As Light as your Footsteps: Altering Walking Sounds to Change Perceived Body Weight, Emotional State and Gait

Ana Tajadura-Jiménez[1], Maria Basia[1], Ophelia Deroy[2], Merle Fairhurst[2], Nicolai Marquardt[1], Nadia Bianchi-Berthouze[1]

[1]UCL UCL Interaction Centre
UCL, London, UK
[a.tajadura, maria.basia.13, n.marquardt, n.berthouze]@ucl.ac.uk

[2]Centre for the Study of the Senses, University of London, London, UK
[ophelia.deroy, merle.fairhurst]@sas.ac.uk

ABSTRACT

An ever more sedentary lifestyle is a serious problem in our society. Enhancing people's exercise adherence through technology remains an important research challenge. We propose a novel approach for a system supporting walking that draws from basic findings in neuroscience research. Our shoe-based prototype senses a person's footsteps and alters in real-time the frequency spectra of the sound they produce while walking. The resulting sounds are consistent with those produced by either a lighter or heavier body. Our user study showed that modified walking sounds change one's own perceived body weight and lead to a related gait pattern. In particular, augmenting the high frequencies of the sound leads to the perception of having a thinner body and enhances the motivation for physical activity inducing a more dynamic swing and a shorter heel strike. We here discuss the opportunities and the questions our findings open.

Author Keywords

Auditory body perception; multimodal interfaces; sonification; interaction styles; emotion; evaluation method

ACM Classification Keywords

H.5.2. User Interfaces: Auditory (non-speech) feedback; interaction styles.

INTRODUCTION

Our societies are seeing an increase in inactive and sedentary lifestyles that causes 6% of deaths each year and is a risk factor for many chronic diseases [36,61]. Further, concern about general body appearance reflects in the growth of the fitness industry and of surgery procedures to change one's appearance [32]. This has led to a raising awareness of the need to make people feel good about their bodies and motivate them toward physical activity so that they stay physically and mentally healthy and independent [33].

CHI 2015, Apr 18-23 2015, Seoul, Republic of Korea
ACM 978-1-4503-3145-6/15/04.
http://dx.doi.org/10.1145/2702123.2702374

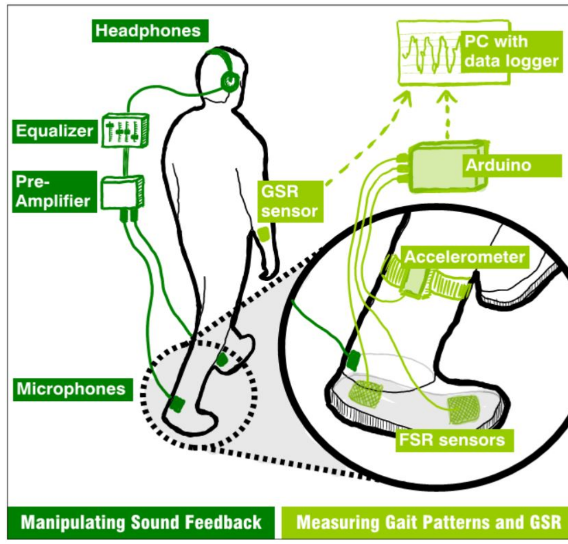

Figure 1. Overview of the experimental setup: (left) manipulating sound feedback; (right) sensing gait and galvanic skin sensor (GSR).

To tackle the problem, various activity tracking devices and applications are appearing on the market, such as *Fitbit* or *Nike Fuelband*. To increase exercise adherence, these technologies typically exploit cognitive behavioral strategies based on setting goals and providing rewards [21]. Here we take a very different and complementary approach that alters the perception of one's own body in order to enhance self-esteem, body feelings and the motivation for and quality of physical activity. Specifically, we propose to exploit the multisensory nature of body perception [55] and induce changes in perceived body weight by manipulating the sound feedback received while walking (Figure 1).

Our physical body is our means of perceiving the world but also our means of expression, of acting and interacting [2, 16,45]. How we perceive our body in terms of its appearance and its action capabilities is thus vital for self-esteem and for engaging in physical activity and social interaction. Interestingly, recent neuroscience research has shown that, rather than being fixed, the perception of our body (mental body model) is continuously updated by the body-related multisensory experiences that accompany our interactions with the environment [3,51,55]. Theories of 'forward internal models' of motor-to-sensory transformations [60] suggest that we predict the sensory feedback (e.g., the sound of our steps) we should receive from our actions by considering, among other factors, the mental model of one's body dimensions and configuration. When the received sensory feedback does not match these predictions an update of our internal body model may occur.

The possibility of altering the perceived physical appearance and the physical capabilities of one's own body through sensory feedback derived from one's actions may offer a practical way to make people feel good about their bodies [9,41], thus facilitating healthy changes in self-esteem and motor behavior. In our paper, we explore how sound feedback received while walking may be altered to induce changes in body perception and related emotion and behavior. Walking was chosen as it is an everyday gentle and easy form of physical activity, fit for people of all ages and most abilities, and with many associated health benefits such as a risk reduction in many chronic diseases [34].

