Emotion Rendering in Plantar Vibro-Tactile Simulations of Imagined Walking Styles

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Abstract—This paper investigates the production and identification of emotional states of a walker using plantar vibro-tactile simulations. In a first experiment, participants were asked to render, according to imagined walking scenarios, five emotions (aggressive, happy, neutral, sad, and tender) by manipulating the parameters of synthetic footstep vibrations simulating various combinations of surface materials and shoes. Results allowed to identify, for the involved emotions and vibration conditions, the mean values and ranges of variation of two parameters, vibration amplitude and temporal distance between consecutive steps. Results were in accordance with those reported in previous studies on real walking, suggesting that the plantar vibro-tactile expression of emotions in walking is independent of the real or imagined motor activity. In a second experiment, participants were asked to identify the emotions portrayed by walking vibrations synthesized by setting the synthesis engine parameters to the mean values found in the first experiment. Results showed that the involved algorithms were successful in conveying the emotional information at a level comparable with previous studies. Results of both experiments revealed strong similarities with those of an analogous study on footstep sounds suggesting that emotionally expressive walking styles are consistently produced and recognized at auditory and plantar vibro-tactile level.

Index Terms—Emotion rendering, walking, footstep sounds, SoleSounds

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1 INTRODUCTION

To date, the use of the sense of touch for expressing or evoking emotions through tactile devices has remained relatively unexplored in the affective computing community. This is particularly true for movies and video games, despite a continuous request from the public and gamers for richer experiences while interacting with such media. Noticeable exceptions are, for instance, the Facial Expression Appearance vibro-tactile System [1], a vibro-tactile chair designed for visually impaired users to render the facial expressions of the person they are communicating with, the Hapticat [2], a robotic device mimicking at tactile level the behavioral responses of a cat in response to users' hands affective touch on it, the Hug [3], a pillow that simulates through vibrations a hug to a loved one far apart, and the TapTap [4], a scarf that provides a user's shoulders with comforting tap of vibration. However, to the authors' best knowledge, no tactile device has been specifically developed and used for communicating emotional content through the feet.

Lately, research has shown that it is possible to simulate walking through the sense of touch in a passive condition, i.e., when the user is not physically walking [5], [6], [7]. Different systems have been developed for this purpose, which are capable of providing vibro-tactile stimulation to the feet, for instance when the user is seated on a chair. Visell et al. developed a floor tile capable of providing to the users' feet the tactile sensation of walking on different ground materials. The vibrations were transmitted using actuators fixed under the tile [8]. Turchet et al. developed a wearable system capable of providing combined auditory and tactile sensations that would be produced in real life while walking on two typologies of surface materials, solid and aggregate (the latter being assumed to possess a granular structure, such as that of gravel) [9]. The system was composed of an audio-tactile synthesis engine based on physical models, and a pair of sandals enhanced with sensors and actuators. Recently that system has been improved at hardware level with a higher number of actuators to provide stronger and more widespread vibrations [10], as well as at software level with a synthesis engine capable of simulating a larger palette of surface materials, shoe types, foot-floors interactions, and some of the walker's anthropomorphic features [11].

Several perceptual results are available about walking simulations through the sense of touch in desktop configurations (see Section 2). However, to date no research exists on the plantar vibro-tactile rendering of emotionally expressive walking styles. This paper investigates how emotions can be rendered and perceived through plantar vibro-tactile simulations of steps in a context not involving physical locomotion. Our investigation aimed at providing guidelines for both the design and control of emotionally expressive computerized tactile footsteps that are more ecologically valid than those rendered at tactile level without performance

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variations. Such research is especially relevant to designers of tactile feedback for videogames or virtual reality contexts where the tactile feedback associated with an avatar's foot-floor interactions can convey its emotional state.

The methodology of this work was based on [12], where the same topic was investigated using the auditory channel. This allows for comparisons between the auditory and plantar vibro-tactile perceptual spaces in the context of passively provided expressive walking styles.

The first experiment involved the production of emotionally expressive walking plantar vibrations according to imagined walking scenarios. It was conducted in a desktop configuration (i.e., without real walking), where participants could manipulate the output of the synthesis engine described in [11], which was used to simulate footstep vibrations. The main goal was to identify for different emotions and for different combinations of surface materials and shoe types, the mean values and ranges of variation of two parameters of the footstep vibrations (temporal distance between subsequent steps and vibration amplitude). Based on the similarities between the tactile and auditory channels regarding simulations of foot-floor interactions reported in previous studies [5], [13], [14], [15], [16], we expected that results would have been similar to those reported in [12] for the rendering at auditory level. Moreover, by asking participants to imagine to produce walking actions, we also tested for similarities between the expression of emotions in real [17], [18] and imagined motor activity. Based on the similarities between imagined and executed actions [19], [20], and locomotion in particular [21], we expected results to be in accordance with those reported in previous studies on real walking.

In the second experiment, participants were asked to identify the emotions portrayed by walking vibrations synthesized by setting the parameters of the synthesis engine to the mean values found in the first experiment. In particular, we were interested in verifying whether the emotions recognition was affected by the type of simulated surface material and shoe. Both experiments involved musically-trained and -untrained participants to test whether musical expertise could influence the quality of the results. The absence of significant differences between the performances of the two groups would be interpreted as lending support to the "motor origin hypothesis of emotional expression in music" [17] extended to the sense of touch.

2 RELATED WORK

Research on the expression, communication, and identification of emotions has provided evidence that many emotions are characterized by specific facial expressions [22], patterns of vocal features [23], as well as body movements and static postures [24], [25]. Research has also focused on affective touch and affective computing related to haptics, despite no research on such topics has addressed the feet. Hertenstein et al. showed that humans can identify emotions from the experience of being touched on the arm, without seeing the touch [26]. They also proved that observers can identify emotions from watching someone being touched on the arm, thus providing evidence that humans can accurately decode distinct emotions by simply watching others communicate via touch. Interestingly, Bailenson et al. investigated the phenomenon of Virtual Interpersonal Touch (VIT), i.e., a person touching one another via force-feedback haptic devices, in the emotional context [27]. Results of their study, which focused on hand-to-hand touch, indicated that humans can express and identify a range of emotions via VIT, although the accuracy of the identification is smaller compared to emotions expressed through real handshakes. In a recent study, Gaffary et al. proposed a classification method to extract discriminative features of tridimensional affective haptic expressions [28]. The results of Gaffary's study, which involved a haptic device enabling the expression of tridimensional movements, provided several general features of affective haptic expressions for various emotions as well as discriminative features between close emotions.

In a different vein, the locomotion interfaces mentioned in Section 1 have been used for various perceptual studies in desktop-based configurations. Terziman et al. used the tile described in [8] for displaying tactile feedback associated with footsteps in combination with visual feedback provided on a screen, to improve the sensation of walking in desktop-based virtual environments (VEs). The resulting system was evaluated through perceptual experiments, which revealed that the designed tactile-visual sensations were successful in producing immersive and enjoyable navigation experiences, and in increasing the sensation of actually walking inside the VE. Moreover, Terziman et al. showed that multimodal feedback was preferred to navigations simulated by using only one modality. The shoe-based audio-tactile system described in [9] was also evaluated in a series of perceptual studies. The study reported in [13] presented the results of a surface recognition experiment, which showed that participants were capable of discriminating the tactile stimuli on the basis of their solid or aggregate typologies. A subsequent study investigated the ability of subjects to match pairs of synthetic auditory and tactile stimuli that simulated the sensation of walking on solid and aggregate surfaces [14]. Results showed that subjects expressed a higher level of semantic congruence for those audio-tactile pairs of materials that belonged to the same typology. The tactile synthesis engine described in [9] was also used to simulate walking on bumps, holes, and flat surfaces [5]. The perceptual validation of those simulations revealed that it is possible to simulate different surface profiles by only varying temporal aspects of footsteps, such as the interval between consecutive steps and between heel and toe strikes. Furthermore, plantar vibro-tactile feedback was also proved to enhance the realism of navigating in multimodal VEs [7]. In that study, subjects were exposed to auditory and audio-visual stimuli presented with and without the tactile feedback. Results of the experiments provided a clear preference towards the simulations enhanced with tactile feedback, showing that the tactile channel can lead to more realistic walking and running experiences in desktop-based VEs.

Various experiments, conducted by using either physical walking in real and virtual settings or passively simulated walking, investigated the identification of surface materials through auditory and tactile stimuli [13], [14], [15], [16]. Their results showed that participants were able to correctly categorize in both modalities the typology of the real or simulated surface materials. Those findings suggested that surface material typology is processed very consistently in the two modalities. Along the same line, the results reported in [5] concerning the auditory and tactile identification of surface profiles simulated by varying temporal aspects of footsteps did not differ in the two modalities. However, no study has been conducted to compare the degree of similarity between footstep sounds and footstep vibrations as far as the production and recognition of emotions is concerned. Footstep sounds have been proved to convey information about the walker's emotional state [17]. Specifically, research has proved that walking with different emotional intentions produces variations of sound level and timing that are similar to those found in expressive music performance [29]. For instance, it has been shown that happy walking styles and music performances communicating happiness are characterized by louder sound level and faster pace/tempo compared to a neutral style, while walking patterns and music performances communicating sadness are characterized by softer sound level and slower pace/tempo.

