Walking Pace Affected by Interactive Sounds Simulating Stepping on Different Terrains

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This article investigates whether auditory feedback affects natural locomotion patterns. Individuals were provided with footstep sounds simulating different surface materials. The sounds were interactively generated using shoes with pressure sensors. Results showed that subjects' walking speed changed as a function of the type of simulated ground material. This effect may arise due to the presence of conflicting information between the auditory and foot-haptic modality, or because of an adjustment of locomotion to the physical properties evoked by the sounds simulating the ground materials. The results reported in this study suggest that auditory feedback may be more important in the regulation of walking in natural environments than has been acknowledged. Furthermore, auditory feedback could be used to develop novel approaches to the design of therapeutic and rehabilitation procedures for locomotion.

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1. INTRODUCTION

Several recent studies have investigated the conditions under which the gait of a walker is influenced by sounds provided both in a noninteractive (i.e., sounds are independent of the walker's actions) and in an interactive fashion (i.e., sounds are the direct consequence of the walker's actions). Such studies have been conducted in both clinical and nonclinical contexts.

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Clinical research studies have made use of external acoustic stimuli, such as metronome beeps or music, to influence the gait of patients affected by different forms of diseases [Staum 1983; Thaut 2005; Thaut and Abiru 2010; Roerdink et al. 2011]. Rhythmic auditory cues are used to synchronize the walkers' motor responses so that a stable coupling is created between footfalls and a specific beat. Indeed, following a rhythm has been proved to be an effective method to improve gait performance (especially walking speed) of patients affected by Parkinson's disease [McIntosh et al. 1997; Rubinstein et al. 2002; Lim et al. 2005], strokes [Thaut et al. 1993; Thaut et al.1997; Van Peppen et al. 2004; Hayden et al. 2009], multiple sclerosis [Conklyn et al. 2010], and cerebral palsy [Kwak 2007; Kim et al. 2011]. Similarly, there is a growing body of research exploring the effects of interactive auditory feedback while walking in the clinical population, although the study of such rehabilitation techniques in motor therapy is still in its infancy. One approach consists of providing a clicking sound in response to each step and asking patients to couple their gait pattern with the auditory cues. This technique proved to be effective in improving walking abilities of patients affected by multiple sclerosis [Baram and Miller 2007] and cerebral palsy [Baram and Lenger 2009]. In the same vein, playing pieces of music with the rhythm adjusted to the walker's strides was revealed to improve the gaits of hemiparetic stroke patients [Schauer and Mauritz 2003].

In nonclinical studies, noninteractive auditory cues have been shown to be effective for detecting and anticipating incoming perturbations such as for obstacle avoidance [Queralt et al. 2008]. In addition, Styns and colleagues investigated the effect of music on gait [Styns et al. 2007]. Results showed that humans are able to synchronize their walking with music over a broad range of tempi and that such synchronization is most optimal around 120 beats per minute. It was also found that walking speed significantly increased under the influence of music compared to a metronome stimulation, indicating that music might be more effective at changing locomotion patterns. Overall, these studies support the notion that rhythm and music provide relevant information for the control of locomotion. However, only a few studies have involved interactive auditory feedback by using sound resulting from walkers' movements. A preliminary research study investigating the impact that sounds, provided interactively with footfalls, have on walkers' gaits has been recently presented [Bresin et al. 2010]. In this study, the authors built an apparatus that provided the walkers with synthesized footstep sounds and foot-haptic sensations generated during their locomotion. Results indicated that the patterns of gait, when walking with specific emotional intentions (e.g., happiness, sadness, aggressiveness, tenderness), can be affected by ecological auditory and vibrotactile underfoot feedback. Such research represents a noticeable exception among the studies investigating the effects of sound on gait, because it made use of everyday sounds instead of the commonly used techniques involving music or sound burst [Gaver 1993b, 1993a]. Nevertheless, if on the one hand this investigation involved audio-haptic stimuli, on the other hand such interactive feedback was applied to test walking when simulating emotional intentions. To date, no research has been done, to our knowledge, to ascertain whether the parameters defining the gait (e.g., velocity and step length) change when healthy walkers are interactively provided with the sound produced by their own footsteps as if they were walking on different terrains (i.e., snow, gravel, wood).

In this article, we test whether changing the auditory perception of the walked-upon material affects the kinematics of locomotion. For this purpose, an experiment was performed in an outdoor environment, where the footstep sounds were provided interactively to the walkers by means of a system consisting of shoes enhanced with pressure sensors that drived a footstep sound synthesis engine. Kinematic variables such as walking velocity, the time and the number of steps taken to cover a defined distance, were extracted from the sensors' data.

