LegSense: Inducing Walking Sensation in Seated VR by Providing Movement Illusion via Electrical Muscle Stimulation

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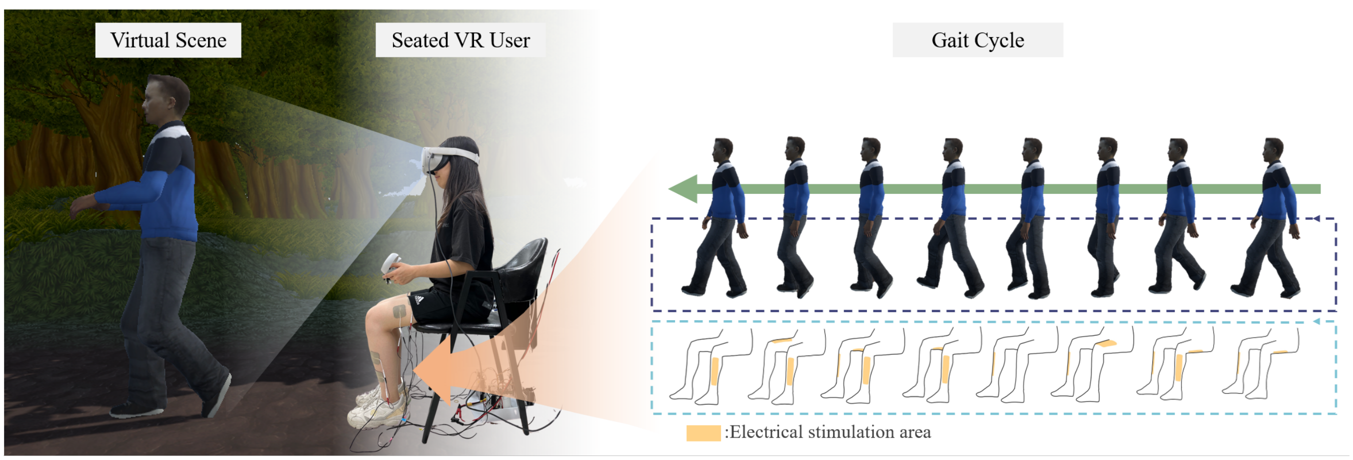

Figure 1: Overview of LegSense, illustrating how electrical muscle stimulation synchronized with the avatar's gait is provided to seated VR users to induce the walking sensation.

Abstract

Providing convincing proprioceptive cues is essential for immersive virtual reality (VR) navigation. However, this is challenging for seated users with restricted mobility. To address this gap, this study proposes LegSense, a method designed to induce the walking sensation in VR via electrical muscle stimulation (EMS). This method activates the leg muscle senses in sync with the gait cycle without requiring physical motion to enhance users' immersion. We evaluated the efficacy of LegSense through a user study and confirmed its potential in terms of walking sensation, embodiment, and presence compared to other static conditions (baseline and vibro-tactile). Additionally, participant interviews confirmed that

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LegSense effectively creates a leg movement illusion, suggesting its potential applications in diverse virtual scenarios to enhance VR experiences for seated users.

CCS Concepts

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

Keywords

Virtual Reality; Haptic; Electrical Muscle Stimulation; Locomotion

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1 Introduction

Recently, virtual reality (VR) usage has increased in environments, such as homes [35] and transportation [3, 9, 17]. However, the limited space in these environments makes it difficult to move freely for interaction [17]. Consequently, seated VR, where users can enjoy VR in a confined space [3, 17] with less physical strain [5, 11, 35], has been adopted. However, restricted mobility in a seated position [1, 22] leads to an innate constraint on walking, which is considered the most natural locomotion method in VR [8, 13, 28]. Walking in VR has significant advantages, such as enhancing presence [34] and improving the accuracy of navigation tasks [30], compared to other locomotion methods. To integrate some of these advantages into seated VR, providing the sensation of walking can be beneficial.

For example, several methods employ leg motions related to movement to provide a walking sensation [3, 8], including footsteps [3] or matching the cycling motion to virtual walking [8]. This method can enhance embodiment and presence; however, as the user must physically move their legs, it involves some effort from them. The other method is to provide tactile sensations felt on the feet while walking through stimuli such as vibro-tactile feedback [19, 21, 27]. This method usually provides vibrations to the soles synchronized with steps, which can induce the walking sensation without actual movement. However, because walking is an activity involving coordinated movements of the joints and muscles [36], providing stimulation only to the feet can result in a lack of embodiment [31, 34].

