As Light as You Aspire to Be: Changing Body Perception with Sound to Support Physical Activity

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ABSTRACT
Supporting exercise adherence through technology remains an important HCI challenge. Recent works showed that altering walking sounds leads people perceiving themselves as thinner/lighter, happier and walking more dynamically. While this novel approach shows potential for physical activity, it raises critical questions impacting technology design. We ran two studies in the context of exertion (gym-step, stairs-climbing) to investigate how individual factors impact the effect of sound and the duration of the after-effects. The results confirm that the effects of sound in body-perception occur even in physically demanding situations and through ubiquitous wearable devices. We also show that the effect of sound interacted with participants' body weight and masculinity/femininity aspirations, but not with gender. Additionally, changes in body-perceptions did not hold once the feedback stopped; however, body-feelings or behavioural changes appeared to persist for longer. We discuss the results in terms of malleability of body-perception and highlight opportunities for supporting exercise adherence.

CCS CONCEPTS
• **Human-centered computing → Interaction paradigms; Auditory feedback.**

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

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1 INTRODUCTION
The increase in inactive and sedentary lifestyles is a serious problem in our society. Globally, 1 in 4 adults and more than 80% of school-going adolescents are not sufficiently active [17,86]; physical inactivity affects a third of the adult population across Europe, causing 1.6 million of the worldwide premature deaths each year [47]. Physical inactivity in adults is a risk factor for obesity and many chronic diseases, including many cardiovascular and age-related diseases, diabetes, chronic pain and some types of cancer; it increases risks for depression and contributes to other negative health and psychosocial outcomes [12,15,28,47,48,87]. How could technology help increase people's adherence to physical activity (PA)?

In the last decade, the HCI research community and the commercial sectors, have attempted to address the problem through activity tracking and motivating feedback by leveraging sensing devices and building on cognitive behavioral theories [26]. However, a recent review of the field [35] has highlighted important limitations on this approach, such as the fact that is not always clear what is causing a change in behaviour and what is the relation between self-insight and behaviour change, which calls for reconsidering other factors that may undermine adherence to PA. This paper responds to this call by investigating one of such factors, which is the influence of people's perception of their own body in the moment of exercise.

To do so, we build on the novel approach proposed in [73] to exploit bottom-up multisensory mechanisms [79] that may lead to alter body perceptions and feelings and activate motor patterns related to such perceptions. In [73] a technological prototype was used to induce changes in perceived body weight by manipulating the sound feedback of one's footsteps. When people used this device to walk on a flat surface for short periods of time, they reported their bodies as thinner/lighter, felt happier and walked with more dynamic swings and shorter heel strikes. We build on this study and investigate how the observed effects interact with people's individual factors with the aim to further inform such technology design.

The present study has three HCI research aims related to the feasibility and potential of using this technology based on a sound-driven body illusion to facilitate PA:

1. To test the potential of this body illusion to facilitate physically demanding PA (use a gym step, climb stairs).
2. To investigate individual differences (weight, gender, masculinity/femininity aspirations) that may affect the body illusion and the behavioural response, given the social stigmas associated to weight and gender [77,81].
3. To investigate if the body illusion and related effects continue after the sound feedback is removed, given the previous reports of rapid recalibration and short duration of sensory-driven body illusions [9,10].

We first revise the background that motivates our work. We then present two user studies conducted to address the above questions. In these studies, a shoe-based prototype was used; initially based on [73], we describe how its design was iteratively refined to create a more compact version of the system and enhance its wearability and ease of use in ubiquitous environments (Figure 1). We finalise by discussing the results and proposing a rethink of PA technologies by embedding psychological factors related to body perception in the design process.

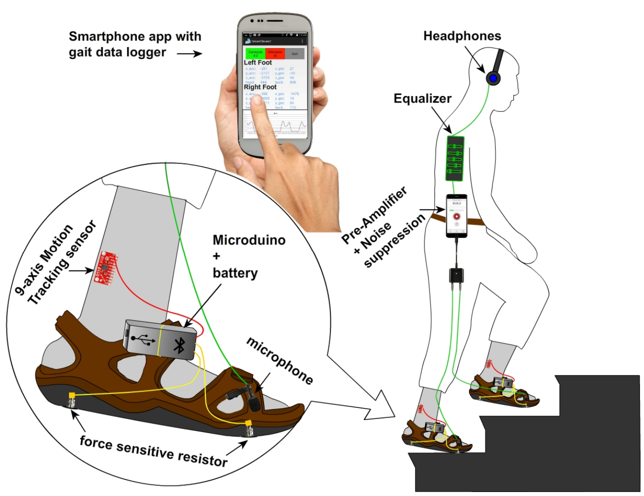

Figure 1: Overview of the device, with detail of the sensing gait system used in Studies 1 and 2, and the most compact version of the sound system (used in Study 2).

2 BACKGROUND AND RELATED WORK

2.1 Benefits of Using Sound in HCI Applications

The use of sound offers a number of interesting advantages for HCI applications, especially those focused on PA, as it does not interfere with movement and allows presenting several streams of information in parallel, continuously and with 360 degrees-field of view [30,39]. A further advantage is that audition operates relatively well even in noisy environments, offering high temporal resolution and high sensitivity for detecting structured motion (rhythm) [30] and rapid changes [33]; this detection is faster than that observed for the visual system [45]. Hence, sounds are beneficial to trigger intuitive, fast and accurate responses in users (see reviews [18,54]), and they are also a source of enjoyment and entertainment [33].

2.2 Using Sound in Applications focused on PA

Sound is currently being used in sports, dance, motor learning and rehabilitation to provide information about the *actual* body to enhance body awareness/coordination, increase motivation, reduce anxiety related to physical performance and enhance the emotional state related to one's body [22,55,58,65,85]. For instance, sound feedback informing on the distance to a target posture can guide movement, facilitate motor learning [62] and increase self-efficacy [65] (see review on sensori-motor learning with sonification [6]). For physical rehabilitation, sound is being used as a source of body information or to address psychological barriers [63]. For example, the use of musical structure can both encourage movement and avoid overdoing on it [46]. For dance, interactive sound feedback position and movement has been shown to increase dancers' physical awareness of their body [82], and feedback on movement qualities has been shown to trigger reflection on movement learning and to change behaviour by inducing movement exploration [19]. There is much less work on using sound for *sensory alteration* of body perception. Only recently this possibility has been considered in the context of HCI, as described in section 2.3, with views at enhancing physical performance, self-esteem and positive attention to one's body.

