SoniFootsteps: Movement-Triggered Footstep Sounds to Modulate Body-Weight Perception, Gait and Emotion

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Abstract

Body movement sonification has gained increasing attention in rehabilitation and healthcare as a means to influence movement, and body perception. Prior research on the Footsteps Illusion demonstrated that real-time pitch manipulation of self-produced footstep sounds can alter perceived body weight and emotional responses. However, the systems used for that illusion rely on microphones that require controlled laboratory conditions, limiting their applicability in natural settings. This study introduces a novel, portable approach that employs prerecorded footstep sounds, played synchronously with walking movements and filtered to evoke sensations of lighter (high-frequency) or heavier (low-frequency) bodies. Participants walked along an indoor circuit while listening to these sounds; their responses were evaluated through self-reports and gait analysis. Results show that prerecorded, movement-triggered sounds can reproduce the perceptual and emotional effects observed in real-time sonification setups. These findings highlight the importance of auditory feedback in shaping body perception and emotional experience. The proposed system extends the Footsteps Illusion beyond the lab, opening possibilities for sound-based Body Transformation Experiences (BTEs) in diverse contexts, such as healthcare, rehabilitation, and everyday movement practices that support well-being.

CCS Concepts

- **Human-centered computing → Auditory feedback**.

Keywords

Body Perception, Sonification, Evaluation Methods, Embodied Interaction, Wearable Computers

ACM Reference Format:
Amar D'Adamo, Frédéric Bevilacqua, Marta Matamala-Gómez, and Ana Tajadura-Jiménez. 2026. SoniFootsteps: Movement-Triggered Footstep Sounds to Modulate Body-Weight Perception, Gait and Emotion. In *MOCO '26: Proceedings of the 10th International Conference on Movement and Computing (MOCO '26), April 23–25, 2026, Montpellier, France.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3802842.3802882

1 Introduction

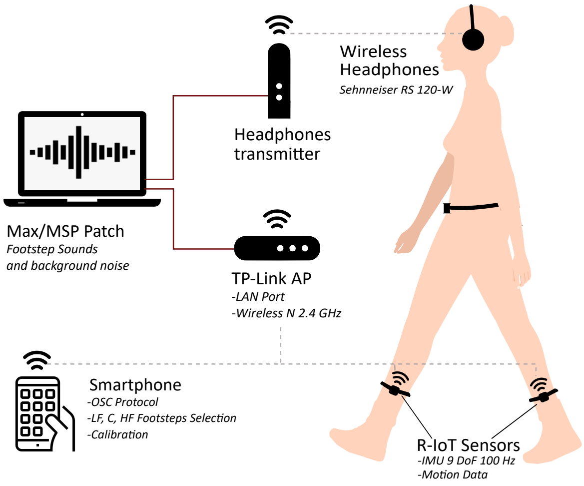

Figure 1: System overview: Prerecorded footstep sounds are delivered via wireless headphones in synchrony with walking movements, tracked by wireless Inertial Measurement Unit (IMU) sensors on the lower legs.

Body sonification—the use of non-speech sound to represent movement or physiological data—has increasingly been used for motor rehabilitation, and movement disciplines, i.e., dance, encouraging physical activity and performance arts [55, 60, 83, 85, 86, 115]. Such technology also offers promising opportunities to address psychological barriers related to body perception, which continue to pose a significant research challenge [55, 90]. One approach to tackling these barriers involves evoking Body Transformation Experiences—designing interactions that alter how individuals perceive or

MOCO '26, Montpellier, France

ACM ISBN 979-8-4007-2500-5/26/04
https://doi.org/10.1145/3802842.3802882

experience their own bodies through sensory feedback. Previous research on body transformation experiences using movement sonification has employed metaphorical sounds that reproduce natural environments—such as synthetically generated wind or water—or synthetic tones and melodies to increase foot speed, rhythm or balance [53, 55, 89]. A recent study extended this approach by using "Wind" and "Mechanical Gear" sonifications to modulate walking symmetry and body perception in individuals with chronic stroke [64]. The "Wind" sound condition led to consistent improvements in walking velocity and symmetry, and enhanced perceptions of body lightness, speed, flexibility and physical capability. These studies build on a growing body of work demonstrating that sensory feedback can alter body perception [5, 46, 50, 52, 70, 72, 74, 88, 104, 105]. In this context, an interactive multisensory system introduced by [98] employs real-time sound feedback to alter perceived body weight by modifying the wearer's footstep sounds—a phenomenon known as the "Footsteps Illusion". It has been shown that a crucial aspect to induce this illusion, is the sense of agency over the provided footstep sounds. The sense of agency has been defined as the sense of having control over body movement and actions [38]. The Footsteps Illusion has since been investigated in diverse domains, including physical inactivity, chronic pain, eating-disorder symptomatology, and rehabilitation after chronic stroke [13, 15, 20, 26, 36, 99–101].

Previous research on the Footsteps Illusion have relied on real-time manipulation of participants' actual footstep sounds, captured with microphones. This microphone-based approach, however, requires controlled laboratory conditions with minimal external noise, as environmental sounds are also captured and distorted during playback. Moreover, although recent developments have improved portability [20], the equipment remains less practical than everyday wearable devices such as fitness bands.

To the best of our knowledge, no prior work on the Footsteps Illusion has used prerecorded footstep sounds that are dynamically triggered to match each step in real time. Such an approach allows auditory feedback to follow natural gait patterns while enhancing ecological realism and supporting deployment beyond laboratory settings.

