WalkingVibe: Reducing Virtual Reality Sickness and Improving Realism while Walking in VR using Unobtrusive Head-mounted Vibrotactile Feedback

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ABSTRACT
Virtual Reality (VR) sickness is common with symptoms such as headaches, nausea, and disorientation, and is a major barrier to using VR. We propose WalkingVibe, which applies unobtrusive vibrotactile feedback for VR walking experiences, and also reduces VR sickness and discomfort while improving realism. Feedback is delivered through two small vibration motors behind the ears at a frequency that strikes a balance in inducing vestibular response while minimizing annoyance. We conducted a 240-person study to explore how visual, audio, and various tactile feedback designs affect the locomotion experience of users walking passively in VR while seated statically in reality. Results showed timing and location for tactile feedback have significant effects on VR sickness and realism. With WalkingVibe, 2-sided step-synchronized design significantly reduces VR sickness and discomfort while significantly improving realism. Furthermore, its unobtrusiveness and ease of integration make WalkingVibe a practical approach for improving VR experiences with new and existing VR headsets.

Author Keywords
Virtual reality sickness; Discomfort; Realism; Vestibular system; Vibrotactile feedback.

CCS Concepts
•**Human-centered computing** → *Virtual reality; Haptic devices;*

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Figure 1. WalkingVibe prototype with 2 vibration motors behind the ears, which provide vibrotactile stimulation synchronized to footsteps in VR. Our 240-person study showed that it significantly reduced discomfort and VR sickness, and significantly improved the realism of the virtual walking experience in VR.

INTRODUCTION
This paper investigates ways to improve Virtual Reality (VR) experiences of walking, which is arguably the most fundamental locomotive experience in real life. A key challenge to walking in VR environments is that motion simulation induces VR sickness, with symptoms such as headaches, nausea, dizziness, disorientation, and fatigue [23]. The disparity in apparent motion between two of the sensory systems—the visual and the vestibular stimuli—is called sensory conflict, and has been thought to be one of the primary reasons for these symptoms [32, 47]. Studies have shown that 80-95% of VR users experience some symptoms of sickness, resulting in up to 50% of users terminating VR sessions early [26].

Several approaches have been shown to reduce VR sickness by reducing the mismatch between the two sensory systems. Galvanic vestibular stimulation (GVS) uses electricity to stimulate vestibular afferent nerves from the skin surface [24, 39, 62]. However, applying electrical stimulation to the skin is often uncomfortable and poses health risks to certain populations. Visual field modification techniques reduce the field of view and optical flow [9, 19], but degrades the sense of immersion in the experience [21, 50, 60]. Active body movement such as Armswing [45] provides walking naturalness and mitigates sickness, while reducing environmental interactions with limbs and causing fatigue more easily.

Another approach is physical stimulation of and near the vestibular system. Bone-conducted transducers vibrating at an audible frequency of 500Hz behind the ears have been shown to be effective [61, 62]. However, studies have shown that frequencies above 150Hz should not be used for vibrating the head due to perceived annoyance and discomfort [30, 41–43], where the authors similarly noted its obtrusiveness and were explicitly motivated by the need for a more unobtrusive approach. Moreover, stimulation was applied to both ears simultaneously, and not applied to the side of each footstep. Our prior work, PhantomLegs, uses servos to alternatingly tap the regions in front of both ears [37]. Although effective in reducing VR sickness, the haptic feedback from tapping the sides of the head could be distracting, and the noise from the servos were noticeable and had affected the VR walking experience. In addition, its servo-based design contributed significant bulk and weight relative to the VR headset.

To balance effectiveness with unobtrusiveness, we looked for a vibrotactile-based approach using frequencies that provide reasonable vestibular response and low perceived annoyance. Prior studies have shown that the vestibular response to bone-conducted vibration peaked around 200-400Hz [52, 58]. However, perceived annoyance and discomfort increases linearly with vibration frequency, and that frequencies above 150Hz should not be used for vibrating the head [30, 41–43]. We therefore selected the frequency of 150Hz in our vibrotactile design and evaluation.

We aim to reduce VR sickness and discomfort—while improving the realism of walking in VR environments—by exploring different vibrotactile stimulation designs that can be readily streamlined into a VR headset. Our exploration was motivated and grounded in various insights such as the need to dynamically re-adjust visual and vestibular stimuli to alleviate VR sickness [23], the similarities in VR sickness occurrences for both standing and sitting conditions [15], and the potential of an incorrect setup of VR displays that can lead to VR sickness [5].

