Enriching footsteps sounds in gait rehabilitation in chronic stroke patients: A pilot study

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Short title: Enriching footsteps sounds in stroke patients.

Abstract

In the context of neurorehabilitation, sound is being increasingly applied for facilitating sensori-motor learning. In this study, we aimed to test the potential value of auditory stimulation for improving gait in chronic stroke patients by inducing alterations of the frequency spectra of walking sounds via a sound system consisting of an amplifier, equalizer and headphones following previous work on healthy subjects. Twenty-two patients with lower extremity paresis were exposed to real-time alterations of their footstep sounds while walking. Changes in body-perception, emotion and gait were quantified. Our results suggest that by altering footsteps sounds, several gait parameters can be modified in terms of left-right foot asymmetry. We observed that augmenting low frequency bands or amplifying the natural walking sounds led to a reduction in the asymmetry index of stance and stride times, whereas it inverted the asymmetry pattern in heel-ground exerted force. In contrast, augmenting high frequency bands led to opposite results. These gait changes might be related to updating of internal forward models, signaling the need for adjustment of the motor system to reduce the perceived discrepancies between predicted-actual sensory feedbacks. Our findings may have potential to enhance gait awareness in stroke patients and other clinical conditions, supporting gait rehabilitation.

Key words: Auditory feedback; forward model; gait rehabilitation; stroke.

1. Introduction

According to the World Health Organization, stroke is the second leading cause of death[1] and disability[2] in countries of the developed world. The ability to walk is impaired in 80% of stroke patients[3,4], characterized by decreased speed, cadence and stride length as well as gait asymmetry between both lower extremities regarding spatial temporal gait parameters[5,6]. Deficits in somatosensory function, leading to sensory loss and altered bodily experiences, are also relatively common after stroke[7,8]. These deficits keep stroke patients from performing their daily activities independently and participating in their community.

Gait control is sustained by an extensive network of neural structures and pathways such as the spinal cord, brainstem, cerebellum, basal ganglia, limbic system, and cerebral cortex, as well as their interactions with the environment[9,10]. Crucially, the cerebellum takes into account both feed-forward information and real-time sensory feedback (visual, auditory, vestibular, tactile, proprioceptive) for providing locomotor adaptation[11].

Over the past few years, new rehabilitation techniques tackling sensorimotor learning are being studied, drawing from the growing evidence supporting the notion body perceptions (mental body models or body-representations) are not fixed but continuously updated by body-related multisensory feedback[12-17]. According to computational theories for motor control such as the 'Comparator hypothesis'[18], the planning and execution of motor actions are re-adjusted when there is a mismatch between the predicted sensory feedback (*efference copy*) and the actual feedback once the action is performed (*afferent inputs*). An important aspect that derives from this model is that planning and execution of motor actions can be partially altered by augmented or distorted external multisensory feedback.

In the context of feedback-based rehabilitation, movement sonification provides real-time auditory information about the *actual* body position supplementing proprioceptive information, increasing body awareness and coordination, guiding movement, providing indication of progress, increasing motivation, reducing anxiety and facilitating sensorimotor learning[19]. For example, musical sonification therapy has been used effectively to enhance gross movements of the upper extremity after stroke[20-

[22] as well as emotionally charged auditory stimulation with happy or sad sounds has been shown to enhance gait velocity and cadence[23]. In the specific case of gait rehabilitation, real-time auditory feedback on walking and step cueing has been used to compensate for limited proprioceptive feedback and to promote correct movement in gait rehabilitation in clinical populations such as Parkinson disease[24,25], children with cerebral palsy[26], patients with multiple sclerosis[27] as well as in modifying gait patterns in healthy older adults[28,29].