2.3 Sound to Alter Body Perception, Behaviour, Emotion

How people perceive their own body in terms of its appearance and physical capabilities, is not fixed. Neuroscience research has shown that these perceptions are continuously updated in response to the sensory inputs about the body received from the environment [10,71,79]. These body models that our brain holds, which are often known as mental body-representations, are necessary for successful and smooth interactions with the environment as they allow to keep track of the configuration and position of our different body parts in space, and of the continuously changing appearance and dimensions of our body [27,44]. Body-representations are tightly linked to self-esteem [13], forming a basis of self-identity [21,42].

Most neuroscientific studies on sensory-driven changes in body-representation have focused on visual, tactile and proprioceptive information (e.g., perceiving and acting as if one's arm was longer) [10,24,36,83]. Recently, sound has also been proven to be effective to change body-representation [2,59,70–73]. For instance, altering the spatial cues of the sounds produced when one's hand taps a surface can lead to perceive one's arm as longer than before [71,76] and to perform reaching actions as if one's arm was indeed longer [69]; but if what is altered are the sound cues related to the applied tapping strength, then changes in perceived own ability to tap, and changes in tapping strength are observed [68]. In addition, with changes in strength-related sound (e.g., increase volume or pitch) we also observed a change in emotional state [68], that is not simply explained by surprise. This could be due to the effect on arousal of either (or both) the effect of volume/pitch [38] and the effect of increased PA [7]. Further, artificially lengthening the time it takes to hear the impact of an object being dropped from one's hand on the ground, leads people to feel taller [75]. Critically, not only manipulating the sounds produced when we touch or hit something can alter body perception but also artificial sounds not typically associated with body movements can produce these changes. For example, playing a rising pitch while people pull on their finger may make people perceived their finger as longer [70]. Finally, body illusions induced by sensory cues other than sound can be respectively enhanced or disturbed by the congruency and incongruency of sound cues with the action [52,72].

Similar principles apply to the perception of the materiality of one's own body. Altering the frequency spectra of sounds produced when rubbing hands together alters the perceived dryness of one's skin [23,32]; altering the sound produced when an object hits one's hand, so that it sounds as if hitting marble, leads to feel one's hand stiffer/heavier [59]; one may feel as "robotized" or made of metal parts, if when exercising one receives in the articulations sound and vibrotactile feedback from recordings of a real robot articulations [37].

In terms of the use of sensory alterations within HCI for PA, they can be used not only to announce progress towards predetermined goals but to support people's self-image and belief in their body capability which is vital for their engagement with continued PA [8,61].

2.4 Using Walking Sounds to Positively Impact on PA by Changing the Perceived body and Emotional State

The studies discussed above evidence that auditory cues are used in the formation of a multisensory body-representation, which is tightly linked to behaviour and emotion. This interaction between sound-driven changes in body-representation, emotion and behaviour was shown in a recent study exploring for the first time how walking sounds can alter the perception of one's own body weight [73]. This study relied on previous reports that listeners can extract properties of the body of an unknown walker just from the acoustic features of his/her walking sounds [84], including the gender, the emotional state, the size/hardness of his/her shoe soles [20], and his/her posture (upright, stooped) [49]. These judgments depend on the sound spectral properties. Indeed, Li et al. [41] found that listeners deduct the gender of a heard walker based on the spectral peak and high-frequency components of the walking sounds, as shifting the spectrum of the sounds to lower frequencies (to 125 Hz) increased the 'male' reports, while shifting it to higher frequencies (1000 Hz) increased the 'female' reports. Importantly, Li et al. also found that the same spectral characteristics changed with the weight of the walker. This finding that heavier bodies produce sounds with lower frequencies than lighter bodies is at the basis of the sound manipulation in [73]. In this study, the frequency spectra of one's own walking sounds changed in real-time across 3 sound conditions. Results showed that augmenting the high-frequencies of the sounds produced when walking on a flat surface made people perceive their body as lighter/thinner, feeling more positive, aroused and faster, and led to "more active" gait patterns.

2.5 Individual Differences in Perceived Footstep Sounds

Li et al. [41] found that the spectral components of the walking sounds changed with the weight of the walker, as well as with the gender of the walker [80], and that these spectral components had an effect on gender judgments of this walker. These findings open two questions related to weight and gender: whether the subject's actual weight and gender may impact the experience, as they will result in different sounds; and whether the sound manipulation in [73] may be affecting not only the perception of weight but also of one's own femininity and masculinity.

In [73] participants' informal reports pointed at that shifting the spectrum to higher frequencies was sometimes associated with "walking with high heels". Such alteration in the sound may lead to different perception of shoe material and style (e.g., high heel vs heavier shoes) [20], and therefore the High Frequency sound condition may link to femininity. A related study with only female participants showed that listening to pre-recorded footstep sounds produced by high heels of different materials and types of ground affects women's emotional state when the sounds occurred in synchrony with their own footsteps [78]. Would the different sounds affect differently male participants? Research has indeed shown that different sounds are preferred for walkers of different genders [84]. However, one may question whether the effects depend on one's own actual gender or rather on one's masculinity/femininity perceptions and aspirations. The latter may be hypothesized given the media pressure on women on body size [77], and now increasingly also on men. It should be noted that in [73] the participant sample did not allow testing gender differences, but that removing the few males in the sample showed even stronger effects in perceived weight, heel contact time, perceived speed and emotional arousal, thus suggesting gender differences and a need for further investigation.

In two user studies, we explore for the first time the potential of this illusion to facilitate exertion (using a gym step, climbing stairs). In addition, Study 1 was set to investigate the effects of this illusion according to individual differences: weight, gender, and masculinity/ femininity perceptions and aspirations. Study 2 was set to investigate the longer term effects of this illusion.

3 USER STUDY 1: USING A GYM STEP

In this study, users wore a shoe-based prototype modifying their walking sounds and measuring gait patterns while they exercised with a gym step. The study was set to test the following three hypotheses:

Hypothesis 1: sound will have an effect on body perception, feelings and gait when using a gym step.

Hypotheses 2: sound effects will vary with subjects' actual weight.

Hypotheses 3: sound effects will vary with subjects' gender and perceptions / aspirations of body masculinity / femininity.

3.1 Method

3.1.1 Participants. Thirty-seven participants (age=19-30, eighteen male and nineteen female, normal hearing) naïve to the study aim, took part in the study. They were paid £6 for their participation. Their mean body weight and height (SD) were 65.51(17.94) Kg and 168.81(8.92) cm.