Sound feedback was chosen for three reasons further developed in the background section. First, sound offers an excellent potential for consumer applications used during walking, when headphones and portable sound devices are often used. Second, the link between walking sounds and the perceived walker's weight is known. Heavier bodies produce lower spectral mode sounds than lighter bodies and listeners pick up on these cues when estimating properties of the heard walker [17,29]. While prior studies explored the effects of passive listening to walking sounds in the perceived body of an unknown walker, our study focuses on changes in the perception of *one's own body* due to altering self-produced walking sounds. Finally, sound has shown to have positive effects in sport, dance and motor rehabilitation [11,19,42,46,58], such as enhancing body awareness and movement coordination. Sensory feedback has shown for example, to ease motor learning by enhancing body-related information, such as the distance to a target posture [30,48], and to improve self-efficacy [49]. Yet, none of these studies has explored the possibility of altering one's own body size perception with sound, to enhance physical performance, self-esteem and positive attention to one's body. Such feedback could be integrated in applications such as *Fitbit* to complement its strategies to increase exercise adherence. Our paper aims to make both a theoretical and technological contribution in this direction by proposing and evaluating a system that effectively uses bodily-related sound feedback to evoke changes in the perceived body and measure changes in behavior and emotion.

BACKGROUND AND RELATED WORK

Walking Patterns (Gait) and Acoustic Signals

Gait is a periodic movement of each of the lower limbs from one position of support to the subsequent one [56]. It highly varies across individuals, due to age, gender or weight. Troje et al. [54] explored the link between gait and these various factors. They developed an application[1], based on motion data captured from eighty walkers, which displays an animated point-light walker whose gait changes according to various settings. In particular, the light-heavy setting appears to change the acceleration of the limbs and the straightness of the walker's posture. Other work showed that obese, as compared to normal weight walkers, display longer heel strike and reduced ankle mechanical joint power that relates to lower acceleration for the forward progression [25].

When walking, the force exerted by the foot against the ground can be represented as a time varying spectrum [57]. The low frequency components (under 300 Hz) are responsible for the displacement of the walker's center of mass. They depend on the walker's weight and walking rate and are essentially independent of footgear or walking surface [15], unlike the high frequency components, which can depend on the footgear and ground material [57]. The impact of the foot on the ground gives rise to acoustic signals, which frequency spectra shares properties with the ground force spectra. For instance, walking sounds produced by heavier bodies contain more energy in the low frequency components than those sounds produced by lighter bodies.

Information Conveyed by Walking Sounds

Listeners can extract various sorts of information from walking sounds (for a review see [57]). For instance, they can discriminate between solid and aggregate ground materials based solely on walking sounds [18]. They can also extract properties of a walker's body from the acoustic features of the walking sounds, including the gender, the emotional state and the size/hardness of the shoe soles of the heard walker [17]. Judgments of gender and shoe characteristics depend on the sound spectral characteristics and judgments of emotional state depend on the sound intensity and temporal features (average pace, pace irregularity). Listeners also rely on the sound spectra when asked to judge the posture of a heard walker (upright, stooped) [37]. Li et al. [29] found that the acoustic features from which listeners deduct the gender of a heard walker, including spectral peak and high frequency components, change with the weight and height of the walker. In fact, these authors demonstrated that shifting the spectral mode of the walking sounds to lower frequencies (at least to 125 Hz) increased the 'male' reports, while shifting it to higher frequencies (1000 Hz) increased the 'female' reports.

Hearing One's Footsteps Changes Gait and Emotion

While several studies have investigated the effects of vibrotactile patterns [59], musical temporal patterns [50] and musically induced arousal [28] on human gait, as well as the effects of a broad range of sounds in emotion [5], few studies have focused on the specific effect of self-produced walking sounds. Some of these studies have suggested that

[1] biomotionlab.ca/Demos/BMLwalker.html

the use of sounds, including footsteps and other sounds, synthesized in real-time from users' gait pattern improves navigation and interaction with a virtual reality (VR) environment [35]. Sound also enhances robot-assisted lower extremity motor adaptation during physical rehabilitation [62]. Another study [31] showed that delaying the provision of self-produced footstep sounds altered the gait period without the walkers being aware of the change. This study also showed that the delays in sound feedback reduced agency, i.e, the feeling of having produced the sounds.

Two recent studies have looked at how changing the perceived ground or shoe material by altering self-produced walking sounds can affect a walker's emotional state and motor behavior. Listening to pre-recorded footstep sounds produced by high heels of different materials and different types of ground affects women's emotional state when these sounds are presented in synchrony with their own footsteps [53]. Similarly, Bresin et al. [7] showed that hearing self-produced footsteps sounds as if they were produced on different ground surfaces seems to influence both walkers' emotion and their walking speed. However, the behavioral results did not reach significance, perhaps due to participants being over-conscious about their movement, as they were asked to walk in a specific emotion-related style.