During all of the experimental trials, participants walked on the same ground, so the haptic information about the walked-upon ground was kept constant across variations in auditory feedback.

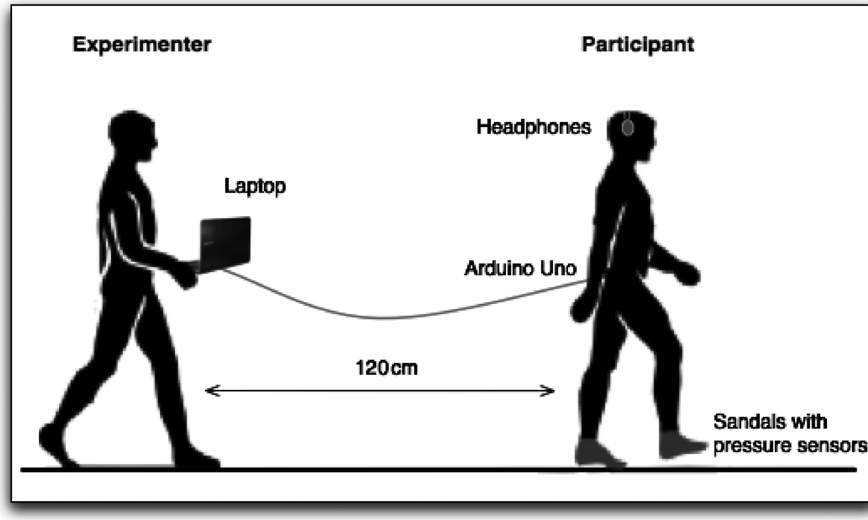

Fig. 1. Experimental setup.

Since the compliance of a surface material is related to the ground-material typology, in this study we also aimed to test whether the proposed auditory feedback can modify the perceived compliance of a walked-upon ground. Such a test was inspired by the results of audio-haptic studies, which reveal that auditory feedback can effectively alter the perception of stiffness (i.e., the inverse of compliance) in a hand-based interaction with virtual objects. Specifically, DiFranco and colleagues found that auditory cues affected the ranking of the stiffness of virtual surfaces tapped by using a force-reflecting haptic interface [DiFranco et al. 1997]. Similarly, Avanzini and coworkers found that the haptic perception of stiffness experienced by a user while tapping on a virtual surface with a rigid probe was influenced by auditory stimuli created with a physically based audio model of impact [Avanzini and Crosato 2006].

After the walking experience, we asked participants to fill in an ad hoc questionnaire (by means of a visual analogue scale [VAS] score). The questionnaire items were correlated with the measured parameters of the walking performance.

2. METHOD

2.1 Participants

Thirteen participants, seven males and six females, between 22 and 38 years of age (mean = 29.69, SD = 5.23), took part in the experiment. All participants reported normal hearing and no locomotion impairments. The procedure, approved by the local ethics committee, was in accordance with the ethical standards of the 1964 Declaration of Helsinki.

2.2 Apparatus

The apparatus consisted of a laptop running a sound synthesis engine, a pair of sandals augmented with pressure sensors, an Arduino UNO board, and a wired headphone set (Sennheiser HD 600). Walking participants were followed by an experimenter holding the laptop for online checking of the synthesis engine, as illustrated in Figure 1.

Although ideally the setup should be wireless, a wired setup allowed us to monitor continuously the time latency between the transmitter and the receiver, and check for data loss. The total latency between the actual footstep fall and the heard synthesized sound was not noticeable (less than 5ms). Two pairs of sandals sizes were available (40 and 43 sizes EUR) to fit a range of participants. A pressure sensor was placed under the sole of each sandal at the level of the heel. The sensors detected foot pressure during the contact with the ground; their analogue signals were digitized by means of the Arduino UNO board and used to drive the footstep sound synthesis engine. The synthesized auditory feedback was then conveyed to the user by means of headphones. Although both shoes and headphones were connected by a wire, participants were barely aware of the presence of the wire while walking because the equipment was light, comfortable, and did not constitute any major constraint to their movements: the light box containing the Arduino UNO board was hung on the back of the user's trousers by means of a small hook; the wires coming out from the shoes and directed to the Arduino UNO board were attached to the user's trousers by means of a tape and secured to the external side of the lower limbs; the USB cable connecting the Arduino UNO board to the laptop was tied together with the wire of the headphones, which was also connected to the laptop. The wires were long enough to allow the participant to move freely.

The footstep sounds were synthesized by means of a sound synthesis engine proposed in previous research and able to simulate the footstep sounds on aggregate and solid surfaces [Turchet et al. 2010] (see Appendix).

