Applied Acoustics 111 (2016) 77–85

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

# What do your footsteps sound like? An investigation on interactive footstep sounds adjustment

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ARTICLE INFO

*Article history:*
Received 3 March 2016
Received in revised form 4 April 2016
Accepted 6 April 2016
Available online 13 April 2016

*Keywords:*
Walking
Interactive auditory feedback
Self-perception

ABSTRACT

This paper presents an experiment where participants were asked to adjust, while walking, the spectral content and the amplitude of synthetic footstep sounds in order to match the sounds of their own footsteps. The sounds were interactively generated by means of a shoe-based system capable of tracking footfalls and delivering real-time auditory feedback via headphones. Results allowed identification of the mean value and the range of variation of spectral centroid and peak level of footstep sounds simulating various combinations of shoe type and ground material. Results showed that the effect of ground material on centroid and peak level depended on the type of shoe. Similarly, the effect of shoe type on the two variables depended on the type of ground material. In particular, participants produced greater amplitudes for hard sole shoes than for soft sole shoes in presence of solid surfaces, while similar amplitudes for both types of shoes were found for aggregate, hybrids, and liquids. No significant correlations were found between each of the two acoustic features and participants' body size. This result might be explained by the fact that while adjusting the sounds participants did not primarily focus on the acoustic rendering of their body. In addition, no significant differences were found between the values of the two acoustic features selected by the experimenters and those adjusted by participants. This result can therefore be considered as a measure of the goodness of the design choices to synthesize the involved footstep sounds for a generic walker. More importantly, this study showed that the relationships between the ground-shoes combinations are not changed when participants are actively walking. This represents the first active listening confirmation of this result, which had previously only been shown in passive listening studies. The results of this research can be used to design ecologically-valid auditory rendering of foot-floor interactions in virtual environments.



## 1. Introduction

Designers of ecologically-valid virtual environments constantly seek to improve their technology in order to create experiences in the virtual world that can be as close as possible to those achievable in a real setting [1]. For a virtual environment to be meaningful in the ecological sense, users must be provided with coherent relations between perception and action. This is especially true for one of the most important tasks in immersive virtual reality, navigation involving real walking [2]. Previous studies demonstrated that real walking is the optimal interaction technique for navigation of immersive virtual environments since it produces a higher sense of immersion, increases naturalness, and improves task performance compared to other solutions [3–7].

One of the most important acoustic signatures associated to walking in virtual environments is that of footstep sounds. Similar to what happens in real settings, these sounds allow one to perceive not only the surrounding environment but also one's own body. In particular, various authors have highlighted the importance of rendering of the virtual body in a way consistent with the user's body in order to produce a strong feeling of body ownership [8,9,1]. Such a feeling plays a relevant role in the user's experience of the sense of presence, that is, the subjective experience of "being there" inside the virtual world [10]. This is particularly true for locomotion-based applications [1].

To achieve compelling simulations of footstep sounds it is fundamental to consider how those sounds are perceived. This can

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http://dx.doi.org/10.1016/j.apacoust.2016.04.007
0003-682X/

inform synthesis techniques based on the analysis-by-synthesis method [11,12]. Such a method consists of designing a model by gathering knowledge about it from data collected via measurements, interviews with experts, or generation of hypotheses, and by successively verifying its validity through synthesis (i.e., by implementing the model in a software tool) and psychophysical tests.

Recently, a novel footstep sound synthesizer based on such a method has been developed [13]. The synthesizer is capable of simulating several types of foot-floor interactions (e.g., different types of steps in walking and running or the sliding of the foot on the floor), different types of shoes and ground materials (solid, aggregate, liquid, and hybrids), as well as some anthropometric features of the walkers (i.e., body size and foot length). The ecological validity of the synthesizer was evaluated by means of listening tests that successfully assessed the effectiveness of the proposed techniques. The synthesizer is based on physical, physically informed, and psychologically informed models, whose control has been designed according to results of various studies about footstep sounds perception in real and virtual settings. The synthesizer can be used in conjunction with several locomotion interfaces (for instance, those developed by Turchet [14]), in order to achieve an interactive sonification of foot-floor interactions [15].

