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Interactive footsteps sounds modulate the sense of effort without affecting the kinematics and metabolic parameters during treadmill-walking

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ABSTRACT

Previous research has shown that walkers provided with interactive simulations of footstep sounds on a surface material different from the one they are walking upon, experience pseudo-haptic illusions and adjust their walking kinematic according to the perceived surfaces' compliance. Since walking on real grounds with different degrees of compliance leads to different metabolic costs, an open question is whether pseudo-haptic illusions created by interactive footstep sounds are able to affect the metabolic parameters.

This study investigated whether metabolic cost and movement's kinematics are affected by such interactive auditory feedback in a constrained condition as walking on a treadmill. Participants were walking on a treadmill under three listening conditions: actual footsteps sounds, interactive simulations of footstep sounds on gravel and snow. The metabolic and kinematic data, as well as the perceived exertion, sense of effort, easiness, and feeling of sinking were recorded.

Results showed that interactive footstep sounds provided during treadmill walking did not affect kinematic and metabolic parameters of walking, while they were effective in modulating participants' perception.

These results suggest that in a constrained and non self-selected pattern of locomotion the sound of action, even though correctly perceived, is not strong enough to induce a change in the metabolic and kinematics of the locomotion.

1. Introduction

The sound generated by footsteps represents one of the most salient auditory cues for self-motion perception [33,34,39,41]. In recent years, various systems have been engineered: (i) to detect foot-floor interactions, (ii) to transform them into realistic simulations of footstep sounds, and (iii) to provide those sounds in real-time to the walker [23,33,38,34,26]. Such systems made possible to study the role of interactive sonic simulations of steps on a terrain different from the walked-upon one, in affecting walking kinetics, kinematics, and perception.

As regards clinical contexts, it has been investigated whether interactive footstep sounds on gravel could affect the gait in patients with Parkinson's disease [26]. Results showed that the provided feedback was effective in reducing step length variability when patients walked at a self-selected speed. Camponogara and colleagues provided further evidence on the influence of interactive sound of footsteps on walking kinematics by means of studying the aftereffect after a treadmill walking in cochlear-implanted individuals. They showed that switching off the cochlear system during a walk in place task after a treadmill walking lead to a reduction of the aftereffect, corroborating the effectiveness of sound feedback on the online control of the walking kinematics [2].

In non-clinical contexts, interactive footstep sounds on gravel and deep snow were shown to significantly influence the walking kinematics on an asphalted road compared to when auditory feedback was not provided or when walking on simulated wood [35].

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Specifically, it was found a scaling effect from higher to lower material compliance (i.e., individuals walked faster and with a higher step frequency when the simulated sound resembled wood than gravel and deep snow). This effect was explained by the combination of the presence of conflicting information between auditory and foot-haptic modalities, along with an adjustment of locomotion to the physical properties evoked by the sounds simulating the ground material. Interestingly, results of a perceptive questionnaire and comments reported by participants revealed additional information about how the sounds of deep snow and gravel were experienced: firstly, such auditory cues created pseudo-haptic illusions (i.e., such as the sensation of sinking into the ground); secondly, they were rated as significantly inducing a sensation of effort during walking (e.g., greater for deep snow than for gravel). Pseudo-haptic illusions were also found in presence of synthetic sounds simulating different surface materials provided while jumping on an elastic trampoline [36]. Some types of auditory feedback were shown to be effective in altering the haptic perception due to the foot-membrane contact (i.e., an increase in the sensation of sinking and hardness).

The study reported in [39] investigated the role of interactive footstep sounds on deep snow and concrete in modulating the inadvertent forward drift experienced while attempting to walk in place with closed eyes following a few minutes of treadmill walking. It was shown that: (i) the strength of such an after-effect in forward drift was higher under the influence of deep snow compared to both concrete and actual footstep sound; (ii) a higher knee angle flexion was found during the deep snow sound condition both before and after treadmill walking; (iii) behavioral results confirmed those of a perceptive questionnaire (i.e., the deep snow sound was effective in producing strong pseudo-haptic illusions and inducing a sensation of effort in walking).