2.3 Stimuli

Four conditions were tested in the experiment. Three conditions consisted of interactively generated footstep sounds simulating two aggregate surface materials (snow and gravel) and a solid one (wood); in the fourth condition, no sound stimuli were provided. The selection of material type was inspired by our previous work showing that these simulated ground materials were easily recognizable [Nordahl et al. 2010]. In particular, this validation study revealed correct classification of the typology of these simulated ground materials. These materials were also chosen because the three signals corresponding to their simulation had different features in terms of duration, amplitude, temporal evolution, and spectrum (Figure 2). The amplitudes of the sounds were set at 55.4, 57.8, and 54.2dB (A) for snow, gravel, and wood, respectively. Such values were chosen according to the results of a previous experiment, in which the goal was to find the appropriate level of amplitude for those synthesized sounds [Turchet and Serafin 2013]. The real surface on which participants were actually walking was asphalt.

2.4 Procedure

The experiment was carried out in a quiet pedestrian street near the campus of the University of Verona (Italy) where participants could walk unconstrained. It took place under excellent weather conditions. Participants were asked to wear the shoes and the headphones and to walk in a straight line for 54m. They were instructed to walk normally with their natural gait and were informed that a change in feedback could occur at each trial. When no auditory feedback was delivered, participants were asked to remove the headphones. In this way, participants could hear their footsteps. When using the headphones, the provided sounds masked the actual sounds produced by the steps on the asphalt. No other instruction was given.

Each participant underwent four conditions, each representing a different sound stimulus. Each condition was repeated twice, in a randomized order, for a total of eight trials.

Small marks were placed on the ground indicating the distance of 50m to be traveled on each trial. They were placed next to the path in such a way that only the experimenter was aware of their presence. Specifically, participants started and finished their walks 2m before and 2m after the starting and finishing marks, respectively, but data collection started and stopped when subjects crossed the marks.

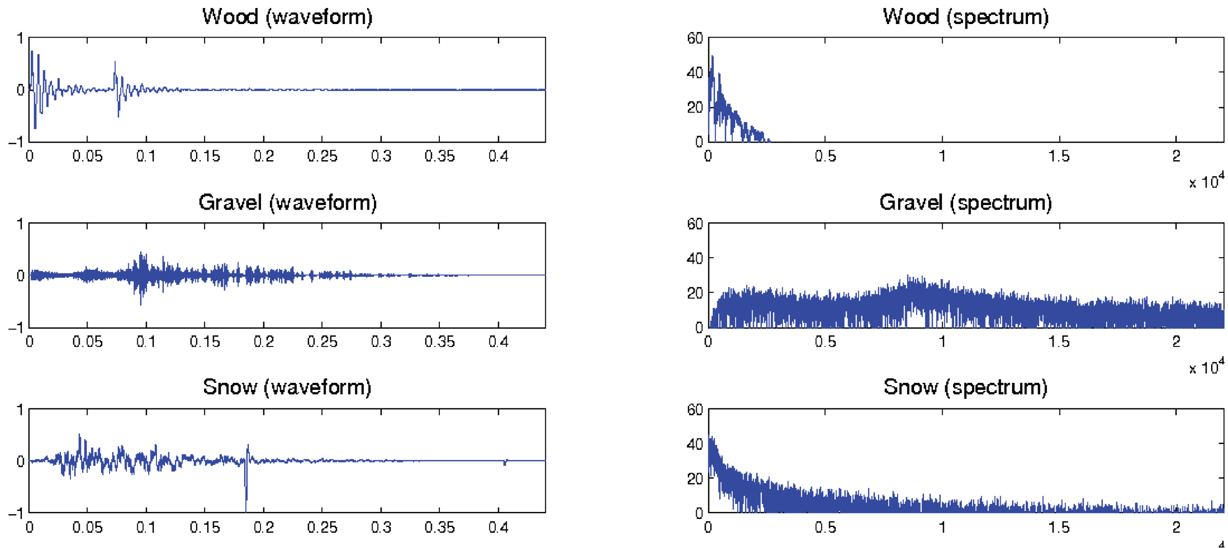

Fig. 2. Typical waveforms (left) and spectra (right) of the three simulated materials. The duration of the waveforms is in seconds, the magnitude of the spectra (in Hz) is in decibels.

Before data collection, participants had the opportunity to listen once to each of the three footstep sounds. They were not provided with information about which material was simulated by the synthesis model.

Participants took, on average, about 25 minutes to complete the experiment.