A recent study [12] investigated how different emotional states of a walker can be rendered and recognized, at the auditory level, by means of the footstep sounds synthesis algorithms described in [11]. In a first experiment, participants were asked to render five emotions (aggressive, happy, neutral, sad, and tender) according to imagined walking scenarios, by manipulating the sound level and the temporal distance between subsequent footstep sounds simulating various combinations of surface materials and shoes types. Results allowed to identify for the involved emotions and sound conditions, the mean values and ranges of variation of the two investigated parameters. Results were in accordance with those reported in previous studies on real walking [17], [18], suggesting that expression of emotions in walking is independent of the real or imagined motor activity. In a second experiment, participants were asked to identify the emotions portrayed by walking sounds synthesized by setting the synthesis engine parameters to the mean values found in the first experiment. Results showed that the involved algorithms were successful in conveying the emotional information at a level comparable with previous studies. That study also aimed at verifying whether the experimental results were consistent with previous findings that revealed similarities between the expression of emotions with a non-musical, everyday motor activity such as walking and the musical expression of emotions as reported in [17] and [18]. Both experiments involved musicians and non-musicians. Despite a similar general trend, significant differences between the two groups were found, especially for the sad emotion. Those results confirmed in part the "motor origin hypothesis of emotional expression in music" (MOH) according to which a motor origin for the expression of emotions is common to all those domains of human activity that result in the generation of an acoustical signal [17].

On a separate note, the study reported in [30] demonstrated that by exploiting a brain-computer interface, humans are capable of walking in VEs by simply imagining the movements of the feet. This suggests that the imagination of the feet movements is a mental task closely related to that of real walking. Interestingly, research has shown that the time taken to actually walk to a previously seen target is almost exactly identical to that of performing the same task with the imagination [21]. This and other results [19] provide support for the hypothesis that motor imagery shares the same neural mechanisms that are involved in motor control of actual actions [20]. Along the same line, the study reported in [31] showed that humans can reenact walking patterns according to those depicted in sequences of footstep sounds.

In summary, from the reviewed literature it emerges that although emotions have been proved to be rendered and identified through technological solutions exploiting the sense of touch, to date no research has been conducted on the plantar vibro-tactile rendering and identification of emotionally expressive walking styles leveraging the existing locomotion interfaces and simulations algorithms for foot-floor interactions. Such a challenge is addressed in the present work, which is based on the reviewed studies that investigated the same topic exploiting the sense of audition.

3 EXPERIMENT 1

The main aim of the first experiment was to identify—for different emotions and various combinations of surface materials and shoe types—the mean and range of variation of two parameters of the footstep vibrations: the time interval between two subsequent heel strikes (heel-to-heel, H2H) and the peak vibration amplitude (PK). The former represented the simulated walker's velocity, the latter represented the magnitude of the foot-floor impact force.

Another goal of the experiment was to compare the auditory and tactile perceptual spaces by checking for similarities with the results reported in [12]. For this reason, the procedure and the stimuli involved in this experiment were similar to those used in [12]. That work used the H2H and PK parameters of footstep sound, since previous research showed that they are the most salient acoustical features involved when producing walks with emotional intentions [17], [18]. Similarity of the present results with those reported in [12], [17], [18] for the auditory channel would suggest that the tactile expression of emotions in walking is independent of the real or imagined motor activity. Similarly to [12], both musically-trained and -untrained participants were involved to investigate the MOH for the tactile channel: the absence of significant differences in the performances of the two groups would lend support to it.

In addition, since participants were asked to imagine themselves walking at a self selected speed, we searched for potential correlations between participants' anthropometric features (height and weight) and the values of the two investigated parameters in each emotion. Such correlations were not present for the auditory case, as reported in [12]. In that work, those correlations were not expected for H2H, in accordance with findings reported in [32], which showed that H2H is not correlated with height and weight when humans walk at a self selected speed without any emotional intention. As a consequence, the validity of this hypothesis for the results of the neutral emotion condition were interpreted as a further proof of the similarity of the mechanisms underlying real and imagined motor activity. Moreover, its validity extended to the other emotions as well as to PK,

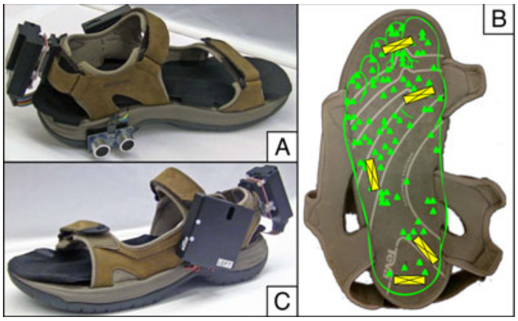

Fig. 1. *SoleSound*, the instrumented footwear used in the experiments (*A*, [10], [33]). Underfoot stimuli are generated by vibro-tactile actuators embedded in the sandal sole (*B*, yellow rectangles), whose disposition approximately follows the map of the cutaneous mechanoreceptors in the foot sole (*B*, green triangles [34]). Actuators are powered by 3W onboard amplifiers (*C*, black housing in the posterolateral side of the sandal).

indicating that the production of emotionally expressive walking sounds in the context of passive sensory motor activity is independent of the anthropometric features of the person imagining the simulated walks.

3.1 Participants

Twenty participants were divided into two groups (n = 10). The first group was composed of musicians (5 M, 5 F) aged between 20 and 31 (mean = 25.36, SD = 3.98) with an average musical experience of 14.2 years. The second group was composed of non-musicians (6 M, 4 F) aged between 23 and 34 (mean = 29.7, SD = 3.52). Participants included in the second group had never played a musical instrument nor taken music lessons. All participants reported neither hearing nor locomotion problems.

3.2 Apparatus

The experimental setup consisted of a laptop (Macbook Pro), a soundcard (Fireface UFX), a closed headphone set with noise cancelling capability (Sennheiser PXC 450) and the instrumented footwear shown in Fig. 1. All experiments took place in a silent room.

The laptop ran the footstep sound synthesizer described in [11] and a graphical user interface, both implemented in Max/MSP sound synthesis and multimedia real-time platform. The former allows to synthesize different combinations of surface materials, shoe types, foot-floor interactions and anthropometric features of the walker. The latter consisted of buttons to start and stop the trials, a label displaying the emotion to be rendered in each trial, and two virtual sliders labelled as “velocity” and “impact force”, allowing subjects to adjust H2H and PK, respectively.

Underfoot vibrations were delivered through *SoleSound*, a pair of instrumented sandals developed at the Columbia University RObotics And Rehabilitation (ROAR) Lab. SoleSound features inertial, piezo-resistive and ultrasonic distance sensors to accurately estimate spatiotemporal gait parameters [33]. This fully portable system can generate action-related auditory and vibro-tactile feedback in response to the measured gait parameters by means of the sound synthesizer described in [11], which runs on a battery-powered, single-board computer enclosed in a hip-pack [10].

To deliver underfoot vibratory stimuli, each sandal houses five recoil-type vibro-tactile actuators (Haptuator Mark II, Tactile Labs Inc.) that are embedded in the stiff foam of the sandal, following the distribution of the cutaneous mechanoreceptors in the foot sole, Fig. 1-B. These actuators are bonded in place to ensure good transmission of the vibrations inside the soles. They have an operational linear bandwidth of 90–1,000 Hz and can provide up to 7.5 G of acceleration when connected to light loads [35]. This nominal bandwidth was regarded as appropriate for the application, since the sensitivity of the cutaneous receptors in the foot shows a peak around 250 Hz, while it substantially degrades at higher frequencies [36]. In this experiment, the sandals were interfaced to the soundcard to allow control of the vibratory stimuli directly from the laptop.

The displacement of a recoil-type vibro-tactile actuator depends on the mechanical impedance in place between its enclosure and the frame. In SoleSound, such impedance is due to the foam surrounding each actuator, and therefore it varies with the amount of pressure applied by the user’s foot on the sandal (which affects the density of the foam). Vibrations in the plantar area also depends on the location and orientation of the actuators embedded in the sole. While a precise characterization of the dynamic response of this apparatus under different loading conditions is beyond the aims of this paper, two simplifying assumptions can be made. Since all the study participants were tested in the seated position, we assumed that differences in the average pressure applied to the footwear across different subjects were negligible. Moreover, SoleSound features five identical actuators per sole, which are distributed at different angles. When the same input command is sent to all actuators—as in this study—the amplitude of the vibrations can be considered approximately uniform across the foot sole at any time instant. Under these simplifying assumptions, the peak vibration amplitude PK was estimated by the peak amplitude of the commanded signal, rather than by the actual peak amplitude of the vibrations in the soles.