We conducted a 240-person study to compare 4 vibrotactile designs with 3 audio-visual conditions and a tactile condition, PhantomLegs [37], as references. The 8 conditions are as follows:

- **4 vibrotactile.** Combinations of 2 placement locations and 2 synchronization timing. The 2 locations are: a) a single vibration motor on the back of the head (shown in Figure 3 (b)) vs. b) 2 vibration motors behind both ears (shown in Figure 3 (a)). The 2 synchronization timing are: a) random vs. b) synchronized to footsteps.
- **2 visual-only.** With head-bobbing and without.
- **1 visual+audio.** With synchronized footstep sounds.
- **1 tactile.** PhantomLegs [37], which alternatingly taps the areas in front of both ears synchronized to footsteps (shown in Figure 3 (c)).

Figure 2. WalkingVibe prototype with 2-sided vibrotactile design.

During the user study sessions, participants were seated *physically* as their view in the VR scene involved walking *passively*. We chose the seated scenario since it is a common scenario used in previous studies on VR sickness [19,37,61]. As for passive control, we chose such a method due to its use in many VR scenarios, including 360° videos and guided VR experiences. Furthermore, we had concerns that active control (e.g., speed, distance, heading) could lead to different durations and levels of VR sickness stimuli for different participants, so we used passive control and controlled speed variations to cover a range of different walking scenarios. Finally, we chose a between-subject study design since multiple study conditions would otherwise lead to significant and cumulative VR sickness.

In order to evaluate a user's walking experience, participants continuously rated perceived discomfort every 20 seconds, while the Simulator Sickness Questionnaire (SSQ) [31] and realism questionnaire were rated at the end of the session. The realism questionnaire referred to the similarity between virtual and physical walking experiences, which specifically denoted how real they felt they were walking. The measurement was adapted from the original Presence Questionnaire (PQ) [3, 63] and had similarly been used in previous VR locomotion studies [13, 40, 51, 53]. The study results showed that all 2-sided tactile designs significantly reduced VR sickness compared to the conditions with no haptic feedback. In addition, WalkingVibe with the 2-sided, footstep-synchronized vibrotactile cues significantly reduced discomfort compared to all other conditions and significantly improved realism compared to all tactile conditions, including tapping-based feedback [37].

The results showed that WalkingVibe is effective in reducing VR sickness and discomfort, and significantly improves realism in the VR walking experience. Our prototype, shown in Figure 1 and Figure 2, uses two small vibration motors controlled by an Arduino microcontroller and is entirely integrated into and powered by the VR headset. The improvement in user experience and ease-of-integration makes WalkingVibe a practical approach for improving the VR walking experience with both new and existing VR headsets.

RELATED WORK

VR Sickness and Corresponding Mitigation

The seriousness of VR sickness (e.g., headache, nausea [35]) has motivated direct investigation on its causes from the research community [16, 34, 35, 48, 54]. Visuo-vestibular recoupling approaches employ physical stimulation around the vestibular system that motivates similarly to our own work. These approaches include galvanic vestibular stimulation (GVS) [24, 39, 62], bone-conductive vibration (BCV) [61, 62], striking (i.e., PhantomLegs) [37], airflow and seat vibration [14], and foot-based vibrotactile feedback [33, 56]. Of these works, WalkingVibe closely relates to the BCV approach [61, 62] and PhantomLegs [37] for mitigating VR sickness. In terms of locomotion, WalkingVibe focuses on vibrotactile feedback for VR walking, similarly to VR drifting with the BCV approach and VR walking with PhantomLegs. In terms of stimulation, WalkingVibe also focuses on coupling stimulation to VR footsteps, similarly to VR angular acceleration to the BCV approach and VR walking with PhantomLegs. One major difference is that WalkingVibe provides unobtrusive feedback with a vibration frequency of 150Hz, which contrasts from BCV's frequency range of 200-400Hz [52, 58] such that individuals experience perceived annoyance and discomfort [30, 41–43]. Another major difference is that WalkingVibe's vibrotactile design achieves greater ease of integration with commodity VR headsets through a smaller form factor, which differs from PhantomLegs' bulkier striking setup [37].

Visual modification approaches employ strategies that adjust how users view their VR surroundings. Teleportation is one visual modification approach where the user's viewpoint instantly teleports them to the desired position after a visual cutout transition (e.g., blurring, vignette, blink) [25], but can disrupt VR immersion [4, 7], diminish presence in realistic environments [21, 50, 60], and lose sense of direction [12]. Reduced field of view (FOV) is another visual modification approach that uses subtle visual cues for smooth movements from the user's viewpoint [9, 19], but has shown to have negative effects on task performance on virtual environments [1], can degrade the sense of immersion in the experience [21, 50, 60], and may be less immersive to users perceiving movement as being more similar to sliding than walking. Body movement approaches either leverage physical devices that drive explicit body movement or leverage other limbs to emulate walking actions, and include treadmill-based solutions for supplementing VR experiences with *walk-in-place* motion [22, 28, 55], rotation chair-based solutions to incorporate physical spinning [49], arm swinging interaction techniques that mimic physical leg walking actions [45], and VR walking that is input with trigger buttons from conventional game controllers' to reduce whole-body movement [51]. While these approaches mitigate sickness from VR walking by incorporating more explicit physical movements, they also differ from our work by either requiring bulkier devices (e.g., treadmills, chairs), larger interaction spaces (e.g., arm swinging), or greater manual effort (e.g., trigger button input).