2.4.1 Questionnaire. After the walking experiment, subjects were asked to complete the following questionnaire and evaluate each question on a VAS. For each simulated surface, four questions were asked:

Q1. Evaluate the sense of effort you experienced while walking [0 = no effort, 10 = high effort]

Q2. Evaluate the degree of easiness with which you walked while listening to the sounds [0 = very hard, 10 = very easy]

Q3. Evaluate to what extent you had the impression that your feet were sinking into the ground [0 = not at all, 10 = very much]

Q4. Evaluate the velocity you kept while walking [0 = very slow, 10 = very fast]

The order of presentation of the questions was randomized using a 4×4 Latin square. At the end of the questionnaire, participants were asked to name the three simulated types of surface and leave an open comment about their experience.

2.5 Data Handling and Statistics

The produced footstep sounds were recorded along with the instants at which a foot hit the ground (Figure 3). Three parameters were calculated from the collected data: total number of steps, total elapsed time, and step time (calculated as the temporal distance between two subsequent steps detected by the pressure sensors). In addition, the three following parameters were derived: average velocity (calculated as 50m over the elapsed time), number of steps per minute (SPM), and step length (calculated as 50m over the number of steps).

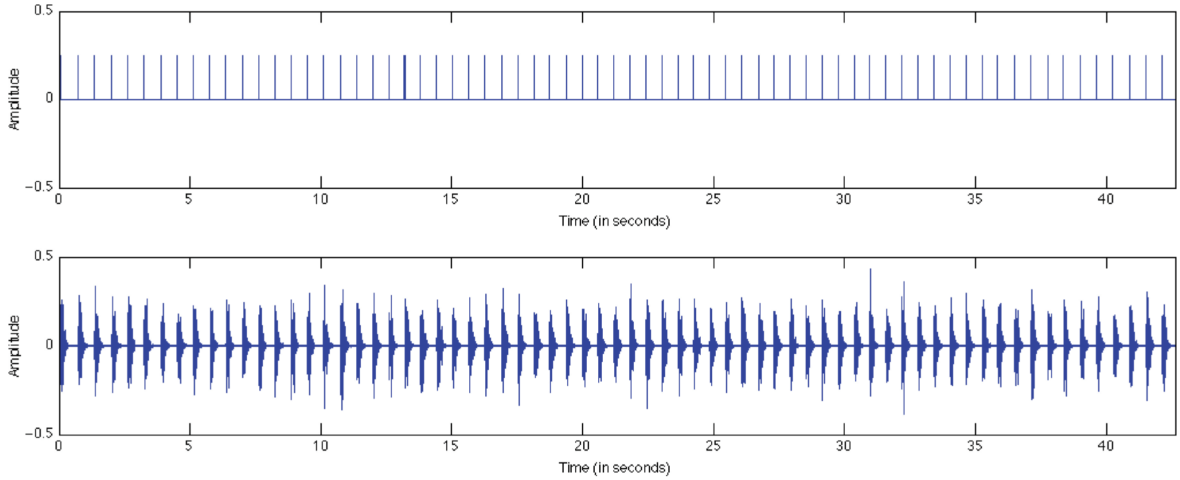

Fig. 3. Instants of heel strikes (top) and waveforms of the corresponding recorded footstep sounds on simulated gravel (bottom).

Statistical analysis was performed on the collected data by means of repeated measures ANOVAs by considering the four conditions (four levels: the three sound conditions plus the no-sound condition) for each of the six dependent variables (total number of steps, total elapsed time, step time, average velocity, SPM, and step length). A further repeated measures ANOVA was performed on the questionnaire data by considering the four conditions (four levels) for each of the four dependent variables (Q1, Q2, Q3, and Q4). All post hoc analyses were performed by using Tukey's procedure (critical p-value = 0.05).

Moreover, a linear mixed-effects model analysis was performed in order to search for correlations between each individual walking measure and each VAS evaluation expressed for each question in the questionnaire.

3. RESULTS

Results are illustrated in Figure 4. Regarding step time, the ANOVA showed a significant main effect for the four sound conditions, $F(3,36) = 12.2$, $p < 0.001$. The post hoc comparisons indicated that step time was significantly lower for the no-sound condition compared to the snow and gravel condition (both $p < 0.001$), and significantly higher for the snow condition compared to the wood and gravel conditions ($p < 0.001$ and $p < 0.05$, respectively). Considering the total elapsed time, the ANOVA yielded a significant main effect, $F(3,36) = 7.208$, $p < 0.001$. The pairwise comparison showed that the total elapsed time was significantly lower for the no-sound condition compared to the snow and the gravel sound conditions (both $p < 0.001$) and significantly lower for the wood compared to the snow sound condition ($p < 0.01$). Similarly, a significant main effect was found for the average velocity, $F(3,36) = 7.531$, $p < 0.001$. The pairwise comparison showed that the average velocity was significantly higher for the no-sound condition compared to the snow and gravel sound condition (both $p < 0.001$) and significantly higher for the wood compared to the snow sound condition ($p < 0.05$). As for the SPM parameter, again a significant main effect was present with $F(3,36) = 13.241$, $p < 0.001$. The pairwise comparison showed that the SPM was significantly higher for the no-sound condition compared to the snow and gravel sound conditions (both $p < 0.001$) and significantly higher for the wood compared to the snow condition ($p < 0.001$). No significant main effects were found either for the number of steps or for the step length ($F(3,36) = 1.11$, $p > 0.3$ and $F(3,36) = 0.946$, $p > 0.4$, respectively).