Before going on, it is important to notice that the auditory feedback involved in all the studies mentioned above consisted of stimuli valid from an ecological point of view [11,12]. This aspect is relevant since outside the laboratory, the environment presents "multi-sensory stimuli" that share spatial and temporal concordances and variations, which might contribute to their binding into specific and unitary events.

Taken together, all these results suggest that interactive footstep sounds are effective in inducing the so-called sense of "presence" [2,26,35,37,39]. In virtual reality contexts, it is usually referred to as *"the sensation of being in the virtual world"* [15]. According to Slater and colleagues, presence corresponds *to "the propensity of people to respond to virtually generated sensory data as if they were real"* [31]. They suggested that a user, experiencing an intense sense of presence in a virtual environment, would exhibit a behavioral response comparable to that produced while experiencing the corresponding real world environment. Interestingly, when humans voluntarily change their joint kinematics during walking, the metabolic cost is affected accordingly. It has been shown that the increase of the knee flexion angle leads to a decrease of the displacement of the vertical center of mass and to an enhanced oxygen consumption compared to when a natural walk is performed [14,21]. Hence, it is plausible to hypothesize that a change of walking kinematics driven by the pseudo-haptic illusions created by interactive footstep sounds could induce a modulation of metabolic parameters.

Many studies have been conducted to investigate how physiological variables change on different types of terrain in human locomotion (e.g., [6,9,13,17,22,24,32,42,43]. These studies indicate that the energy cost of walking (i.e., the energy spent to cover a unit distance) increases on natural (e.g., grass, sand and snow) and uneven surfaces compared to rigid and even surfaces. In some of these works (e.g., [17,42] the recorded kinematics and electromyography (EMG) data suggest that the increase in energy cost is associated to, can be explained by, change in mechanical work of the lower limbs and by changes in muscle activation (and in the level of co-contractions).

Following this strand of research, a relevant question is whether metabolic changes can occur while hearing interactive synthetic sounds simulating steps on different surface materials. More importantly, an open question concerns the extent to which interactive footstep sounds are able to affect walkers' physiology, kinematics, and perception.

In order to investigate these aspects regarding the effect of such auditory feedback, we designed an experiment where physiological and kinematic variables were bounded to small variations due to a drastically constrained condition: walking on a treadmill at a speed of 4 km h^{-1} (i.e., the speed generally "*self-selected*" when walking without constrains on a flat terrain). Indeed, based on the literature stride amplitude and frequency are rather constant during treadmill walking in self-selected speed (e.g., [5], as well as the energy cost (e.g., [25,45]. Therefore, if physiological and kinematic variations would occur in such a constrained situation, then this would mean that interactive footstep sounds have a strong power in altering walkers' metabolic and kinematic parameters. In addition, it would be a measure of the intensity of the sense of presence [31] induced by the involved virtual auditory stimuli.

In more detail, footstep sounds were provided interactively to the walkers by means of a system consisting of shoes augmented with pressure sensors that drove a footstep sound synthesis engine [40]. Energy cost was measured, at a constant speed (close to the self-selected speed of walking), along with steps kinematics and rates of perceived exertion (RPE), a parameter related to the metabolic demands of exercise [8,19,28,29,30]. At the end of the experiment, participants were asked to fill in an ad hoc questionnaire (by means of a visual analogue scale [VAS] score) to assess post-perceptual appreciations of the simulated surfaces and to correlate these with walking performance.

Our hypothesis was that the sense of presence induced by the injected sounds would have been perceived as vivid and would have been effective in altering both the kinematics of the action (e.g., step length and frequency) and the metabolic parameters.

2. Methods

2.1. Participants

Twenty participants, eight males and twelve females took part to the experiment (age: 23.1 ± 3.4 years; body mass: 61.9 ± 10.2 kg; height: 1.71 ± 0.1 m). All participants reported normal hearing and no muscular-skeletal impairments.