Immersion in VR Experiences with Sensory Feedback

Enhancing immersion in VR experiences is another area that has been extensively explored by researchers, with some approaches supplementing VR devices with haptic stimulation for bridging both virtual and physical realities. One approach employed an around-head vibrotactile grid array to increase the user's perceived presence in VR scenes [29]. Other approaches have focused attention on enhancing the user's perception of surrounding environmental objects, such as with an on-head vibrotactile display [11] and around-head vibrotactile headband [10]. Additional approaches have focused on improving sense of direction of out-of-view objects with various modalities that include clutch-based vibrotactile controllers [38], shoe-embedded vibrotactile actuators [59], torso-worn vibrotactile actuators [18], and force feedback device [17]. Moreover, a tangentially-related work [20] proposed an out-of-view interaction that does not explicitly provide vibrotactile feedback, but instead provides the illusion of tactile feedback using a virtual long arm visualization. Researchers have also investigated expanding modalities even further for more immersive virtual experiences. For expanding haptic-driven modalities, multimodal feedback have included additionally incorporating on-face thermal actuators and electrical muscle stimulation (EMS) controllers [64] and auxiliary audio-visual stimuli [59]. For other types of sensory feedback, alternative modalities have included supplementing VR experiences with smell-based interactions [8, 44]. These prior approaches' various efforts in enhancing immersion in VR navigation with sensory feedback have inspired the vibrotactile feedback design for WalkingVibe, which similarly enhances immersion in VR walking while also mitigating its associated VR sickness.

USER STUDY

To evaluate how the visual, auditory, and tactile feedback affected the VR walking experiences, we conducted an 8-condition, 240-person between-subjects study, in order to compare the different types of feedback that were used in similar design and evaluation methodologies of previous works [37, 61]. The main task of the study consisted of participants walking passively in VR through a 9-minute long path. We used an *HTC Vive Pro Eye* VR system—operated by a VR-ready desktop computer that is equipped with an Intel i7-8700K CPU and NVIDIA GTX1080ti GPU—to display the VR walking environment. To prevent extraneous factors from affecting our results, we ensured that sufficient frames per second (FPS) were maintained during the experiment. In order to increase uncertainty in the VR walking experiences, we also designed walking speeds that look visually different during the study. As for the accompanying vibrotactile feedback that is applied during the VR walking activity, our goal was to make the feedback unobtrusive, allow for ease of integration, be able to mitigate discomfort, and maintain an appropriate perception of walking for users. The following describes the implementation details, including our feedback conditions and the configurations of the visual and tactile feedback in our study.

Feedback Conditions

We considered two factors for the vibrotactile feedback design of WalkingVibe: 1) synchronization and 2) placement.

1. The synchronized tactile feedback was the haptic stimulations that aligned with the visual head-bobbing cues, while the random stimulation provided tactile feedback at random intervals. We confirmed that both aligned and non-aligned

visual-tactile feedback had the same total count of stimulations.

2. As for placement, the two-sided and backside positions (Figure 3a and Figure 3b, respectively) were chosen based on the settings of the commercial bone-conducted earphone and other previous systems [61,62]. We also confirmed that the total number of stimulations at each applied placement was identical.

By combining the different visual, auditory, and tactile stimulations, a total of eight feedback conditions were applied for our VR walking study (Table 1):

- **Visual-only.** Two visual-only conditions: one with and one without visual head-bobbing pattern usage.
- **Audio.** Step-synchronized gait sounds aligned with visual step cues.
- **2-sided tapping.** Step-synchronized tapping feedback on both sides of the head, from our prior PhantomLegs project [37] (Figure 3c).
- **2-sided vibration.** Two patterns of 2-sided vibrotactile feedback: step-synchronized stimulation and random stimulation (Figure 3a).
- **Backside vibration.** Two patterns of backside vibrotactile feedback: step-synchronized stimulation and random stimulation (Figure 3b).

Visual Stimulation

Prior research has successfully explored the use of a visual oscillation pattern [36,46], and its use in conjunction with haptic feedback for reducing VR sickness [37]. As we were interested in how our prototype performed with such visual feedback, we replicated timed head-bobbing patterns from [37,51] that synchronized vibrations to VR footsteps. The head-bobbing's frequency and amplitude were fixed during implementation, so that users moved at a single velocity.

To decrease the predictability found in VR experiences, we extended the prior works' approach for supporting various moving speeds. We also needed to examine the effects of the stride frequency in terms of speed for generating appropriate timings of the vibration cues. As striding behavior varies per person, we used a polynomial regression model [2] for translating speed to stride length, which can then be translated back to frequency through arithmetic division.

