# PHYSICALLY BASED SOUND SYNTHESIS AND CONTROL OF JUMPING SOUNDS ON AN ELASTIC TRAMPOLINE

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**ABSTRACT**

This paper describes a system to interactively sonify the foot-floor contacts resulting from jumping on an elastic trampoline. The sonification was achieved by means of a synthesis engine based on physical models reproducing the sounds of jumping on several surface materials. The engine was controlled in real-time by processing the signal captured by a contact microphone which was attached to the membrane of the trampoline in order to detect each jump. A user study was conducted to evaluate the quality of the interactive sonification. Results proved the success of the proposed algorithms and their control. In addition, results provided indications that the proposed auditory feedback can modulate the perception of the foot-haptic sensations of the surface utilized when jumping. The system can find application in augmented reality contexts for sport and entertainment, and is suitable for studies on multi-sensory perception involving the auditory and the foot-haptic modalities.

## 1. INTRODUCTION

The engineering of locomotion interfaces has received in last decades an increasing attention not only of researchers (for reviews see [1], [2], and [3]), but also of industry (e.g., Nintendo Wii Fit, Nike Plus). Such interfaces (e.g., special treadmill, shoes enhanced with sensors) find application in several contexts, including virtual reality, entertainment, training, gait analysis and rehabilitation [4, 5, 6, 7, 8, 9, 10]. Particular interest has recently been devoted to those solutions capable of providing both unimodal and multimodal feedback during the user's locomotion [3].

Typically the foot-floor interactions mostly investigated for the development of the interfaces mentioned above are walking and running, while scarce attention has been devoted to solutions designed for the act of jumping. In this paper we present a novel interface which interactively sonifies a user's feet movements into synthetic jumping sounds on different surface materials. The developed architecture is a wireless, non intrusive, shoe-independent system which allows the user to jump unconstrained. Our goal is to provide the user with stimuli valid from the ecological point of view [11, 12, 13].

Most of the research efforts on the synthesis of footstep sounds have been focused on algorithmic solutions not suitable for a direct parametric control during the act of walking [14, 15, 16, 17]. In recent years, however, the interest for the interactive sonification [18] of foot-floor interactions has grown [3, 8, 19]. This has been facilitated by the recent advances in sensors technology and user interface design, along with the increased computational power of computers, which have allowed interaction designers to carry out custom made devices for locomotion interactions feasible at affordable cost and in reasonable time.

In [8] a sound synthesis engine able to interactively simulate footstep sounds on various types of surface materials was proposed. Such an engine was based on physical and physically inspired models which were driven by a unique signal interactively generated by different locomotion interfaces capable to detect the walker's feet movements [8, 20, 21]. The strength of the engine relied on the fact that the control of the sound models was independent from the locomotion interface generating the signal and from the system utilized for the auditory display. The ecological validity of the generated synthetic auditory stimuli was assessed in [22]. Results of an interactive listening experiment showed that most of the synthesized surfaces were recognized with high accuracy. Similar accuracy was noticed in the recognition of real recorded footstep sounds, which was an indication of the success of the proposed algorithms and their control.

Recently that work has been extended, allowing the simulation of a greater number of foot-floor interactions including jumping sounds. In addition, a larger palette of surface materials was implemented along with the simulation of various types of shoes and the modeling of some anthropomorphic features such as gender and weight of the walker [23].

In the next sections we present the design, implementation and evaluation of a system capable of interactively sonifying jumps on an elastic trampoline into sounds corresponding to jumps on different surface materials. The evaluation was inspired by the study reported in [22] as well as by a recent research presented in [24].