The procedure, approved by the local ethics committee, was in accordance with the ethical standards of the Declaration of Helsinki. All subjects gave their written informed consent.

2.2. Stimuli

Three types of stimuli were utilized in the experiment: two consisted of interactively generated footstep sounds simulating aggregate surface materials (gravel and deep snow), while the third type, considered as a control, consisted of no additional auditory feedback, such that participants could hear the natural sound of their footsteps. The gravel and deep snow sounds were simulated in real-time by means of the footstep sounds synthesis engine reported in [40], which is based on physical, physically inspired, and perceptually inspired models.

The selection of these two surface materials was inspired by our previous work, which showed that they are effective in modulating the walking kinematics [35], and they are among those most easily recognizable [39,40]. More importantly, gravel and deep snow present two different levels of material compliance: the compliance of gravel differs from the one of the treadmill's platform actually walked upon by participants, and even more for deep snow. These two materials were also chosen because the signals corresponding to their simulation had different features in terms of duration, amplitude, temporal evolution, and spectrum (Fig. 1). The amplitudes of the sounds were set at 57.8 and 55.4 dB (A) for gravel and deep snow respectively [35,37]. These sound amplitudes were effective in completely masking the actual footstep sounds produced by participants. The choice of the two sonically simulated surface materials was also due to our aim to check the presence of expected pseudo-haptic illusions capable of altering the foot-haptic perception of hardness of the treadmill's platform.

The experiment was conducted in a laboratory (background noise 46.7 dB (A), Leq, 1-h). The headphones' noise canceling system further stopped participants hearing any background noise from the room and drastically reduced that created by the treadmill during its use.

2.3. Apparatus

The interactive footstep sounds apparatus consisted of a laptop running the sound synthesis engine described in Turchet [39], which was connected to a pair of sandals augmented with pressure sensors, and to a wired closed headphone set with a noise cancelling system (Sennheiser, PXC 450). The sandals' shape was adjustable so that it fitted the range of participants' feet size. A pressure sensor was placed under the sole of each sandal at the level of the heel. The sensors detected feet pressure during contact with the ground; their analogue signals were digitized by an 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 the headphones. The total latency between the actual footstep fall and the heard synthesized sound was not noticeable (less than 5 ms).

The equipment was light (90 g), comfortable and did not constitute any major constraint to participants' movements: the small box containing the Arduino UNO board was hung on the back of the user's trousers by means of a belt; the wires coming out from the shoes were attached to the user's trousers by means of a tape and secured to the external side of the lower limbs; the cable connecting the Arduino UNO board to the laptop was tied together with the wire of the headphones.

Before data collection, participants got used to wearing the shoes and experienced the sounds, familiarizing with the system for about 5 min. They were not provided with information about the type of material that was simulated by the synthesis model.

2.4. Experimental procedure

The experiments were performed twice for each sound condition (no additional sound, gravel and snow sounds) in a randomized order.

2.4.1. Metabolic data

Participants were requested to walk, at a constant speed of 1.11 m s^{-1} (4 km h^{-1}) on a treadmill (HP/Cosmos/Saturn 300/100r) for six minutes in each condition; this speed was close to the natural customary walking speed (i.e., self-selected speed) of healthy adults (e.g., [45]. Before performing the walking trials, participants were asked to sit on a chair positioned onto the treadmill for at least five minutes. This allowed for the recording of metabolic data at rest.

Expired ventilation (V′E), oxygen consumption ($V'O_2$), heart rate (HR), and respiratory exchange ratio (RER) were collected on a breath-by-breath basis by means of a metabograph (Quark, Cosmed). Data were gathered both before (at rest) and during exercise. Average values of metabolic variables were calculated in correspondence of the last minute of exercise, in each experimental condition.