Building on previous research on the Footstep Illusion, the present study introduces a new method and system designed to induce this illusion and examine its effects on body feelings, emotional experience, and movement. Whereas earlier work manipulated the real-time auditory feedback of participants' own footsteps, our approach employs a portable device that delivers prerecorded footstep sounds, synchronously triggered by individual walking patterns and filtered using parameters adapted from [20, 98]. The filters reproduce auditory cues typically associated with lighter bodies (high-frequency, HF) or heavier bodies (low-frequency, LF). This setup enables controlled and replicable testing of the Footstep Illusion beyond laboratory conditions. We evaluated the system through an experiment incorporating quantitative measures, visualization tasks, and interviews.

In the study, participants walked while prerecorded footstep sounds were played synchronously with their footsteps. Using self-reports and behavioral measures (i.e., gait and body visualization), we tested the hypothesis that frequency manipulations of the provided footsteps sounds would replicate earlier findings: participants would perceive their bodies as lighter and slimmer in HF compared to LF. We also measured whether participants felt agency over the sounds, as previous works have shown that significant disparities between modalities or delays in action-feedback reduce sensory-induced body illusions [65, 104].

This study presents two main contributions:

- Evidence that the effects on perceived body weight reported in previous Footsteps Illusion studies can also be elicited with prerecorded, pitch-altered footstep sounds triggered by their own steps, rather than to modified versions of their actual footsteps sounds, along with the related effects on body behavior and emotional experience.
- A prototype enabling a portable version of the Footsteps Illusion, which would enable studies outside the lab and opening new research avenues, such as exploring long-term effects or the influence of contextual factors tested through in-the-wild studies.

This work extends prior research on interactive sound and body perception, focused on body sonification (e.g., [6, 12, 29, 30, 34, 37, 40, 54, 55, 60, 69, 78, 79, 89, 91, 92, 110, 113]) by showing that movement-activated, prerecorded footstep sounds can evoke perceptual effects, comparable to those reported in studies on the Footstep Illusion that used modified versions of participants' actual footstep sounds captured via microphones [20, 98]. These findings open promising directions for creating and studying sound-based Body Transformation Experiences (BTEs) in daily life interactions, with far-reaching implications for well-being, rehabilitation, sport, and artistic practice.

2 Background

2.1 Malleability of Body Perception

Neuroscience research has shown that body perception is highly malleable and shaped by sensory signals [47, 63, 97]. It has been shown that synchronous multisensory stimulation, even for a session of a few seconds, may induce individuals in perceiving dummy limbs [8], tools [63], or virtual bodies [47, 97] as part of their own body. Such updates in body perception enable us to be aware and adapt to, the positioning and movement of our body parts and to our continuously changing physical appearance and dimensions [23]. Beyond this kinesthetic role, body perception is also influenced by cognitive factors (e.g., prior beliefs about one's body and social perception [2, 4, 7, 25, 26, 32]) and emotional processes [15, 76, 95, 102]. For instance, when we feel happy, we may experience our bodies as lighter and more agile, whereas sadness can make us perceive them as heavier [39].

2.1.1 Changing Perceived Body Weight through Footstep Sounds: the Footsteps Illusion. The Footsteps Illusion [98] shows that altering real-time footstep sounds can change perceived body weight. By manipulating the spectral profile of recorded steps, a wearable system produced LF and HF variants—corresponding to heavier and lighter bodies, respectively (see also [59, 106]). Short-term exposure to these pitch-altered sounds changed participants' perceived body size and weight, with HF sounds evoking lighter, more dynamic gait patterns [107, 114] and more positive mood. Subsequent studies linked the illusion to shifts in gender identity [15, 20, 101] and exercise motivation [101], and examined its potential in rehabilitation [36, 99], as well as eating disorders contexts [100]. Originally based on an analog equalizer and shoe-mounted microphones, the system later evolved into the portable, digital Soni-Weight Shoes [20, 22], enabling larger-scale studies on individual differences [20, 26]. Despite robust laboratory results, microphone-based setups limit real-world use due to the presence of noise in the environment.

2.2 Sensorimotor Signals: Body Perception and Agency

Body perception can be altered when sensory feedback meets four principles: semantic, temporal, and spatial congruency, as well as agency [45, 46, 61, 108]. Although semantic congruency can be can be reduced or partially violated [68, 82, 96], the sense of agency (i.e.,perceiving feedback as self-generated) remains essential [103]. In the Footsteps Illusion, delaying footstep sounds while walking is known to disrupt agency and the sense of body ownership [65]. Human Computer Interaction (HCI) works similarly show that movement-linked haptic cues or muscle stimulation induce embodiment only when synchronized with user motion [24, 43, 93, 94]. Thus, temporal coupling between movement and sensory feedback is critical for sustaining the sense of body ownership and agency. The present study evaluates whether it is possible to elicit the Footsteps Illusion by using prerecorded, pitch-altered footstep sounds that are temporally synchronized with individuals' walking movements.