The latter study involved a system composed by the synthesis engine described in [8], and shoes enhanced with pressure sensors. It was used in an uncontrolled outdoor environment paved with asphalt to investigate the role of interactive auditory feedback in modulating the pattern of locomotion. Results showed that locomotion was significantly affected when walkers were interactively provided with sounds simulating steps on a terrain different from that they were trampling on. In particular, 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. The rationale for these results was attributed to three possible plausible explanations: an audio-foot haptic semantic incongruence, an audio-foot haptic temporal conflict, or an adjustment to the perceived sonically simulated surface material. In addition, participants reported for each simulated material different ratings of both the impression that their feet were sinking into the ground and the effort perceived when walking. This effect is a form of "pseudo-haptic illusion", i.e., a haptic sensation generated by non-haptic stimulation [25]. Such results motivated us to extend that research to the case of jumping on a compliant surface like that of a trampoline.

## 2. APPARATUS

The developed apparatus consisted of an elastic trampoline (Energetics 40 Inch Mini Exercise Trampoline), a contact microphone (Schaller Oyster External Pickup 723), two loudspeakers (Genelec 1031A) placed on opposite sides of the trampoline, and a laptop running the synthesis engine. Figure 1 shows a schematic representation of the architecture developed.

The contact microphone was attached to the membrane of the trampoline using flexible duck-tape. In order not to hinder the jumpers' actions, it was placed under the membrane, at a position of 80 cm from the centre. Such a position was found to allow the achievement of a high accuracy in the detection of the dynamics of the captured signals corresponding to each jump, without any distortion.

The system was designed in order to achieve the following features: i) non intrusiveness and shoe-independency; ii) real-time control of the jumping sounds synthesizer; iii) accuracy of the feet movements detection in order to achieve a large range of dynamics in the produced sound; iv) low latency between action and auditory feedback.

## 3. SYNTHESIS AND CONTROL OF JUMPING SOUNDS

The synthesis of jumping sounds was based on the approaches used in previous research [8, 23] for the synthesis of footstep sounds occurring during walking, i.e., modeling a footstep sound as the result of an impact between an exciter (the shoe) and a resonator (the floor). For this purpose, physical and physically inspired models were utilized, and were controlled in real-time by a signal expressing the type of foot-floor interaction. Specifically, the involved sound models were those described in [26, 27] for impacts, in [28] for frictions, in [29] for crumpling events, in [14] for particles interactions (PhISM), and in [23] for solid-liquid interactions. By using such models either alone or in combination with each other, the simulation of a large palette of footstep sounds on solid (e.g., wood), liquid (e.g., puddles), and aggregate surfaces (e.g., gravel) was achieved. In more details, the synthesis algorithms and their control were achieved following the cartoonification approach [30], i.e., the simplification of the underlying physics and emphasis on the main acoustic features, able to express ecological attributes of the simulated sound source.

### 3.1. Sonification process

Within the act of jumping, the physical phenomenon under consideration is the interaction of the foot with the trampoline's membrane. From a sonic interaction perspective the most relevant feature describing such phenomenon is the force exerted by the foot onto the membrane.

The proposed sonification scheme was based on the following three steps: i) detection of the foot-floor interaction by means of the contact microphone attached to the trampoline's membrane; ii) processing of the detected signal to achieve the control of the jumping sounds synthesis engine consistently with the involved force; iii) sound synthesis and display.

Jumping sounds are generally characterized by a duration shorter than that of the sounds produced during a normal walk. In addition, they are generally louder than those generated during running and walking because a stronger interaction with the floor occurs. Therefore, the involved sound models were tuned using a parametrization allowing a greater amplitude for each jump, and a shorter duration.

As far as the control of the sound models is concerned, an exciter signal expressing the interaction of the feet with the floor during the act of jumping was utilized. It was generated in real-time according to a triggering mechanism illustrated in Figure 2. Such an exciter (see Figure 2(d)) was ad-hoc created by building a signal having the temporal evolution of a typical foot-floor interaction (more details can be found in [23]). This type of exciter was also chosen because it allowed to better simulate a solid surface when utilizing the impact model. The same type of exciter was used for all the synthesized surfaces.