Net oxygen uptake ($V'O_{2net}$, l min^{-1}) was calculated by subtracting to the exercise $V'O_2$ the values measured at rest. To calculate the energy cost of walking, $V'O_{2net}$ was expressed in W (by taking into account the respiratory exchange ratio, as suggested by [10] and then divided by the walking speed (expressed in m s^{-1}) and

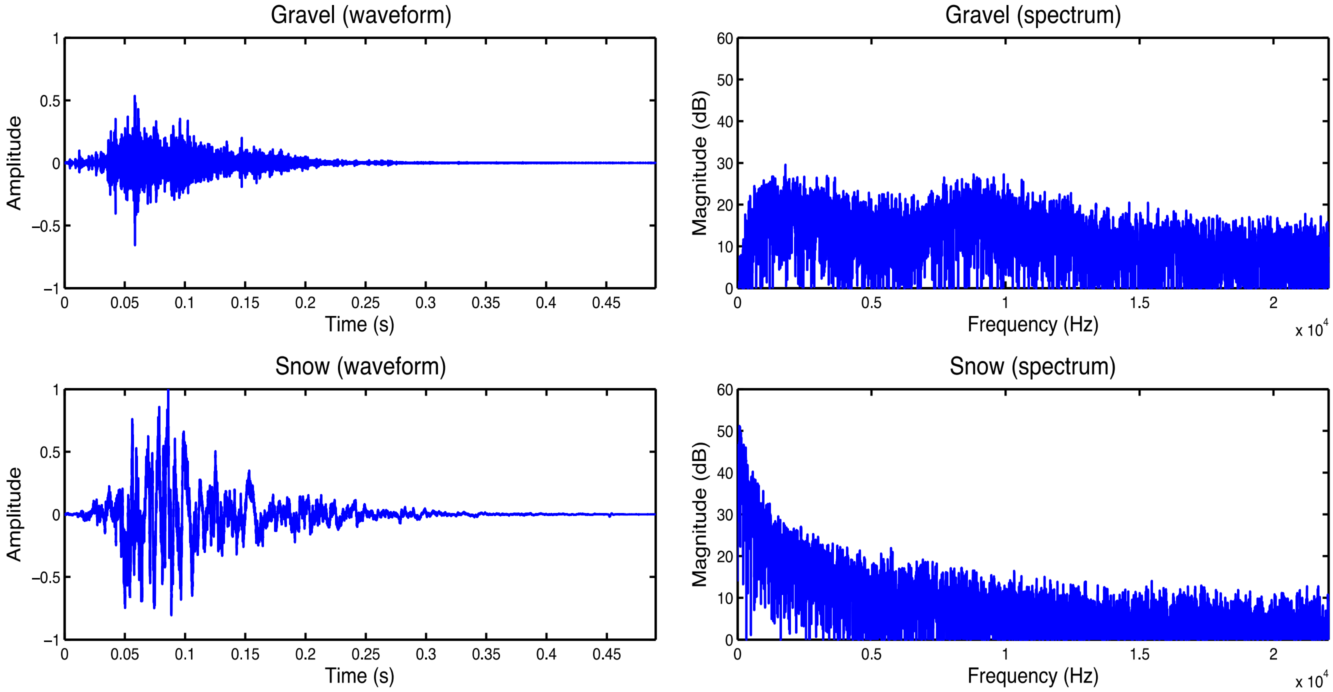

Fig. 1. Typical waveforms (left) and spectra (right) of the two simulated materials: gravel and deep snow.

by the subject's body mass; C was thus expressed in $J\ m^{-1}\ kg^{-1}$ and represented the energy needed to move 1 kg of body mass for 1 m distance.

Immediately after the end of each trial/condition, participants were asked to rate their perceived effort on a Borg's 6-20 scale [1].

2.4.2. Kinematic data

During the walking trials 3D body motion was recorded by a 8 MX13 cameras system (Vicon MX, Oxford Metrics, UK), at a sampling rate of 100 Hz. The spatial coordinates of 10 reflective markers located bilaterally on the following joint centers were recorded: greater trochanter, lateral femoral condyle, lateral malleolus, calcaneus, 5th metatarsal head.