2.3 Beyond Microphones: Synthesis and Prerecorded Footstep Sounds

Research on footstep sound synthesis [109] introduces a physically inspired approach, combining physical models with additive synthesis, to simulate foot–floor interactions, shoe types, ground materials, and walker characteristics simultaneously and in real time [51, 112, 116]. Further, this system has been employed in [110], showing how footstep sounds are shaped by various combinations of shoe type and ground materials, and paving the way to design ecologically-valid auditory renderings of foot-floor interactions. Synthesizing sounds offers the advantage of maintaining the desired auditory qualities even when environmental conditions change in real time. On the other hand, prerecorded sounds—traditionally sourced from libraries or recorded by Foley artists [121]—provide authentic detail and realism: they convey movement convincingly in films and animation [120]. Studies also show that recorded footsteps support immersive media, successfully conveying walker traits in 3D avatar contexts [19]. However, sequences of footstep sounds created by concatenating the same isolated recording are often perceived by listeners as mechanical [17, 31]. Randomization strategies, such as the one employed in our work, are therefore key to achieving ecological validity. Footstep sounds hold the potential to enhance user experience in interactive systems and virtual environments. [12] explored the expressive sonification of footstep sounds, using both synthesized and prerecorded sounds, varying the reproduced surface, e.g., snow, mud, wood, linoleum, investigating how variations in walking sounds can convey different qualities or emotions in interactive contexts. They employed force sensors installed in sandals, and allowed tuning a threshold, set based on the individual's weight and foot size. Similarly, Turchet and Serafin [111] investigated how temporal cues (timing between heel-and-toe contact and the time interval between footsteps) alone can support the perception of uneven surfaces (bumps or holes) during walking. They showed that varying just these temporal intervals was sufficient to induce correct perceptions of bumps or holes. Soundscape choices [62] and shoe size [35] have also been shown to play a key role in altering body perception during walking. Recent work has focused on footstep detection, for instance through pressure measurement. [117] proposed a knowledge-assisted gait analysis system to support clinicians in making clinical decisions based on objective data. A footstep recognition matching method was proposed by using pressure-sensitive floor to collect the pressure signal and using semi-Markov models to detect footsteps from the floor data [49]. The sound of walking was also employed to recognize footsteps and achieved nearly 80% recognition accuracy [9]. Some researchers detect the gait through vision method, e.g., proposing gait-based human identification method by recognize the gait of a person in the video and achieved a over 97% recognition accuracy [3]. Wearable sensors are nowadays the most common tools for quantitatively analyzing gait to support clinical diagnosis and treatment procedures [14, 66]. Sock-embedded sensors are also use [41]. Optical fiber sensors have achieved up to 86% accuracy [87], with applications in gait-based clinical diagnosis or person identification.

2.4 Sonification Applications in Healthcare

Recent research has highlighted the potential of sonification as a promising tool in healthcare and rehabilitation. Other possible ways to increase physical activity include mindfulness training [80].To counter physically inactive lifestyles, which pose a risk for health issues, [53, 89] used triggered pitch-varying sounds to motivate individuals movement and improve emotional state. Sonification has also been applied to gait rehabilitation in [119]. Sonification can enhance motor perception and engagement by coupling auditory feedback with physical actions, thereby reinforcing sensorimotor integration. For example, observing movements accompanied by congruent sonification activates multisensory and motor networks [118]. In clinical applications, musical sonification of handwriting movements [21] and gravel-footstep sounds representing different spatio-temporal gait parameters, such as step duration and length [81], significantly improved motor control in patients with Parkinson's disease. Similarly, recent studies on upper-limb rehabilitation indicate that different types of sonification—such as pitch, tempo, or environmental sounds—can improve movement duration and user motivation in both hemiparetic and healthy individuals [67]. Together, these findings suggest that movement-accompanied sound can serve as an effective multisensory feedback mechanism for enhancing rehabilitation outcomes.

While these methods employ sound and its combination with movement, haptic feedback has also revealed its potential for increasing awareness on material experiences while walking, see [94]. Further, barefoot walking has been found to significantly increase cognitive speed and concentration and decrease brain stress in adolescents [48], opening the potential for footsteps sonification application in barefoot walking.

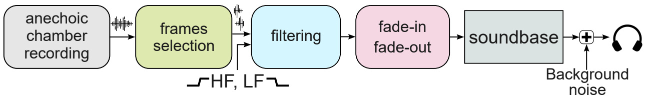

Figure 2: Sound processing. Footstep sounds were recorded in an anechoic chamber; after selection, the sounds were trimmed and filtered, and fade-in and -out were applied; final background noise was added.

3 System Implementation

3.1 Crafting the Sound Stimuli

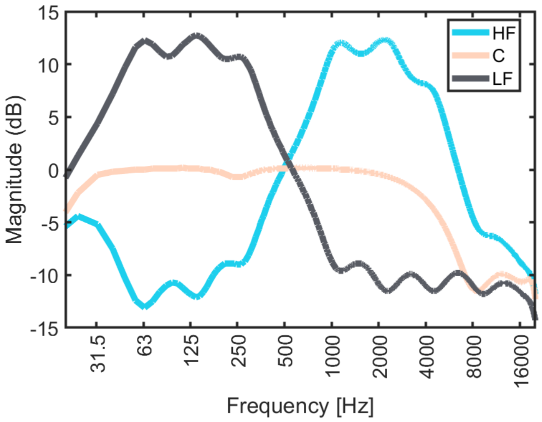

Figure 3: Frequency response of the High Frequency (HF), Low Frequency (LF) and Control (C) sound condition filters.