On the contrary, much less work has been done using sound as a source of *sensory alteration* or distortion of one's own body, augmenting or distorting the actual natural feedback recalibrating the feed-forward motor commands of the action performed, impacting motor behavior and body-representation. For example, studies manipulating the auditory feedback during singing[30] or speech production[31] have shown involuntary adjustment and compensation over the unexpected feedback. Menzer et al.[32] induced an alteration in gait (walking speed) and in sense of agency by delaying the provision of self-produced footsteps sounds. In a series of studies, Tajadura-Jiménez and colleagues provided evidence about the manipulation of participant's perceived body appearance, behavior and emotion, introducing altered auditory feedback synchronized to the participant's movement. For example, altering the spatial cues of sounds produced when one's hand taps a surface can lead to perceive one's arm as longer than before[33] or to perform reaching actions as if one's arm was longer[34]. Recently Tajadura-Jiménez et al. (2015) reported new evidences on this possibility using a new developed wearable technology allowing to manipulate real-time walking sounds[35]. Augmenting the high-frequencies of the walking sounds made people perceive their body as lighter/thinner leading to "more active" gait patterns. More recently, this study was replicated[36] in the context of exertion, confirming that the effects of sound in body-perception occur even in physically demanding situations. Changes in body–perception, as well as gait variations have also been evaluated in a proof-of-principle study[37] with complex regional pain syndrome (CRPS) patients suffering from chronic pain and distortions in body-perception, showing changes in body–perception disturbances, as well as gait variations, depending on the sound feedback condition.

To date this approach tackling bottom-up mechanisms by which changes in body-perception lead to changes in gait and bodily feelings has not been trialed in chronic stroke patients. Such approach may have a potential value for these patients, given the anomalous gait and bodily sensations often observed in them[5-8]. With this purpose in mind, we applied the same wearable technology used in previous studies[35-37] in order to test whether we could modify dysfunctional gait patterns in this group of patients by manipulating the perceived auditory feedback of their footsteps sounds, expecting to induce changes in the patients' perception of their body leading to changes in gait asymmetry.

2. Materials and Methods

2.1. Participants

Twenty-four chronic stroke patients with lower extremity paresis participated in the experiment. The recruitment of participants was done using a database of stroke patients who had received an outpatient rehabilitation program at the Department of Rehabilitation and Physical Medicine from Hospitals del Mar i l'Esperança (Barcelona, Spain). Medical records from this database were reviewed and patients were interviewed by phone regarding their difficulties when walking. To be eligible as a participant, inclusion criteria were hemiparesis of the lower extremity after a first ever stroke, more than 6 months since the stroke, no major cognitive problems affecting language comprehension (difficulties in understanding task instructions or procedures, questionnaire statements, etc.) and no other psychiatric or neurologic comorbidity. From the initial sample of 24 participants, one participant could not complete the experiment due to fatigue and there were technical problems with another participant during the experiment to consider his data valid. Therefore, the final sample was composed by 22 participants (18 males and 4 women, mean age 67.6 ±7) the majority of whom had suffered an ischemic stroke (81.8%). Lesions were mainly located at the subcortical level and in the brainstem, and the mean time since the stroke onset was 1 year and 10 months (although the range was from 6 months up to 5 years post-stroke). Most participants had a slight-to-moderate paresis of the lower extremity as measured with the lower extremity subtest from the Fugl-Meyer Assessment of Motor Recovery after Stroke[38] (mean score 29.7 ±4.8) (Table 1 provides a description of the patient's demographic and clinical characteristics including the score obtained in the Fugl-

Meyer Assessment, the Barthel Index and the results of the 10-m walking test performed before the experiment).

All patients signed an informed consent form for participation in this study and the protocol was approved by the Ethical Committee of the Hospital del Mar Medical Research Institute (Barcelona, Spain).

2.2. Apparatus and Materials

Participants were asked to wear a system, which will be referred to as "sonic shoes", previously described in detail in Tajadura-Jiménez et al.[35-37], which allows the dynamic modification of footstep sounds while walking and measure behavioral changes. As shown in Figure 1A, the system is comprised of a pair of strap sandals with hard rubber sole. Two microphones are attached to the sandals to capture the walking sounds (Core Sound). The microphones are connected to a small stereo pre-amplifier (SP-24B), which connects to a stereo 9-band graphic equalizer (Behringer FBQ800) that changes sound spectra. The resulting sound is fed back via closed headphones (Sennheiser HDA300) with high passive ambient noise attenuation (>30 dBA) that muffle the actual sound of footsteps. The analogue sound loop has minimal latency (<1 ms). Pre-amp and equalizer are fitted into a small backpack that the walker carries (~2 Kg, 35x29x10 cm).