Motion capture signals were examined by means of a customized Matlab R_2012a program. The following variables were calculated for each trial/condition: stride length (SL), stride duration (StD), Stance Duration (SD) and knee range of motion angle (knee ROM). From the 3D coordinates of calcaneus and 5th metatarsal head we calculated: (1) SL taken as the distance covered by the left foot on the traversal plane, (2) CT as the duration of the left foot stance phase, and (3) SD as the duration of the left foot swing phase.

From the greater trochanter, lateral femoral condyle and lateral malleolus 3D coordinates we calculated the thigh and tibia Euclidean vectors. Their magnitudes and the dot product were used to compute the knee flexion angle. Each footstep was then detected by separating consecutive toe off, defined as the time in which the point between the calcaneus and 5th metatarsal head started to rise [20]. For each footstep, the knee ROM was calculated by means of subtracting the knee flexion angle from the maximum extension angle reached during the step. Its value was then averaged for the total number of angles calculated during the trial (which corresponded to the total number of footsteps) for each subject.

Kinematic data were sampled in three selected instances along the entire trial: at the beginning (from 15 to 45 s after t_0; i.e., the starting time), in the middle (from 150 to 180 s after t_0) and at the end (from 285 to 315 s after t_0) of each walking trial.

2.5. Questionnaire

Immediately after the end of experimental data collection the subjects were asked to fill in a questionnaire inspired by those already utilized in Turchet et al. [35,36,39]. For each sound condition the subjects had to answer to the following questions by means of a Visual Analogue Scale (VAS):

- [Effort] Evaluate the sense of effort you experienced while walking [0 = no effort, 10 = high effort];
- [Easiness] Evaluate the degree of easiness with which you walked while listening to the sounds [0 = very hard, 10 = very easy];
- [Sinking] Evaluate the extent to which you had the impression that your feet were sinking into the ground [0 = not at all, 10 = very much];
- [Hardness] Evaluate the impression of hardness of the floor you walked on [0 = not hard at all, 10 = very hard];
- [Influence on walking] Evaluate the extent to which the sound influenced your way of walking [0 = not at all, 10 = very much];
- [Influence on breathing] Evaluate the extent to which the sound influenced your way of breathing [0 = not at all, 10 = very much].

The order of presentation of the questions was randomized using a 6×6 Latin square. At the end of the questionnaire participants were asked to identify the two simulated surface materials, with no possibility to select from a list and each individual was invited just to guess the material perceived.

2.6. Statistics

Before running all the ANOVAs, we checked for normality of data distribution by means of a Shapiro-Wilk test; a Mauchly's test was applied for verifying if the assumption of sphericity had been met for the investigated factors. Repeated measures ANOVAs were performed by considering the three sounds (no sound, gravel, snow) as within factor for each of the dependent variables separately: metabolic data, kinematic data, Borg rates and questionnaire related parameters. All post hoc were performed using a Bonferroni post hoc test (critical p-value < 0.05).

3. Results

For metabolic (ventilation, oxygen uptake, heart rate, respiratory exchange ratio and energy cost of walking) and kinematic variables (SL, StD, SD and knee ROM) none significant main effect was observed. Metabolic and kinematic data are reported in Tables 1 and 2 respectively.

Data collected by means of the questionnaire (VAS scores) and the rates of perceived effort (Borg scale) are reported in Fig. 2. Significant main effects were observed for all variables: Borg rates, $F_{(2,38)} = 8.499$, $p < 0.001$; Effort, $F_{(2,38)} = 6.659$, $p < 0.01$; Easiness, $F_{(2,38)} = 2.866$, $p < 0.05$; Sinking, $F_{(2,38)} = 16.01$, $p < 0.001$; Hardness, $F_{(2,38)} = 3.114$, $p < 0.05$; Influence on walking, $F_{(2,38)} = 8.956$, $p < 0.001$; Influence on breathing, $F_{(2,38)} = 6.82$, $p < 0.01$. The post hoc analyses revealed significant differences for the combination no sound-snow in all cases ($p < 0.01$), for the combination no sound-gravel in all cases ($p < 0.01$) but for Hardness; for the combination gravel-snow only for Sinking ($p < 0.001$). Notice the constant significant difference across variables comparing the no-sound condition and the snow condition. The sound of snow was indeed the one presenting the strongest differentiation with the condition where none additional sound was present.