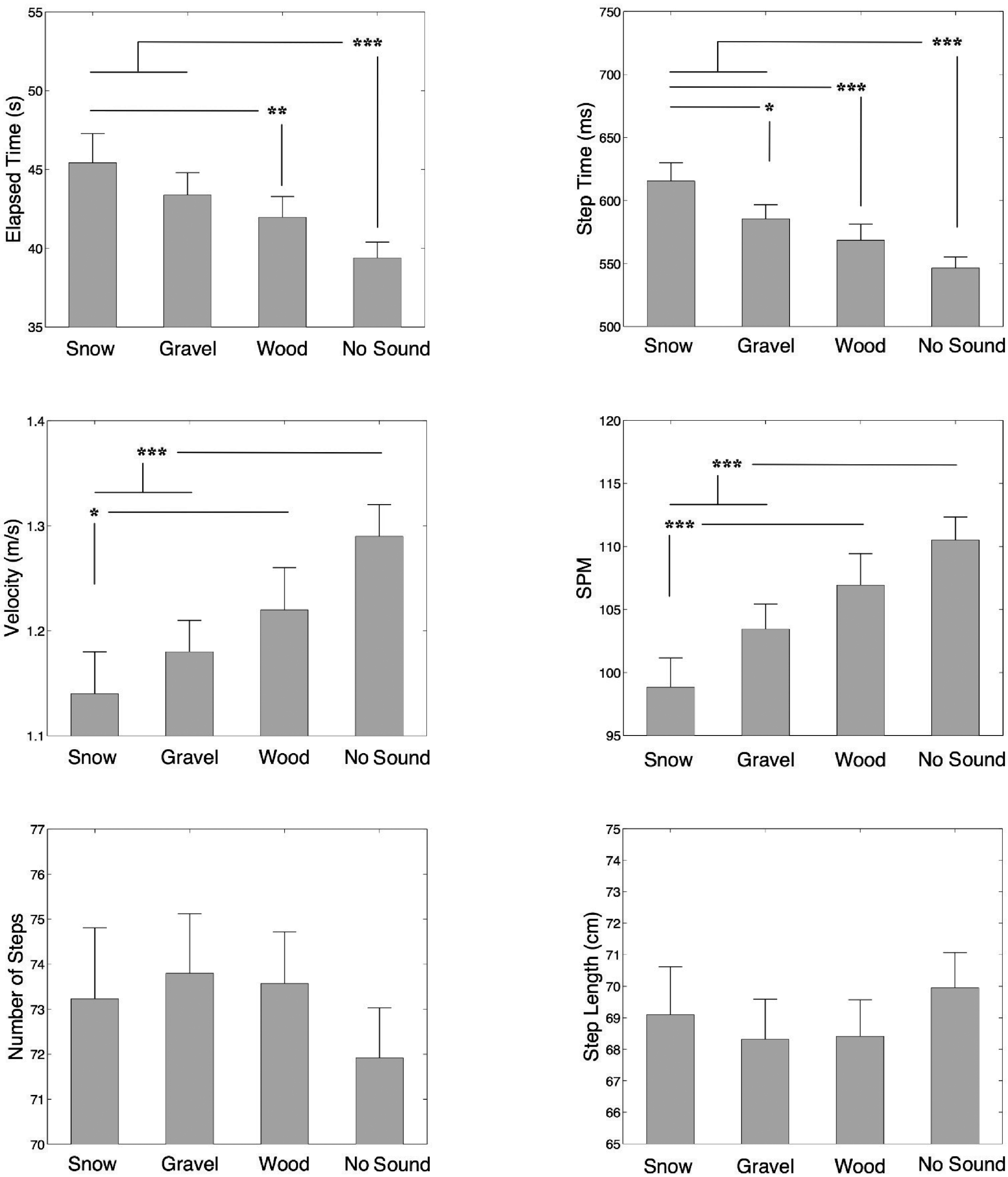

Fig. 4. Graphical representation of the mean and the standard error for participants' walking parameters. Legend: *represents $p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