To test whether the Footsteps Illusion effects were elicited also with a setup that triggers footstep sounds in correspondence with the participants' walking activity, the stimuli were systematically prepared. The footstep sounds were recorded, selected and trimmed, then processed using filters that replicate the ones used in [20, 98]. Finally the sounds were organized in a soundbase, following the diagram showed in Fig. 2. The recording was performed in an anechoic chamber: three people, wearing binaural microphones (one on each shoe) performed multiple sessions employing various materials, footwear, walking speed, and, for half of the sessions, wearing additional weights, with the objective of covering broader participants body weight ranges: 50-55 kg, 55-60 kg, 60-65 kg, 65-70 kg, 70-75 kg and 75-80 kg. Piloting sessions were conducted with the objective of selecting the sounds that better resembled the own person's footsteps. During these sessions, we played the sound corresponding to the own weight of the piloting participant and decided on the materials and footwear that sounded the most plausible to the participants. It is worth mentioning—as it influences the footstep sound duration-that the selected walking speed was 100 bpm. For a detailed description of the recording and piloting sessions, see Supplementary Material. Later, for each weight range set of sounds we selected six footsteps pairs (left-right) and subsequently divided them in separate left- and right-steps (each approx. 500 ms long). A Matlab script was then used to filter the sounds (see Fig. 3 for the filters' frequency response) and apply fade-in (10 ms) and fade-out (50 ms). The results was a soundbase of HF, LF and C footstep sounds (six for left and six for right) for each of the six body weight ranges. Having multiple sounds for each weight range allow triggering randomly the sounds and avoid perceiving the footsteps feedback as repetitive. Using a ZOOM H2 recorder, we acquired environmental noise in the experiment location. The noise was later reproduced in background to make the session less frustrating and increase the immersiviness of the experience.

3.2 SoniFootsteps: a Wearable Sonification Device to Change Body Weight Perception

In order to investigate the effect of triggered footstep sounds on body perception, we extended SoniShoes, a wearable device that sonifies movement through metaphorical sounds [57]. The revised wearable device consists of wireless sensors, i.e., IMUs, that capture people's bodily movements as inputs mapped to different sound samples and processing. Note that this differs from the prototype used in [20] in which the actual footstep sounds were modified in real-time. Apart from playing and modifying prerecorded footsteps sounds, the system also allows for the measurement of IMU data to quantify user behavior. The version of the wearable device we used here (see Fig. 1) is composed of two Bitalino R-IoT sensor modules that embed a 9-axis IMU sensor with 3 accelerometers, 3 gyroscopes and 3 magnetometers, all sampled in 16 bit. As shown in Fig. 1, the sensor modules were attached to the left and right lower legs. The data are sent over Wi-Fi using OSC protocol to a computer running a dedicated software using the Max/MSP environment (Cyling'74, [1]). Our software allows for triggering recorded footstep sounds, used as auditory feedback. The patch was set to trigger the sounds employing a threshold on the R-IoTs' gyroscope value on the axis of ankle rotation during gait. This value is reached between the mid-swing and the terminal-swing phases, anticipating the heel strike. Compared to other triggering options, for example using accelerometer data, the use of this gyroscope axis was found the most robust for triggering. To ensure the sound aligns with the actual moment of heel strike, a customizable delay parameter was added, allowing accurate synchronization with the heel-to-ground contact. A calibration phase was included in the experiment to set the delay, so that it matched the synchronization with the actual footstep event, based on the participants' judgment.

An Android smartphone, connected over Wi-Fi to the same LAN network, with OSC Controller [44] was configured to select the footstep tracks. The Max/MSP patch was programmed to receive the OSC commands sent from the app, to let the experimenter choose, from an 18-pad interface, the footsteps frames (i.e., LF, C, HF) for each weight range. Additionally, it allowed to perform the calibration task and it integrated a test-button to reproduce one of the sounds from the selected group.

4 Methods

4.1 Participants

12 participants (mean age ± SD: 26.00 ± 3.16 years, range: 20-32; sex: 7 males and 5 females; mean weight ± SD: 66.68 ± 11.23 kg; mean height ± SD: 176.00 ± 10.41 cm) naïve to the research aim, took part in the study. They were recruited through the UMR 9912

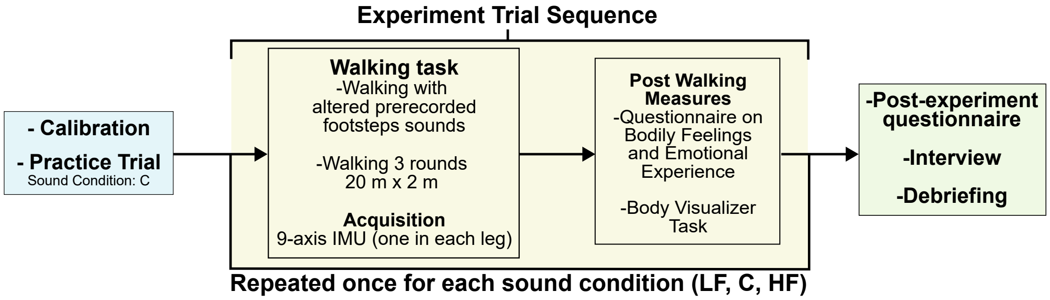

Figure 4: Experiment procedure. After delay calibration and a practice trial (C) the walking task, which was repeated once for each sound condition (LF, C, HF), involved walking three times along a 2 x 20 m circuit while listening to the triggered footsteps sounds. Acceleration data was acquired from the lower legs and after the walking these measures were collected: Questionnaire on Bodily Feelings and Emotional State and Body Visualizer Task. The session was concluded with a Post-Experiment Questionnaire and Feedback Interview.