Using Walking Sounds to Change the Perceived Body

Most of neuroscience studies on the plasticity of our mental body model have focused on visual and tactile feedback to alter people's perception of their body (e.g., perceiving and acting as if one's arm was longer). Recently, a few studies have shown that sound can also be used for this purpose. For example, sounds generated by tapping one's hand on a surface inform us of how long our tapping arm is [51] as well as the strength applied when tapping [14]: altering these sounds results in changes in arm extent and strength, as well as in movements and emotional state [14]. Sound may also change the perceived body material properties. For example, one's hand feels stiffer and heavier when altering the sound received when an object hits the hand so that it resembles the sound produced when the object hits marble [47]; or one's body feels as composed of metallic parts or 'robotized' if, when moving it, one receives sound and vibro-tactile feedback constructed from recordings of a real robot actuation [26]. The variation of sound spectra and amplitude also alters the perceived body material properties. Increasing both the high frequency components and the overall amplitude of the sound elicited when rubbing two hands together increases the perceived smoothness and the perceived dryness of the skin [20,24].

The studies discussed above suggest we use the sounds derived from bodily movements to build a model of our body appearance and of its capabilities for interaction, and that these sounds influence behavior and emotion. Here we explore for the first time how these sounds can alter the perception of one's own body weight, and look at how these changes may impact on emotion and gait behavior.

METHOD

Motivation and Hypothesis

The aim of the study is to investigate the effects of walking sounds on one's body perception to inform the design of ubiquitous technology for behavioral changes and wellbeing. Given the previous work showing how shifting the frequency mode of walking sounds influences the perceived weight of the heard walker (i.e., another person's body [29]), we posited that altering self-produced footstep sounds may likewise result in changes in the perceived weight of one's own body. We hypothesized that shifting the spectral mode of self-produced footstep sounds to lower frequencies may result in a perceived heavier body, while shifting it to higher frequencies may result in a perceived lighter body.

We further posit that these changes in perceived body weight may come together with behavioral and emotional changes given the tight links between these three dimensions: by perceiving one's body as lighter, one may feel more positive about this body and behave as if it were lighter. For instance, this perception may accelerate movements of the lower limbs [25,54] or induce an upright posture, which in turn may affect emotional arousal and dominance (i.e., feeling in control, stronger). Indeed, upright posture and dominance are known to relate to each other [8,37,54]. On the contrary, feeling heavier may result in a longer heel strike [25] or/and a larger exerted force of the feet against the ground [15,57]. Feeling lighter may also reflect in other experiential aspects, like for instance, one may feel faster or stronger, with this new body.

Participants

Twenty-two paid participants (age=18-35, four male and eighteen female, normal hearing) naïve to the study aim took part in the experiment. Their mean body weight and height (SD) was 59.25(10.55) Kg and 164.82(6.91) cm.

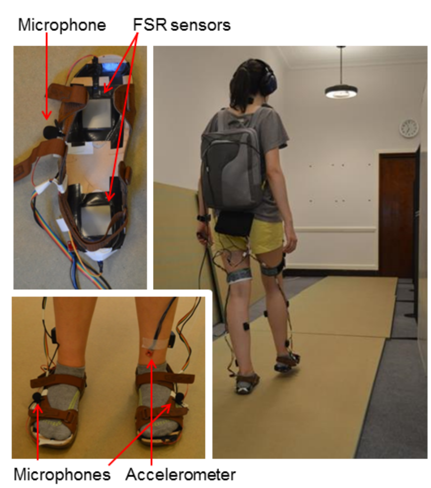

Figure 2. (left) Sandals with microphones, FSRs and accelerometer; (right) a participant during one condition[2].

[2] Ten additional EMG/accelerometer sensors were attached to walker's body for further analyses (not presented here).

Materials

Our prototype allows the dynamic modification of footstep sounds, as people walk, and measurement of walking behavior changes. We used strap sandals (EU size 42) that are easy to wear, fit a wide range of foot sizes, and have hard rubber sole, so that they elicited clear and distinctive footstep sounds. As shown in Figures 1 and 2, each sandal was equipped with a microphone (Core Sound, frequency response 20 Hz-20 kHz) that captured the walking sounds and two force-sensitive resistors (FSR; 1.75x1.5" sensing area) attached to the front and the rear part of the sandal insole that detected the exerted force by feet against the ground (as in [7]). A triple axis accelerometer (Sparkfun) was attached to the walker's left ankle. FSRs and an accelerometer were connected to an Arduino Uno microcontroller board linked via Bluetooth (Arduino XBee) to a computer that acquired their data (Arduino 1.0.5, Processing 2).