The signal captured by the microphone during each jump was composed of two parts (see Figure 2(a)): the first corresponded to the actual contact between the feet and the membrane (downward action), the second to the membrane vibrations occurring after the contact (upward action). Since we were only interested in sonifying the contact of the feet with the membrane, the first part was isolated and used to control the synthesis engine.

As shown in Figure 2(a), a peak with rapid onset was generated in the captured signal in correspondence to each feet-membrane impact. This behavior was exploited to trigger the exciter signal. Firstly, the captured signal $x$ was processed by means of a rectifying non-linear low-pass filter proposed in [31] in order to extract its amplitude envelope $e$:

$$e(n) = (1 - b(n))|x(n)| + b(n)e(n-1)$$

where

$$b = \begin{cases} b_{up} & \text{if } |x(n)| > e(n-1) \\ b_{down} & \text{otherwise} \end{cases}$$

where $n$ and $n-1$ indicate respectively the current and previous sample (sample rate 44100 Hz) of the discretized variable they refer to. This filter emphasizes rising slopes and dampens downgoing parts by assigning the two parameters $b_{up}$ and $b_{down}$; in this case 0.8 and 0.995 were used respectively. Figure 2(b) shows the envelope extracted from the signal illustrated in Figure 2(a).

Secondly, the first derivative of the extracted envelope was computed (see Figure 2(c)). To detect the instants in which to trigger the exciter, a threshold on the derivative values was used;

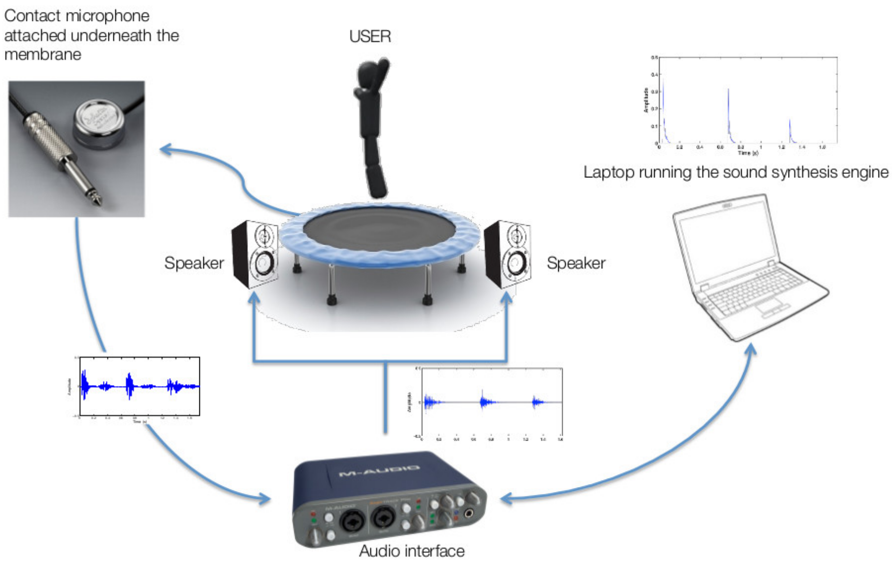


Figure 1: Schematic representation of the overall architecture developed.

furthermore, a minimum temporal distance (600 ms) was set between the detection of subsequent jumps.

Thirdly, in order to render the signal dynamic associated to each jump (which is related to the involved impact force), the amplitude of the exciter was controlled by the maximum value of the derivative (see Figure 2(e)). Finally the exciter was fed to the synthesis engine to simulate the wanted surface material. As illustrated in Figures 2(f), 2(g), and 2(h) the differences in the amplitude corresponding to the impacts in the captured signal, (and subsequently in the corresponding first derivative), were well mapped to the amplitudes of the synthesized sounds.