Other prior research works have explored the effect of walking speed through vertical head movement [27]. However, their data only described the relationship between speed and vertical translation by up to 2.2m/s; no other work had covered this relationship beyond walking speed. This topic was beyond the scope of our work, so we conducted a preliminary test based on the previous work's pilot study [37]. During the test, we first recorded and tracked the HMD positions of three users with different walking and running speeds, and then generated a linear model for amplitude multiplication. As for the study's stimulation, we applied the head-bobbing pattern [6,36,57] for all feedback other than visual-only conditions, which served as a visual indicator for our study.

Tactile Stimulation

Due to varying head sizes among users wearing the VR system's head-mounted display (HMD), we attached Velcro strips onto a headband that can be adjusted for individual fit and achieve flexible positioning from our prototype's haptic vibrations (Figure 2). On the outer rim of the headband, we added a plastic strip layer and sewed together an array of cells of fixed

Figure 3. The setup for each category of tactile feedback: (a) 2-sided vibration, (b) backside vibration, (c) 2-sided tapping feedback replicated from PhantomLegs [37] project.

factors \ conditions	visual-only (w/o head bobbing)	visual-only	audio	2-sided tapping (synchronized)	2-sided vibration (synchronized)	2-sided vibration (random)	backside vibration (synchronized)	backside vibration (random)
visual (head bobbing)		✓	✓	✓	✓	✓	✓	✓
audio (step sound)			✓					
type of haptic				tapping	vibration	vibration	vibration	vibration
position				2-sided	2-sided	2-sided	backside	backside
synchronization (with visual)			✓	✓	✓		✓	

Table 1. Configurations of each feedback condition in the study.

lengths of 15 mm. Each cell has an opening on the top of the headband, which provides an enclosure for easy installation of the vibration motors.

For producing vibrations, we used Parallax servos—12 mm coin-style, 3.3 V/90 mA, freq=9000 rpm—that operate at 150 Hz, which lies within the suggested range of 32 to 150Hz for preventing head discomfort from vibrations [30, 41, 42] and whose amplitudes can be controlled by voltage. To control the servos, we placed an Arduino Nano microcontroller board on top of the HMD. This board was connected to the computer via the HMD's USB-C port, and listened to signals sent from the controlled VR application that was written in Unity 2019.1.4f1.

Participants

We chose a sample size of 30 participants for each condition, and elected to replace participants who could not complete the experiment until the sample size was met. 12 participants had terminated the study during the testing process due to a high level of VR sickness, and their data was not included in the final analysis. In total, 240 participants (138 female) from ages 20 to 49 years (mean=24.06, SD=4.42) were recruited and had completed the study. All participants either had normal or corrective vision. Around one-fifth of all participants self-reported no experience with playing either VR or first-person view (FPV) games, with three-fifths having little experience on either VR or FPV, and the remaining participant having experience with both applications. All study participants were monetarily compensated $5 USD for their participation.

Study Procedure

In our study, 240 participants were equally distributed among the 8 conditions, such that there were 30 unique participants that were measured for each feedback. Before the study, participants were asked to fill out a questionnaire about their personal information and any experiences related to FPV or VR applications. At the start of the study, each tactile feedback was applied to the users, where participants were able to adjust the amplitude level of the stimulation to a level that was comfortable for that time slot. During the experiment, participants were seated statically and passively walked through the VR environment. The study decision for using a passive walking approach stemmed from insights in the literature that this approach could induce stronger rates of sickness [61]. The passive control has also been widely used in many VR scenarios, including 360° videos and guided VR experiences (e.g., most current VR experiences at theme parks). Meanwhile, we chose a seated scenario since it has been commonly used in prior studies on VR sickness [19, 37, 61]. For the study task, participants passed through virtual checkpoints (Figure 4c) that were scattered in three designed VR scenes: a city in Figure 4(a)(d), a forest in Figure 4(b)(e), and a science fiction-themed passage in Figure 4(c)(f). We incorporated three counterbalanced walking speeds in our study: 2m/s, 4m/s, and 6m/s. The variations in walking speed were to provide experiences of uncertainty during the participants' VR session. As the three walking paces alternated during the VR session, we controlled the time duration of passing through two consecutive checkpoints to