3.1.2 Materials. Our prototype allows the dynamic modification of footstep sounds, as people walk, and measurement of walking behaviour changes. The system was an adaptation of the one used in [73]: the gait data collection part was modified to minimize the system thus enhancing its wearability. The system (Figure 1) is comprised of a pair of strap sandals with hard rubber sole; four force sensitive resistors (FSR; 1.75×1.5′′ sensing area) attached to front and rear of sandal insoles and that detect the exerted force by feet against the ground; and two 9-axis MotionTracking devices (MEMS; Sparkfun MPU-9150) attached to the participant's ankles. FSRs and MEMS in each foot connect to a Microduino microcontroller board with Microduino Core, Bluetooth 4.0 and USBTTL shields, and a battery. This board was integrated into the sandals, linking the sensors via Bluetooth to a smartphone that acquired their data. The smartphone app SmartShoes was developed in Android Studio and ran on an LG Nexus-5 D821 with Android 4.4.

As shown in Figure 1, two microphones were attached to the sandals to capture the walking sounds (Core Sound). The microphones connected to a small stereo pre-amplifier (SP-24B) followed by a stereo 9-band graphic equalizer (Behringer FBQ800) that changed the sound spectra. The resulting sound was fed back via closed headphones (Sennheiser HDA300) with high passive ambient noise attenuation (>30 dBA) that muffled the actual sound of footsteps. The analogue sound loop had minimal latency (<1 ms). Pre-amp and equalizer were fitted into a small backpack the walker could carry (~2 Kg, 35x29x10 cm).

The experiment was conducted in a quiet laboratory room. A 100x35x10cm (width x length x height) plastic gym step was placed on the floor and against a wall, with a wooden board on top (65x33x3cm), and with a rubber mat in between the two to prevent the board from sliding. This resulted in a total height of the gym step of 13 cm. A second wooden board was placed on the floor next to the gym step (89x45x1cm) so that participants always step on wooden boards. Ground and footwear materials are relevant as they affect the resulting sounds [41,73]. The hard rubber soles in contact with the wooden board produce clear sounds. A computer was placed on the right side of the step to collect participants' body estimates (see next section).

3.1.3 Experimental Design

3.1.3.1 Sound Feedback Conditions. As in [73] (based on [41]) three sound conditions were created by dynamically modifying the footstep sounds people produce as they exercise: a "Control" condition in which participants heard their natural footsteps sounds equally amplified across frequency bands; a "High Frequency" condition in which the frequency components in the range 1–4 kHz were amplified by 12 dB and those in the range 83–250 Hz attenuated by 12 dB; and a "Low Frequency" condition in which components in the range 83–250 Hz were amplified by 12 dB and those above 1 kHz attenuated by 12 dB.

3.1.3.2 Demographic/Individual variables. Gender and body weight data were collected. Participants also gave a score to express their feelings for 2 statements, which range from: "I consider myself to be very feminine" to "I consider myself to be very masculine" (Masculine Being); "I wish to be very feminine" to "I wish to be very masculine" (Masculine Wish; 7-point Likert-type response items). Table 1 summarizes these variable values. All participants reported that they never used a gym step.

Table 1. Mean(SD) weight and median(range) masculine being/wish. *marks significant gender differences.

Variable	Male(N=18)	Female(N=19)	Total(N=37)
Weight (kg)*	74.94(19.83)	56.58(10.0)	65.51(17.9)
Masc. being*	5 (3-7)	3 (1-5)	4 (1-7)
Masc. wish*	5 (4-7)	3 (1-5)	4 (1-7)

3.1.3.3 Multi-Measurement Approach. The effects of sound feedback during the exercise periods were evaluated by combining behavioural measures and self-reporting:

<u>Changes in Perceived Body Dimensions/Weight:</u> As in [73], a 3D avatar was displayed (bodyvisualizer.com); the gender and 'height' of the avatar corresponded with participants' actual height. The 'weight' of the avatar was set to match the participant's weight ± 25%, with the task

being repeated twice in one trial, one for +25% and one for -25% (this was counterbalanced across two repetitions). Participants pressed two keys to adjust the 'weight' dimension of the avatar's body to correspond to their perceived body size [14,40,51].

Changes in PA (Gait) Patterns: Gait biomechanics measured both implicit changes in perceived body weight [73] and the effects in PA. FSR data served to quantify the exerted force of heel and toe against the ground and their contact times, as well as the stance and the gait cycle times. MEMS data quantified the foot lifting/downward acceleration during the swing phase.

Changes in Emotional State: Self-assessment manikin [11] was used to measure valence, dominance, and arousal.

Changes in Body Feelings: These were quantified with a questionnaire comprised of 7 statements (7-point Likert-type response items) which ranged from: "I felt slow" to "I felt quick" (Speed); "I felt light" to "I felt heavy" (Weight); "I felt weak" to "I felt strong" (Strength); "I felt very feminine" to "I felt very masculine (Masculinity); "I felt very incapable" to "I felt very capable (Capability); "I found the exercise very easy" to "I found the exercise very difficult" (Difficulty); "I found the exercise not tiring at all" to "I found the exercise very tiring" (Tiredness).

3.1.4 Experimental Procedure. As in [73] we used a within-subjects design, given the great inter-subject variability of body perception [29], and adopted two strategies to compensate for practice bias: condition randomization and varying the initial avatar's weight across trials to avoid anchor effects of the initial value.

After participants had been equipped and practiced all the tasks, they completed three experimental blocks (Low Frequency, High Frequency and Control) in a randomized order (Repetition 1). Then, the three blocks were repeated in another randomized order to collect more data (Repetition 2). In each block, participants first walked in place for 10 s on the wooden board on the floor (marching phase). After a go-ahead signal, they stepped up and down the gym step for 10 times (step phase). As in [73], the marching phase was aimed to increase sound exposure but the gait analyses focused on the step phase. Participants were asked to walk at a self-paced, comfortable speed. After the step phase, participants adjusted twice the avatar (the initial avatar weight varied) and completed the questionnaire (emotional state and body feelings). The full procedure took 50 minutes.

3.1.5 Data Analyses. A specifically developed piece of software, described in detail in [74], was used to extract the gait parameters. The net acceleration was calculated as the square root of the sum of the squares of the 3 axes [73]; data were low passed filtered to reduce noise [25,34], and the first derivative was calculated. For FSR data, the foot is considered to touch the ground when the FSR value exceeds a threshold value; erroneous detections of the foot leaving the ground are avoided by considering the rate of acceleration change. Once all steps had been identified within the data sets, we extracted for each foot and step these parameters: mean exerted force of heel/toes against the ground, stance or contact time (difference between initial strike time and last contact time), gait cycle time and foot upward/downward acceleration. For each trial and parameter, we calculated the average of all steps in the walking phase and LOG-transformed the data for normalization. Data from both feet were averaged since we did not expect feet differences due to feedback.