3.3 Stimuli

Stimuli consisted of tactile vibrations generated by the sandals. Specifically, the engine produced audio signals that were amplified and fed into the actuators embedded in the shoes. The use of the same signal for auditory and tactile simulations was motivated by the fact that in real life acoustic and vibrational signatures are originated by the same signal, resulting from the impact of the foot with the floor. What changes is the medium of propagation, which takes the form of air in one case and of shoes in the other. Nevertheless, the audio frequency range, viz. 20 Hz-20 kHz, is far wider than the vibro-tactile frequency range, viz. 10 Hz-1.0 kHz. In order to simulate the three materials at haptic level, the audio signals were converted into vibro-tactile signals by means of amplitude adjustment and spectrum truncation. The latter was the result of the frequency response of both the actuators and the shoes.

In more detail, the synthesis engine was set to simulate vibro-tactile footsteps on four surface materials (two solid, wood and metal, and two aggregate, snow and gravel) performed by a genderless walker wearing two types of shoes (dress shoes and sneakers). These materials and shoe types were chosen in accordance with the experimental protocol used in [12]. The resulting eight combinations gave rise to a

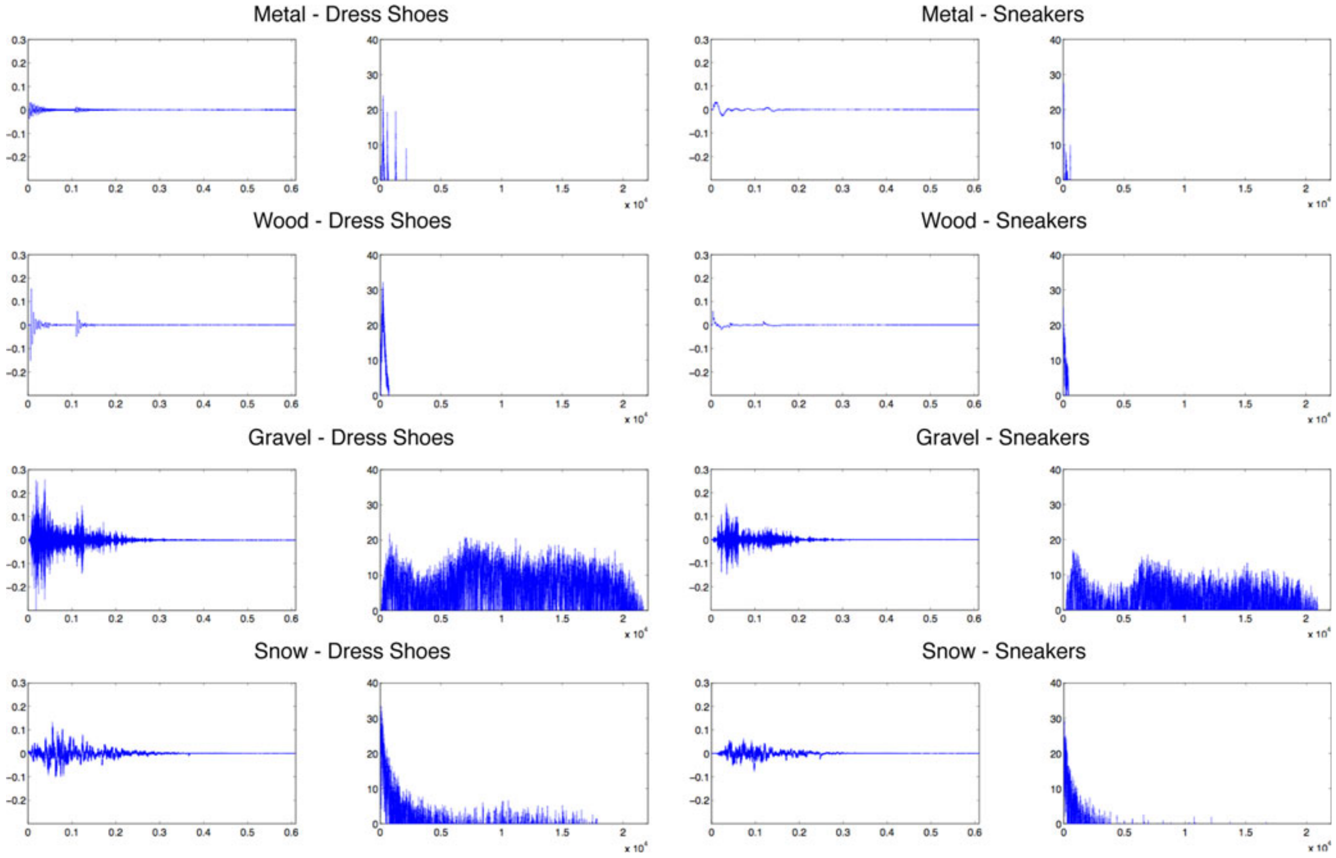

Fig. 2. Typical waveforms (left) and spectra (right) of the eight combinations of shoe type and surface materials. The duration of the waveforms is in seconds, the magnitude of the spectra is in decibel.

rather comprehensive palette of footstep vibrations, which had a variety of temporal and spectral features. The surface materials were the same as the ones utilized in [18]. They were characterized by different features in terms of duration, amplitude, onset type, temporal profile, and spectrum. Similarly, the two types of shoes presented two levels of sole hardness (hard and medium) that were simulated by producing signals with different properties in terms of onset, peak, and duration. Specifically, sneakers produced longer onset, lower peak and shorter duration compared to dress shoes [11]. Fig. 2 illustrates the waveforms and the spectra of the eight combinations of shoe type and surface material.

Participants could continuously adjust the H2H parameter in the range of [319, 1276] ms. A logarithmic scale for the slider associated with the H2H parameter was utilized according to the logarithmic perception of time changes by humans (Weber-Fechner law). The time range was chosen to be as the half and the double of 638 ms. Such value was calculated by averaging the H2H values collected from 20 individuals (10 M and 10 F) who participated in the interactive experiment [18], walking with the neutral emotion intention while listening to the sounds of the surface materials described above. The time range was checked in an informal session in which the authors manipulated the time of the experiment stimuli. Outside this range the performance resulted unrealistic: larger values of H2H were not perceived as continuous walking and lower values were indistinguishable from a running action.

In the experiment, participants could continuously adjust the vibration amplitude by moving the corresponding slider in the range of [0, 24] dB to deviate from the nominal vibration amplitude of each stimulus. Such a range was checked in an informal listening session in which the authors manipulated PK. Outside this range the performance resulted unrealistic for simulating a walk: too large values of PK were not perceived as footstep vibrations, while too small values were not clearly sensed.

During each trial, participants wore ear plugs and were also provided with a continuous 60 dB sound pressure level white noise over the headphones to mask the audible output generated by the sandals as result of the activation of the actuators. This method, adopted also in previous studies [14], [16], was proven to completely mask any sound produced by the shoes.

3.4 Procedure

Participants were presented with written instructions. They were asked to sit on a chair, put on the sandals, the earplugs, and the headphones, and interact with the graphical interface using a mouse as a control device. Participants were instructed to sit normally, having the plant of the feet resting on the ground for the full duration of the experiment. The task consisted in manipulating the "velocity" and "impact force" sliders to produce five emotional intentions (happy, aggressive, tender, sad, and neutral) for each of the eight types of stimuli, for a total of forty trials. For each emotion, participants were instructed to adjust the two parameters as if they were walking in one of the following scenarios:

Sad: "You are walking in a cemetery during the funeral of a dear friend".

Happy: "It is a wonderful sunny day, you have won the lottery and you are walking towards the lottery headquarter to get the money".

Tender: "You are walking and carrying a three-month-old baby in your arms".

Aggressive: "You are angry with your neighbour since the loudness of his music does not allow you to sleep, so you are walking towards his flat to ask him for the umpteenth time to lower the volume down".

Neutral: "Walk normally, without any emotional intention".

These scenarios were the same involved in [12] and [18]. The choice of happiness, sadness, aggressiveness, and tenderness was due to the fact that these emotions have been involved in several studies on emotional expression in music (see [37] for an overview), and that they cover the four quadrants of the two-dimensional Activity-Valence space [38]: happy (high activity, positive valence), aggressive (high activity, negative valence), tender (low activity, positive valence), and sad (low activity, negative valence). Furthermore, such emotions give a quite comprehensive overview on the use of the musical parameters sound level and tempo, which have been previously analyzed in walking [17]. The neutral emotion was used as a control condition. In previous studies on expressive music performance, tempo and sound level in emotionally neutral performances received smaller values than those in happy and aggressive performances and larger values than those in sad and tender performances [39].

Trials were presented in randomized order. Each trial was presented once, but participants were allowed to experience each stimulus for as long as needed to make their choice. Before the beginning of the experimental session, participants practiced ten trials to familiarize with the setup. Those trials, not included in the data analysis, consisted of four stimuli resulting from the combination of the two types of shoes and two surface materials, concrete and forest underbrush. The ten trials were randomly chosen among the twenty trials resulting from the combination of the four stimuli and five emotions. Participants were not informed about the types of shoes and surface materials involved.