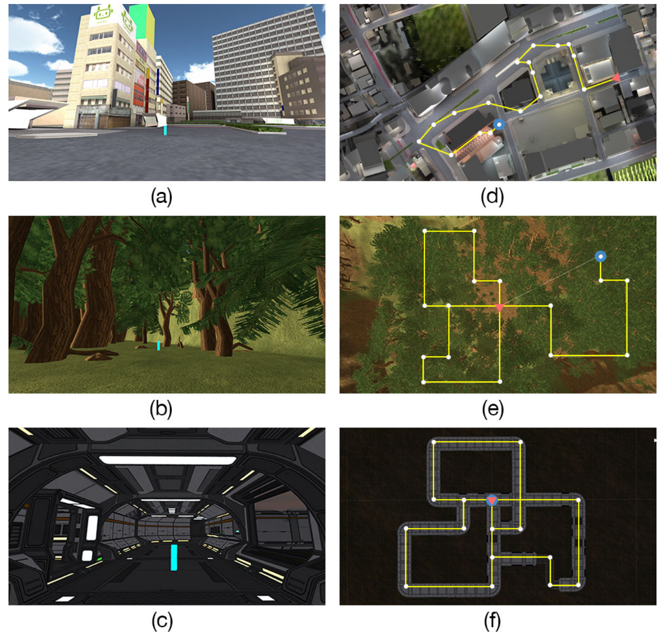

Figure 4. Screenshots of three scenes and paths of the virtual walking environment: (a)(d) the city, (b)(e) the forest, and (c)(f) the sci-fi Passage.

ten seconds. In total, each participant passed through fifty-four (54) checkpoints in their VR session.

For our study's measurements, we conducted three different questionnaires throughout the experiment. The first measurement was the discomfort score, which was included in order to collect continuous data on VR sickness in the experiment. We adapted this measurement from previous works on VR sickness [19, 37], and further improved the data collection method to use verbal input instead of gamepad controller input to reduce the required cognitive load. That is, participants were prompted during the experiment—after passing every two checkpoints for twenty seconds each—with a played audio recording, which asked for their perceived level of discomfort that ranged from 0 (no feeling) to 10 (inclination to terminate the current experiment immediately). If the participant reported a discomfort score of a 10, we immediately terminated the study and accommodated the participants to rest. The second measurement was a *Simulator Sickness Questionnaire* (SSQ) [31], where participants were asked before and after the study about sickness symptoms on several factors. We calculated the *relative sickness score* (RSS) for each participant in accordance to guidelines from [31], and which were similarly adapted from similar studies (e.g., [37, 61]). Specifically, the participant's recorded SSQ score after the test was subtracted from their score before the test, in order to assess the participant's self-reported sickness levels. The final measure was perceived realism, where participants were asked: "*How similar was the walking experience you just experienced compared to the walking experience in the real world?*", which denoted how real they felt they were walking from 0 (completely unrealistic) to 10 (completely realistic). This measurement was adapted from the original Presence Questionnaire (PQ) [3, 63] and was included similarly by several VR locomotion stud-

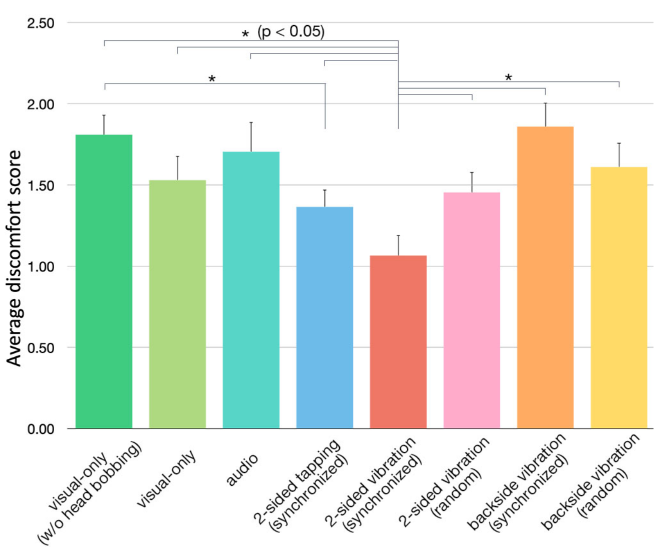

Figure 5. The average and standard deviation (in parentheses) of discomfort scores (from left to right) are: 1.81 (0.61), 1.53 (0.75), 1.70 (0.92), 1.36 (0.53), 1.07 (0.62), 1.45 (0.63), 1.86 (0.74), 1.61 (0.75).

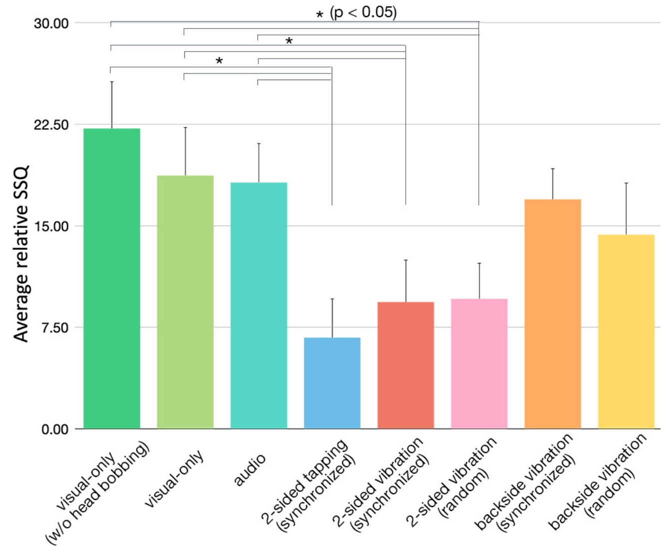

Figure 6. The average and standard deviation (in parentheses) of RSS (from left to right) are: 22.19 (18.60), 18.70 (19.17), 18.20 (15.47), 6.73 (15.46), 9.35 (16.75), 9.60 (14.18), 16.95 (12.16), 14.34 (20.55).