IRCAM participant pool and social networking. Inclusion criteria were: age over 18 years; normal hearing; no disabling orthopedic or neuromuscular conditions affecting walking; proficiency in English; and the ability to understand study information, provide informed consent, and communicate effectively. Participants provided the following information during recruitment: demographics, including age, sex. Anthropometric measurements (height and weight) were collected before the experiment and were used for the body visualizer task (see section 4.2) and to select the footsteps sounds used in the study. The study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments and was approved by the Committee of Ethics in Research of Universidad Carlos III de Madrid. All participants provided informed consent before participating and received €10 cash as compensation for their time.

4.2 Measures

4.2.1 Questionnaire on Body Feelings and Emotional Experience. A Likert-type questionnaire (see Supplementary Material), adapted from [20, 98, 101], was used to assess body feelings. Nine statements addressed felt walking speed (*Quickness*), body weight (*Weight*), *Strength*, posture (*Straightness*), and femininity/masculinity (*Masculinity*), *Experience Vividness*, *Surprise*, *Agency* over sounds [65, 104], and foot localization (*Proprioception*) [104]. Emotional experience was assessed with the Self-Assessment Manikin (SAM) questionnaire [11], comprising three 9-point graphic scales for *Valence*, *Arousal*, and *Dominance*. Widely used to evaluate emotional responses to acoustic stimuli [10], the SAM has also been applied in studies on the Footsteps Illusion [20, 98, 99, 101].

4.2.2 Body Visualization. Participants' visual estimates of their body weight were assessed using the *Body Visualizer* tool [75], displayed on a laptop 16" screen. This tool has been used in similar studies [20, 73, 98–101]. After each trial, participants completed the Body Visualization task twice. The experimenter set the avatar's gender and height to match those of the participant and initialized its weight at either 85% or 115% of the participant's actual weight. Using keyboard arrows, participants adjusted the avatar's 'weight' dimension to match their perceived body size (see [20, 98, 100, 101]). The initial weight condition was counterbalanced across trials to avoid anchoring effects of the starting value [73, 98], and analyses used the average estimate for each sound condition.

4.2.3 Gait Biomechanics. Gait features were used as an implicit measures of changes in body perception, following previous studies [20, 98] showing that the sound-driven illusion of altered body weight (i.e., the Footsteps Illusion) modulate gait towards patterns typical of lighter or heavier bodies. As in those studies, we quantified *walking velocity*, *foot acceleration* and *step duration* (time between two successive steps of the same foot and averaged across both legs, since we assume that any bilateral asymmetries in walking are negligible) [18]. Gait patterns in heavier bodies are typically characterized by slower speed and longer step durations [107, 114].

4.2.4 Post-Experiment Questionnaire and Feedback Interview. At the end of the experiment participants completed a post-experiment questionnaire including 7-point Likert scales assessing the *synchronization of the sounds with their actual footsteps* and *plausibility* of the triggered sounds. They also rated their level of *perceptual exhaustion* [42, 84] after the experience (see Supplementary Material). The session concluded with two open-ended questions to gather feedback on the study and system design.

4.3 Procedure

Fig. 4 shows a graphical overview of the experimental procedure. Participants were asked to wear sport shoes throughout the session. The experiment consisted of four two-minute trials. Each trial involved walking for three times on a linoleum floor along a 20 x 2 m circuit while using the wearables and a pair of wireless headphones.

First, participants conducted a calibration round, in which the triggering delay was set, followed by a practice trial (C) to familiarize themselves with the experimental tasks. Participants were instructed to walk at a speed of approx. 100 bpm. They then completed the HF, LF and C trials in randomized order. During each trial, movement data from the IMU sensor placed on each leg (lower leg) were acquired. The sensors were secured with textile elastic bands to ensure comfort and stability during walking, and their lightweight design minimized interference with natural movement.

At the end of each trial, participants performed the body visualization task and filled in the Questionnaire on Body Feelings and Emotional Experience. To conclude the experiment, after the walking sessions, they completed the Post-Experiment questionnaire and the Feedback Interview on the experiment and setup design.

4.4 Statistical Analyses and Data Treatment

Gait data was processed in Matlab (version R2022a). Gyroscope, acceleration and intensity signals were plotted and gait features for each sound condition were then exported for further analyses. These values were averaged across the signals from the left and right legs. Statistical analyses were conducted in R (version 4.3.1, R Core Team, 2018). Alpha levels were set at 0.05, with p-values adjusted for multiple comparisons, using Bonferroni correction. Non-parametric data (i.e., questionnaires) were analyzed using aligned rank transform ANOVAs (ART ANOVA [28]) with sound condition as the single factor, followed by Wilcoxon signed-rank tests when significant. Parametric data were analyzed using one-way ANOVAs with sound condition as the factor, with significant effects followed up by t-tests, also applying Bonferroni correction.

5 Results

We present here the results on the bodily illusion, including body feelings and emotional experience, body visualization and gait biomechanics. Finally we report participants' feedback on the study.

5.1 Body Feelings and Emotional Experience

Here, we report the statistical results only when a significant effect of sound condition was found.