A linear model analysis was performed to search for correlations between each individual kinematic and metabolic measure and each VAS evaluation expressed for each question in the questionnaire. No significant correlation was found.

Not all participants identified correctly the simulated material: while fourteen participants recognized the snow material, one interpreted the snow as sand, one as gravel, one as high grass, one as dry leaves, whereas two could not identify the material. Seventeen participants identified correctly the gravel material; one participant interpreted gravel as forest underbrush, one as dry leaves, whereas one could not identify the material. This result on the identification performance is in accordance with the findings reported in our previous identification study using the same footstep sounds engine [39].

Table 1
Metabolic data for each sound condition. Values are expressed as mean ± SD.

	No sound	Gravel	Snow
$V'E\ (l\ min^{-1})$	23.61 ± 4.46	24.42 ± 4.40	23.84 ± 4.58
$V'O_{2net}\ (ml\ min^{-1}\ kg^{-1})$	8.83 ± 1.70	9.18 ± 1.90	8.89 ± 1.80
HR (bpm)	99.70 ± 12.12	100.85 ± 13.64	99.08 ± 11.77
RER	0.82 ± 0.06	0.82 ± 0.05	0.82 ± 0.05
$C\ (J\ kg^{-1}\ m^{-1})$	2.41 ± 0.42	2.49 ± 0.47	2.40 ± 0.43

Legend: $V'E$: ventilation; $V'O_2$: oxygen uptake; HR: heart rate; RER: respiratory exchange ratio; C: energy cost of walking.

Table 2
Kinematic data for each sound condition. Values are expressed as mean ± SD.

	No sound	Gravel	Snow
Stride length (m)	0.72 ± 0.014	0.72 ± 0.015	0.71 ± 0.017
Stride duration (s)	1.13 ± 0.01	1.14 ± 0.01	1.14 ± 0.01
Stance duration (s)	0.73 ± 0.01	0.73 ± 0.01	0.73 ± 0.01
Knee ROM (°)	62.98 ± 0.92	63.88 ± 1.09	63.76 ± 1.18

4. Discussion

In this experiment we investigated whether interactive footstep sounds could influence metabolic, kinematic and perceptual data while walking on a treadmill at constant speed. Overall, we found an effect of the provided auditory feedback on the perceptual variables, but not in kinematic and metabolic ones. Contrarily to previous studies, where walking kinematics modulated along with perception [35], we found no change of the kinematic variables between snow, gravel and no sound conditions. As already mentioned in the introduction, this could have been due to the biomechanical constraints that the treadmill imposed to the participants' walk. Differently from the study of Turchet et al. [35], we injected the sounds of snow or gravel while participants were walking on a treadmill, and not over-ground. This condition imposed a substantial difference in walking biomechanics compared to over-ground walking. As a matter of fact, it has been shown that treadmill