ies [13, 40, 51, 53]. The reason why we made such an adaption was because we found the questions such as the "presence for the experience" in the PQ to be too broad and that responses were affected primarily by visual appearance and other factors during our pilot study. We additionally included qualitative feedback questions for participants to elaborate on their reasons for selecting their given scores and how the feedback affected their individual experiment session. Our general hypothesis for the study was that compared to non-haptic stimulation, tactile feedback can effectively reduce VR sickness and discomfort for passive VR walking experiences by employing a natural visual head-bobbing pattern. In total, participants spent approximately half an hour to complete their experiment session and study questionnaires.

RESULTS

We analyzed the data from the participants' responses of perceived discomfort, VR sickness, and realism from the study (shown in Figure 5, 6 and 7, where error bars in each figure denoted standard error of the mean value), and report our findings in the following.

Discomfort

The collected discomfort scores ranged from 0 to 10, and were recorded every 20 seconds—the duration of passing two checkpoints—in the VR walking experience. We analyzed the discomfort level by averaging all the participants' discomfort scores—which were recorded at the same checkpoint—as the overall discomfort level for that checkpoint under a specific feedback. In total, there was 27 averaged discomfort values for each condition. We performed such an analysis to avoid the impact of cumulative effect over time. Based on these results, we employed a non-parametric Kruskal-Wallis test for determining whether there was any significant difference among the data (Figure 5). Our results demonstrated that there were indeed significant differences between the conditions (χ^2=23.59, p=0.0013<0.05, df=7). We then ran a post-hoc pairwise Conover test to compare the different paired conditions. Our results demonstrated that *2-sided vibration (synchronized)* feedback received significantly less perceived discomfort compared to all other conditions. Furthermore, *2-sided tapping (synchronized)* feedback had significantly lower discomfort than *visual-only (without head-bobbing)* feedback. Our computed significance comparisons can be found in Figure 5, and are stated directly in the following:

- ***2-sided tapping (synchronized)*** vs. *visual-only (without head-bobbing)*: p=0.0096<0.05;
- ***2-sided vibration (synchronized)*** vs. *visual-only (without head-bobbing)*: p=0.00012<0.05; vs. *visual-only*: p=0.01778<0.05; vs. *audio*: p=0.00694<0.05; vs. *two-sided tapping (s)*: p=0.037872<0.05; vs. *2-sided vibration (random)*: p=0.0232< 0.05; vs. *backside vibration (synchronized)*: p=0.0002<0.05; vs. *backside vibration (random)*: p=0.01046<0.05.

VR Sickness

We first calculated the RSS by taking the difference of the SSQ scores recorded before and after the study. We then applied statistical analysis on the RSS measurement to further examine the significant differences between the conditions. Finally, we ran a one-way Anova analysis to discover whether there existed any significant differences among the RSS reported for each feedback condition (Figure 6). The reason why we directly applied such an analysis was due to having a large enough sample size (>=30), and to also ensure that each condition was normally distributed. To ensure normal distribution, we ran a Shapiro-Wilks normality test to confirm that the data in each condition was normally distributed (i.e., p>0.05 for every condition to reject the non-normality hypothesis). Our results demonstrated that there was significant differences among all feedback conditions: F(7, 232)=3.0636, p=0.0042<0.05, η^2=0.085. Specifically, three tactile conditions (i.e., *2-sided tapping (synchronized)*, *2-sided vibration (synchronized and random)*) significantly reduced participants' VR sickness— compared with *two visual-only (with and without head-bobbing)*, *audio*, and *backside vibration (synchronized)* conditions—by running post-hoc pairwise Tukey's HSD test. The significant comparisons can be found in Figure 6 and are described as follows:

- ***2-sided tapping (synchronized)*** vs. *visual-only (without head-bobbing)*: p=0.000539<0.05; vs. *visual-only*: p=0.005647< 0.05; vs. *audio*: p=0.003249<0.05; vs. *backside vibration (synchronized)*: p=0.003484<0.05.

- ***2-sided vibration (synchronized)*** vs. *visual-only (without head-bobbing)*: p=0.003831<0.05; vs. *visual-only*: p=0.026331< 0.05; vs. *audio*: p=0.020479<0.05; vs. *backside vibration (synchronized)*: p=0.026319<0.05.