We propose **LegSense**, a method that enhances walking sensation and embodiment by stimulating the muscles used in walking in sync with the gait cycle, thereby creating an illusion of leg movement without the user's active movement. LegSense stimulates the muscles at an intensity enough to avoid involuntary movement but sufficient to activate the muscle senses through electrical muscle stimulation (EMS). Although EMS is typically used to simulate external force feedback by contracting muscles [14, 25, 26], we focused solely on conveying the sensation of muscle activation without the need to contract the muscles. In this study, we conducted a user study to compare LegSense with two other conditions: a baseline condition with only visual input and a vibro-tactile condition that provides tactile sensation on the feet through vibration, to determine whether LegSense could enhance embodiment, walking sensation and presence.

2 Related Work

2.1 Walking in Virtual Reality

Walking is regarded as the most natural locomotion method in VR [8, 13, 28]. However, replicating walking in VR has limitations owing to the need for large spaces [12, 23, 24, 28]. Therefore, providing a walking sensation regardless of user posture has been extensively studied in VR [27]. Since walking is a complex activity that provides visual, proprioceptive, and kinesthetic cues [16, 32], applying stimuli similar to walking can induce the walking sensation [27].

For example, certain methods utilize leg movements to provide a walking sensation. Specific approaches based on lower limb motions used in walking include stepping [3, 29] and marching [2]. Other approaches match the motion of avatar walking with the cycling motions generated using a mini bike [8]. These methods enhance presence and embodiment as they involve direct leg movements by the user. However, this involves effort from the user. To address this trade-off, studies have utilized motorized devices [15, 28]. For example, Moullec et al. [28] proposed utilizing a motorized bike that automatically generates cycling motion without user effort. However, these methods can be challenging owing to the need for relatively large equipment. Another method is to provide tactile sensations on the feet during walking through vibro-tactile feedback [19, 21, 27]. For example, Kitazaki et al. [19] found that foot vibration synchronized with visual motion cues generated the sense of walking. Moreover, Kruijff et al. [21] reported that haptic cues provided on the feet help in judging self-motion speed and travel distance. These methods provide the walking sensation without user movement. However, the lack of physical action tends to reduce embodiment [31, 34].

Thus, we devised a method to enhance walking sensation and embodiment by activating leg muscle senses in sync with the avatar's walking using EMS, thereby providing a sensation of leg movement without actual movement.

2.2 Electrical Muscle Stimulation for Virtual Reality

EMS contracts muscles by stimulating them via an electrical pulse [4]. In VR, EMS is primarily used to provide external force feedback by contracting muscles [14, 25, 26]. For example, Lopes et al. [25] provided punch feedback in a boxing simulation by pulling the user's arm back using EMS. For lower limb applications, Hwang et al. [14] used EMS to provide force feedback in scenarios such as crossing a river or kicking a ball. These studies used EMS to induce joint movements via muscle contraction. Recently, a study used EMS that did not induce involuntary limb movements [4]. They proposed paired-EMS in a boxing simulation to provide external force feedback by stimulating both normally targeted and user-activated muscles. The appropriate intensity was explored to apply to user-activated muscles and it was found that participants preferred the intensity that activated muscles without causing joint movements. The study ultimately reported that stimulating user-activated muscles simultaneously provided balanced feedback. The results support our idea of using EMS to provide the sensation of muscle use.

3 User Study

In the experiment, participants were tasked to move an avatar forward using a VR controller joystick and observe its walking for a set time (40 s). The avatar stood on a linear path within the forest, progressing at a constant speed following the joystick input. The participants observed the avatar walking in first-person view while seated in a fixed chair and wearing a VR headset.

