties [19], [43], [44]. It would be interesting to investigate if similar sensations can be displayed in the hands and still interpreted as the simulation of ground properties.

VI. Conclusion

In this work, we investigated the interest of vibrations displayed in the hands to augment walking simulations with self-avatar in Virtual Reality. To do so, we conducted a user study in which vibrations in the hand have been compared to no vibration and vibrations under the feet in terms of sensation of walking, embodiment, comfort and cybersickness.

Results showed that vibrations displayed in the hands elicit a higher sensation of walking and embodiment than no vibration. No significant difference between vibrations in the hands and under the feet was found concerning the sensation of walking, but foot-based feedback produce a greater embodiment. No significant differences of cybersickness or comfort were observed between vibrations displayed in the hands and under the feet. Overall these results encourage the use of vibrations displayed in hands in VR applications involving virtual walking with a self-avatar.

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