- ***2-sided vibration (random)*** vs. *visual-only (without head-bobbing)*: p=0.002638<0.05; vs. *visual-only*: p=0.044353< 0.05; vs. *audio*: p=0.015641<0.05; vs. *backside vibration (synchronized)*: p=0.019156<0.05.

In order to further analyze the effect of our proposed design factors from the vibrotactile feedback, including the synchronization and placement factors, we ran a mixed-factor 2 $\times$ 2 ANOVA on the RSS for the factors of visual-tactile alignment (*synchronized* vs. *random*) and tactile placement (*two-sided* vs. *backside*). Our results demonstrated that there was no interaction effect between these two analyzed factors (p=0.6324, η^2=0.02). As for the effect led by both factors, there was a main effect of the vibration placement on the RSS (p=0.0427<0.05, η^2=0.034), while there was no main effect found on the step-synchronization for reducing the RSS (p=0.6992, η^2=0.011). We subsequently conducted a follow-up estimated marginal mean analysis on the placement types for vibration. Our results suggested that *two-sided vibrotactile feedback* received lower RSS compared to *backside stimulation* (p=0.0206<0.05).

Realism

In addition to the effect that each feedback exerted on VR sickness and discomfort, we also analyzed participants' perceived realism while applying different stimulation, in order to evaluate their overall VR walking experiences. We calculated the average realism level from a score range of 0 to 10, in order to statistically compare each condition (Figure 7). Following a similar procedure from testing the VR sickness score, we ran a one-way ANOVA on all conditions and discovered that there were significant differences in terms of perceived realism under the feedback conditions: F(7, 232)=4.1186, p=0.0003<0.05, η^2=0.11. Two feedback conditions—*audio* and *2-sided vibration (synchronized)*—provided significantly higher realism than most of the other conditions except for *visual-only feedback*: *2-sided vibration (synchronized)* vs. *visual-only*: 0.093; *audio* vs. *visual-only*: 0.095. We also conducted pairwise comparisons as evaluated by a Tukey's HSD post-hoc test and as listed in the following:

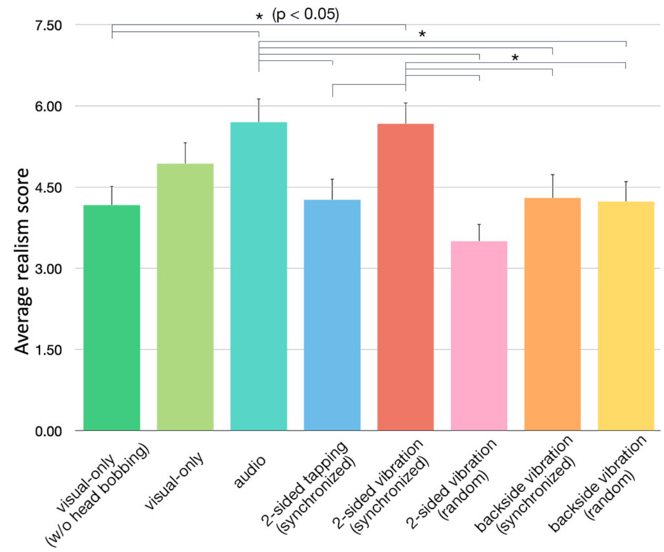

Figure 7. The average and standard deviation (in parentheses) of realism score (from left to right) are: 4.17 (1.86), 4.93 (2.08), 5.70 (2.31), 4.27 (2.03), 5.67 (2.08), 3.50 (1.69), 4.30 (2.31), 4.23 (1.98).

- ***audio*** vs. *visual-only (w/o head bobbing)*: 0.003648<0.05; vs. *two-sided tapping*: p=0.007482<0.05; vs. *2-sided vibration (random)*: p=0.000057< 0.05; vs. *backside vibration (synchronized)*: p=0.012345<0.05; vs. *backside vibration (random)*: p=0.005962<0.05.

- ***2-sided vibration (synchronized)*** vs. *visual-only (w/o head bobbing)*: p=0.002727<0.05; vs. *two-sided tapping (s)*: p=0.006085<0.05; vs. *2-sided vibration (random)*: p=0.000028< 0.05; vs. *backside vibration (synchronized)*: p=0.010745<0.05; vs. *backside vibration (random)*: p=0.004728<0.05.

DISCUSSION

We discuss the user feedback for improving the VR walking experience, the effects from the placement and synchronization of the vibration cues for VR walking interactions, and the limitations and potential next steps.