At the end of the experimental session, participants were asked to fill a questionnaire about two anthropometric features (height and weight) and about their level of musical expertise. Finally, they were given the possibility to leave an open comment about their experience.

3.5 Results

Fig. 3 illustrates the experimental results for H2H and PK for the two groups of participants. Table 1 and 2 report the means, their standard error, and the confidence intervals for the two investigated parameters, averaged between musicians and non-musicians.

Statistical analysis was performed on the collected data by means of repeated measures ANOVA. All post-hoc analyses were performed with Holm-Bonferroni's procedure (significance level $\alpha = .05$). Both H2H and PK were subjected to a four-way analysis of variance having five levels of emotion (happy, aggressive, tender, sad, and neutral), four levels of material (metal, wood, gravel, and snow), two levels of shoe type (dress shoes and sneakers), and two levels of musical expertise (musicians and non-musicians). Before running the four-way ANOVA, Mauchly's test was applied to verify if the assumption of sphericity had been met for the within-subjects factors and for the interactions. In the following sections, we report corrected degrees of freedom (using Greenhouse-Geisser estimates of sphericity ϵ) for the factors that violated the assumption of sphericity.

As far as H2H is concerned, a significant main effect was found for emotion, F(2.5,44.2) = 90.751, $p < .001$, as well as for material, F(3,54) = 7.107, $p < .001$. Mauchly's test indicated that the assumption of sphericity had been violated for emotion ($\chi^2(9)$= 23.101, $p < .01$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ϵ = .614). Pairwise comparisons for emotion showed that H2H was significantly smaller for aggressive compared to happy ($p < .05$) and to neutral, tender, and sad ($p < .001$), for happy compared to neutral, tender, and sad ($p < .001$), and for neutral compared to tender and sad ($p < .001$). In terms of materials, H2H was significantly smaller for metal compared to wood and snow ($p < .05$), and for gravel compared to snow ($p < .05$). No significant main effects of musical expertise or shoe type were found on H2H, and the interactions between factors were not significant.

As far as PK is concerned, a significant main effect was found for emotion, F(4,72) = 35.341, $p < .001$, for material, F (1.5,27.3) = 146.103, $p < .001$, and for shoe type, F(1,18) = 20.537, $p < .001$ (compared to sneakers, dress shoes resulted in significantly higher PK). There was also a significant interaction between shoe type and material F(1.9,33.9) = 33.944, $p < .001$. Mauchly's test indicated that the assumption of sphericity had been violated for material ($\chi^2(5)$= 26.430, $p < .001$) and for the interaction effect between shoe type and material ($\chi^2(5)$= 15.205 $p < .01$). Therefore, Greenhouse-Geisser correction was applied (ϵ = .506 for material, and ϵ = .629 for the interaction effect between shoe type and material). Pairwise comparisons showed that PK was significantly greater for aggressive compared to all the other emotions ($p < .001$) and significantly smaller for tender compared to happy ($p < .001$), neutral ($p < .01$) and sad ($p < .05$). The effect of material on PK depended on the type of shoes, as evidenced by the significant interaction between shoe type and material (see Fig. 4). Separate 1-way ANOVAs showed that the effect of material was significant for both dress shoes and sneakers ($p < .001$). However, for the dress shoes, PK was greater for gravel compared to all the other materials, for wood compared to metal and snow, and for metal compared to snow ($p < .001$). For the sneakers, instead, PK was greater for wood compared to all the other materials and for metal and gravel compared to snow ($p < .001$), while no significant difference was found between metal and gravel. No significant main effects of musical expertise on PK were found.

The Pearson's correlation coefficient between the two investigated parameters was computed, showing a significantly negative correlation between H2H and PK (r = -0.45, p = $\leq$ .001; df = 798). A linear mixed-effects model analysis was performed for each emotion separately, considering the possible correlations between the two investigated parameters and the collected participants' anthropometric features (weight and height). This analysis revealed that for tender, H2H was linearly related to participants' height (β = -5.487, t(18) = -2.07, $p < .05$); for sad, H2H was linearly related to participants' weight (β = -7.45, t(18) = -3.233, $p < .01$) and

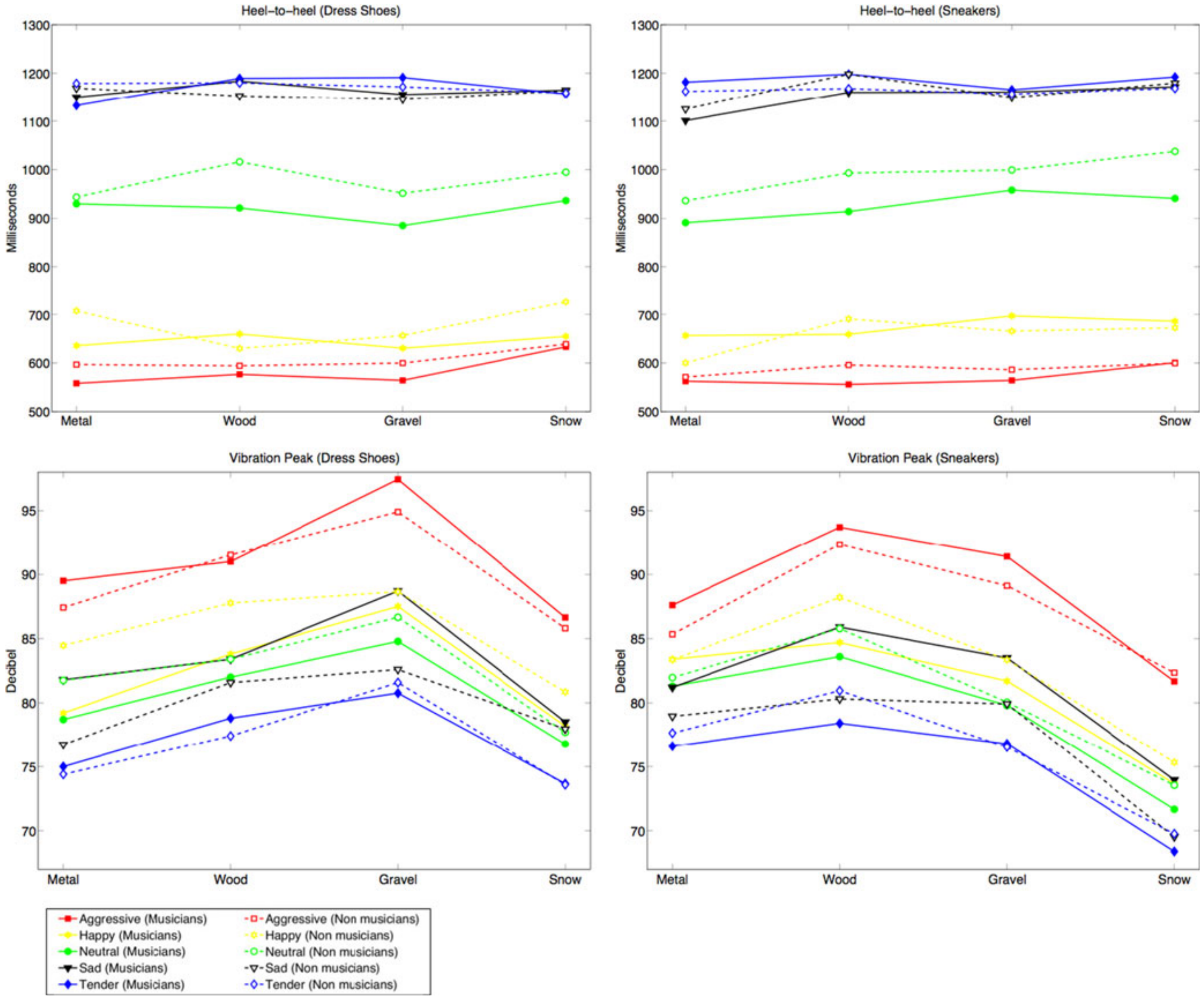

Fig. 3. Results of the experiment 1.

height (β = -8.761, t(18) = -3.852, $p < .01$). Conversely, for all emotions, PK was not related to the two investigated anthropometric features.

3.6 Discussion

This experiment allowed to identify the mean values and ranges of variation of PK and H2H for different emotions and different combinations of surface materials and shoe types. These results can be used to build a synthesizer for emotionally expressive footstep vibrations.

What emerges from these results is that the two investigated parameters were manipulated in the same direction as reported in [12], which were in accordance with previous research on real walks performed with emotional intentions [17], [18]. These, in turn, were consistent with studies on emotional expressive music performance [37], [39]. In agreement with [12], PK showed a negative correlation with H2H.