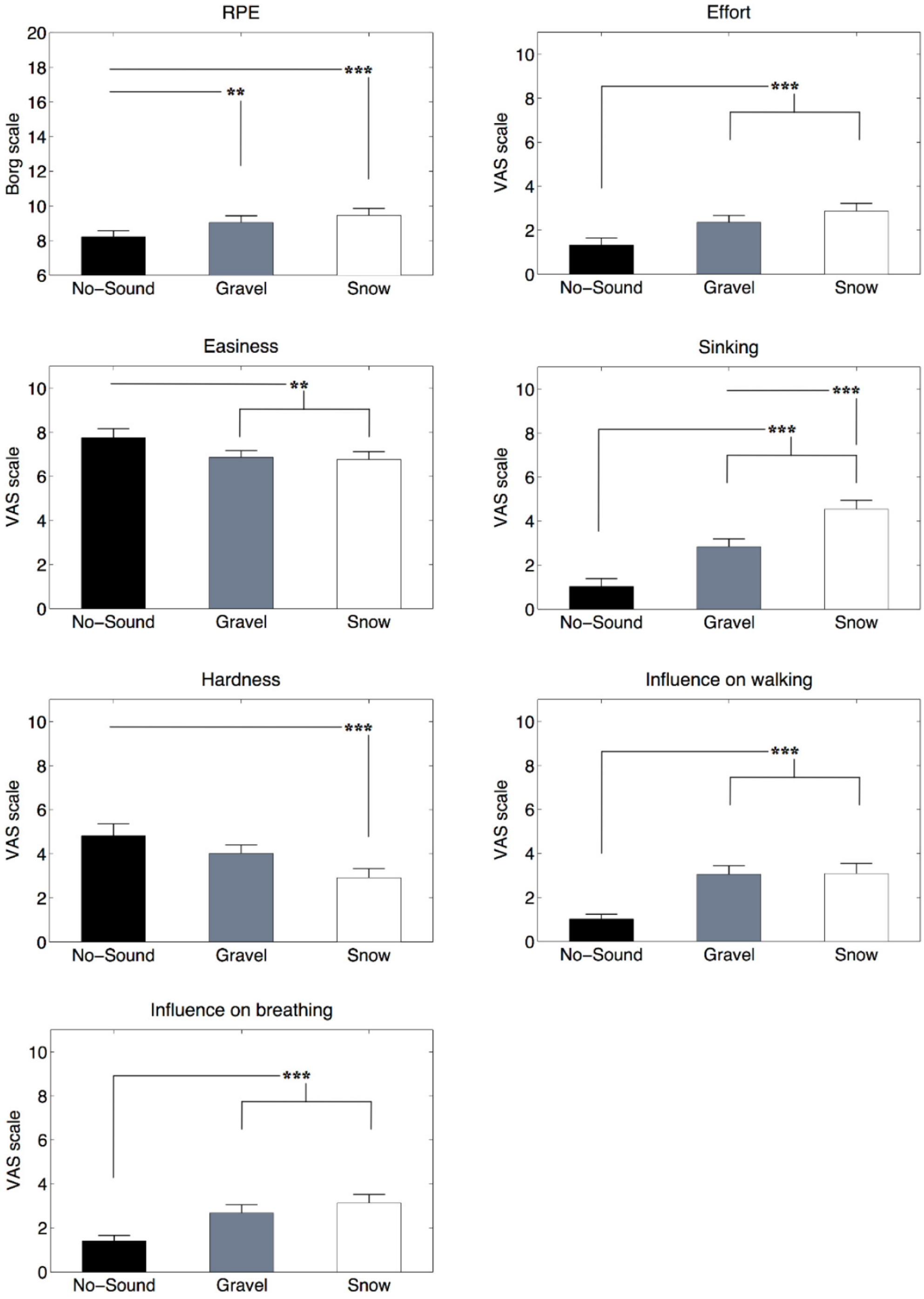

Fig. 2. Graphical representation of the mean and the standard error for participants' ratings on the Borg scale and answers to questionnaire for the three sound conditions. Legend: ** represents $p < 0.01$, and *** $p < 0.001$.

walking leads to a significantly lower stance period, contact time and knee range of motion compared to over-ground walking [16,44]. Our StD, SD and kneeROM values were in line with the ones of the studies reported in [44] and [16], which showed that walking on a treadmill at ~4 km h^{-1} led approximately to a 0.7 s of StD [44] and 67° of kneeROM [16] (see Table 2).