User Feedback to Improve VR Walking Experiences

According to our study results, we discovered that all 2-sided tactile feedback are viable as effective solutions for alleviating VR sickness. However, not all of these methods were appropriate for use in VR walking in terms of overall user experience. That is, based on our realism measurement, we discovered that *2-sided step-synchronized vibration* not only provided significantly higher realism for effectively reducing sickness compared to other 2-sided tactile feedback, but also led to the highest average realism compared with all the other feedback methods. Although we did not directly compare the different feedback due to the nature of our between-subjects study design, we still received qualitative feedback from participants for clarifying our results. From the participants' responses, half of the participants who experienced *2-sided step synchronized* vibration during their VR walking session had expressed that such a technique could both improve their VR immersion while reducing their VR sickness. "It seemed like I was getting massaged while walking, which felt really comfortable" (P125, P136, P144). "The vibrotactile feedback that matched with the visual bobbing gave me a sense of walking in the environment" (P134, P147, P150, P151). Based on the participants' responses, we also discovered that the synchronization between the tactile and visual-bobbing was important for the overall VR walking experience. Moreover, 25 of the 30 participants who received *2-sided vibration with a random stimulation pattern* stated that the feedback was apparently distracting and made it challenging to focus on the experience, causing it to be reported as the least realistic walking experience when such feedback was applied.

In regards to the tapping tactile feedback of PhantomLegs [37], 10 of the 30 participants expressed difficulties in correlating the feedback to physical walking experiences, and reported that the tactile impact was analogous to being constantly struck in the head. Moreover, 2 of the 30 participants pointed out that the noise from the servo motors—as similarly reported previously—was a factor that made the experience unrealistic. "The audio [that the servo motors] made it sound like it was a robot walking instead of me" (P85, P103). This feedback further implied that vibrations could be a better tactile stimulation for improving VR walking experiences compared to tapping feedback [37], since users could potentially better correlate the vibrations with the walking experience more intuitively. Based on the qualitative and quantitative results, we recommend that WalkingVibe with a *2-sided step-synchronization* vibration design as the most effective technique for improving users' VR walking experiences, not only in consideration of mitigating VR sickness and discomfort, but also in enhancing perceived realism. Follow-up studies for combining visual, auditory, and tactile feedback as stimulation for VR walking are also worth exploring as potential next steps.

Placement and Synchronization of Vibration

Based on our mixed-factor statistical analysis, results showed that the position of the vibration is an important factor for alleviating VR sickness, while visual-tactile synchronization did not seem to demonstrate a significant effect on VR sickness during the VR walking experience. Particularly, vibrotactile feedback positioned behind both ears significantly reduced VR sickness compared with being positioned behind the head.

For participants who were assigned *backside step-synchronized* vibration, 16 of the participants stated that tactile signals were ignored after a certain period of time. "I think I could easily ignore the haptic feedback after getting used to it, due to the regular stimuli that was received" (P237, P241, P249). Similar feedback was also received from participants who were assigned *applied backside random* vibration. These responses implied that participants tended to ignore the backside stimulation compared with the 2-sided design. Furthermore, due to the potential disregard for the backside stimulated position that we selected, the synchronization effect for that feedback on different placements was also varied. For instance, synchronization could effectively improve realism for two-sided vibrotactile feedback compared with random stimulation, while showing no significant realism improvement on the backside vibration feedback. Since the placements were found to be an important factor for the sickness mitigation, further studies are worth considering to be conducted for exploring how other stimulated regions on head can affect VR experiences.

Potential Generalization, Limitations and Future work

Due to the large number of study conditions and the already large scale of our study, we did not get to explore active vs. passive control and seated vs. standing conditions, as those would double and quadruple the study size. However, our approach should generalize reasonably well to active control because the vestibular stimulation mechanism is similar to PhantomLegs [37], which had been shown to significantly reduce VR sickness under active control conditions. As for generalizing to other posture such as standing, researchers are still debating the physiological differences that could possibly cause different levels of sickness [15], and more research is needed in this space.

Most of the feedback in our study was coupled with visual head-bobbing patterns, because of the effective results reported previously [37] that also applied visual and corresponding haptic feedback for VR walking experiences. Although we compared this technique with the visual-only condition that removed visual oscillation, we plan to further explore the effect of the visual stimuli.

In addition, the time that we gave to users for experiencing VR walking was still limited. A longitudinal experience study on how each feedback affected VR sickness and discomfort across hours or days remains a future task for exploration. Finally, while this paper focused on the VR walking experience, we plan to explore vibrotactile feedback designs for other locomotive experiences such as driving, cycling, and flying.

CONCLUSION

In our work, we conducted a 240-person study to explore how head-region tactile feedback affects VR sickness, perceived discomfort, and realism for VR walking experiences. We compared four vibrotactile designs for our proposed WalkingVibe method, which applied unobtrusive haptic feedback on the head with other visual-only, audio-visual, and tactile conditions. Our study results demonstrated that *two-sided step-synchronized* vibration feedback can improve user's virtual walking experiences by not only mitigating VR sickness and discomfort, but also enhancing walking realism. With improvements in locomotion experience and ease of integration, WalkingVibe is a practical approach for improving VR walking experiences for current and future VR commodity devices.

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