Besides these strong similarities between the performances of participants exposed to tactile and auditory stimuli, some significant differences were also found. One difference is that for the tactile case participants were less accurate in the discrimination of the various emotions as far as PK is concerned. For instance, while in the auditory case sadness was produced with PK values significantly lower than happiness, for the tactile case this difference was not significant. Unlike [12], but in agreement with [17] and [18], musical expertise did not yield significantly different results. This result, therefore, lends support to the MOH extended to the tactile channel. Specifically, in [12] it was found that for each emotion, musicians' choices of H2H and PK were respectively lower and greater compared to those of non-musicians. Authors were not able to find a plausible explanation for this different behavior. The predominant difference between the two groups concerned the average values of PK for the sad emotion for all the combinations of surface material and shoe type. Moreover, non-musicians chose very similar values of H2H and PK both for sad and tender walkings, showing that they were not able to differentiate these two emotions, unlike musicians who chose higher PK values for sad in respect to tender. That result could be explained by a greater ability of musicians in controlling music-related parameters such as tempo and intensity. Therefore, those results for the auditory case lent support to the MOH only in part, which is a difference with the results of the present work.

TABLE 1
Means, Standard Errors and Confidence Intervals for the Two Variables H2H and PK as Rendered by Participants for the Five Emotions and for the Trials Involving Dress Shoes

Material	Emotion	H2H (ms)			PK (dB)		
		Mean	Std. Error	95% Confidence interval	Mean	Std. Error	95% Confidence interval
Metal	Aggressive	575	40	[489, 661]	88.6	1.2	[86, 91.1]
	Happy	668	32	[599, 736]	81.6	1.6	[78.1, 85]
	Neutral	935	41	[847, 1023]	80.1	0.9	[78.1, 82.1]
	Tender	1153	29	[1092, 1214]	74.7	0.8	[72.9, 76.6]
	Sad	1158	29	[1096, 1220]	79.5	1.7	[75.9, 83.2]
Wood	Aggressive	584	36	[509, 660]	91.5	1.5	[88.2, 94.7]
	Happy	646	32	[578, 714]	85.6	1.5	[82.4, 88.8]
	Neutral	963	40	[878, 1048]	82.6	1.3	[79.8, 85.4]
	Tender	1184	24	[1133, 1235]	78.2	0.7	[76.6, 79.7]
	Sad	1169	28	[1109, 1229]	82.6	1.6	[79, 86.1]
Gravel	Aggressive	580	36	[502, 657]	96.3	0.9	[94.2, 98.3]
	Happy	642	29	[580, 703]	88	1.5	[84.8, 91.1]
	Neutral	914	40	[828, 1000]	85.6	1	[83.5, 87.7]
	Tender	1182	21	[1136, 1227]	81.1	0.9	[79.1, 83.1]
	Sad	1150	31	[1085, 1216]	85.9	1.6	[82.5, 89.3]
Snow	Aggressive	635	45	[541, 730]	86.2	1.7	[82.6, 89.8]
	Happy	687	40	[603, 770]	79.3	1.4	[76.3, 82.4]
	Neutral	962	47	[862, 1062]	77.1	1.2	[74.6, 79.7]
	Tender	1157	28	[1097, 1217]	73.6	0.5	[72.5, 74.6]
	Sad	1164	29	[1102, 1225]	78.2	1.4	[75.1, 81.3]

Participants' choices of H2H were independent of the type of shoe and surface material sonically simulated for each emotion. This result differed from [12] were the choices of H2H depended on the surface material. Instead, similarly to the auditory case, participants' choices of PK depended both on shoe type and surface material.

The hypothesis of similarities between real and imagined motor activity in expression of emotions was partially confirmed. H2H ratings were consistent for each emotion with those found in previous studies involving real walking (e.g., sad walks received higher ratings of H2H compared to happy walks) [17], [18], while PK ratings were in agreement with

TABLE 2
Means, Standard Errors and Confidence Intervals for the Two Variables H2H and PK as Rendered by Participants for the Five Emotions and for the Trials Involving Sneakers

Material	Emotion	H2H (ms)			PK (dB)		
		Mean	Std. Error	95% Confidence interval	Mean	Std. Error	95% Confidence interval
Metal	Aggressive	566	39	[483, 649]	86.6	0.6	[85.2, 87.9]
	Happy	631	29	[569, 693]	83.3	0.7	[81.8, 84.9]
	Neutral	911	40	[826, 995]	81.6	0.8	[79.7, 83.4]
	Tender	1172	26	[1116, 1229]	77.1	1	[74.8, 79.4]
	Sad	1111	44	[1019, 1204]	80.2	1.6	[76.8, 83.6]
Wood	Aggressive	573	38	[494, 653]	93.1	0.8	[91.3, 94.8]
	Happy	673	27	[615, 730]	86.2	1	[84.1, 88.4]
	Neutral	949	40	[864, 1034]	84.6	0.9	[82.5, 86.6]
	Tender	1184	21	[1139, 1228]	79.6	1	[77.4, 81.7]
	Sad	1177	23	[1126, 1227]	83.3	1.3	[80.5, 86.1]
Gravel	Aggressive	574	43	[482, 665]	90.4	1.1	[87.9, 92.8]
	Happy	683	32	[614, 751]	82.4	1.3	[79.5, 85.3]
	Neutral	976	34	[903, 1048]	79.9	1	[77.7, 82.1]
	Tender	1161	30	[1097, 1225]	76.7	1.1	[74.3, 79]
	Sad	1155	32	[1088, 1223]	81.9	1.7	[78.2, 85.5]
Snow	Aggressive	600	38	[520, 680]	81.9	1.4	[78.8, 85]
	Happy	680	32	[612, 747]	74.4	1.6	[70.9, 77.8]
	Neutral	984	43	[892, 1075]	72.5	1.1	[70, 74.9]
	Tender	1181	25	[1128, 1234]	69	0.6	[67.6, 70.3]
	Sad	1157	30	[1111, 1238]	71.9	1.3	[69.2, 74.7]

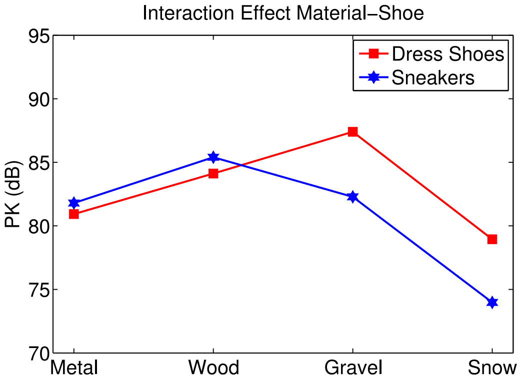

Fig. 4. Interaction effect between Shoe and Material for PK.

previous studies as far as aggressiveness and tenderness are concerned. In addition, unexpected correlations were found between the values of the two investigated parameters and participants' height and weight. Notably, those correlations were found only for sad and tender emotions as far as H2H is concerned. This result differed from [12], where no correlations were found, in accordance with findings reported in [32] for H2H in the neutral emotion condition.

4 EXPERIMENT 2

The aim of the second experiment was to verify to what extent the emotional intentions portrayed by the plantar vibrations generated by setting the synthesis engine with the mean values resulting from the first experiment could be recognized, and whether the recognition was modulated by the type of surface material and type of shoe simulated sonically. As in the first experiment, we used two groups of participants, musicians and non-musicians. The rationale for using these two groups was to assess whether the participants' musical expertise could yield different results. Based on the results of similar listening tests reported in [12], [17], [18], we hypotesized that listeners would not have used music-related knowledge to recognize emotions in walking vibrations.

4.1 Participants

Twenty participants, none of whom were involved in the first experiment, were divided into 2 groups (n = 10) to perform the experiment. The first group was composed of musicians (9 M, 1F), aged between 23 and 28 (mean = 24.3, SD = 1.63), with an average musical experience of 12.5 years. The second group was composed of non-musicians (9 M, 1F), aged between 20 and 28 (mean = 25.9, SD = 3.41). Participants who belonged to this group never played any musical instrument nor took music lessons. All participants reported neither hearing nor locomotion problems.

4.2 Apparatus

The experiment was set up in a silent room and involved the same apparatus utilized in the first experiment, with the exception of the graphical user interface. This interface consisted of two parts. The first part was composed of buttons to start and stop the trials. The second part was composed of five virtual sliders, each labelled with one of the five emotions (happy, sad, aggressive, tender, and neutral). Using a mouse device, the position of each slider could be continuously varied between a minimum value indicated with "not at all" and a maximum value indicated with "very much".

4.3 Stimuli

Stimuli consisted of 40 tactile signals generated by setting the synthesis engine to simulate the same 40 combinations of emotion, surface material, and shoe type involved in the first experiment. Each emotion was rendered by using the mean values of PK and H2H reported in Table 1 and 2. Each tactile signal consisted of six steps.