As shown in Figure 1, the microphones connected to a small stereo pre-amplifier (SP-24B) and this connected to a stereo 9-band graphic equalizer (Behringer FBQ800) that changed the sound spectra. The resulting sound was fed back via closed headphones (Sennheiser HDA 300) with high passive ambient noise attenuation (>30 dBA) that muffled the actual sound of footsteps. The analogue sound loop had minimal latency (<1 ms). Arduino board, pre-amp and equalizer were fitted into a small backpack the walker could carry (~2 Kg, 35x29x10 cm). The cables from sandals to backpack were attached with Velcro straps to the walker's legs. Finally, a GSR sensor (Affectiva Q Sensor; 32 Hz) in the walker's wrist measured emotional arousal [4].

The experiment was conducted in a quiet and dimly lit room, with an 8.5x1.22 m corridor created by using wooden boards (medium-density fiber, 2.5 cm thick; Figure 2). The ground and footwear materials are relevant as they affect the resulting sounds [29]. The hard rubber soles in contact with the wooden board produce clear sounds. We placed vertical panels on the corridor side to occlude objects in the lab that could distract people's attention or could have served as a reference when judging one's body dimensions.

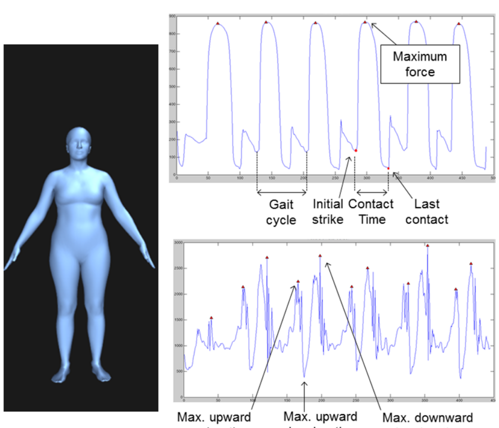

Figure 3. (left) Body visualization tool; (right-top) examples of FSR and (right-bottom) and accelerometer data.

Experimental Design

Sound Feedback Conditions

Three sound feedback conditions were designed based on [29]: a 'Control' condition in which participants were provided with their natural footsteps sounds equally amplified across frequency bands; a 'High frequency' condition in which the frequency components of the footsteps sounds in the range 1–4 kHz were further amplified by 12 dB and those in the range 83–250 Hz were attenuated by 12 dB; and a 'Low Frequency' condition in which the frequency components in the range 83–250 Hz were further amplified by 12 dB and those above 1 kHz were attenuated by 12 dB.

Multi-Measurement Approach

The user experience was evaluated by combining self-reporting, physiological and objective behavioral measures:

<u>Perceived Body Weight:</u> To measure perceived body weight, we used a body visualization tool (bodyvisualizer.com; see Figure 3) adopted by other studies for the same purpose [39]. People adjusted the weight related dimension of the body of a 3D avatar displayed on the screen to correspond to their perceived body size [10,27,39].

<u>Behavioral Changes (Gait Patterns):</u> The 'stance' and the 'swing' of the two phases of a gait cycle (i.e., the time between two successive steps made by one foot [12]) were analysed. The stance phase starts with the strike of the heel on the ground and ends when the toes lose contact with the ground. The FSR data of the left foot was used to quantify the exerted force (peak and mean values) of the heel and toes against the ground and their contact times, as well as the stance and the gait cycle times (see Figure 3). We focused on data from the left foot since we did not have any specific hypothesis on left/right asymmetries (additionally, data from one right sensor seemed abnormal). The swing phase starts with the foot lifting, first accelerating and then decelerating (midswing) while preparing for the next heel strike and while the other foot is on the ground. The foot accelerates again when the flexor muscles are activated to move the foot forward and downwards [56]. The accelerometer data was used to quantify the foot lifting acceleration and deceleration, as well as the downward acceleration.

<u>Emotional Responses:</u> Emotional valence, dominance, and arousal felt by participants were quantified by using the 9-item graphic scales of the self-assessment manikin questionnaire [6]. Arousal was also quantified based on physiological changes recorded by the GSR biosensor [4].

<u>Perceived Body Behavior:</u> We quantified other aspects of the experience by asking participants to rate their level of agreement with some statements (7-point Likert-type response items, from strongly disagree to strongly agree). We checked whether participants felt as if they were the agents of the sounds (agency [31]), as many studies have shown that large discrepancies between modalities and delays between actions and sensory feedback disrupt agency and diminish the sensory-induced bodily illusions [31,51]. The

questionnaire included statements assessing whether participants had a vivid feeling (vividness [51]) or had unexpected feelings about their body (surprise). We also looked at feet localization as sound may interact with proprioception [51], and used 7-point Likert-type response items to assess the perceived walking speed (slow vs. quick), body weight (light vs. heavy), body strength (weak vs. strong) and body straightness (stooped/hunched vs. straight).