The part of the system dedicated to measure gait data is comprised of four force sensitive resistors (FSR; 1.75 × 1.5″ sensing area) attached to the front and rear part of the sandal insoles; and two 9-axis MotionTracking devices (MEMS; Sparkfun MPU-9150) placed on the participant's ankles. FSRs and MEMS in each foot connect to a Microduino microcontroller board, which combines a Microduino Core, a Microduino Shield Bluetooth 4.0, and a Microduino USBTTL Shield, and a battery. This board is placed into a plastic box attached to the sandals, linking the sensors via Bluetooth to a smartphone. An especially developed app (*SmartShoes*) captures 3-axis acceleration, 3-axis gyroscope and FSR data for both feet and save it as TXT file on quitting.

2.3. Procedure

2.3.1. Experimental design

A within-subjects design was carried out given the variability of this clinical population. The experiment was conducted at a quiet and adapted room (45 m^2), made of a hard rubber material surface, in which patients were instructed to perform a specific track at a self-paced, comfortable speed (see Fig. 1B).

The experiment started in all cases with a Baseline condition in order to obtain a neat measure on the patients' gait performance without providing any kind of additional auditory feedback but their natural footsteps sound. Next, they completed three experimental blocks, which differed in the sound feedback received when walking. The three feedback conditions were created by dynamically modifying the footstep sounds people produce as they walk (based on[35-37]: (a) a 'Control' condition in which patients were provided with their natural footsteps sounds equally amplified across frequency bands, (b) a 'Low frequency' condition in which the frequencies of the walking sounds in the range 83-250 Hz were amplified by 12 dB and those above 1 kHz were attenuated by 12 dB, so that the resulting sounds are consistent with those produced by a heavier body, and (c) a 'High frequency' condition in which the frequency components in the range 1-4 kHz were amplified by 12 dB and those between 83-250 Hz were attenuated by 12 dB, so that the resulting sounds are consistent with those produced by a lighter body. The 3 experimental conditions were randomized across subjects to account for possible effects of order on our results. At the end of each track, the patient was asked to sit down and complete 2 self-assessed questionnaires regarding their body feelings and emotional responses.

2.3.2. Questionnaires

Firstly, a questionnaire[39] was used to quantify the patients' body feelings by asking them to use 7-point Likert-type response items to rate their felt speed (slow vs. quick), body weight (light vs. heavy), body strength (weak vs. strong) and body straightness (stooped/hunched vs. straight). In addition, patients were asked to rate their level of agreement with four statements (7-level Likert-type response items, from strongly agree to strongly disagree) regarding agency of the walking sounds they heard, vividness of the bodily experience, surprise about the bodily feelings and feet localization. The Vividness and Surprise items were excluded due to verbal comprehension difficulties regarding concept understanding.

Emotional valence, arousal and dominance were quantified using the three 9-item graphic scales of the self-assessment manikin questionnaire[40]. Both measures were collected after the Baseline and after all 3 experimental conditions. Data from 2 patients were not registered due to patient's fatigue reports.

2.3.3. Gait measures

Raw sensor data were analyzed using MATLAB software. As in Tajadura-Jiménez et al.[35] the net acceleration was calculated as the square root of the sum of the squares of the 3 axes; the same procedure was followed to calculate the net gyroscope data. Setting thresholds on the rate of gyroscope change allowed identifying the touch-down and toe-off events of individual steps within the data sets. Then we extracted for each foot and step these parameters: mean exerted force of the heel against the ground, stance or contact time (time period from initial heel contact (touch-down event) to last toe contact (toe-off event)), stride time (time between two touch-down events, from which cadence and gait velocity can be derived), and foot upward/downward acceleration. For each trial, foot and parameter, we calculated the average of all steps in the walking phase and we subtracted the data of the non-affected foot from the data of the affected foot in order to investigate the effects of sound on asymmetry between both lower extremities[4,5]. We transformed the resulting data into normalized z-scores following a normal distribution curve.

2.4. Data analyses

Non-parametric Kruskal-Wallis test for ordinal data was employed for comparing patients' responses to the questionnaires for the different sound conditions. The Wilcoxon signed rank test for non-parametrical data was used for testing the differences in time (not normally distributed), with the significance alpha level adjusted to multiple comparisons (with Bonferroni correction, the significance level was set at $p < 0.012$). We analyzed normal parametrical gait data (normality tested with Shaphiro–Wilk) with repeated measures analyses of variance (ANOVA), with the factor sound condition ("Baseline", "Control," "High frequency," and "Low frequency"). Further, we added participant's weight as covariate as it is known to interact with the effect of sound condition[27]. Significant effects were followed by paired samples two-tailed t-tests, with the significance alpha level adjusted for multiple comparisons (with Bonferroni correction, the significance level was set at $p < 0.017$).