4.4 Procedure

Participants were instructed to sit on a chair, put on earplugs, headphones and sandals, and interact with the interface described in Section 4.2. They were asked to rate each stimulus on the five scales expressing the emotions happiness, sadness, aggressiveness, tenderness, and emotionless. Each of the 40 stimuli was repeated twice for a total of 80 trials, which were presented in randomized order. When activated, each stimulus was looped with an interval of 2 seconds between the repetitions. Participants could feel it for as long as they wanted before providing an answer. When the answer was chosen, the sound stopped and all the sliders of the interface were automatically set to the minimum value. At this point, participants could not change the answer to the previous stimuli. Before performing the experiment, they practiced with five tactile signals not included in the experiment in order to familiarize with the setup and with the rating procedure. These consisted of six footstep vibrations produced on concrete and on forest underbrush by using dress shoes. The values of H2H and PK of these stimuli were those utilized for the wood and gravel respectively reported in Table 1.

After the completion of the experiment, participants were provided with a survey consisting of two parts. The first part had to be completed before the second part was displayed, and consisted of the following assignment: "*Describe the criteria you used to evaluate the vibrations*". In the second part, participants were asked to rate on a visual analogue scale (VAS) to what extent they had relied on the following criteria to perform the evaluations: Q1: volume of each footstep vibration, Q2: duration of each footstep vibration, Q3: temporal distance between each footstep vibration. The order of presentation of the questions was randomized. Finally, they were given the possibility to leave an open comment about their experience.

4.5 Results

Each subject evaluated the 80 stimuli on five continuous evaluation scales. To obtain more reliable and generalizable results, the ratings were treated as ordinal (ranked) values [40] and non parametric statistical tests were applied.

First of all, we assessed whether the subjects were able to recognize the emotion portrayed by the stimuli, confirming the results of experiment 1. In other words, we wanted to verify the hypothesis that the walking sounds generated using the values of PK and H2H reported in Table 1 and 2 were effective in conveying the emotions listed in those tables. Table 3 shows the median and the interquartile range (IQR) of the subjects' ratings on the five evaluation scales, grouping the values on the basis of the emotion portrayed by the stimuli. According to the Friedman one-way analysis of variance by ranks, a significant effect of the evaluation scales was

TABLE 3
Subjects' Rating on the Five Evaluation Scales of the Stimuli Generated for the Experiment 2 [Median (IQR)]. The Values Are Grouped for the Emotion Portrayed by the Stimuli According to the Results of Experiment 1

Emotion portrayed by the stimuli	**Evaluation scale**				
	Aggressive	**Happy**	**Neutral**	**Sad**	**Tender**
Aggressive	**4.29** (0–7.68)	0.79 (0–5.37)	0 (0–3.03)	0 (0–0)	0 (0–0)
Happy	0.63 (0–4.98)	1.58 (0–5.3)	**2.52** (0–6)	0 (0–0)	0 (0–0)
Neutral	0 (0–0.16)	0 (0–0.81)	**3.43** (0–5.83)	0.04 (0–3.47)	0.67 (0–4.25)
Sad	0 (0–0)	0 (0–0)	1.34 (0–4.09)	**2.84** (0–6.55)	1.06 (0–4.49)
Tender	0 (0–0)	0 (0–0)	1.42 (0–4.21)	1.46 (0–4.98)	**2.99** (0–7.09)

found for every emotion portrayed by the stimuli ($\chi^2(4) = 101.25$, $p < .001$). Table 4 shows the results of a multiple comparison test, carried out with a non-parametric version of the Tukey's method (significance level $\alpha = .05$) [41]. According to the median values, the subjects rated the aggressive stimuli as more aggressive (median = 4.29) and the pairwise comparison showed that this value was significantly greater ($p < .001$) than happy, neutral, tender, and sad; happy stimuli were rated as neutral (median = 2.52), a value that was not significantly different from happy (median = 1.58, $p = .915$) and aggressive (median = .63, $p = .178$), but was significantly greater ($p < .001$) than tender and sad; neutral stimuli were rated as neutral (median = 3.43), a value significantly greater ($p < .05$) than all the other evaluation scales; sad stimuli were rated as sad (median = 2.84) but the value was not significantly different from tender (median = 1.06, $p = .139$) and neutral (median = 1.34, $p = .086$); finally, tender stimuli were rated as tender (median = 2.99), a value that was significantly greater than all the other evaluation scales.

To emphasize the effect of the factors surface material and shoe type on the recognition task, the subjects' rates were analyzed separately for dress shoes (see Table 5) and sneakers (see Table 6), grouping the values by surface material. The aggressive stimuli were generally well recognized in almost every condition, except for these three cases: metal–dress shoes, for which the median value of the aggressive scale (1.69) was less than the happy scale (4.72) although a multiple comparison test showed that this difference was not significant ($p = .999$); metal–sneakers, with aggressive being significantly less than happy ($p < .05$); gravel–sneakers, with aggressive being less than neutral ($p = .970$). For both types of shoe, the values received by the snow material on the aggressive scale were significantly greater than those of metal, gravel, and wood ($p < .001$).

The recognition of the happy stimuli was more problematic: they were often rated as neutral, especially in the trials involving the sneakers, and sometimes (with snow material) as aggressive. However, under the conditions metal–dress shoes, the happy scale received the greatest median (4.17), although this value was not significantly different from the neutral scale ($p = .850$). For both the types of shoe, the median values of the snow materials were significantly lower than gravel, metal, and wood ($p < .001$).

As far as the recognition of the neutral stimuli is concerned, subjects assigned the highest values on the neutral slide in all conditions but metal–sneakers and wood–sneakers, when the stimuli were judged as more tender than neutral.

Overall, the sad stimuli were well recognized by the subjects, except for the conditions gravel–dress shoes, wood–dress shoes, and metal–sneakers. With the snow material, subjects correctly recognized the sad stimuli, both with dress shoes (median = 4.06) and sneakers (median = 5.35). Overall, the median value of snow was significantly greater than that of metal ($p < .01$).

Finally, the tender stimuli received the greatest median ratings in the tender scale under the conditions gravel–dress shoes (5.2), wood–dress shoes (2.72), wood-sneakers (7.13), and metal–sneakers (7.76); in the last two conditions, the median values on the tender scale were significantly greater that the other scales ($p < .01$). Overall, the median values of snow was significantly lower than metal, gravel and wood ($p < .01$).

A further statistical analysis was inspired by the works presented in [42] and [17]. Firstly, the relationships between both H2H and PK, and listeners' judgments was measured. For this purpose, the Kendall's correlations between each of the two acoustical features and the listeners' judgments were calculated. For example, the correlation between PK and sadness judgment indicates the extent to which the rating of sadness tends to increase or decrease when the sound level increases. Results are illustrated in Table 7. The Kendall's correlation test was adopted in place of the Pearson's correlation test used in [42], based on the recent evidence that subjective ratings should be transformed to ordinal representations for obtaining more reliable and generalizable models of affect [40].

To assess whether participants with musical expertise performed better at recognizing the emotional walking intention, we also calculated the phi correlation coefficient for binary classes for each material and emotion, considering the accuracy of recognition for each group of participants. Trials for

TABLE 4
Pairwise Comparisons between the Median Ratings of Experiment 2 (*p*-value)

Comparison	**Emotion portrayed by the stimuli**				
	Aggressive	**Happy**	**Neutral**	**Sad**	**Tender**
Aggressive–Happy	$< .001$	.915	.990	1.000	$< .05$
Aggressive–Neutral	$< .001$	.178	$< .001$	$< .001$	$< .001$
Aggressive–Sad	$< .001$	$< .001$	$< .001$	$< .001$	$< .001$
Aggressive–Tender	$< .001$	$< .001$	$< .001$	$< .001$	$< .001$
Happy–Neutral	.179	.618	$< .001$	$< .001$	$< .001$
Happy–Sad	$< .001$	$< .001$	$< .001$	$< .001$	$< .001$
Happy–Tender	$< .001$	$< .001$	$< .001$	$< .001$	$< .001$
Neutral–Sad	$< .001$	$< .001$	$< .001$	.086	.9990
Neutral–Tender	$< .001$	$< .001$	$< .05$	1.000	$< .01$
Sad–Tender	.3329	1.000	.760	.139	$< .05$