For questionnaire data, non-parametric Wilcoxon tests were first used to analyse the main effects of the within-subject factors sound condition and repetition. Then, to test the hypotheses related to individual differences, we used repeated measures analyses of variance (ANOVA) on aligned ranked-transformed data as these allow analysing interactions in non-parametric data [16]. The ANOVAs had 3x2 within-subject factors sound condition and repetition. We added the participant's actual weight as covariate to test Hypothesis 2. Hypothesis 3 was tested by adding on top gender, as a between-subject factor, and participant's self-reports of "masculine being" and "masculine wish" as covariates. We ran similar ANOVAs to analyse the effects on body visualization and gait. Interaction effects of sound with the individual factors used as covariates were followed by linear regression analyses, to investigate the effect of the sound condition according to the individual factor.

3.2 Results

3.2.1 Effects on Bodily Feelings (Questionnaire data). Wilcoxon paired comparisons on the questionnaire data did not reveal an effect of repetition except for emotional valence and tiredness; for the rest of the items we averaged the data across repetitions and used further Wilcoxon tests to compare the three sound conditions.

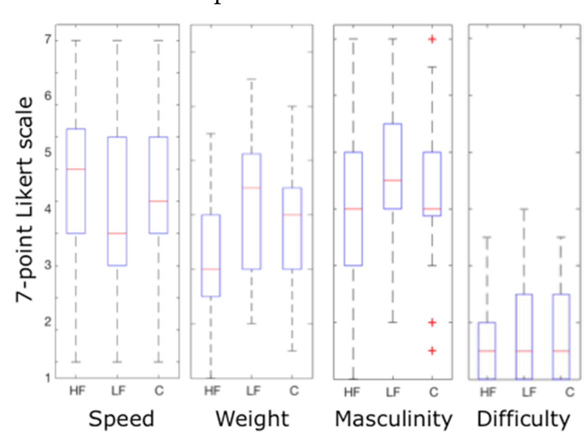

Figure 2: Median(±Range) for questionnaire items for which there were significant effects of sound condition (HF-High Frequency, LF-Low Frequency, C-Control).

As shown in Figure 2, participants felt **quicker** in High than in Low Frequency (z=-3.01, p=0.003) and Control (z=-2.55, p=0.011); **lighter** in High than in Low Frequency (z=-3.93, p<0.001) and Control (z=-2.75, p=0.006) and **heavier** in Low Frequency than in Control (z=-2.52, p=0.012); more **feminine** in High than in Low Frequency (z=-2.89, p=0.004) and Control (z=-2.41, p=0.016) and more **masculine** in Low Frequency than in Control (z=-2.23, p=0.025). They found more **difficult** in terms of effort the Low than the High Frequency (z=-3.12, p=0.002) and Control (z=-2.08, p=0.038) conditions. No significant effects emerged for other questionnaire items.

These overall effects revealed more complex interactions related to individual differences. When adding the participant's actual weight as covariate to 3x2 ANOVAs on aligned ranked-transformed data, no significant interactions appear. When further adding gender and masculine being/wish reports, the ANOVA showed that, for difficulty, there was a triple interaction between sound, repetition and weight ($F(2,64)=3.17$, $p=0.048$, $\eta^2=0.085$); for **heavier participants**, there were larger differences in **difficulty** across conditions; this difference became larger in repetition 2 when they judged High Frequency as the easiest condition. Moreover, for strength, there was a double interaction between sound and masculine being ($F(2,64)=3.42$, $p=0.039$, $\eta^2=0.1$); those perceiving themselves as more **masculine** felt **stronger** in Low Frequency than those with more feminine percepts.

Regarding repetition, participants felt **happier** in the first Control repetition than in the second one (z=-2.55, p=0.011). For **tiredness**, they also felt less tired in the first High Frequency repetition (z=-2.18, p=0.029) and first Control repetition (z=-2.40, p=0.016), than in the second one. For tiredness, there were triple interactions between sound, repetition and weight ($F(2,64)=3.3$, $p=0.043$, $\eta^2=0.93$) and sound, repetition and gender ($F(2,64)=3.52$, $p=0.035$, $\eta^2=0.099$). Splitting participants according to weight showed that overall participants found the High-Frequency condition less tiring than the others in the first repetition, but only for **heavier participants** this effect was maintained (and enhanced) in repetition 2.

3.2.2 Effects on Perceived Body Weight (Visualization). The ANOVA with weight as covariate showed significant effects of sound ($F(2,70)=5.76$, $p=0.005$, $\eta^2=0.14$), and an interaction between sound and actual weight ($F(2,70)=8.23$, $p=0.001$, $\eta^2=0.19$). Pairwise comparisons between sound conditions revealed that **Low Frequency** was associated with a significantly **heavier body** than High Frequency (p=0.033) and Control (p=0.049).

To further explore the sound interaction with actual weight, we calculated the difference in perceived body weight between High Frequency and Control, and between Low Frequency and Control, and performed linear regression analyses between these two variables and actual weight. Higher actual body weight predicted larger shifts from Control in High Frequency ($r^2=0.23$, $b=-.48$, $p=0.003$) but not in Low Frequency. As seen in Figure 3 – left, the effect of sound was larger for **heavier participants,** who represented their body as **thinner in High Frequency** vs Control. For further data visualization, see Figure 3 – right showing the ratio perceived-actual body weight for low/high weight participants (median split). Note that while in Figure 3 there are two subjects with higher weight for which the sound effect is larger, the finding holds beyond these two subjects: shifts in perceived weight in High Frequency are larger for heavier subjects. Splitting (median) participants in "Low" & "High weight", the mean shifts in perceived weight from Control to High Frequency are: +0.014kg (Low weight), -1.026 kg (High weight; -0.6 kg without last 2 subjects). Future studies should test a bigger sample to make these findings generalizable and inform technology to support PA.