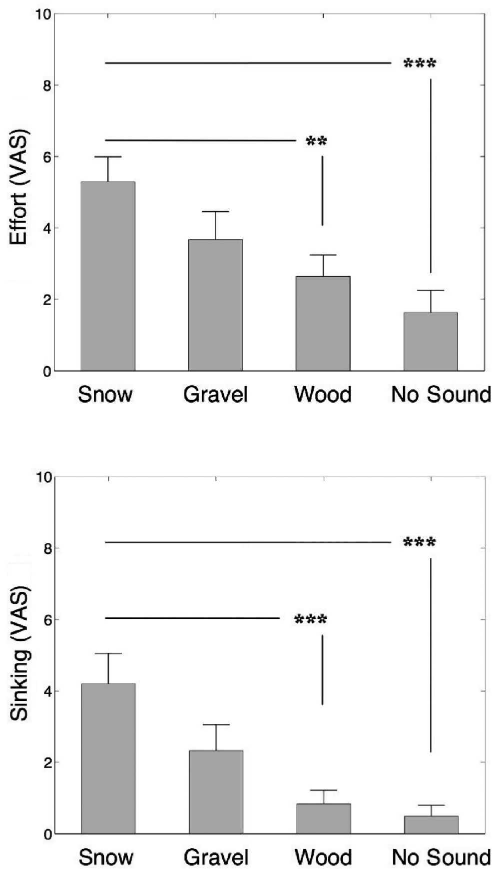

Fig. 5. Graphical representation of the mean and the standard error for participants' answers to questionnaire items Q1 (top left), Q2 (top right), Q3 (bottom left), and Q4 (bottom right). Legend: *represents $p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

Figure 5 shows the evaluations expressed as VAS score for the questions from Q1 to Q4. The ANOVA revealed a significant effect for all questions: for Q1, F(3,36) = 7.288, $p < 0.001$; for Q2, F(3,36) = 5.026, $p < 0.01$; for Q3, F(3,36) = 10.696, $p < 0.001$; for, Q4 F(3,36) = 4.314, $p < 0.05$. The Tukey's post hoc analyses revealed significant differences for the combination snow–no-sound in all the questions (for Q1, $p < 0.001$; for Q2, $p < 0.01$; for Q3, $p < 0.001$; for Q4, $p < 0.01$), for the combination snow–wood for question Q1 ($p < 0.01$) and Q3 ($p < 0.001$), and for the combination gravel–no-sound for question Q2 ($p < 0.05$).

The analyses using a linear mixed-effects model revealed that (i) the step time was linearly related to perceived effort, easiness, sinking, and velocity; (ii) the total elapsed time was linearly related to perceived effort, easiness, sinking, and velocity; (iii) the average velocity was linearly related to perceived effort, easiness, sinking, and velocity; and (iv) the SPM was linearly related to perceived effort, easiness, sinking, and velocity. No significant linear correlations were found between the VAS evaluation expressed for each question in the questionnaire and either number of steps or step length. Table I reports details of the significant linear correlations.

Not all participants recognized the simulated material correctly: seven participants recognized snow, eight recognized gravel, and eleven recognized wood; two participants interpreted the snow as

Table I. Significant Correlations in the Linear Mixed-Effect Model Analysis

Predicted by predictor	β weight	t-test
Effort by step time	23.17	$t(90) = 5.283$
Easiness by step time	−20.43	$t(90) = -4.165$
Sinking by step time	24.38	$t(90) = 6.396$
Velocity by step time	−16.08	$t(90) = -4.878$
Effort by elapsed time	0.22	$t(90) = 5.239$
Easiness by elapsed time	−0.18	$t(90) = -3.862$
Sinking by elapsed time	0.24	$t(90) = 6.486$
Velocity by elapsed time	−0.17	$t(90) = -5.013$
Effort by velocity	−7.23	$t(90) = -4.214$
Easiness by velocity	−7.44	$t(90) = 4.069$
Sinking by velocity	−8.63	$t(90) = -5.748$
Velocity by velocity	5.54	$t(90) = 4.489$
Effort by SPM	−0.11	$t(90) = -4.553$
Easiness by SPM	0.11	$t(90) = 4.150$
Sinking by SPM	−0.12	$t(90) = -5.588$
Velocity by SPM	0.08	$t(90) = 4.561$

All t-tests are significant at $p < 0.001$.

polystyrene, whereas four could not name a material; for gravel, two participants reported pieces of broken glass, one dry leaves, one pieces of metal, and one could not name a material; for wood, two participants were not able to name a material. Therefore, considering both correct and incorrect answers, participants perceived clearly the difference between solid and aggregate surfaces, and this result is in accordance with the findings reported in our previous study using the same footstep sounds engine [Nordahl et al. 2010].