TABLE 5
Subjects' Ratings of the Experiment 2

Material	Emotion portrayed by the stimuli	Evaluation scale				
		Aggressive	Happy	Neutral	Sad	Tender
Gravel	**Aggressive**	**5.04** (0.35–6.32)	1.93 (0–6.59)	0 (0–1.52)	0 (0–0)	0 (0–0)
	Happy	0.39 (0–1.99)	2.91 (0–5.16)	**5.12** (2.36–7.17)	0 (0–0)	0 (0–0)
	Neutral	0 (0–0.18)	0 (0–0)	**3.9** (0.32–7.22)	0 (0–1.58)	0.75 (0–3.64)
	Sad	0 (0–0)	0 (0–0.35)	0.55 (0–4.78)	0.63 (0–4.63)	**2.01** (0–4.65)
	Tender	0 (0–0)	0 (0–0)	2.13 (0–6.85)	2.24 (0–5.02)	**5.2** (1.69–6.97)
Metal	**Aggressive**	1.65 (0–8.19)	**4.72** (0–6.5)	1.58 (0–3.8)	0 (0–0)	0 (0–0)
	Happy	1.46 (0–2.74)	**4.17** (0.65–6.56)	2.32 (0–4.51)	0 (0–0)	0 (0–0)
	Neutral	0 (0–0)	0 (0–1.81)	**2.83** (0–4.96)	0 (0–0.1)	0.51 (0–2.62)
	Sad	0 (0–0)	0 (0–0)	0.2 (0–4.17)	**4.09** (1–6.73)	0.79 (0–3.58)
	Tender	0 (0–0)	0 (0–0)	**2.83** (0.18–5.06)	0.91 (0–3.09)	1.54 (0–3.33)
Snow	**Aggressive**	**7.91** (5.79–9.94)	0 (0–1)	0 (0–0.49)	0 (0–0.02)	0 (0–0)
	Happy	**6.06** (3.52–7.56)	0 (0–0.37)	0 (0–2.93)	0 (0–0.47)	0 (0–0)
	Neutral	0 (0–2.18)	0 (0–0)	**2.56** (0–6.38)	1.57 (0–4.78)	0 (0–1.26)
	Sad	0 (0–2.46)	0 (0–0)	2.87 (0–3.98)	**4.06** (0.85–7.64)	0 (0–0.22)
	Tender	0 (0–0)	0 (0–0.16)	0.75 (0–2.52)	**4.76** (0.06–6.59)	1.93 (0–5.51)
Wood	**Aggressive**	**4.06** (1.28–7.74)	1.06 (0–3.48)	0 (0–3.33)	0 (0–0)	0 (0–0)
	Happy	0.35 (0–3.21)	2.13 (0–5.91)	**2.36** (0–5.41)	0 (0–0.04)	0 (0–0)
	Neutral	0 (0–0)	0 (0–0.47)	**3.7** (0.95–5.65)	0.75 (0–2.54)	0.32 (0–2.13)
	Sad	0 (0–0.45)	0 (0–0.55)	**2.17** (0–4.06)	0.75 (0–4.47)	0.71 (0–4.13)
	Tender	0 (0–0)	0 (0–0)	1.54 (0–2.99)	1.89 (0.79–5.59)	**2.72** (0.35–7.26)

The values [Median (IQR)], grouped for surface material, refer only to trials involving dress shoes.

which the performed emotion was rated with the highest value were considered as correct. Results showed that all the correlations were low (all $\phi < .35$, with an average absolute value of .13 and SD = .09). This suggests that musical expertise was not associated with a significant increase in the ability to recognize the emotions portrayed by the footstep vibrations.

As for the questionnaire, Fig. 5 shows the evaluations expressed by both groups of participants for each questionnaire item. Separate Friedman Tests were performed for each group of participants to assess whether the differences between the ratings of the questionnaire items Q1, Q2, and Q3 were significant. A significant main effect was found for

TABLE 6
Subjects' Ratings of the Experiment 2

Material	Emotion portrayed by the stimuli	Evaluation scale				
		Aggressive	Happy	Neutral	Sad	Tender
Gravel	**Aggressive**	1.3 (0–7.38)	1.22 (0–6.87)	**1.61** (0–3.54)	0 (0–0)	0 (0–0)
	Happy	0 (0–1.99)	0.95 (0–4.43)	**5** (1.48–6.63)	0 (0–0.37)	0 (0–0)
	Neutral	0 (0–0.18)	0 (0–0.55)	**4.17** (1.83–5.95)	0.43 (0–2.44)	1.1 (0–2.64)
	Sad	0 (0–0)	0 (0–0)	2.05 (0.35–3.64)	**4.65** (0.24–6.34)	1.38 (0–4.29)
	Tender	0 (0–0)	0 (0–0.63)	**2.64** (0–4.63)	0.87 (0–3.96)	2.17 (0–4.8)
Metal	**Aggressive**	0 (0–1.79)	**5.32** (0.41–7.32)	1.89 (0–4.15)	0 (0–0)	0 (0–0)
	Happy	0 (0–0.14)	2.24 (0–4.76)	**3.15** (0–6.08)	0 (0–0)	1.02 (0–3.66)
	Neutral	0 (0–0)	0 (0–0.61)	1.18 (0–5.1)	0 (0–1.36)	**4.88** (0.59–7.68)
	Sad	0 (0–0)	0 (0–0)	1.42 (0–4.41)	0.51 (0–2.3)	**5.24** (1.2–7.76)
	Tender	0 (0–0)	0 (0–0.61)	0 (0–0.85)	0 (0–2.36)	**7.76** (4.47–9.61)
Snow	**Aggressive**	**7.52** (6.69–9.65)	0 (0–0)	0 (0–0.83)	0 (0–0)	0 (0–0)
	Happy	**6.38** (1.52–7.42)	0 (0–1.91)	0.35 (0–2.74)	0 (0–0.3)	0 (0–0)
	Neutral	1.81 (0–2.74)	0 (0–1.65)	**4.06** (0–5.91)	0.04 (0–4.63)	0 (0–0.57)
	Sad	0.35 (0–3.05)	0 (0–1.63)	0.32 (0–2.32)	**5.35** (0.77–7.89)	0 (0–2.74)
	Tender	0 (0–1.2)	0 (0–0)	1.81 (0–5.89)	**2.13** (0–5.37)	0.12 (0–2.42)
Wood	**Aggressive**	**4.13** (0–5.79)	1.3 (0–4.02)	0.71 (0–4.25)	0 (0–0)	0 (0–0)
	Happy	0 (0–0.91)	2.99 (1–6.38)	**3.82** (0–7.52)	0 (0–0.26)	0 (0–3.11)
	Neutral	0 (0–0)	0 (0–1.36)	1.73 (0–5.65)	0.51 (0–5.04)	**2.64** (1.44–5.75)
	Sad	0 (0–0)	0 (0–0.91)	0 (0–3.98)	**3.54** (0.24–6.87)	3.43 (0.06–5.34)
	Tender	0 (0–0)	0 (0–0.55)	0.63 (0–2.13)	0 (0–4.78)	**7.13** (3.82–9.88)

The values [Median (IQR)], grouped for surface material, refer only to trials involving sneakers.

TABLE 7
Results of the Recognition Experiment: Kendall's Correlations between Each of the Two Acoustical Features (H2H and PK) and the Listeners Judgments for Each Emotion and Shoe Type

		Metal		**Wood**		**Gravel**		**Snow**	
		H2H	**PK**	**H2H**	**PK**	**H2H**	**PK**	**H2H**	**PK**
Sadness	**Dress Shoes**	0.4***	-0.32***	0.35***	-0.36***	0.4***	-0.36***	0.37***	-0.3***
	Sneakers	0.27***	-0.27***	0.26**	-0.26**	0.32***	-0.24**	0.32***	-0.32***
Tenderness	**Dress Shoes**	0.41***	-0.41***	0.42***	-0.43***	0.47***	-0.44***	0.22**	-0.36***
	Sneakers	0.44***	-0.44***	0.49***	-0.49***	0.37***	-0.35***	0.32***	-0.32***
Neutralness	**Dress Shoes**	0.02	-0.07	0.04	-0.07	0.08	-0.12	0.19*	-0.14
	Sneakers	-0.12	0.12	-0.07	0.07	-0.01	-0.04	0.18*	-0.18*
Happiness	**Dress Shoes**	-0.44***	0.42***	-0.22**	0.23**	-0.34***	0.38***	-0.13	0.07
	Sneakers	-0.35***	0.35***	-0.23**	0.23**	-0.26**	0.24**	-0.04	0.04
Aggressiveness	**Dress Shoes**	-0.36***	0.37***	-0.41***	0.46***	-0.45***	0.41***	-0.45***	0.5***
	Sneakers	-0.33***	0.33***	-0.4***	0.4***	-0.42	0.39**	-0.48***	0.48***

** represents $p < .05$, ** $p < .01$ and *** $p < .001$.*

the group of the non-musicians, $\chi^2(2)= 16.9$, $p < .001$. The post-hoc analysis, performed by using the Wilcoxon-Nemenyi-McDonald-Thompson Test, revealed that non-musicians relied less on the duration of the footstep vibration than on the temporal distance between subsequent footstep to perform the evaluations ($p < .05$). No significant main effect was found for musicians. In addition, a Mann-Whitney-Wilcoxon Test was conducted, for each questionnaire item, on the evaluations of the two groups of participants. The test revealed that for Q3 musicians expressed higher evaluations than non-musicians (U = 79, $p < .05$.), while their evaluations were not significantly different for Q1 and Q2.

4.6 Discussion

The results of the second experiment showed that, in general , participants correctly identified the emotions portrayed by the synthetic stimuli. Specifically, aggressiveness was the best recognized emotion, followed by tenderness, while the stimuli portraying happiness received lower ratings on the happy scale compared to the neutral scale.