We established three conditions based on the applied stimuli to compare embodiment, walking sensation, and presence. The first condition was the baseline with only visual information. The second condition was a vibro-tactile condition with vibrations applied to the heels and forefeet synchronized with virtual walking. This method is supported by previous studies [8, 19, 21, 27], which have shown enhanced walking sensation with rhythmic foot stimulation synchronized with the avatar's walking. The final condition was our proposed method, LegSense. We hypothesized that LegSense would exhibit higher embodiment, walking sensation, and presence than other conditions, as walking is an activity involving coordinated movements of joints and muscles [36]. To assess this, we evaluated the aforementioned three metrics in comparison with the other two conditions. The experiment was approved by the Institutional Review Board.

3.1 Measures

Participants completed questionnaires that measured walking sensation, embodiment, and presence after each condition. In this context, embodiment is the sense when an avatar's physical attributes are accepted as one's own body [18], and presence is the feeling of existing in an environment [31]. Walking sensation was evaluated through the item designed by Kokkinara et al. [20] ("*During the experiment, I felt like I was walking.*"). Embodiment was assessed using the Avatar Embodiment Questionnaire [10], focusing on 10 items related to body ownership, agency, and self-location according to the classification by Kilteni et al. [18]. Presence was measured using Witmer and Singer's presence questionnaire [37]. Similar to studies that adjusted the items to fit their systems [38], we excluded items that were not relevant to our system. More specifically, the sub-scales for presence included Involvement/Control (items 1, 2, 5, 10, 13, 14, 18, 23, 25, 26, 27, 32), Natural (items 3, 7, 12), Resolution (items 19, 20), Interface Quality (items 29, 30), and additional items (items 11, 24) not classified in Witmer and Singer's sub-scales. All items were rated on a 7-point Likert scale.

3.2 Implementation

For the LegSense condition, we activated the muscle senses using a motorized EMS generator [7], synchronized with the timing of the avatar's walking (Figure 2 A). The EMS device used was the TENS 7000 unit (pulse width = 300 μs; rate = 300 Hz), and each EMS channel was controlled by servo motors (HiTEC–HS-5065MG) attached to the device. We identified the muscles used in the gait cycle [36] and conducted a pilot test to determine which muscles

(A) (B)

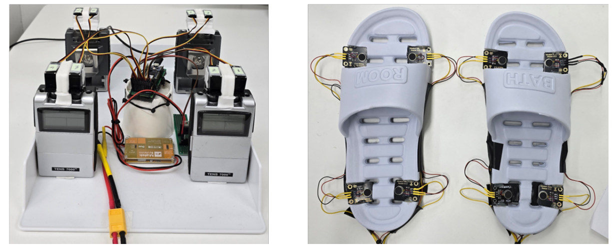


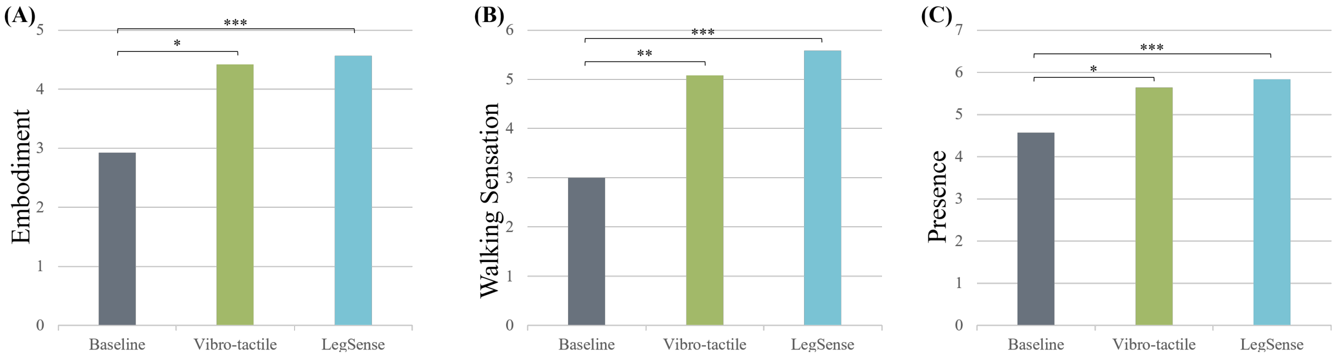
Figure 2: Apparatus used in the experiment. (A) Motorized EMS generator, (B) Vibro-tactile shoes