4. DISCUSSION

In this experiment, we provide evidence that walking is influenced by sounds produced while stepping on simulated grounds. Participants walked faster when auditory feedback was not provided than when walking in the presence of footstep simulated sounds. More importantly, there was a scaling effect from higher to lower material compliance such that individuals walked faster when the simulated sound resembled wood than with gravel and snow.

There are at least three possible plausible explanations for these results. The first is that the effects may be due to a conflict between the provided sounds and the sensory feedback received from the soles of the feet on the actual compliance of the walking surface (which was asphalt in all trials): the smaller the conflict, the less pronounced the departure from normal gait parameters. Participants indeed walked slightly slower than in the no-sound condition for the sonic simulation of a wooden floor—which is in terms of material compliance not too dissimilar from asphalt—and much slower for the two other conditions of snow and gravel where the conflict between actual and feedback surface compliance is fairly large.

This interpretation is supported by several factors. First, the excellent somatosensory capacities of the human feet have been demonstrated to be capable of discriminating with high accuracy different types of surfaces [Kobayashi et al. 2008; Giordano et al. 2012]. Second, results of perceptual identification ability of ground materials simulated either with auditory [Nordahl et al. 2010] or with haptic [Serafin et al. 2010] information revealed, in accordance with Giordano et al. [2012], that the material typology (i.e., aggregate or solid) is consistently recognized by using both modalities. Third, and more importantly, each type of auditory feedback turned out to be effective in inducing the illusion of walking on the specific compliance of a ground surface at the behavioral level as well as when individuals were asked to report verbally the sensations obtained. Participants rated the perceived degree of sinking according to the sonically simulated material, despite the fact that the compliance of the ground on which they were walking was asphalt for all tests.

The second explanation is that the effects may be due to a purely audio-haptic temporal conflict—that is, the effects could be related to the differences in the duration of the sound stimuli and of the haptic sensory feedback. One of the salient differences between the footstep sounds on aggregate and solid surfaces is the longer duration of the first compared to the second. Since the time of impact of the foot with the floor can be estimated by both haptic and auditory information, the longer duration of the aggregate sounds could be associated with higher feedback latency. Delayed sensory feedback is known to make performance more variable and slow in several contexts (i.e., virtual reality [Ferrell 1965; Sheridan 1992; Ware and Balakrishnan 1994], speech production [Yates 1963; Perkell et al. 1997], hand clapping [Kalmus et al. 1955], tapping [Lee 1951; Chase et al. 1959], and handwriting [Van Berggeijk and David 1959]). Delay in the present context would translate in more insecure walking, slower pace, and higher sense of effort due to the number of corrective actions required.

A third alternative explanation is that the subjects perceived the surface material on which they were walking to be consistent with the sounds they were hearing and slowed their steps accordingly. In support of this hypothesis is the fact that the subjects reported that they felt their feet sinking into the surface more for the snow and gravel sounds. Nevertheless, the effects shown in Figure 5 for effort, sinking, and velocity VAS measures could be the result of the change in walking pace. In this case, the mediator of perceived effort, sinking and velocity, would be the walking speed per se, not sounds.

Further research is needed to investigate more accurately whether the effects revealed in this study are due to an audio-haptic semantic incongruence, to an audio-haptic temporal conflict, or to an adjustment to the perceived material.

These results indicate that this type of auditory feedback can induce different reports in the sensation of sinking into a ground surface. Such an effect, along with the detected differences in performance, presents analogies with the studies that show the influence of auditory feedback on the perceived stiffness in a hand-based interaction [DiFranco et al. 1997; Avanzini and Crosato 2006].

However, further investigation would be needed to assess if similar effects are present while walking on a real compliant surface. If the audio-haptic semantic incongruence hypothesis holds, then our findings may suggest that while walking on a compliant surface, such as gravel, and listening to a non-compliant surface, such as wood, walking speed would significantly decrease due to the conflict between the auditory and haptic modality. Similarly, in such a scenario, a temporal incongruence between the haptic and the auditory stimuli could induce uncertainty in walking. Conversely, if the hypothesis of an adjustment of the locomotion to the perceived surface material is true, then when subjects perceive a harder surface than the one on which they are walking, they would walk faster.

Moreover, it is worthwhile to notice that participants delivered interesting additional comments at the end of the experimental session. One participant reported that when walking on the simulated wood, he had the impression of sinking less compared to the condition without auditory feedback. Another participant reported that she felt like she was walking with high heels on the simulated wood surface. When footstep sounds on snow were provided, one participant reported having the impression of wearing snow boots, whereas another felt so immersed in the snowy landscape created by the sounds that he felt a strong contraction of the lower leg muscles. Another participant reported balance instability. Moreover, in presence of simulated gravel, one participant indicated the impression of having a sense of effort exerted on the feet.