Experimental Procedure

A within-subjects design was preferred given the greater variability of body size perception between subjects [22] due to psychological condition, thoughts about ideal body size, media exposure or body dissatisfaction [39]. As in other studies assessing perceived body size [10,27,39] we adopted various strategies to compensate for practice /habituation bias. First, condition randomization served to discard differences due to practice. Second, while the avatar's parameters were set to match the participant's gender and height, the initial avatar's weight varied across trials to avoid anchor effects of the initial value [10,27,39]. This was set to match the participant's weight ± 25% (whether it was + or - was counterbalanced across the two repetitions). Participants changed the avatar's weight by pressing two keys. Finally, to distract participants from the manipulation of one's body weight, we mixed the avatar's task with two other 'fake' tasks related to objects weight: a 'spanner task' and a 'lifting weights task'. For the 'spanner task' we showed participants three metal spanners (13, 15, 17 mm) and told them that in each trial they would have to carry one of them and later provide assessments of its length and weight. In fact, in order to keep weight constant we always gave participants the 15 mm spanner, though this was not made clear to them. For the 'lifting weights task' we used a self-efficacy scale assessing the perceived ability to lift various weights [1]. Participants were fully debriefed as to the purpose of the study after the experiment ended.

After participants had been equipped with all the sensors and had been provided with task instructions, they performed two initial practice blocks (one without and one with the equipment on) in order to familiarize themselves with the task. Next, they completed a set of three experimental blocks differing in the sound feedback condition (Low frequency, High frequency and Control) presented in a randomized order. Then, the full set of three conditions, in another randomized order was repeated, in order to collect more data points. In each block, participants were given the 15 mm spanner and, while holding it in their hand, they walked in place for 10 s (marching phase). After a go-ahead signal they walked along the 8.5 m wooden-floor corridor (walking phase). Note that the marching phase was introduced to increase sound exposure but that the analyses of gait patterns focused on the walking phase. Participants were asked to walk at a self-paced, comfortable speed. At the end of the corridor, participants placed the spanner on a black cloth bag and adjusted the avatar on the body visualization tool so that it matched their own perceived body dimensions (see Figure 3 – left).

After this body visualization task, participants were asked to complete the questionnaire that assessed, in this order, (1) the perceived spanner length and weight; (2) self-efficacy regarding lifting different weight objects; (3) body feelings (speed, weight, strength, straightness, agency over footstep sounds, vividness, surprise, feet localization); and (4) emotional feelings (valence, arousal, dominance).

RESULTS

First of all, we confirm that all participants attributed the sounds to themselves, as a product of walking. As shown in Table 1, participants agreed that the sounds they heard were produced by their own body (agency scale), and did not find the experience more or less vivid or surprising than normal (non-significant differences between conditions). Given the confirmation of perceived agency, we proceeded with the analysis of the other collected data.

For the gait analyses (FSR and accelerometer), for each trial and for each extracted parameter (see Methods) we calculated the average of all steps in the walking phase. Then, for all physiological data (FSR, accelerometer and GSR), individual z-scores were calculated to reduce intra-subject variability [4]. We analyzed normal data (normality tested with Shaphiro-Wilk) with two-way repeated measures analyses of variance (ANOVA), with 3x2 within-subject factors sound condition and repetition. Significant effects were followed by paired samples one-tailed t-tests, with the significance alpha level adjusted to multiple comparisons. If the ANOVA did not show an effect of repetition, we averaged the data across repetitions and used t-tests to compare the three sound conditions[3]. In case of non-normal data, we attempted normalization by LOG-transformation. If normalization was not achieved (i.e., GSR and questionnaire data) we analyzed the data with non-parametric Wilcoxon tests. Results of these analyses are presented in the next sections.

Perceived Body Weight (Body Visualization)

As shown in Figure 4, the sound condition affected perceived body weight, as measured by the body visualization tool. The ANOVA on the LOG-transformed data showed significant differences between sound conditions ($F(2,42)=4.02$, $p=0.026$, $\eta^2=0.16$). T-tests comparing the three sound conditions revealed that the High frequency feedback was associated with a significantly lighter body than the Control feedback ($t(21)=2.73$; $p=0.006$). The High vs. Low frequency comparison indicated a trend towards statistical significance ($p=0.04$), but the Control vs. Low frequency comparison was far from significance ($p>0.2$). *These results indicate that the High frequency condition caused participants to feel as having a thinner body.*

[3] A p-value equal to 0.017 corresponds to a significance level of alpha=0.05 when Bonferroni correction for 3 levels is applied.

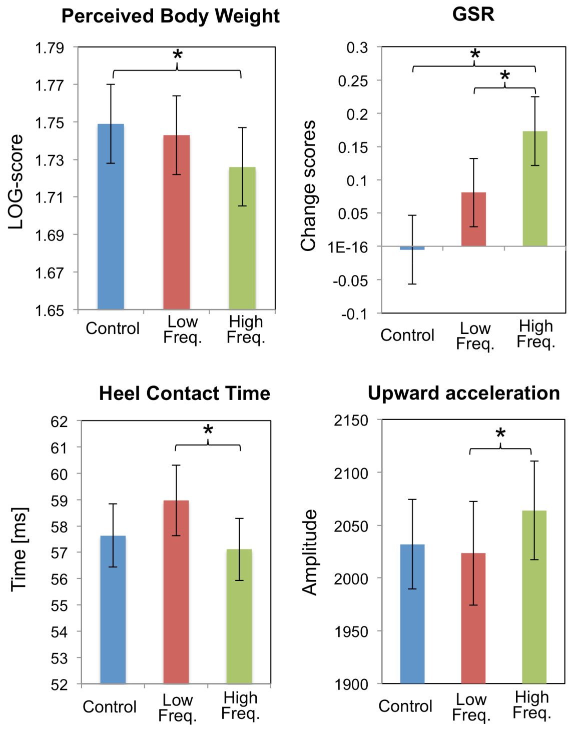

Figure 4. Mean (±SE) results for all three sound conditions. * marks significant differences between means.