Questionnaire data showed a significant effect of sound condition on *Weight*, *Quickness*, and *Proprioception*, see Table 1 and Fig. 5 a), b) and c). Post-hoc tests showed that participants reported feeling lighter in HF than in LF and C, and quicker in HF compared to LF. The effect sizes were large for both *Quickness* and *Weight* [16]. Even if a main effect was found for *Proprioception*, indicating larger scores for the pitch-altered conditions than for C, this effect was not significant in the post-hoc tests. Importantly, no significant differences between conditions were observed for the feeling of *Agency* (i.e., the feeling of producing the sounds). While agency ratings were generally not high, the filtered sound conditions did not reduce the perceived sense of producing the sounds.

Regarding emotional experience variables, participants reported feeling relatively positive, and aroused across sound conditions. Dominance values were also high, with no difference between conditions. These findings suggest that the sound manipulations did not negatively affect participants' mood or their sense of control over the task.

5.2 Body Visualization

Results from the ANOVA tests on body visualized weight did not reveal a significant effect of sound condition. To obtain a measure of perceived weight distortion due to the sound condition, body visualizers weight values were normalized to each participant's actual weight. The mean weight distortion values (± SD) were: HF: -3 (± 13) %, C: -2 (± 11) % and LF: -1 (± 13) %.

5.3 Gait Biomechanics

Results from the gait biomechanics analysis showed significant main effects for *Step Duration* (F=3.95, p=0.036, $\eta_p^2 = 0.28$): participants steps were shorter in time for HF compared to LF (t=2.03, p=0.029). Means (± SD) were for HF: 1.23 (± 0.08) s, C: 1.25 (± 0.09) s and LF: 1.26 (± 0.10) s, see Fig. 5 d). Although the ANOVA for participants walking speed did not reach statistical significance (F=3.33, p=0.056, $\eta_p^2 = 0.25$), the result approached significance, indicating a potential effect worth further investigation. Velocity means (± SD) were for HF: 0.61 (± 0.41) steps/s, C: 0.60 (± 0.46) steps/s and LF: 0.59 (± 0.48) steps/s.

5.4 Post-Experiment Feedback

The questionnaires at the end of the experiment revealed very good synchronization, Median (Range): 6 (3), moderate plausibility of the footstep sounds: 5 (5) and very low perceptual exhaustion: 1 (3).

During the interview, participants described clear differences in how they experienced their bodies depending on the sound condition. HF was associated with feelings of lightness, agility, and energy. Many said they felt as if they were "walking on their toes" or that their steps became "more dynamic." Some mentioned that these sounds made them feel "faster" or "more confident", and even influenced their mood, with several describing the experience as "uplifting". In contrast, LF was associated with heaviness and groundedness. Participants reported feeling their steps as "heavier" or "closer to the ground," sometimes leading them to slow down or feel "more stable but less free"; one participant described that their steps became "bouncier" and one "sounding like heart-beat sounds." A few participants described these sounds as making them "more aware" of their body weight or "more connected to the floor." Participants also reflected on changes in how they related to their own bodies, influencing how they moved. For instance, walking "with more presence" or "feeling taller"; One participant walked with their arms crossed during LF. However, around a third of the participants also pointed out that the sound felt artificial, delayed, or repetitive. These mixed reactions highlight both the potential and the limitations of the sound-based feedback used in this study to influence body perception. Participants also commented on the sound levels and the character of the footstep recordings. One participant noted that the sounds felt "too loud" and a few mentioned they were produced "very close to their ears". This perception is likely related to the recording method, as the original footstep sounds were captured using microphones mounted directly on the shoes, replicating the microphone location used in previous studies of the Footsteps Illusion [20, 103].

6 Discussion

The following sections discuss the study findings, focusing on device implementation and its effects related to the Footsteps Illusion in healthy participants. We also reflect on methodological opportunities and design implications for future research in this area. These advancements could help extend BTEs to more complex, real-world (in-the-wild) scenarios.

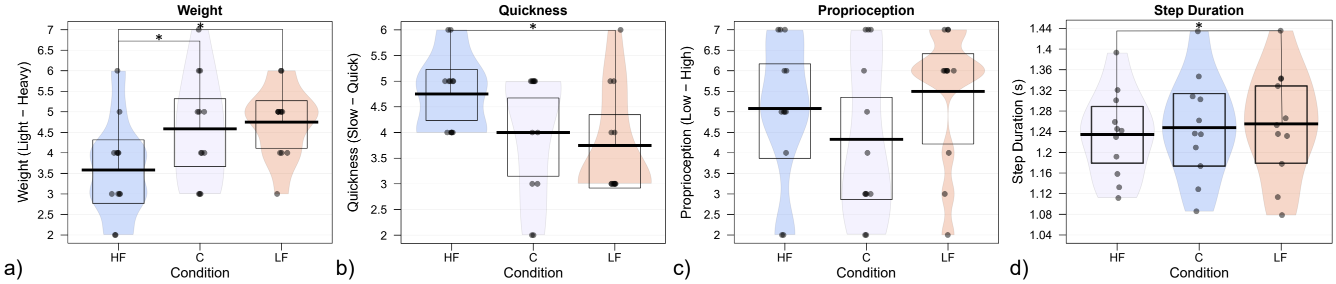

Figure 5: Experiment 1 Results. Questionnaire on Body Feelings and Emotional Experience items: a) Weight, b) Quickness and c) Proprioception; d) Step Duration (* denotes p<.05).

Table 1: Effects of Sound Condition for questionnaire data (7-level Likert items except for 9-level valence, arousal and dominance scales): median(Range) values and results of ANOVAs on aligned-ranked data, corrected Wilcoxon Pairwise Comparisons.