3. Results

3.1. Questionnaires

Regarding the results from the questionnaires, no significant differences between conditions were found neither on the body feelings questionnaire[35] (Fig. 2A) nor on the self-assessment manikin questionnaire[40] (see Fig. 2B) when computing the non-parametric Kruskal-Wallis test for ordinal data.

3.2. Effect of sound condition on time for completing the track

When looking at the time (in seconds) needed for completing the track, significant differences were found between the Baseline and the Control conditions [mean Baseline = 1.677 s ± 0.756; mean Control = 1.453 s ± 0.626; $Z(22) = -2.555$; $p = 0.011$] when computing the Wilcoxon signed rank test for non-parametrical data, evidencing an increase in the time needed to complete the track in the Baseline condition. Also, differences between the Baseline and Low frequency conditions were also found to be significant [mean Baseline = 1.677 ± 0.756; mean Low frequency = 1.497 ± 0.667; $Z(22) = -2.470$; $p = 0.014$], showing faster times for the Low Frequency feedback condition. Interestingly, when looking at the differences between the Baseline condition and the combined auditory feedback conditions, a reduction in time was observed when auditory feedback was provided [mean Baseline = 1.677 ± 0.756; mean Combined feedback = 1.497 ± 0.633; $Z(22) = -2.062$; $p = 0.039$], although not reaching adjusted alpha level of significance.

3.3. Effects of sound condition on Gait (Sensors data)

Reviewing the effects of sound on all the gait parameters, the stance time showed a significant effect of sound condition [$F(3, 57) = 3.70$, $p = 0.017$]. While in the Baseline participants spent more time with their affected foot (vs. non-affected) in the ground, this shifted in the High Frequency condition [$t(19) = 4.07$; $p = 0.001$], showing an inverted pattern of asymmetry resulting in a longer stance time on the non-affected hemibody (see Fig. 3A). On the contrary, in Figure 3A it can be seen how the stance time's asymmetries for the Low Frequency and Control conditions seem to disappear.

A similar related effect of sound condition was found for stride time (time between two touch-down events, related to gait velocity and cadence), [$F(3, 57) = 5.13$, $p = 0.003$]: The stride time was longer with the affected foot (vs non-affected) in the Baseline condition, but this shifted in the High Frequency condition, resulting in a longer stride time for the non-affected side [$t(19) = 4.69$; $p < 0.001$] (see Fig. 3B). On the other hand, the asymmetry index for the Low Frequency and Control conditions are approaching zero, although these conditions did not differ significantly from the Baseline (Baseline vs Low $p = 0.066$; Baseline vs Control $p = 0.15$). For heel mean exerted force there was also a significant effect of sound condition [$F(3, 39) = 3.42$, $p = 0.011$]. As it can be seen in Figure 3C, while in the Baseline participants exerted more force on the ground with the non-affected foot (vs. affected), this shifted with the sound conditions, especially in the Low Frequency [$t(13) = -3.45$; $p = 0.004$] and Control [$t(13) = -3.62$; $p = 0.003$] conditions, with the asymmetry score for the High Control condition falling near zero. No significant effects on gait outcome measures were found when including lesion localization (Cerebrum vs brain stem) as a covariate in the ANOVA's

When adding participants' weight as a covariate, we found a main effect of sound condition for foot downward acceleration and an interaction of sound condition and weight [sound effect: $F(3, 54) = 3.24$, $p = 0.029$; sound*weight effect: $F(3, 54) = 2.90$, $p = 0.043$]. It was found that the Baseline and Low Frequency conditions resulted in lower acceleration for the affected foot (vs. non-affected) but this shifted for the other two sound conditions (see Fig. 3D). Further, weight significantly predicted the difference between the Baseline value and the other conditions: Low Frequency [$R2 = 0.199$, $b = 0.049$, $p = 0.049$], the High Frequency [$R2 = 0.197$, $b = 0.068$, $p = 0.050$] and Control [$R2 = 0.258$, $b = 0.064$, $p = 0.022$].