Using the algorithms and the sound design paradigms described in previous sections, a comprehensive collection of jumping sounds were implemented. The jumping sounds synthesizer was developed under Max/MSP sound synthesis and multimedia realtime platform. Specifically, the implementations of the models for impact, friction and crumpling, present in the Sound Design Toolkit [32] were utilized. The PhISM and the liquid model were implemented in C++ as external libraries. The exciter signal was created with MATLAB. The total latency of the system was less than 3 milliseconds.

## 4. SYSTEM EVALUATION

### 4.1. Participants

Twelve participants, 11 males and 1 female, aged between 27 and 60 (M = 32, SD = 9.15), took part to the experiment. All participants reported normal hearing and no movement impairments.

### 4.2. Stimuli

The sound synthesis engine was set to simulate jumping sounds of three different surface materials: wood, gravel, and water puddle. These materials were chosen because they were proven to be correctly recognized and classified in the corresponding solid, aggregate, and liquid surface typology [22]. In addition a fourth condition where no sound stimuli were provided was involved. When the sound stimuli were provided their amplitude was tuned such that the original sound of the trampoline's membrane was masked.

### 4.3. Procedure

After the instructor explained the scope of the experiment and provided the definition of the three surface typologies, participants were asked to take off their shoes and to jump on the trampoline (with the socks) as they pleased. It was explained to them they had neither time limitation nor a task to accomplish and they could stop jumping whenever they felt to have explored enough the interaction with the trampoline system. After each jumping trial, participants were asked to complete the following questionnaire and evaluate each question on a visual analogue scale (VAS), where 0 = not at all, and 10 = very much:

**Q1 (Naturalness):** How natural is the interaction with the system?

**Q2 (Sound Influence):** To what extent did the sound influence your way of jumping?

**Q3 (Effort):** Evaluate the sense of effort you experienced while jumping

**Q4 (Sinking):** Evaluate to what extent you had the impression that your feet were sinking into the ground

**Q5 (Softness):** Evaluate the softness of the trampoline's surface

**Q6 (Hardness):** Evaluate the hardness of the trampoline's surface

**Q7 (Accuracy):** How accurate is the system in reproducing interactively the jumping sounds?

**Q8 (Realism):** How realistic are the simulated jumping sounds?

Also they were asked to classify and recognize each simulated surface:

**Q9 (Classification):** Classify the typology of the simulated surface material (aggregate, solid or liquid).

**Q10 (Recognition):** Recognize (name) the simulated surface material.

All these questions were inspired by the questionnaires reported in [24] and [22].

The participants had the chance to go back to the trampoline any time they wanted in order to answer certain questions. The order of presentation of the four conditions was randomized and repeated twice. The order of presentation of the questions was also randomized. At the end of the experiment, participants were asked to leave an open comment about their experience.

### 4.4. Hypotheses

Based on the results presented in previous research some hypotheses were formulated. According to the findings reported in [24], some pseudo-haptic illusions were expected.

First of all, we hypothesised an influence of the provided sounds on the reports of impression of sinking. Specifically, higher sinking impressions were expected for gravel condition compared to both no-sound and wood conditions, as well as for no-sound condition compared to wood condition. Also, we expected that the water puddle sound would have produced an effect on the sinking perception, more similar to that of gravel rather than that of wood.

Secondly, we hypothesized that the perceived softness and hardness of the membrane of the trampoline would have changed in presence of auditory feedback. Specifically, higher values of hardness (and consequently, lower values of softness) were expected for wood condition compared to the other three conditions.

Yet in accordance with the findings reported in [24], we expected that the provided sounds would have had an influence on the perceived effort while jumping. Specifically, higher reports of efforts were expected for wood condition compared to the other three conditions since the membrane of the trampoline was a compliant material and therefore a stronger audio-haptic conflict would have arisen.

As a consequence of these hypotheses, we expected that the perceived naturalness of the interaction would have been proportional to the degree of coherence between the provided sound and the foot-haptic sensation resulting from the feet-membrane interaction. Specifically, higher reports of naturalness were expected for no-sound condition compared to the other three conditions, with the wood condition producing the lowest scores.

