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

Luca Turchet [a,b,*], Ivan Camponogara [d], Francesca Nardello [c], Paola Zamparo [c], Paola Cesari [c]

[a] Department of Architecture, Design and Media Technology, Aalborg University Copenhagen, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark
[b] Center for Digital Music, Queen Mary University of London, Mile End Road, London E1 4NS, UK
[c] Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Via Casorati 43, 37100 Verona, Italy
[d] Department of Psychology, New York University Abu Dhabi, Saadyiat Island, PO Box 129188, Abu Dhabi, United Arab Emirates

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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].

* Corresponding author at: Center for Digital Music, Queen Mary University of London, Mile End Road, London E1 4NS, UK.

E-mail addresses: luca.turchet@qmul.ac.uk (L. Turchet), ivan.camponogara@nyu.edu (I. Camponogara), narfra@yahoo.it (F. Nardello), paola.zamparo@univr.it (P. Zamparo), paola.cesari@univr.it (P. Cesari).

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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