4. Discussion

As revealed by previous research, auditory feedback can alter body-perception in healthy controls[15,16,35-37] as well as in clinical populations[21,22,24-27]. In this proof-of-principle pilot study, our main aim was to assess the possibility of modifying dysfunctional gait asymmetry patterns in chronic stroke patients with lower limb hemiparesis by providing manipulated auditory feedback of their walking sounds. While there are a number of applications for movement rehabilitation using sound with information about the *actual* body position or movement, our study is novel in that it shows the potential of using sound in gait rehabilitation by means of the introduction of changes in body perception in chronic stroke patients. Our results suggest that by altering footsteps sounds, different gait parameters can be modified.

Traditionally, different techniques have been developed with the aim of restoring the walking ability, mainly from a compensatory perspective[41,42]. Over the past few years, new rehabilitation techniques relying on sensori-motor learning are being studied, as is the case of sound[43-49], offering a number of interesting advantages in the context of applications for movement rehabilitation, such as no interference with the ongoing movement, provision of a continuous flow of information[50], high temporal resolution and high sensitivity for detecting structured motion [51-53].

Real-time alteration of the sound feedback resulting from motor actions may influence body-perception by means of the 'forward model' computations that occur during sensory-motor transformations[18]. As multisensory feedback accompanies motor actions providing information about the actual state of the body, this online external input is of crucial importance for informing the system about discrepancies between the predicted feedback (*efference copy*) and the actual feedback (*afferent inputs*). Such discrepancies signal the need for re-adjustments and changes in body dynamics which lead to sensori-motor adaptation. This flexibility offers a valuable opportunity for designing novel interventions based on the updating of forward sensory predictions as a consequence of altering the expected sensory feedback of the actions performed.

In the current study, the effects of sound feedback on gait mechanics were quantified in terms of the asymmetry index, by subtracting the data of the non-affected foot from the data of the affected foot. We focused on studying the effects of the different sound conditions in several gait parameters, more specifically, in the stance time, the stride time, heel mean force and acceleration measures. When examining the stance time, a clinically significant reduction on the asymmetry index was found under the Control and the Low frequency conditions as compared to Baseline, meaning that the stance time of the affected and the non-affected foot were very similar (Fig. 3A). Differences between Baseline and Control conditions might be driven by the presence of feedback amplification on the Control condition (note that Baseline condition was performed without headphones, but in the Control condition participants heard the sounds of their footsteps amplified). On the contrary, when amplifying the high frequency bands of walking sounds (High frequency condition), patients tended to invert their asymmetry pattern: while their Baseline gait is characterized by larger stance times for the affected vs. non-affected side, the High Frequency condition led to an increase of the stance time of their non-affected side vs. the affected side. Very similar results were obtained for the stride time, showing that the asymmetry between the affected vs. non-affected hemibody observed in the Baseline period disappeared for the Control and the Low frequency conditions. Contrarily, when presented with the High frequency amplification of their footsteps sounds, a clear inverted asymmetry pattern (see Fig. 3B) was obtained. Considering these two gait parameters in a combined manner, we observe that both the Control and Low frequency conditions result in an asymmetry reduction, while the High frequency lead to an inverted asymmetry pattern, probably reflecting a larger compensatory response mediated by a an auditory feedback signaling less weight applied on the floor (High frequency condition), leading to the creation of new corrective patterns.

When looking at the heel mean force, an opposite pattern was found regarding the sound conditions and the asymmetry index. In this case, we saw that the condition showing larger asymmetry reduction was the High frequency condition, depicting a balanced heel force between the two feet for this condition (Fig. 3C), maybe driven by the quality of the feedback that relates to less pressure applied on the ground. In contrast, when the patients were exposed to the Control and Low frequency conditions, a reversed asymmetry towards the affected hemibody was found, reflecting more force applied on the affected foot in these conditions. Hence, time and force parameters show different patterns of adaptation.

Finally, regarding foot downward acceleration, we found a main effect of sound condition: while in Baseline and Low Frequency conditions participants showed lower acceleration for the affected foot, the asymmetry shifted in the other two sound conditions (Fig. 3D). Going back to gait biomechanics, during walking upwards acceleration (as in toe-off) an increase in physical effort due to the vertical load or force to hold our own weight occurs. Meanwhile, downwards acceleration reflects a reduction in the vertical load, as lower applied force to hold own weight is needed[52]. Thus, the reduced downward acceleration observed for the Baseline and Low Frequency for the affected foot links to a higher applied force to hold the foot when approaching the ground, probably indicating an increased effort to control the foot.