	ANOVA on aligned-rank transformed data				Wilcoxon Pairwise Comparisons		
Variable	**C(n)**	**LF(n)**	**HF(n)**	**Effect of Sound Condition**	**HF vs C**	**HF vs LF**	**LF vs C**
Valence	5(4)	6(4)	6(3)	F = 0.76, p = 0.479, η_p^2 = 0.06	z=-0.36 p=0.219	z=-0.06 p=0.829	z=-0.27 p=0.351
Arousal	5(6)	5(7)	5(4)	F = 0.12, p = 0.886, η_p^2 = 0.01	z=-0.11 p=0.714	z=-0.07 p=0.796	z=-0.12 p=0.670
Dominance	5(4)	6(3)	6(5)	F = 2.01, p = 0.157, η_p^2 = 0.15	z=-0.15 p=0.609	z=-0.28 p=0.335	z=-0.68 p=0.019
Quickness	**5(4)**	**3(4)**	**5(2)**	**F = 3.55, p = 0.046, η_p^2 = 0.24**	z=-0.43 p=0.140	**z=0.60 p=0.037**	z=-0.23 p=0.429
Weight	**4(5)**	**5(3)**	**3(4)**	**F = 4.98, p = 0.016, η_p^2 = 0.31**	**z=-0.70 p=0.015**	**z=-0.63 p=0.028**	z=-0.06 p=0.834
Strength	4(4)	5(3)	5(3)	F = 0.80, p = 0.460, η_p^2 = 0.07	z=-0.27 p=0.345	z=-0.02 p=0.932	z=-0.27 p=0.343
Straightness	5(5)	4(3)	5(4)	F = 0.36, p = 0.702, η_p^2 = 0.03	z=-0.03 p=0.930	z=-0.21 p=0.468	z=-0.10 p=0.719
Masculinity	4(4)	4(4)	4(4)	F = 1.97, p = 0.162, η_p^2 = 0.15	z=-0.48 p=0.098	z=-0.32 p=0.269	z=-0.04 p=0.890
Proprioception	**4(5)**	**6(5)**	**5(5)**	**F = 3.80, p = 0.038, η_p^2 = 0.26**	z=-0.55 p=0.058	z=-0.23 p=0.430	z=-0.52 p=0.072
Vividness	3(5)	4(5)	2(5)	F = 2.80, p = 0.082, η_p^2 = 0.20	z=-0.21 p=0.457	z=-0.32 p=0.267	z=-0.62 p=0.031
Surprise	3(6)	3(5)	4(5)	F = 0.49, p = 0.618, η_p^2 = 0.04	z=0.00 p=1.000	z=-0.21 p=0.457	z=-0.27 p=0.354
Agency	3(6)	3(5)	3(6)	F = 0.41, p = 0.668, η_p^2 = 0.04	z=-0.16 p=0.586	z=-0.14 p=0.621	z=-0.07 p=0.811

6.1 Interpreting the Findings

This work explored how the Footsteps Illusion can be induced to shape body perception using synchronously triggered prerecorded footstep sounds altered in sound frequency to resemble lighter or heavier bodies. Our results confirmed that pitch-altered sounds influenced participants' bodily sensations, emotional state, and movement behavior, offering a promising step toward more portable systems for sound-induced BTEs.

Our work provides the first evidence that the Footsteps Illusion can be elicited using prerecorded, pitch-altered footstep sounds that are synchronously triggered by participants' walking movement, rather than through real-time manipulation of their own footstep sounds. Participants perceived their bodies as lighter in HF and heavier in LF, consistent with previous findings showing that increasing the high-frequency components of footstep sounds evokes sensations of quickness and reduced body weight, whereas emphasizing low frequencies produces the opposite effect [13, 20, 98]. Participants also reported feeling quicker in HF compared to LF, replicating prior results [20, 36, 100, 103]. These findings confirm that sound-driven body sensations can emerge even without real-time alteration of one's own footsteps. This suggests that the illusion relies not solely on the self-origin of sound but on the perceptual interpretation of action-consequent auditory patterns that align with expectations of body weight and movement dynamics, extending prior work on body sonification that has shown effects on these variables [53, 55, 89].

Proprioception results also differed significantly across sound conditions, in line with [20]. Importantly, no significant changes were observed in participants' sense of agency over the sounds. While synchronization ratings were generally high, agency ratings were not. Several participants described the sounds as somewhat artificial or detached from their bodily actions. This aligns with previous research showing that delays [65, 104] or unfamiliar sounds [77] can reduce the sense of agency over the sounds, as well as the integration of auditory feedback into the body representation. Although agency was not reduced to the point of preventing perceptual effects, these qualitative observations indicate that further refinement of temporal alignment and sound variability will be essential to enhance embodiment in real-world uses. Overall, these results demonstrate that using one's movements to trigger externally generated auditory cues, can effectively alter body perception, reinforcing prior evidence from works employing body sonification [53, 55, 89].

The pitch-altered footstep sounds also changed the way participants walked. We observed shorter step durations in the HF condition compared to LF, consistent with previous studies in which LF was associated with longer foot-ground contact times [98]. Walking speed did not significantly differ across conditions, although a trend toward increased velocity in the HF condition suggests that step-timing changes may accumulate into broader gait adaptations over longer periods. Body visualization measures did not differ significantly across conditions, contrasting with earlier findings showing that footstep-based sound manipulation can influence the visualized body size [98, 101]. One possible explanations relates to the smaller display used for the body visualization tool in the present study. Using a larger screen, as in previous studies, e.g., [20], may facilitate the body size adjustment task and yield larger differences across sound conditions.