On the other hand Turchet and colleagues found that listening to the sound of compliant surface materials while walking at a self-selected speed on a solid terrain leads to a modulation of kinematic parameters (such as walking speed and traveled distance) [35]. They found that the speed of a walk on a solid ground without any additional sound feedback was ~4.60 km h^{-1}, which was in line with a self selected speed of a 19–29 years old man [4], while interactively injecting the sound of the snow reduced the walking speed up to ~3.9 km h^{-1}. Those differences had been confirmed also by the step time, which was ~550 ms when natural footsteps sound was heard and ~650 ms when the interactive snow sound was delivered. Hence, it could be that in our experiment the treadmill-walking constrained participants' kinematics and covered the "real" kinematic that they had if they were freely walking over-ground.

The values of energy cost of walking presented in this study are in the range of those reported for healthy adults at the self-selected speed (e.g., about 2 J m^{-1} kg^{-1}, see [27]. No significant differences in energy cost, as well as in the other physiological parameters, were observed among conditions. This finding could be attributed to the fact that the energy cost of walking is a rather stable parameter in healthy subjects and in standardized conditions (e.g., treadmill-walking at a given, submaximal speed). Indeed, walking is a well-practiced motor task and thus the energy cost of walking, at a given speed, is rather independent of age (in adulthood), sex, and training status (e.g., [25]. Data reported in the literature indicate a significant influence of the type of terrain on the energy cost of walking (see Section 1); however, no differences in energy cost were observed in this study when the walking surface is "sound-simulated". Thus, this seems to be not a sufficient stimulus to influence the energy demands of walking (at a given, constrained, speed).

The major finding of this study is that although no differences in the metabolic and kinematic data were observed among conditions, significant changes did occur in the rates of perceived exertion and in all perceptual parameters when changing the "sound-simulated" conditions.

This is an intriguing result, as far as the RPE values are regarded, since the changes observed in this study are not coherent with the invariance in the metabolic parameters. Indeed, RPE scores have been reported to be linearly related with metabolic data: the larger the exercise intensity the higher the RPE score (e.g., [28]. This strong correlation is indeed "utilized" to control for exercise intensity (*a posteriori*) based on RPE values in many sport activities. Nevertheless, a meta-analysis has questioned the validity of RPE scores as a measure of exercise intensity [3]; these authors have pointed out that the relationship between RPE scores and metabolic values is strong at near maximal effort but rather weak at low exercise intensities. As pointed out by Morgan [18], the unexplained variance between perception of exertion and metabolic variables may be caused by "psychological factors". Indeed the changes in RPE among conditions follow the same trend of the perceptual parameters such as sense of effort, influence of breathing and of walking (see Fig. 2). Thus, data reported in this study confirm that, at low exercise intensities (such as is the case of walking on the level at the self selected speed for healthy adults) a mismatch between RPE and metabolic data does indeed occur.

The results of the perceptual questionnaire are in line with those reported in previous studies [35,36,39]. Both sounds were judged as being effective in altering the perception of effort and sinking with one's feet into the ground, as well as in influencing the way of walking and breathing compared to the no-additional sound condition. In particular, the sound resembling a footstep on snow induced the highest impression of sinking and was effective in altering the tactile perception of hardness of the treadmill's platform. This indicates the presence of strong pseudo-haptic illusions since such an auditory cue created haptic sensations that have no basis in the mechanical signals perceived by the feet.

Taken together, these results show that even in a highly constrained condition such as walking at a pre-defined treadmill velocity, interactive footstep sounds are effective in changing walkers' perception but not in changing the action kinematics and metabolic parameters. As a consequence, it seems that the sense of presence induced by interactive footstep sounds is higher during unconstrained walking rather than during a constrained treadmill-walking [35]. Treadmill-walking imposes to the walker a predefined velocity that might drive the central pattern generator for a stable step length and frequency and, as a consequence, a stable energy consumption [7].

5. Conclusion

In this paper we showed that even when the speed of locomotion is pre-imposed, different sonically simulated surfaces affect walking perceptions. Interestingly kinematic and metabolic parameters did not change across the different sound conditions showing the prevalence of the mechanical (and physiological) constraints over the perceptual ones.

Acknowledgments

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