All of these comments suggest that the involved auditory cues created vivid haptic sensations that have no basis in the physical signals arriving to the feet. This phenomenon presents strong analogies with what has been termed *pseudohaptic feedback*, in which visual cues can create haptic sensations of stiffness in absence of haptic interfaces [Lécuyer 2009]. Moreover, in Rocchesso et al. [2004], it has been shown that pseudo-haptic illusions can also be generated by means of contact sounds.

Results of the analysis of gathered data were consistent with the evaluations expressed in the questionnaire at the end of the experimental sessions. Participants perceived velocity as correlated with the actual velocity, the number of SPM applied, step duration, and the total elapsed time. In the same vein, participants combined their sense of effort, easiness, and sinking with the actual walking velocity with the total time taken to perform the task, with the step duration, and with the number of SPM. However, two participants reported having ignored the interactive auditory feedback, and indeed their performances turned out to be less influenced by the sounds compared to the rest of the group. Therefore, the individual propensity to be involved in the simulation had an influence on the performance [Scott et al. 2007].

The apparatus and the sonic simulations adopted in this study might find application in rehabilitation therapy in place of the standard techniques involving nonecological external auditory pacing and auditory feedback. In this regard, future research could investigate whether clinical patients walking on a real rubber mat would actually speed up their pace when hearing at the same time a simulated wood/marble floor. Interestingly, these findings could be applied to locomotion training scenarios to induce a sense of effort in walkers and runners by using sounds of compliant surfaces.

Finally, the results reported here suggest that the proposed auditory cues can be successfully used to augment and modulate the haptic display of compliance of grounds rendered with different types of locomotion interfaces for haptic feedback in virtual reality contexts [Fontana and Visell 2012]. This is especially the case when the features of the foot-haptic interface limit the range for surface compliance rendering.

5. CONCLUSION

In this article, we investigated the influence of interactive auditory feedback in changing the pattern of walking in an uncontrolled outdoor environment. Results of the experiment confirmed our original hypotheses by showing that different sound-simulated surfaces affect gait kinematics differently. Plausible explanations for this effect lie in the presence of conflicting semantic or temporal information between the auditory and the foot–haptic modality, or in the adaptation of locomotion to the physical properties evoked by the sounds simulating the ground materials. In addition, results would indicate that the proposed auditory feedback can induce the perception of a specific ground surface compliance while walking, showing therefore its effectiveness in modulating the foot-haptic perception of compliance.

The results reported in this study suggest that auditory feedback may be more involved in the regulation of walking in natural environments than has been acknowledged. Furthermore, this could have implications not only for therapy and rehabilitation purposes, such as the control of balance or locomotion in presence of sensory impairments, but also for locomotion training.

APPENDIX: FOOTSTEP SOUND SYNTHESIS ENGINE

The developed footstep engine uses a sound synthesis technique known as physical modeling, where the physics of sound production mechanism is simulated. Specifically, we adopted the impact model described in [Avanzini and Rocchesso 2001] and a physically informed sonic model (PhiSM) [Cook

1997]. These models were used to simulate walking on solid and aggregate surfaces, respectively. The two approaches are briefly recalled next.

The interaction between solid surfaces can be expressed by the force (f) between two bodies [Hunt and Crossley 1975]:

$$f(x, \dot{x}) = -kx^{\alpha} - \lambda x^{\alpha}\dot{x} \quad \text{if } x > 0, \quad 0 \text{ otherwise,}$$

where x represents the contact interpenetration, k accounts for the material stiffness, λ represents the force dissipation due to internal friction during the impact, and α is a coefficient that depends on the local geometry around the contact surface. The model described has been discretized using the numerical method proposed in Avanzini and Rocchesso [2001].

In order to simulate particle interactions typical of aggregate surfaces, we adopted a PhiSM model. In this model, the interaction between a foot and the floor can be represented using a simple Poisson distribution, where the sound probability is constant at each time step, giving rise to an exponential probability weighting time between events.

In the experiment described in this article, the footstep sounds synthesis is driven interactively by the user wearing the shoes. From the real acoustical signal of a footstep sound, the ground reaction force (GRF) is estimated (i.e., the reaction force supplied by the ground at every step). Such GRF is used to drive the described physical models, as explained in detail in Turchet et al. [2010].

A description of the control algorithms based on the analysis of the values of the pressure sensors embedded in the shoes can be found in Turchet et al. [2010]. The sound synthesis engine and the relative control algorithms were implemented using the Max/MSP sound synthesis and multimedia real-time platform.

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