could be stimulated without interfering with the walking sensation. Consequently, we decided to target the quadriceps femoris, hamstrings, and tibialis anterior, using six EMS channels. We extracted the timing of muscle contractions in the gait cycle based on the moments of concentric contraction for each muscle. Using Unity 3D's animation event function, we synchronized muscle stimulation with the extracted timings of the avatar's walking animation. For instance, during the leg swing phase in actual walking, the tibialis anterior muscle near the shin contracts; thus, during the avatar's leg swing phase, electrical stimulation was administered to the user's tibialis anterior muscle. Similarly, when each muscle contracts during the avatar's gait cycle, electrical stimulation was applied to the corresponding muscle (Figure 1). For muscle stimulation, the EMS patches were attached to the targeted muscles, specifically two patches affixed to each of the anterior thigh, posterior thigh, and shin. Prior to the experiment, the EMS intensity was calibrated for each participant as in previous studies [4, 7]. Using a staircase protocol from the lowest setting (0–99 scale), we explored the minimum intensity at which the stimulus is detectable and the maximum intensity at which the muscle actually contracts, causing leg movement. Subsequently, within the range between the minimum and maximum intensities, we determined the optimal intensity of muscle sense activation, avoiding involuntary leg movements while ensuring participant comfort.

For the vibro-tactile condition, we designed shoes with vibrator modules (Vibration Motor JK-0327) (Figure 2 B). Consistent with previous studies [19, 21, 27], these modules provided vibrations synchronized with the avatar's heel and forefoot strikes using Unity 3D's animation event function.

3.3 Procedure

Twelve participants (age: M = 24.167, SD = 1.528, 9 males, 3 females) took part in the experiment. They had no disabilities affecting their experience with visual and haptic cues and had used VR to some extent. Most had occasionally used EMS and had no contraindications, such as cardiovascular disease or skin disease. The order of conditions was counter-balanced through a balanced Latin square. Before the trials, the participants were briefed on the procedure and equipment and provided demographic information. EMS intensity was calibrated as described in section 3.2. Participants then wore the VR headset and vibro-tactile shoes and underwent each condition while seated. After each trial, they completed questionnaires and post-experiment interviews were conducted once all trials were



	(A) Baseline	(A) Vibro-tactile	(A) LegSense	(B) Baseline	(B) Vibro-tactile	(B) LegSense	(C) Baseline	(C) Vibro-tactile	(C) LegSense
M	2.925	4.417	4.567	3.000	5.083	5.583	4.567	5.635	5.833
SD	1.089	0.733	0.836	1.651	1.311	1.165	1.112	0.738	0.595

Figure 3: User study results. (A) Embodiment, (B) Walking Sensation, (C) Presence. Significance levels are indicated: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

finished. During participant interviews, participants responded to questions about their overall experience with LegSense, the impact of the provided haptic stimuli on walking sensation, and the leg areas that most convincingly contributed to the walking sensation.

4 Results

The experiment compared the effects of LegSense with the baseline and vibro-tactile conditions in terms of embodiment, walking sensation, and presence. We conducted non-parametric analysis using the Friedman test for each evaluation metric and performed pairwise comparisons using Conover's post-hoc test (Figure 3). P-values less than 0.05 were considered statistically significant.

Embodiment. The total embodiment scores were determined by averaging the scores for all items. Significant variations were observed between conditions ($p < 0.001, \chi^2(2) = 15.167$), with vibro-tactile and LegSense being significantly higher compared to the baseline ($p = 0.035$ and $p < 0.001$, respectively). Moreover, LegSense had the highest mean among the three conditions, suggesting that LegSense is likely to provide a notable increase in embodiment. **Walking sensation**. There were significant differences between conditions regarding the walking sensation ($p < 0.001, \chi^2(2) = 17.282$). More specifically, both vibro-tactile and LegSense were significantly better than the baseline ($p = 0.003$ and $p < 0.001$, correspondingly). Although no significant difference was found between LegSense and vibro-tactile, LegSense exhibited the highest mean, indicating that LegSense is promising in offering the walking sensation. **Presence**. The results indicated significant differences across conditions ($p < 0.001, \chi^2(2) = 15.362$), with vibro-tactile and LegSense scoring significantly higher than the baseline (respectively, $p = 0.014$ and $p < 0.001$). Similarly, while the variation between vibro-tactile and LegSense was not significant, LegSense had the highest mean, suggesting that LegSense holds potential for delivering presence. Conclusively, the highest mean scores observed for LegSense, which were consistent, partially confirmed our hypothesis that LegSense would enhance embodiment, walking sensation, and presence compared to other conditions.