The correlations reported in Table 7 suggest that the two acoustical features had considerable effects on the listeners' judgments of the emotional expression. With the exception of the neutral and happy emotions for the snow material (with both types of shoes), all the correlations were statistically significant. 94 percent of these correlations were medium or large, according to the guidelines for interpretation of the effects provided by Cohen [43] (also used in [42]), i.e., small (r ≥ .1), medium (r ≥ .3), and large (r ≥ .5), adapted to the Kendall's analysis as indicated in [44], i.e., small ($\tau \geq .065$), medium ($\tau \geq .195$), and large ($\tau \geq .335$). As expected, and consistently with the results reported in [12], [18], [39], the neutral emotion was not associated with medium or large increases or decreases in the two acoustical features considered.

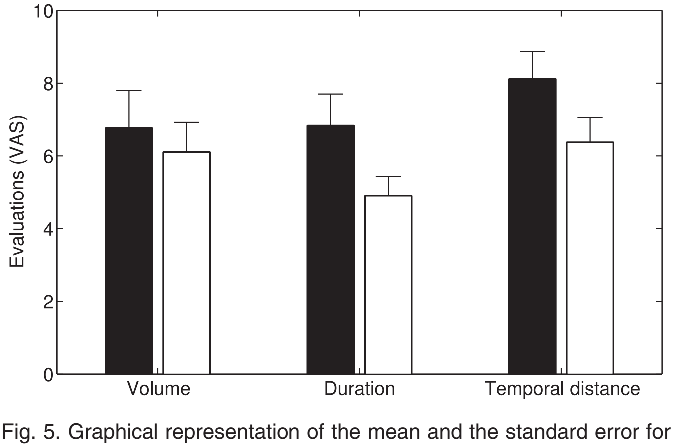

Fig. 5. Graphical representation of the mean and the standard error for participants' answers to questionnaire items Q1, Q2, and Q3. In black the ratings of the musicians and in white those of the non-musicians.

Some trends were found regarding the influence of a particular sonically simulated ground material on the recognition of the emotions: for both shoes, snow was the best material associated with the aggressive emotion, while metal was the worst one; metal with dress shoes was better associated with happiness than the other three materials; metal and wood with sneakers were better associated with tenderness.

In addition, in line with the results presented in [12], [17], [18], [45], the comparison between the performances of the two groups of participants revealed that musical expertise did not yield a significant increase in the ability to recognize emotions at plantar vibro-tactile level.

Musicians expressed no preference about the subjective criteria they relied on to evaluate the expressive content of the tactile stimuli (i.e., the first questionnaire item). Conversely, the temporal distance between consecutive footstep vibrations was much more important than the duration of the vibrations for non-musicians. Considering both the open comments and the second question about the indicated criteria that participants relied on to evaluate the tactile stimuli, the majority of participants in both groups reported having based their choices on walking speed and on the strength of the footstep vibrations. Specifically, they reported to have associated walking excerpts characterized by slow paces and soft vibrations with sad and tender emotions, and fast paces and strong vibrations with happy and aggressive emotions.

5 GENERAL DISCUSSION

The results of the first experiment showed that participants rendered the various emotions using different amplitude and temporal variations, similar to those of the corresponding experiment reported in [12] for the auditory case. In turn, results presented in [12] were similar to those reported in previous studies on real and synthesized footstep sounds [17], [18], as well as those on expressive music performance [29], [39]. One noticeable difference from the corresponding experiment reported in [12] for the auditory case is that participants were less accurate in the discrimination of the various emotions as far as PK was concerned. In particular, while in the auditory case sadness was produced with PK values significantly lower than happiness, for the tactile case such a difference was not significant.

The second experiment revealed that the algorithms involved in the synthesis of the five expressive walking styles were as successful in conveying the emotional information as those used in [12]. The best performance was achieved for the recognition of the aggressive emotion. Conversely, happiness was the least recognized emotion, perhaps because a constant H2H was involved. In a musical context, previous studies showed that happy emotion is often associated with specific rhythmic patterns, such as dotted or syncopated rhythms [46]. A possible rationale is that dotted or syncopated rhythms for happy music may reflect associations between specific actions (e.g., skipping, jumping, dancing) and positive mood. Further experiments are necessary to verify whether the introduction of such rhythms to control the footstep synthesizer is effective in improving the rendering of the happy emotion. A difference from the corresponding experiment reported in [12] for the auditory case is that tenderness was well distinguished from sadness and neutralness.

The results of the two experiments seem to indicate that aggressiveness and tenderness are more characterized at tactile level compared to happiness and sadness in both production and recognition tasks. A possible explanation for this lies in the fact that aggressiveness and tenderness are more related to the sense of touch. Notably, those emotions are related to the affective dimension of arousal [38]. Arousal, on the other hand, is predominantly associated with motor-based aspects while the valence dimension (which sadness and happiness are more related to) implies a positive or negative evaluation that often requires a cognitive task [47], [48].

The performances of musically-trained and -untrained subjects were similar in both experiments. This result lends support to the MOH [17] applied to the tactile channel. However, it is interesting to notice that it partially differs from the results found for the auditory case: in the production experiment reported in [12], for each emotion, musicians' choices of the two investigated variables were different compared to those of non-musicians.

On a separate note, the similarities between the results of the first experiment and those of the corresponding experiment in the auditory case [12], which, in turn, paralleled those reported in previous studies on real walking [17], [18], suggest that both auditory and plantar-vibro-tactile expression of emotions in walking are independent of the real or imagined motor activity. This result parallels those of various studies reporting similarities between the somatotopic activation patterns of motor imagery tasks and those of the corresponding physical movements [19], [20], [21]. Moreover, our results suggest that the production of emotionally expressive walking vibrations in the context of passive sensory motor activity is almost always independent of the anthropometric features of the person imagining the simulated walks. Nevertheless, differently from the auditory case, significant correlations between participants' weight and height and H2H were found for sadness and tenderness.

Taken together, the comparisons between results of the present experiments and those reported in [12] revealed strong similarities, indicating that emotionally expressive walking styles are consistently produced and recognized at auditory and plantar vibro-tactile levels. This result is in accordance with findings of previous studies investigating the identification of the typology of real or simulated surface materials [13], [14], [15], [16] as well as of virtual surface profiles [5] in both sensory modalities. Notably, the similarities between the two modalities concerned more temporal aspects than amplitude ones. However, on the one hand the identification performances were better in the auditory experiment compared to the tactile one for the material-shoe combinations metal-sneakers and gravel-sneakers in aggressiveness, metal-sneakers and wood-sneakers in neutralness, gravel-dress shoes and wood-dress shoes in sadness. On the other hand, the identification performances for tenderness were on average better in the tactile experiment compared to the auditory one, allowing in particular to discriminate tenderness from sadness. These differences suggest that the combined use of audio-tactile stimuli could lead to better simulations of emotionally expressive walking styles compared to the separate use of the two sensorial modalities.

6 CONCLUSIONS AND FUTURE WORKS

The results of this study showed that humans can express and recognize five emotions (aggressiveness, happyness, neutralness, sadness, and tenderness) through digital tactile stimuli provided at the feet. The results of the production experiment allowed to identify, for the involved emotions and vibration conditions, the mean values and ranges of variation of vibration amplitude and temporal distance between consecutive steps. Such results were in accordance with those reported in previous studies on real walking, suggesting that the plantar vibro-tactile expression of emotions in walking is independent of the real or imagined motor activity. The results of the identification experiment showed that the involved algorithms were successful in conveying the emotional information at a level comparable with previous studies. Results of both experiments revealed strong similarities with those of an analogous study on footstep sounds suggesting that emotionally expressive walking styles are consistently produced and recognized at the auditory and the plantar vibro-tactile levels. Nevertheless, the differences between the identification performances in the auditory and tactile modalities suggest that the use of combined audio-tactile stimuli should be preferred in applicative scenarios, since the two modalities could complement each other, thus achieving better simulations of emotionally expressive walking styles. We plan to validate this hypothesis in future research. In our future work, we also plan to investigate temporal variations, such as dotted or syncopated rhythms, in both sensory modalities, which could lead to better rendering and identifications of the happy emotion.

The results of this study allow for both the design and control of emotionally expressive computerized walking vibrations that are more ecologically valid than vibrations without performance variations. They can be practically used as guidelines by designers of footstep vibrations for videogames or virtual reality in contexts where a control model for artificial walking vibrations patterns is required to convey the emotional state of an avatar. The results presented in this work can be also coupled with results reported in [12] to achieve an audio-tactile emotional rendering that can lead to the enhancement of the realism of navigating in multimodal desktop-based VEs [7].

Finally, the results reported in this study might find applications in the field of emotional exposure therapy [49]. Currently, most of emotional exposure techniques are based on videos and pictures, or virtual reality settings [50]. The use of emotional tactile stimuli provided by SoleSound might contribute to achieve more engaging and effective forms of emotional exposure therapies involving walking scenarios.

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