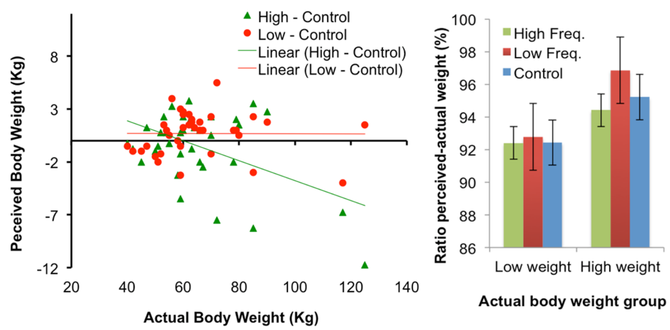

Figure 3: (Left) Regressions between perceived and actual weight for the High and Low Frequency conditions using Control condition as baseline. (Right) mean (±SE) ratio perceived-actual body weight for low/high weight participants (median split) for all sound conditions.

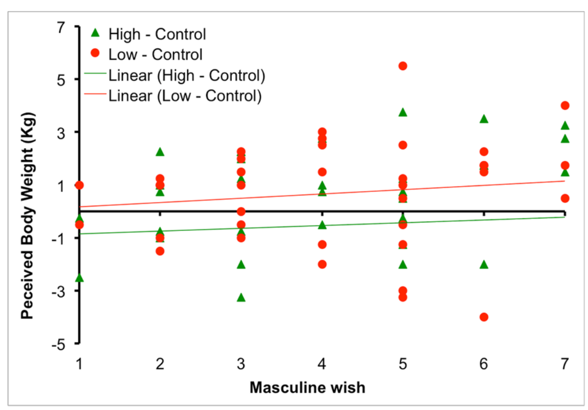

Figure 4: Regressions between perceived weight and masculine wish for High and Low Frequency conditions using Control condition as baseline. Masculine wish, ranges from "very feminine" (1) to "very masculine" (7).

Adding gender and masculine being/wish as covariates showed the reported significant interaction between sound and participant's weight ($F(2,64)=8.37$, $p=0.001$, $\eta^2=0.21$), and an interaction between sound and "masculine wish" ($F(2,64)=3.77$, $p=0.028$, $\eta^2=0.11$), but no interaction between sound and gender or reported "masculine being". Regression analyses between "masculine wish" and the difference in perceived body weight from Control in High Frequency and Low Frequency, were not significant, but the regression lines in Figure 4 suggest that for **participants wishing to be more feminine** the High Frequency condition differentiated from the others, making them feel **thinner;** in contrast, for participants **wishing to be more masculine** the Low Frequency condition differentiated from the others, making them feel **heavier**.

3.2.3 Effects on Gait (Sensors Data). Gait data for 8 participants, for 3 participants' right foot, for 4 participants' left foot and for one trial for 3 participants were lost. We tested our hypotheses with the remaining data from 29 participants. The ANOVAs with participant's actual weight as covariate showed significant effects on exerted heel force against the ground and upward foot acceleration. Heel force showed a significant double interaction between sound and repetition ($F(2,46)=3.34$, $p=0.044$, $\eta 2=0.127$) and a significant triple interaction sound, repetition and weight ($F(2,46)=4.21$, $p=0.021$, $\eta 2=0.155$). The latter triple interaction was also found for the upward foot acceleration ($F(2,46)=3.93$, $p=0.027$, $\eta 2=0.15$).

Follow-up separate ANOVAs for each repetition were not significant for heel force. This is explained by the fact that the effects of sound reversed across repetitions (Figure 5). Similar analyses for upward acceleration showed, only for repetition 2, a significant effect of sound ($F(2,50)=4.11$, $p=0.022$, $\eta 2=0.14$) and an interaction between sound and weight ($F(2,50)=6.05$, $p=0.005$, $\eta 2=0.195$) (Figure 5).

The interactions with actual body weight were followed by regression analyses between actual body weight and the difference in heel force or acceleration from Control in High and Low Frequency. For both heel force and acceleration there were significant effects only in repetition 2, where higher actual body weight predicted larger shifts from Control in Low Frequency (heel force: $r^2=0.2$, $b=-.45$, $p=0.017$; acceleration: $r^2=0.15$, $b=-.39$, $p=0.039$). As seen in Figure 5, in repetition 2 participants **accelerated the foot less** in Low Frequency; this effect was more noticeable for **heavier participants,** who also applied less force in Low Frequency vs Control. While the effects of repetition did not show in the body visualizer, they emerged for gait suggesting that more exposure to feedback may result in bigger changes in behavior. That the effect was bigger for heavier participants and Low Frequency sound may suggest an effort to counter the effects of feeling heavier.

Adding gender and masculine being/wish reports to the ANOVA showed the already reported triple interactions between sound, repetition and participant's weight for heel force ($F(2,40)=4.80$, $p=0.014$, $\eta^2=0.19$) and upward foot acceleration ($F(2,40)=3.20$, $p= 0.051$, $\eta^2=0.14$). However, there were no significant individual differences on the effects of sound condition according to gender and perceptions/aspirations of body masculinity/femininity.

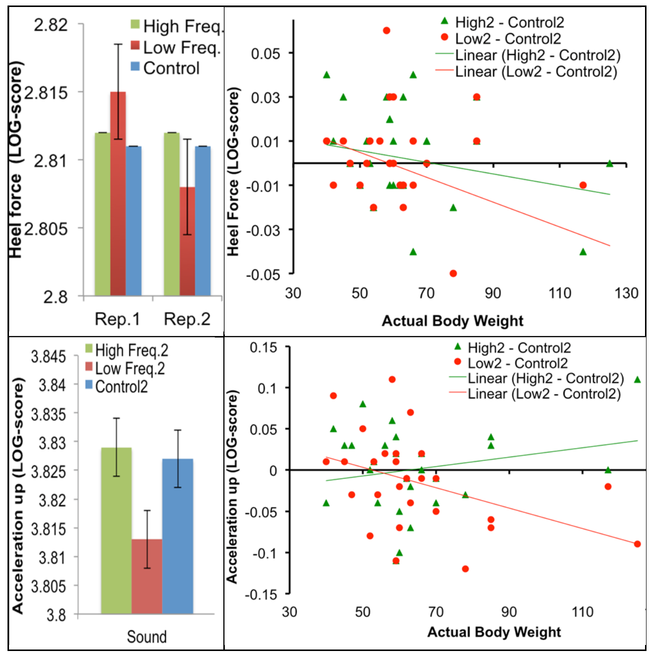

Figure 5: (Left) Mean (±SE) heel force across repetitions (top) and foot upward acceleration in repetition 2 (bottom) for all sounds. (Right) regression between actual weight and heel force (top) and acceleration (bottom) in repetition 2 for High and Low Frequency conditions with Control as baseline.