These changes in gait patterns caused by altered sound feedback might be related to the Comparator hypothesis/Forward model[18] accounts for motor control, if one considers them as caused by an attempt to readjust for the perceived discrepancies between the predicted and the actual sensory feedback, in a similar manner to the changes observed after visual adaptation using prisms, a technique used in some rehabilitation therapies reported in vision[55]. A possible explanation for our results showing gait changes in terms of asymmetry may result from the system's attempt to reduce the discrepancies between the predicted and the actual sensory input, informing the system about the need to update these sensory predictions and generating an inverse compensatory pattern. These perceived discrepancies in the expected feedback added to the increased uncertainty (i.e., surprise) and salience of the modified sensory input might have caused an enhancement of gait awareness in our patients. Indeed, this effect of increased attention and awareness is parsimonious considering the well-known effects of novelty, surprise and conflict in modulating arousal levels[56]. In order to reduce uncertainty and conflict between the expected and actual sensory consequences of movements, patients needed to build up a new internal model leading to sensori-motor adjustments. Changes in motor planning and execution as well as increases in awareness of motor control may have led to the observed over-correction patterns. Similarly, gaze shifts have been observed when people walked in uncertain terrains, which probably help them in accruing relevant information and reducing foot-placement errors[57]. In our context, the over-correction may be beneficial as part of the motor re-learning process, as previous studies on sensory entrainment during gait rehabilitation have been reported[58]. This challenging idea opens the possibility to exploit sensorimotor bottom-up mechanisms in different contexts, including sports, health, and the rehabilitation of distorted or negative body-representations and motor deficits that accompany certain clinical conditions, such as stroke. Moreover, the use of sound for gait rehabilitation can easily complement other principles of motor learning. Sound can be used in task-specific training where mass repetition of movements is involved, providing a valuable feedback about the motor performance that can be individualized to the needs and progress of the patient. The attained findings may help shed light on new therapeutic interventions using auditory stimulation methods for gait rehabilitation in clinical settings.

Conclusions

This proof-of-principle pilot study was aimed to help to ascertain the potential value of auditory stimulation for enhancing gait patterns, through the induction of changes in body-representation and its related bodily feelings, in chronic stroke patients affected by lower limb hemiparesis. We have demonstrated the potential use of sound feedback on gait rehabilitation offering a new treatment approach for patients with lower limb hemiparesis. The implementation of real-time alteration of walking sounds using the *SmartShoes* resulted in changes on different gait parameters. In general terms, we observed that when providing amplified natural walking sounds (Control condition) or amplification of the low frequency bands (83-250 Hz) (Low frequency condition), significant changes in gait parameters were observed, either showing a major reduction in the asymmetry index, as is the case for the stance time and stride time parameters, or inverted asymmetry patterns, as in the heel mean force variable. Our results can be interpreted in terms of the Comparator hypothesis/Forward model[18] as an attempt of the system to reduce sensory discrepancies introduced by the sound feedback, contributing to the updating of internal models leading to sensori-motor adjustments. These findings may contribute to further develop the experimental protocol and provide potential applications for compensating altered body-representations and its related bodily feelings in clinical populations with gait disturbances.

Limitations

This is a proof-of-principle study and therefore, there are some limitations regarding the design and possible generalization. Given the variability of the gait patterns in our sample, the most significant is the number of participants, in our case chronic stroke patients with lower limb hemiparesis, mainly due to setting constraints. We used measures of motor impairment and function for clinically describing our sample but future studies could also consider the impact of paresis and spasticity severity on the study outcomes. Our study also had a slight predominance for right-sided brain lesions (15/22), as well as lesion heterogeneity concerning cerebrum vs brain stem lesions, probably affecting the extrapolation of our results to other clinical populations. Further studies may tackle this concern by selecting a larger and balanced sample in terms of brain lesion lateralization and site. In a similar manner, Baseline measures included in the analysis may reflect an effect of order as it was always assessed in first place, an issue that should be addressed in upcoming studies. Finally, our results on the questionnaires assessing emotional changes and body feelings might be biased due to a reduced understanding of the statements presented, maybe due to the level of complexity of the employed vocabulary. Further studies examining this relationship might reinforce previous findings linking changes in body-perception, emotion and gait, [23,33,37,59,60]. Future studies could be performed addressing these issues by performing multicenter collaborations and randomized controlled trials for testing the feasibility of this new technology.