Foot Pressure (FSR Sensor Data)

The pressure data for one participant and for one trial for two participants were lost. For the remaining 21 participants, data showed an average of 5.34 (SD=0.64) steps in each walking phase. Of all parameters, only the heel contact time with the ground revealed a significant effect of sound condition ($F(2,36)=6.38$, $p=0.004$, $\eta^2=0.26$; Figure 4). T-tests on the z-scored data revealed that the heel remained in longer contact with the ground in the Low than in the High frequency condition ($t(20)=2.79$, $p=0.006$). The Low frequency vs. Control comparison indicated a trend towards statistical significance ($p=0.039$). No other differences were found. *These results suggest an increase in body weight perception in the Low frequency condition*.

Foot Acceleration (Accelerometer Data)

Acceleration data for one participant and for one trial for another participant were lost. For the remaining 21 participants, the net acceleration was calculated as the square root of the sum of the squares of the three acceleration components. Of all parameters, only the upward foot acceleration revealed significant effects of sound condition ($F(2,38)=3.94$, $p=0.028$, $\eta^2=0.17$; Figure 4). T-tests on the z-scored data revealed larger acceleration during the foot upward movement in the High than in the Low frequency condition ($t(20)=2.62$; $p=0.008$). The High frequency vs. Control comparison indicated a trend towards statistical significance ($p=0.029$), but no other differences were identified. *These results suggest a decrease in body weight perception in the High frequency condition.*

Scales	Control	High freq	Low freq
Emotional valence*	5.5(2.5-7.5)	6(5-8.5)	5.25(3-8)
Arousal	4.5(2-7.5)	5(2.5-7.5)	4.5(2-7.5)
Dominance	5(2.5-8.5)	5.5(4-8.5)	5(2.5-8)
Speed*	4(2-6.5)	5(3-6.5)	4 (1.5-6)
Weight	4(2-6.5)	4(1.5-5.5)	4.25(2-6.5)
Strength	4(2.5-6)	4.5(3.5-6)	4(2.5-5.5)
Straightness	5.25(2.5-7)	5.25(2.5-7)	5(2-7)
Agency	6(1-7)	6.5(1-7)	6.5(2-7)
Vividness	3(1-6)	2.75(1-6.5)	3.5(1-6)
Surprise	4(1-6.5)	4.25(1-7)	4(1-7)
Feet localization*	5.25(3-7)	6(4-7)	5.5(2-7)

Table 1. Median(Range) for questionnaire data (7-level Likert items except for 9-level valence, arousal and dominance scales). * marks significant mean differences.

Emotional Response (GSR, Self-assessment Manikin)

GSR data from three participants were lost due to technical problems. For the remaining 19 participants, GSR change scores were calculated for each condition by subtracting the minimum from the maximum response during each condition (from the beginning of the marching phase to the end of the walking phase). Wilcoxon paired comparisons on the z-scored data did not reveal an effect of repetition; thus we averaged the data across repetitions and used further Wilcoxon tests to compare the three sound conditions[3]. As shown in Figure 4, the sound condition affected the GSR scores. Higher changes were elicited by the High than the Low frequency ($T=39$, $p=0.011$) and the Control condition ($T=28$, $p=0.003$), while the Low frequency vs. Control comparison did not achieve statistical significance.

The questionnaire data provided further insight into participants' emotional feelings. As shown in Table 1, they felt more positive in the High than in the Low frequency condition ($T=22$, $p=0.008$). A trend towards statistical significance was observed for the High frequency vs. Control comparison ($p=0.037$). No significant main effects of sound condition on arousal and dominance were found, but results indicate a trend in the direction of greater feelings of arousal in the High frequency than in the Control condition ($p=0.029$). There was also a trend towards greater feelings of dominance in the High frequency than in the Low frequency ($p=0.022$) and the Control conditions ($p=0.041$). *In brief, our results indicate that the High frequency condition caused participants to feel more aroused and positive.*

Perceived Body Behavior

For the questionnaire items on perceived body behavior, Wilcoxon paired comparisons did not reveal a repetition effect; thus we used further Wilcoxon tests to compare the three sound conditions (mean across repetitions). We report the comparisons that reached significance ($p<0.017$) or that showed a trend towards significance ($p<0.05$).