4 USER STUDY 2: CLIMBING UP STAIRS

In this study, the shoe-based prototype was further modified to increase its wearability and ease-of-use in ubiquitous environments, thus allowing participants to wear it while exercising climbing up stairs. This scenario is by far more common in everyday life than the scenario of using a gym step. Indeed, all of the participants in Experiment 1 reported that they had never used a gym step. Moreover, people with difficulty in PA do value differently exercises (gymstep) and functional activity (FA; i.e., movement necessary to every activity – e.g., climbing stairs to exit the subway or at home). FA raises different barriers (social exposure/pressure, lack of control on the activity – e.g., length steepness) that may affect body perception. In therapies both activities are addressed because exercise-gained capabilities alone do not transfer to FA [63,64] even if related (e.g., using gymstep and climbing stairs) and FA avoidance limits work/social/family activities. Therefore, testing the effects on this scenario is interesting for the long-term goal that is to propose a technology to support physical activity in everyday life. Study 2 was also set to investigate the duration of the effects – will the effects hold once the feedback is removed? While studies on body illusions elicited through senses other than audition have reported short-term effects, this duration has been rarely measured and never in sound-driven illusions. Therefore, it is a question worth investigating given the implications on behavioural changes technology design. The hypotheses tested in Study 2 were:

Hypothesis 4: sound will have an effect on body perception and feelings when climbing up stairs.

Hypotheses 5: the effects of sound feedback will hold for at least one flight of stairs once feedback is removed.

4.1 Method

4.1.1 Participants. Twenty-two paid participants (age=18-28, eleven male and eleven female, normal hearing) naïve to the study aim took part in the study. Their mean body weight and height (SD) were 66.77(16.82) Kg and 171.14(10.78) cm.

4.1.2 Materials. The experiment was conducted in a quiet staircase with concrete flooring. Each flight of stairs between one landing and the next was comprised of 10 steps (13 cm height). The system was an adaptation of the one in Study 1. The audio part was modified to minimize the system and make possible its use in a staircase (Figure 1). Here, two microphones (Røde Smartlav+, 20–20000Hz) were attached to the sandals and connected to a smartphone (iPhone 5S). The commercial smartphone app Sound Fun (©Bitcapsula) was used to amplify the sounds picked up by the microphones and perform noise suppression. The output of the smartphone connected to a small stereo 7-band graphic equalizer (Source Audio™) that changed the sound spectra as in Study 1. The resulting sound was fed back via closed headphones (Sennheiser HDA300). The walker could carry this minimized version of the system consisting of a smartphone and small equalizer in their hands. A laptop computer was used for the body visualization task.

4.1.3 Experimental Design.

4.1.3.1 Sound Feedback Conditions. The same sound feedback conditions as in Study 1 were used (High Frequency, Low Frequency and Control). The only difference was that in the Control condition participants did not wear the headphones in order to listen to their natural footstep sounds, without frequency or amplification changes. In this way, the Control condition was similar to the everyday experience of climbing stairs.

4.1.3.2 Multi-Measurement Approach. The effects of sound feedback were evaluated with the same "body visualization" task described in Study 1, and a questionnaire with a slight modification from the one used in Study 1. Instead of the "capability" statement, there was a "Posture" statement ranging from "I felt slouched" to "I felt up straight".

4.1.4 Experimental Procedure. Similar procedure as in Study 1 was followed. Participants completed a set of three experimental blocks (Low Frequency, High Frequency, Control) presented in a randomized order. The three blocks were then repeated in another randomized order. In each block, participants first walked in place for 10s on the landing before the first flight of stairs (marching phase 1). After a go-ahead signal, they went up the first flight of stairs consisting of 10 steps (flight 1) with the sound on. After the first flight stairs participants adjusted the avatar (the initial weight of the avatar varied between trials) and completed the questionnaire. Next, participants walked in place again for 10 s on the landing before the second flight of stairs with the headphones on (marching phase 2). After a go-ahead signal, they removed the headphones and went up another flight of stairs consisting of 10 steps (flight 2). Next, they adjusted the avatar and completed the questionnaire. The full procedure lasted 50 minutes.

4.2 Results

4.2.1. Questionnaire Data. 3x2x2 ANOVAs (sound, flight, repetition) on aligned ranked-transformed data showed (see Figure 6) that sound had an effect on arousal ($F(2,40)=3.31$; $p=0.047$, $\eta^2=0.14$): participants felt more **aroused** in High than in Low Frequency ($p=0.038$) and Control ($p=0.028$). For perceived weight, there was an effect of flight ($F(1,21)=17.24$; $p<0.001$, $\eta^2=0.45$) and an interaction sound*flight ($F(2,42)=3.47$; $p=0.040$, $\eta^2=0.14$): participants felt **heavier** in flight 1 (sound on) than in flight 2 (sound off); only **for flight 1** they felt **heavier** in Low than in High Frequency ($p=0.019$) and Control ($p=0.020$). For masculinity, flight had an effect ($F(1,21)=9.23$; $p=0.006$, $\eta^2=0.30$); participants felt more masculine in flight 1 (sound on) than in flight 2 (sound off; $p=0.031$). For feelings of being **up straight,** sound and flight interacted ($F(2,42)=4.97$; $p=0.012$, $\eta^2=0.19$); only for flight 1 (sound on) participants felt more up straight in Control than in High Frequency ($p=0.003$). For speed, there was an effect of flight ($F(1,21)=6.31$; $p=0.020$, $\eta^2=0.32$), as participants felt **quicker** in flight 2 (sound off), and an interaction sound*flight ($F(2,42)=3.81$; $p=0.030$, $\eta^2=0.15$) as participants felt significantly quicker in Low than in High Frequency in flight 2 (sound off; $p=0.043$), but with no significant differences in flight 1 (sound on). For tiredness, there was an effect of repetition ($F(1,21)=9.11$; $p=0.007$, $\eta^2=0.30$), as participants felt **more tired** in repetition 2; an effect of sound ($F(2,42)=3.34$; $p=0.045$, $\eta^2=0.14$) as participants **felt more tired in Low** than in High Frequency (p=0.024); and an interaction repetition*flight (F(1,21)=5.55; p=0.028, η^2=0.21) with participants being more tired in the last flight and repetition. No significant effects emerged for other items.