In addition, participant interviews provided insights into the movement illusion and walking sensation experienced via LegSense.

- "*It felt as if someone else was making me walk, rather than me walking on my own (P2).*"
- "*It felt like walking with effort, as if trudging through mud (P4).*"
- "*The right shin stimulation was slightly stronger, making it feel like limping (P6).*"
- "*Compared to the vibrational stimulation, the sensation of moving the legs was definite but slightly unnatural (P7).*"

The feeling of EMS was also described diversely.

- "*It felt realistic (P1).*"
- "*The tingling sensation was somewhat distracting, but it was well-synchronized with the gait cycle and felt vivid (P3).*"
- "*Uneven intensity in both legs was disappointing (P4, P8).*"
- "*There was a slight tickling sensation, but it was similar to the feeling of actual muscle movement (P9).*"

5 Discussion

Overall, LegSense showed higher embodiment, walking sensation, and presence compared to the baseline. If the sensation of muscle use resulted in improvements over the baseline condition with visual input only, this result aligns with findings that higher levels of embodiment and presence occur when users' muscles are actively engaged [31, 34]. However, the difference with vibro-tactile was not significant, potentially because participants reported a similar influence from foot vibration and muscle sense activation on the walking sensation.

In addition, based on participant interviews (*P2, P4, P6, P7*), we noted that while LegSense induced a leg movement illusion, the descriptions of this sensation varied. These findings suggest the potential applications of LegSense in various scenarios beyond simple walking, such as simulating injured legs or walking in challenging environments, including flowing water [14] or high gravity scenarios. Moreover, activities with clear muscle movements, such as climbing stairs or turning, could benefit from more vivid feedback through LegSense. If LegSense can induce a movement illusion, future studies could compare it with methods involving actual leg movements [3, 8] or muscle vibration for kinesthetic stimulation and walking motion perception [33]. However, the slight unnaturalness of the leg movement illusion reported in the participant interviews (*P2, P7*) suggests that LegSense effectively mimicked the sensation of walking but was not entirely accurate. This can be interpreted as LegSense providing the sensation of muscle movement during walking, but lacking the joint movement associated with real walking [36]. Future research could explore the combination of LegSense with other systems that provide joint movement illusion, such as tendon stimulation [6]. Interviews also indicated a division of opinions on the most convincing muscle area for walking sensation, between the shins and thighs. Participants noted that vibrations felt the strongest in the shins when stepping (*P1, P2, P5, P6, P10*), whereas the thigh muscles felt more convincing in supporting body weight (*P3, P4, P7, P9, P11, P12*). Future research could explore the effects of stimulating different leg muscle areas on walking sensation. Furthermore, future investigations could examine the integration or comparison of other seated VR locomotion methods that involve upper body movements, such as leaning [39], in terms of extended aspects, including VR sickness and spatial cognition.

This study additionally has the potential for further development. According to participant interviews (*P1, P3, P4, P8, P9*), the feeling of EMS varied among participants, affecting their overall impression of LegSense. This variation is interpreted as differing muscle thresholds that did not harmonize. Future research can address this by adding stages that provide a more integrated sensation of electrical stimulation and vary the timing and intensity of EMS for each muscle to personalize the walking sensation. Moreover, since the fixed movement speed (0.35 m/s; approximately 13.7 m of movement) of the avatar may have influenced immersion, future studies could investigate the walking sensation across various walking speeds by allowing participants to control the movement speed. Also, future research should include a larger sample size to provide a more comprehensive evaluation of all metrics.

6 Conclusion

This study introduced LegSense, a method designed to induce the walking sensation in seated VR users by activating the muscle senses in sync with the gait cycle via EMS. The results from the user study demonstrated that LegSense enhances embodiment, walking sensation, and presence compared to the baseline condition. Although no significant differences were found between LegSense and the vibro-tactile condition across all metrics, participant interviews confirmed the effectiveness of LegSense in creating a leg movement illusion, suggesting its potential for various VR applications, such as simulating different types of terrain or movement-related events.

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