The sound condition affected perceived speed. As shown in Table 1, participants felt quicker in the High than in the Low frequency condition (T=23, p=0.005), and they tended to feel quicker in the High frequency than in the Control condition (p=0.022). Although no significant effects of sound condition were found for perceived body weight, strength and straightness of the body the statistical comparisons revealed trends towards a significant lighter (p=0.024), stronger (p=0.037) and straighter (p=0.029) body in the High than in the Low frequency condition.

Attention to one's body

Finally, it was found that participants were more confident in localizing their feet in the High frequency than in the Control condition (T=100, p=0.011); moreover they tended to feel more confident in the High than in the Low frequency condition (p=0.020). *These results and the more positive emotion reported suggest that the High frequency condition may have enhanced the proprioceptive feedback or possibly even generated a more positive attention to one's body.*

DISCUSSION

We investigated the alteration of one's footsteps sounds to modulate the perception of one's body and enhance self-esteem, body feelings and the quality of walking. We found that shifting the frequency of self-produced footstep sounds alters the perceived body weight, emotional state, perceived physical abilities and gait. This modulation process could be used to improve the efficacy of technology for wellbeing and for motivating physical activity. The next sections discuss the specific effects and their implications and possible applications, and perspectives for further work.

Body dimensions

We had hypothesized that shifting the spectral mode of self-produced footstep sounds to lower frequencies may result in a perceived heavier body, while shifting it to higher frequencies may result in a perceived lighter body. The second part of this hypothesis was confirmed by our results in the body visualization task as, after the High frequency feedback, participants set the dimensions of the avatar that represented their body to correspond to a lighter body. We also observed that participants tended to feel lighter in the High than in the Low frequency condition (questionnaire data).

Our approach exploits the multisensory nature of body perception and builds on previous neuroscience research showing that how people perceive their body can be changed by altering body-related multisensory cues [3,13,38,51,55]. Our findings constitute a novel contribution to this research in which the majority of works have focused on visual, tactile and proprioceptive cues. Although walkers receive information about their body from vision, sound, touch (via the tactile sensory receptors in the skin of the feet) and proprioception [57], we show that altering sound cues alone can change perceived body weight and other related body percepts. In this way we contribute to the growing interest in HCI on the possibilities offered by multisensory integration mechanisms for enhancing the user experience.

Moreover, our findings advance current research looking specifically at walking sounds as a source of information about events. While previous research has explored how material identity in VR can be conveyed even when some modalities are absent [14], we focused on walking sounds as a way of altering body perception. A few studies have looked at walking sounds as information on the appearance of an unknown walker's body during passive listening [17,29,37]. However, to the best of our knowledge, this is the first study looking at walking sounds as a source of real-time information as to the appearance of one's own body.

Emotional State and Physical Abilities

We further hypothesized that changes in perceived body weight would come together with emotional changes, given the tight links between body perception and self-esteem [9,41]. We showed that listening to walking sounds with higher frequencies resulted in people reporting feeling more positive. People were also more physiologically aroused during this sound feedback condition, as evidenced by the GSR recordings. In addition, we observed trends towards an increase in participants' perceived abilities, as they reported feeling more in control (dominance ratings) when listening to the high frequency version of their footsteps.

There were further changes in participants' perception of their physical capabilities as they felt quicker and more confident in localizing their feet (i.e., better proprioception) after this condition. They also tended to feel stronger. The enhancement in perceived strength and proprioception caused by changes in self-produced footstep sounds relates to previous findings showing similar effects of self-produced tapping sounds [14]. Finally, we observed that participants tended to feel as if they were walking with a straighter posture when listening to higher than lower frequency versions of their footsteps. This adds to previous findings on the links between the perceived posture of the heard walker and the spectral frequency of walking sounds [37] and between body posture and emotional state [8].

The possibility of operating at the level of the perception of one's own body using sound feedback can apply to the design of systems aimed to enhance wellbeing. In fact, feeling more positive and energized, quicker and in better control of one's body relates to enhanced self-esteem and a better predisposition for physical activity. These systems could benefit the increasing number of people who are concerned with the appearance of their bodies [32] and about what their body can do. There are a number of clinical cases of body- and action-distortions leading to body-impairments [9] and to deficits in emotional states, such as some cases of chronic pain [49] or anorexia nervosa [41]. Apart from these cases, many young people in their teen years, older adults, and a significant proportion of the remaining population often have these concerns to the detriment of their emotional state and motor performance. Altered feedback on walking sounds might help to recalibrate distorted feelings of one's own body weight and capabilities, and to feel more positive and in control of one's body. Our findings can inform the design of more effective therapies using VR and serious gaming technologies to enhance wellbeing. Sound feedback in these applications can optimize user's embodiment in a virtual character that may have different anthropomorphic characteristics than the user [44,57].

Gait

We further posited a link between changes in perceived body weight and gait. Based on prior research we hypothesized that a condition eliciting a lighter perceived body would result in a larger acceleration of lower limbs [25,54], while a condition eliciting a heavier perceived body would result in longer duration of the heel strike [25] and a larger exerted force by the feet against the ground [15].