6.2 Insights on Methodological Challenges and Limitations

The study we presented required participants to walk at a constant speed along a fixed circuit. The need for these specific conditions to ensure accurate synchronization of footstep sounds while walking limits the freedom of movement desirable for an optimal embodied experience. Importantly, the results-already replicating previous findings of the Footsteps Illusion-could potentially be enhanced with more precise timing and adaptive feedback, consistent with the critical role of temporal coupling between actions and sensory feedback for agency and body ownership [65, 94, 103, 104]. Considering participants' agency ratings, the system design could benefit from improvements in sound triggering. Interviews revealed that participants were attentive to the mismatches between the footstep sounds they heard and the sounds they expected based on their own movements. For example, feedback such as "I have bigger shoes than the ones in the sounds" (P13) highlights the importance of semantic congruency and individual differences in sensorimotor integration [45, 61].

These observations point to opportunities for alternative sound-triggering strategies, including enhanced footstep detection [3, 9], adjustments to R-IoT sensor placement, and refinement of kinematic measurement thresholds. Such improvements in timing could reinforce agency and embodiment, as HCI studies show that movement-linked sensory feedback is effective only when precisely synchronized with user motion [24, 93]. Although adjusting the threshold settings could make it possible to detect the precise moment of heel-strike, the current setup still introduces too much latency for this to be practical. An alternative approach would be to use multiple sensors (for example, placing one on the lower leg or heel and another on the tip of the shoe). This would provide more precise information about the motion of the foot and allow for more accurate triggering strategies. In this setup, different sounds could be activated for distinct phases of each footstep, effectively dividing steps into multiple temporal segments. This approach would also improve adaptability to variations in shoe size across individuals and aligns with research showing that temporal and spatial nuances in auditory cues enhance the perception of gait and surface interactions [12, 111]. Finally, synthesizing real-time footstep sounds [109, 110] could further increase the device's adaptability to individual users and environmental conditions, which are continuously changing in more complex, dynamic settings.

6.3 Toward Real-World Body Transformation Experiences

The choice to use prerecorded footstep sounds, rather than real-time synthesized sounds (see [109, 110]), was motivated by the goal of extending the setup to less controlled environments, such as outdoor settings. Unlike more complex—rapidly changing—scenarios involving multiple walking conditions (e.g., slow walking to running), diverse walking surfaces (e.g., leaves, mud, snow, concrete), footwear variations, and walker characteristics, this study focused specifically on the frequency spectra content of footsteps sounds and their effects on body perception, mainly body weight perception. The experimental conditions of this study were deliberately kept nearly constant to maintain control. Extending from this, sounds that we perceive less natural and we are not used to hearing during the situations in which we hear them, may be leading the listener into focusing more on the sounds, as shown in [71], potentially amplifying cross-modal effects on body perception, including the ones evoked by pitch-modulated sounds, as in the Footsteps Illusion.

Texture and surface cues in natural sounds increase plausibility and the likelihood that sounds are perceived as belonging to the walker [33], which may also support awareness of the activity (e.g., hearing gravel while hiking). Metaphorical or added sonifications have been shown to increase motivation for exercising, affective valence and movement coordination [53, 89]—making them suitable for augmenting routine activities such as commuting or home exercise.

Furthermore, the system we developed is flexible and can be adapted to use a variety of sounds beyond footsteps. For example, it could integrate environmental sounds or specially designed soundscapes for artistic performances or workshops, to evoke different experiential or emotional states. This aligns with research demonstrating that sound can be tailored to reinforce sensorimotor learning, affective states, or environmental awareness [21, 118, 119], opening the door to a wider range of BTEs and affective interventions in diverse contexts. In clinical populations, such as individuals suffering from neurological disorders, chronic pain, or psychiatric disorders, nature based interventions—which engage participants in immersive natural experiences—have been shown to improve mental health and well-being [58]. Hence, such advances pave the way to the use of sound based immersive technologies for mental health applications and well-being.

In this context, our work also aligns with recent approaches to designing technologies for health and well-being by leveraging multisensory feedback to address barriers related to body perceptions. Feelings of heaviness are common in various conditions, including physical inactivity, [56], chronic pain [99], chronic stroke [36], and depression [27]. Sound-based feedback targeting body perception, and in particular perceived body weight—such as that implemented in this study—may thus provide new opportunities to support rehabilitation, emotional regulation, and engagement in physical activity through embodied multisensory interventions.

7 Conclusion

This work shows that prerecorded, movement-triggered footstep sounds can alter body feelings and walking activity, replicating key aspects of the Footsteps Illusion without requiring real-time microphone feedback. These results demonstrate the feasibility of portable, wearable systems for sound-induced body transformation and highlight the potential for extending the approach to other sounds for applications in well-being, rehabilitation, and artistic contexts.

In sum, our work confirms that auditory feedback can meaningfully shape body perception and movement, opening new opportunities for in-the-wild interventions and multisensory bodily experiences.

Acknowledgments

The authors would like to express their gratitude to Léo Mercier and the other collaborators who took part in the study organization at IRCAM, Paris. This research was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 101002711; project BODYinTRANSIT).

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