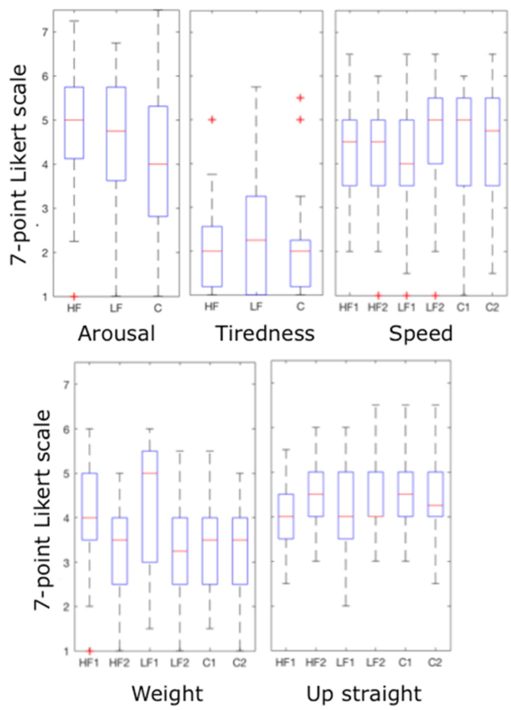

Figure 6: Median(±Range) for questionnaire items for which there were significant effects of Sound (HF-High Frequency, LF-Low Frequency, C-Control) or Sound*Flight interaction.

For perceived weight, there was an effect of flight (F(1,21)=17.24; p<0.001, η^2=0.45) and an interaction sound*flight (F(2,42)=3.47; p=0.040, η^2=0.14): participants felt **heavier** in flight 1 (sound on) than in flight 2 (sound off); only **for flight 1** they felt **heavier** in Low than in High Frequency (p=0.019) and Control (p=0.020). For masculinity, flight had an effect (F(1,21)=9.23; p=0.006, η^2=0.30); participants felt more masculine in flight 1 (sound on) than in flight 2 (sound off; p=0.031). For feelings of being **up straight,** sound and flight interacted (F(2,42)=4.97; p=0.012, η^2=0.19); only for flight 1 (sound on) participants felt more up straight in Control than in High Frequency (p=0.003). For speed, there was an effect of flight (F(1,21)=6.31; p=0.020, η^2=0.32), as participants felt **quicker** in flight 2 (sound off), and an interaction sound*flight (F(2,42)=3.81; p=0.030, η^2=0.15) as participants felt significantly quicker in Low than in High Frequency in flight 2 (sound off; p=0.043), but with no significant differences in flight 1 (sound on). For tiredness, there was an effect of repetition (F(1,21)=9.11; p=0.007, η^2=0.30), as participants felt **more tired** in repetition 2; an effect of sound (F(2,42)=3.34; p=0.045, η^2=0.14) as participants **felt more tired in Low** than in High Frequency (p=0.024); and an interaction repetition*flight (F(1,21)=5.55; p=0.028, η^2=0.21) with participants being more tired in the last flight and repetition. No significant effects emerged for other items.

4.2.2 Perceived Body Weight (Visualization). Results from the 3x2 ANOVA on LOG-transformed data, with within-subject factors sound condition and flight, showed a significant interaction between sound and flight (*F*(2,42)=4.04, p=0.025, η^2=0.16). Separate ANOVAs for each flight revealed a significant effect of sound for flight 1 (sound on; *F*(2,42)=5.21, p=0.010, η^2=0.16), but not for flight 2 (sound off; p=0.95). Pairwise comparisons for the three sound conditions in flight 1 revealed that High Frequency was associated with a significantly lighter body than Low Frequency (p=0.012) and Control (p=0.042), with no significant differences between Low Frequency and Control (see Figure 7). These results indicate that sound condition had an effect when climbing up stairs, with participants representing their body as thinner in High Frequency, but only for flight 1, i.e., when sound feedback was on. Overall, results from Study 2 show that body alteration possibly occurs when sound feedback is on, but that some effects on body feelings may last after the feedback is removed.

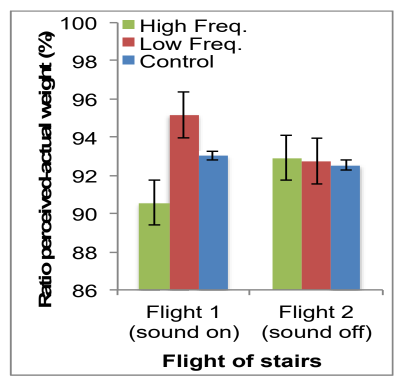

Figure 7: Mean(±SE) ratio perceived-actual weight for all sounds conditions in flight 1 and 2 (feedback on vs off).

5 DISCUSSION

This pair of studies confirms and expands previous works [73,74], by demonstrating how altered footsteps affects people's body perception, bodily feelings and patterns of PA during exertion exercise. In relation to Hypotheses 1 and 4, we show that, overall, the Low Frequency sound feedback led to a heavier body perception and lower foot acceleration, making participants feel more masculine and find exercise more difficult. On the contrary, the High Frequency sound feedback led participants to perceive their body as lighter, feel quicker and more feminine than in the other conditions. Most importantly, in relation to Hypotheses 2 and 3, the studies uncover complex interactions in terms of one's body weight and other personal factors related to body image rather than gender *per se* as suggested in previous work [73]. Finally, in relation to Hypothesis 5, we show that while the effect of altered sound feedback on body alteration may not last once the feedback is removed, some other effects appear to emerge (e.g., feeling quicker after Low Frequency; being less tired after High than after Low Frequency). Our results are important for the design of technology-based interventions to facilitate behavior changes, with possible applications also for rehabilitation, sports and virtual reality/gaming. We discuss below the main interactions identified and their HCI implications.

5.1 Individual's weight impact (Hypotheses 2)

Our results show that body weight plays an important role in the effects of the employed sound feedback in body perception and exercise. In Study 1 we found a significant interaction between sound and participant's actual weight in the various measures used. As compared to the Control condition, heavier participants represented their body as thinner in the High Frequency condition, and in repetition 2 of the Low Frequency condition they applied less force and acceleration when exercising. The latter may suggest an effort to counter a possible unwanted effect of feeling heavier experience due to the sound. This hypothesis may be supported by the finding that the Low Frequency sound made participants find the exercise more difficult, while the High Frequency one, which was found to be the easiest and least tiring condition, became even easier/less tiring for heavier participants in repetition 2, as perhaps they were not pressed to try to counter the effects. The fact that the effects on tiredness were found to last after the sound was removed suggests that they may emerge with longer exposure to the sound feedback. The interaction of weight with sound effect could be explained by the fact that heavier people may perceive their weight (or the stigma associated with it) as a barrier to exercise [3,81].