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Competing interests

All authors declare that no competing interests relevant to the subject of the manuscript exist.

Author contributions

A. G-A., J. G-S., E. D., A. R-F., and A. T-J. contributed to the conception and design of the work. A. G-A. and J. G-S. acquired the data, A. G-A. and A. T-J. conducted the analyses, prepared figures and interpreted the results, and A. G-A., J. G-S., E. D., A. R-F., and A. T-J contributed to the drafting of the manuscript. A. G-A., A. R-F., and A. T-J accepted responsibility for the integrity of data analyzed.

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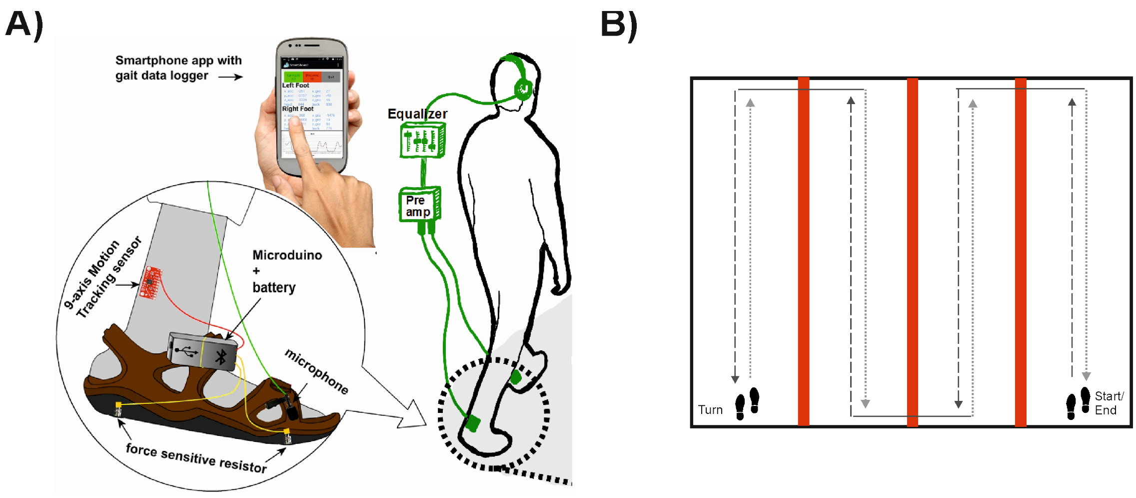

Figure 1: A) Apparatus (*SmartShoes*) fitting and B) plan of the room (45 m^2) depicting and the track participants were instructed to walk (separate lanes are marked in red).

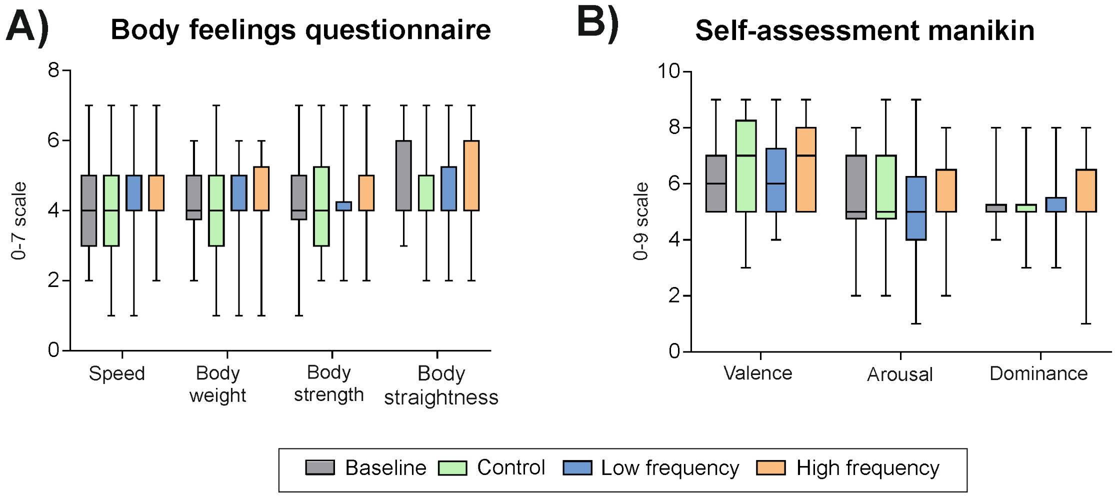

Figure 2: Subjective reports for the A) Body feelings Questionnaire[46] and B) Self-assessment manikin[50] after each condition (Baseline and sound conditions).