Research about auditory perception of both real and synthesized walked-upon ground materials has shown that humans are capable of classifying with high accuracy the material typology, such as solid (e.g., concrete, wood), aggregate (e.g., gravel, snow), liquid (e.g., water) or hybrid (e.g., mud), but are less precise in discriminating materials belonging to the same typology (e.g., wood can be identified as concrete) [16,17,13]. Along the same lines, it has been proven that the hardness of the sole of the shoes is clearly identifiable both in real footstep sounds produced by walking on solid ground materials [18], and in synthesized footstep sounds simulating walking on materials of various typologies [13]. Various studies have also shown that both real and synthesized footstep sounds are effective in conveying information about gender and anthropometric features of the walker [19,18,20,13]. All those studies consistently revealed that the auditory perception of gender, height, and weight of a walker depends primarily on the footstep sound spectral characteristics. Specifically, footstep sounds having spectra with a predominant high frequency component are associated with females and small body sizes, while maleness and big body sizes are related to spectral dominancy of the low frequencies. Furthermore, research has shown that listeners can identify the emotional state of a walker from the content of both real and synthesized footstep sounds and that such an identification depends on the sound intensity and temporal features (average pace, pace irregularity) [18,21].

Interestingly, Tajadura-Jiménez et al. showed that altering in real-time the spectral content of non-synthesized sounds produced while walking is effective in changing one's own perceived body weight and leads to a related gait pattern [22]. Specifically, their results showed that augmenting the amount of high frequency components of footstep sound not only led to the perception of having a thinner body, but also enhanced the motivation for physical activity, inducing a more dynamic swing and a shorter heel strike. In addition, the increment of high frequency components caused participants to feel more aroused and positive. In a different vein, providing synthetic footstep sounds simulating a surface material having a degree of compliance different from that of the walked-upon one has been proven to affect the locomotion pace of subjects naturally walking at a self-selected speed, as well as to alter the perception of effort and to induce the sensation of sinking into the ground [23].

Following the tenets of the analysis-by-synthesis method, a relevant research question that can inform the synthesis models in order to achieve better simulations and consistent with users' expectations is how sounds are manipulated when subjects are asked to render their own footstep sounds. This is especially important in interactive scenarios where real walking is involved. While prior studies in virtual settings explored the effects of passive listening to synthesized footstep sounds of an unknown walker, limited research has been conducted so far on the interactive adjustment of the parameters of self-produced synthesized footstep sounds. An exception is the work reported in [24] that faced the issue arising when designing interactive sound rendering for virtual environments, about how to choose the amplitude at which the footstep sounds are delivered. Subjects were asked to adjust the amplitude of interactive footstep sounds on various ground materials, generated by means of a shoe-based system, to the extent they felt appropriate for each of those sounds. Results allowed one to identify for each synthesized material the amplitude mean value and range of variation that could be considered appropriate for different subjects. However, that study did not take into account the spectral properties of the sounds during the adjustment task, nor did the analysis consider eventual correlations between the participants' choices of amplitude and their anthropometric features. From the studies reviewed above it emerges that amplitude and spectral centroid are two parameters of footstep sounds that can be related to the auditory perception of body properties and emotional state, as well as to the rendering of various types of materials and shoes.

In this paper we present an experiment where we asked participants to adjust the spectral content and the amplitude of synthetic footstep sounds in order to match the sounds of their own footsteps. The sounds were provided interactively by means of a shoe-based system capable of tracking footfalls and delivering real-time auditory feedback. Our main goals were: interactively validate the design choices of centroid and peak level for different combinations of ground material and shoe type; assess whether and how these parameters change in relation to actual and perceived body properties; identify the mean values and ranges of variation of the two parameters. This research aimed also at assessing to what extent participants consciously focused on their body properties during their choices of the sounds' parameters. For this purpose we provided participants with rating scales to compare the criteria on which participants relied to perform their choices.

Based on the results about the auditory perception of sole hardness in footstep sounds reported by Giordano et al. [18] and Turchet [13], we hypothesized that participants would have produced greater amplitudes for hard sole shoes than for soft sole shoes in presence of solid surfaces, while similar amplitudes for both types of shoes would have been found for aggregate, hybrids, and liquids. In addition, given that previous works showed how shifting the spectral content of walking sounds influences not only the perceived body size of a heard walker [19,18,20,13], but also the self body size perception [22], we expected a negative correlation between participants' size and spectral centroid. Along the same lines, we hypothesized a positive correlation between participants' size and participants' choices of the sounds' amplitude since the heavier and taller the person, the greater the ground reaction force, i.e., the reaction force produced by the ground at every step [25], and consequently the louder the sound.

With this production-based experimental design we aimed at assessing the goodness of the sound design choices for a generic walker reported in [13]. The footstep sounds involved in the experiment were designed to simulate a genderless walker with a medium body size. The absence of the hypothesized strong correlations between participants' body size and centroid and peak level, as well as the absence of a statistical difference between the participants' and experimenters' choices of the two parameters would