Our results provide support for these hypotheses. First, a higher frequency mode resulted in larger acceleration of the upward movement of the lower limbs during walking, which is consistent with previously observed gait patterns of lighter walkers [25,54]. This result is interesting from the point of view of increase in physical activity. Second, a lower frequency mode resulted in an increase in the time participants kept their heel in contact with the ground, as measured by the force sensitive resistors, which is consistent with walking with "heavier" steps [25]. It should be noted that, although most of the self-reported changes seem to derive from shifting the spectral mode to higher but not to lower frequencies, we were able to observe behavioral changes for the low frequency mode. Thus, these changes seem to occur without users being aware of them [51].

Our study provides more insight into the updating of 'forward internal models' of motor-to-sensory transformations [60], as sound has rarely been investigated as feedback to body models. We suggest that the observed gait changes may result from an attempt to reduce the sensory discrepancies that our feedback introduces. Gait changes may have contributed to maintain the sound-induced bodily illusion. In fact, all observed changes in body perception, emotion and gait may reinforce each other during the process [43].

Sound feedback is currently used in many HCI applications aimed at increasing exercise adherence, facilitating movement and enhancing positive emotions, including applications used in sport and motor rehabilitation contexts [11,19,42,45,46,58]. Here we show that operating at the level of the perception of one's body by using sound feedback can also enhance physical performance (reflected in the acceleration of lower limbs), self-esteem and positive attention to one's body. While we show the short-term effect of brief exposure to manipulated walking sounds, it remains to be tested whether the effects may differ after longer exposure due to habituation [40], or generalize to other environments with different lighting, environmental noise or ground/footgear materials [29,53], as well as the longer term effects. Moreover, while our subject sample does not allow testing gender differences, it is possible they exist given the media pressure on women on body size [52]. Further, as alteration in the sound can lead to different perception of shoe material and style (e.g., high heel vs. heavier shoes), the subject's gender may have inhibitory or enhancing effects on the experience. Research has indeed shown that different sounds are preferred for walkers of different genders [57]. We observed that when removing the four males in the current sample, the data show even stronger effects in perceived body weight (sound condition: $p=0.021$), heel contact time (sound condition: $p=0.001$), perceived speed (High vs. Low: $p=0.003$) and emotional arousal (High vs. Control: $p=0.016$), thus suggesting gender differences and the need for further investigation.

Implications Beyond Walking

In this study, we focused on walking but future research should explore a similar approach of using sound feedback to enhance other types of physical activity. It should be noted that we used shifts in frequency mode due to their relation to body weight [17,29] but that different sound manipulations might be needed to induce similar effects during physical activities other than walking. Our study highlights the importance of a careful selection of sounds in order to optimize the desired effects. Prior research has shown the importance of keeping sensorimotor discrepancies under a certain threshold to maintain the feeling of agency and enhance the multisensory-induced effects [31,51]. Furthermore, we suggest that the relative contributions of shifts in frequency spectra and in loudness to our observed effects need to be considered. We were surprised to see that the perceived body weight, as quantified in the body visualization task, was slightly (but not significantly) higher in the Control than in the Low frequency condition. While the self-reported weight in the questionnaire was not higher for the Control condition, it is possible that the muffling of the high frequencies in the Low frequency condition was not completely achieved or that our results might depend on an interaction between spectral mode and loudness, rather than spectral mode alone. We opted for manipulating frequency spectra based on prior research findings [29], but this resulted in the three sounds conditions differing also in loudness [23]. Past studies have demonstrated that overall sound amplification of body-related sounds (e.g., rubbing hands) may lead to changes in perceived sound source characteristics [20,24]. Future research may also test the optimum magnitude of frequency shifts.

Finally, while we presented results from a lab study, our prototype could be further developed to allow running studies in the open. A more refined and compact version of our system could be comprised of wireless headphones and microphones connected to a smartphone in which sound equalization takes place and in which the integrated accelerometer/gyroscopes are used to record the body activity. This system could be used for walking, running or physical rehabilitation applications that could increase the users' performance, creating a more pleasurable experience of physical activity and providing motivation for it [49].

CONCLUSIONS

Our results broaden the understanding of how auditory sensory feedback can be used to design technology that changes the perceived physical appearance and physical capabilities of one's body. We make a theoretical contribution to HCI, by bridging psychological research on multisensory stimuli updating one's body model and HCI research on the design of sensory-augmentation technologies supporting wellbeing. This study therefore forms the basis of a larger effort to design sound and motion technology that triggers changes in how we perceive and use our bodies. Technologies integrating our proposed feedback may become an extension of the users themselves, providing a different experience of their bodies and impacting their self-esteem and motivation to perform physical activity.

ACKNOWLEDGMENT

Supported by and ESRC ES/K001477/1 grant 'The Hearing Body' and partially by AHRC AH/L007053/1 'Rethinking the Senses' and EPSRC EP/H016988/1 'Emo&Pain' grants. We also thank Dr Torsten Marquardt for his advice.

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