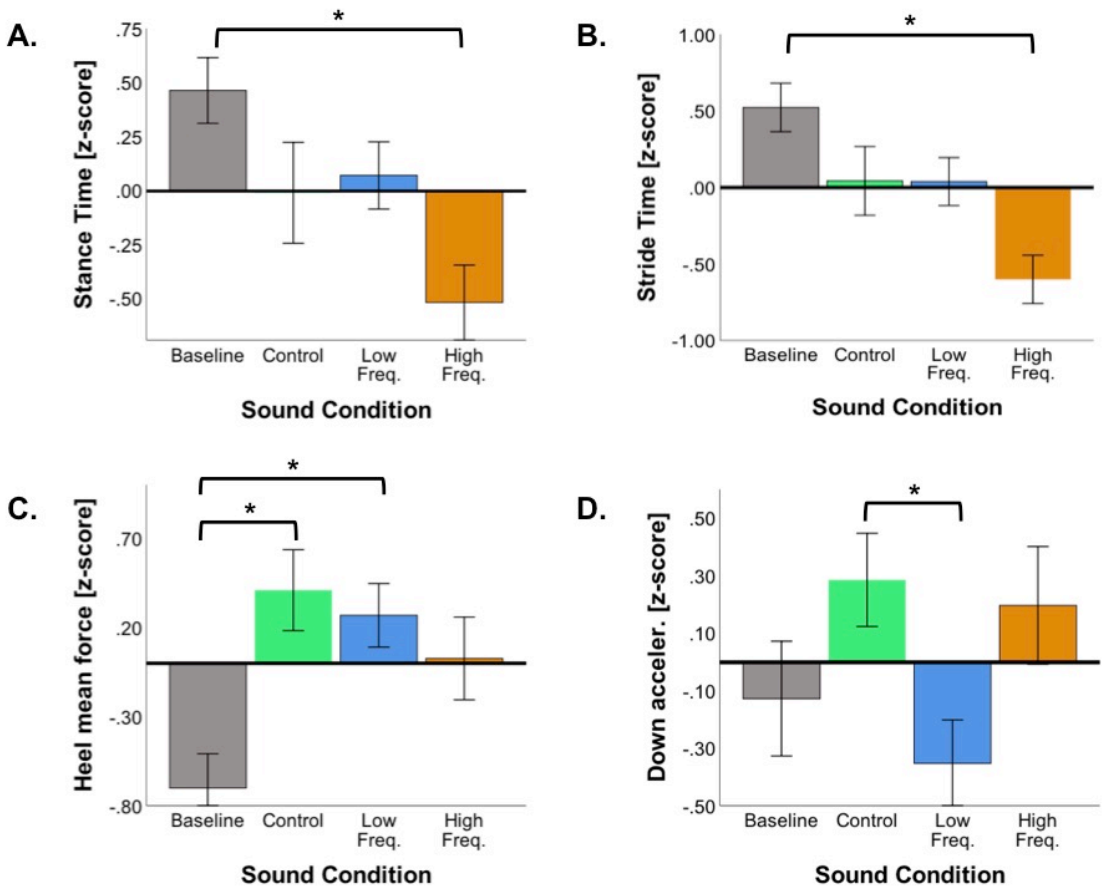

Figure 3: Mean (±SE) z-scores for asymmetry gait variables. (A) Stance time. Positive values indicate longer time on the ground for the affected foot vs the non-affected foot. (B) Stride time. Positive values indicate longer time between the two touch-down events for the affected vs the non-affected foot. (C) Heel force. Positive values indicate higher force exerted on the ground with the affected foot. (D) Foot downwards acceleration, for all conditions (Baseline and sound conditions). Panel D shows the results on foot downwards acceleration with participant's weight added as covariate. * marks significant mean differences.