5.2 Gender & gender perceptions impact (Hypothesis 3)

We show how the effects of the sound are impacted, not by one's gender, but by body perceptions, aspirations or wishes related to gender (i.e., masculinity/femininity). For participants wanting to be feminine, the High Frequency condition led them to perceive their body as thinner/lighter, while for participants wanting to be masculine the Low Frequency condition led them to perceive their body as wider/heavier. Our results also show that gender perceptions interacted with the sound condition with regards to body strength, with participants perceiving themselves as more masculine feeling stronger in the Low Frequency condition. This implies that the design of sensory feedback may be linked not strictly to an individual's gender but to his/her gender-related perceptions and aspirations. We see potential in exploiting the associations between Low Frequency and higher body strength, size and weight to build on positive feelings related to masculinity (e.g., being stronger) that may facilitate PA adherence in people that feel less suited to the typical athlete stereotype, while exploiting the opposite associations in relation to femininity.

Changes in body perception, emotion and motor behaviour may indeed reinforce each other during the process [56]. According to current theories of body perception, the formation of body-representations is complex and modulated by various factors: sensory [10] and interoceptive signals [1] are integrated and modulated by expectations, emotional and socially relevant signals [60]. Social and cultural pressure related to ideal body appearance, and individual experience of the sound [53], may exert top-down influences on the effects of sound: according to their ideal body shape and the social stigma associated to weight (see Hypotheses 2 (H2) results) and gender [3,20,73,81], people may link (even unconsciously) High/Low Frequency sounds respectively to high heel/heavy shoes [20], small/big bodies [41], weak/strong bodies or walking style [21] and thus different effects emerge. Sound designs must consider these top-down influences, often linked to the aspirations of the individual or one's feared stigma (H2), to achieve a positive effect.

5.3 Duration of sound effects (Hypotheses 5)

Study 2 demonstrates that the reported effect of altered sound feedback may not last once the feedback is removed. This is not surprising, as the malleability of the mechanism requires these quick effects; however, it shows the importance of making use of this kind of sound feedback in the moment of exercise. Other works with sensory-driven body illusions have also reported short-term effects but suggested that this may be due to the short exposure to feedback and that repeated/prolonged interventions might show prolonged effects [9]. Results from Study 1 indeed show that, while the effects of repetition did not show in the body visualizer, repeated feedback resulted in bigger changes in gait behavior and bodily feelings (e.g., finding exercise easier), possibly derived from a higher level of awareness of the effects of the sound on body perception. This hypothesis needs to be further tested in terms of intervention and technology application possibilities.

Despite its short duration effects on body perception, such sensory-driven illusions have been shown to have a lasting psychological impact in terms of changes in attitudes for other modalities [43], such as decreasing implicit racial bias after embodying an avatar of a racial outgroup [50]; or allocating more money for one's retirement after embodying an avatar that looks like an aged version of oneself [31]. Coming back to our results, we show that, while the effect of body alteration possibly occurs when the sound feedback is on, after the feedback is removed some effects on body feelings last (e.g., being less tired after High vs Low Frequency) and some new effects may emerge (i.e., feeling quicker when switching off the Low Frequency sound). Thus, the experience of sound feedback, though short, may impact subsequent PA patterns, as there is indeed evidence that participation in previous exertion activities is a facilitator towards PA [5,67] if changes in other factors occur. We suggest that the effects of body alteration taking place during the moment of exercise, and which may be enhanced through repeated interventions over time, may help to overcome barriers related to body perception, building on self-efficacy and self-confidence, as well as to change attitudes towards one's body and PA, and in turn, support PA [61,66].

5.4 Body-centred feedback technologies: Scenarios

Our results open a number of design opportunities. We present possible application scenarios considering the use of altered sensory feedback that changes body perception.

Scenario 1: Overcoming barriers in general PA and sports. The main focus of our paper is on the application of this kind of feedback to support everyday exercise routines. Altered feedback like this could be used to support people who struggle with PA due to low self-efficacy and to those who experience stigma due to their weight [3,61]. This type of altered footstep sounds could be a powerful tool for supporting PA, changing body perceptions during the moment of exercise while people build self-confidence, and ultimately helping people to form a long-term PA routine [66]. For short-term exposure, using Low Frequency feedback to make one feel heavier and then switching it off to make one feel faster may work well. Further, our results provide suggestions on how to account for individual differences (gender norm, weight perception). Our proposed feedback may be useful to design technologies for high performance sports, dance or motor learning [22,55,58,65,85]. It may trigger awareness or reflection on one's body dimension, weight, movement qualities; invite exploration by comparing body perceptions in the different sound conditions; or trigger specific motor changes.

Scenario 2: Overcoming barriers in physical rehabilitation. The type of feedback used in this study may be also useful in rehabilitation contexts in which body perception is important to one's on-going activity, as it may allow focusing on a specific body sensation or building an understanding of the malleability of body perception, which may be useful in some contexts (e.g., body perception altered by chronic pain [63,65,74] or eating disorders [40]). For instance, a bodily illusion (i.e., virtual walking) to treat neuropathic pain in people with paraplegia has shown longer duration of pain relief as compared with other techniques [9]. Another study on physical rehabilitation of people with chronic pain showed how using wearable technology with sound feedback on one's body movement, for a longer period (10 days), helped to acquire abilities for everyday function and to apply strategies for becoming more active [64]. Our study contributes to this body by highlighting new important factors that are critical for self-esteem in this condition (weight, masculinity/femininity) as people going through long term conditions needs to deal with rebuilding their social norm and role.

Scenario 3: Virtual reality and gaming. Our findings may inform the design of avatars in VR and gaming technologies for entertainment or therapy. For example, the study in [4] shows how different sound synthesis techniques can be used to give a perception of robotic movements, providing the *"experience of being a fictional robotic hero"*, which may be useful in gaming contexts. A careful design of the sensory feedback used in these contexts may lead to stronger user's embodiment in a virtual character that may have different anthropomorphic characteristics than the user [57], but as our results show it is also important to consider individual factors interacting with the effects of feedback.

6 CONCLUSION

In this paper, we present, how altered footstep sounds can be used to change body perceptions during exertion exercise. Moreover, the studies show how individual differences impact how these altered sounds are perceived. This demonstrates the importance of designing for the individual when considering real-time feedback for PA - design sound (or generally speaking, sensory feedback) not only thinking to the sound properties but to the different people, their perceptions and values.

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