Finally, in accordance with results reported in [22], we hypothesized a better than chance recognition of the three surface materials, and a high percentage of correct classification of the sound simulations in the corresponding surface typologies.

### 4.5. Results

Results are illustrated in Figures 3 and 4. Statistical analysis was performed on the collected data by means of one-way repeated measures ANOVAs by considering i) the four conditions (4 levels: the three sound conditions plus the no-sound condition) for each of the dependent variables Q1, Q2, Q3, Q4, Q5, and Q6; ii) the three sound conditions for each of the dependent variables Q7, Q8, Q9, and Q10. All post hoc comparisons were performed by using Tukey's procedure (critical p-value = 0.05).

Regarding Q1 (naturalness) the ANOVA showed a significant main effect for the four sound conditions, F(3,88) = 2.719, $p < 0.05$. The post hoc comparisons indicated that Q1 was significantly lower for wood condition compared to no-sound condition ($p < 0.01$). Considering Q2 (Sound Influence), the ANOVA yielded a significant main effect F(3,88) = 4.275, $p < 0.01$. The pair wise comparison showed that participants reported an influence of all the three provided sounds on their way of jumping compared to the case in which the original trampoline's membrane sound was heard ($p < 0.001$).

A significant main effect was not found for the remaining questionnaire items. However, the pair wise comparison was proved significant for Q4 (sinking), Q5 (softness) and Q6 (hardness). Specifically, Q4 was significantly lower for wood condition compared to gravel and water puddle conditions (both $p < 0.001$), and greater for water puddle condition compared to no-sound condition ($p < 0.05$); Q5 was lower for wood condition compared to no-sound ($p < 0.001$), gravel ($p < 0.01$), and water puddle ($p < 0.001$) conditions; analogously, Q6 was higher for wood condition compared to all the other conditions ($p < 0.001$).

In the free-form comments at the end of the experiment, the perceived conflict between the foot-haptic and auditory modalities was arisen by many participants. They reported to be following the sound after a while and ignore the awareness of being jumping on the original trampoline surface. For some this reflected in a "hard time" answering the questionnaire, not knowing whether to reflect their sensation (physical and psychological) or rather obey to the unmodified visual appearance of the trampoline. Some people, recurring to a cartoon metaphor resolved this conflict by feeling transformed themselves: "I think of my self as something else: like a ball, like something that makes a different sound". Indeed most of the participants found the quality of the sound they heard not very realistic although they could quite easily recognize the materials. They often referred to them as a cartoonish version of the original. For some, this quality of the sound was actually beneficial in making the whole experience more playful and enjoying.

Those participants who found the sound and the haptic sensation disconnected in the case of the simulated hard surface, felt more acceptable and pleasant the water condition, as a case where sound and haptic feeling would be more connectable.

In general, participants showed their interest in exploring the different sound dynamics and the range of timbral characteristics they could achieve as a result of their jumping style. The wood condition was used by many to reach the loudest sounds possible while the puddle condition invited more subtle movements which are not associated to the jumping action.

Interestingly, in the wood condition seven participants reported the sensation of wearing shoes despite being barefoot. Specifically, four of those used terms as "high-hills shoes", "wooden shoes" and "hard shoes". All the participants appreciated the possibility of affecting the sound with their actions, sometimes deliberately adjusting their jumping style as a consequence of the sound being produced ("I found the most comfortable way of jumping to suit that sound" and "it has a big influence" or "if I jumped too much the sound didn't feel appropriate anymore thus I jumped less strongly"). Some reported that once they got used to the presence of the additional sound on top of the original trampoline sound, they felt the condition with no added sound dull and boring.

When asked which of the four conditions they preferred, ten participants chose one of the three sound conditions. The synthesized liquid material was the one most appreciated by participants who valued this sound as the most evocative of a playful and enjoyable situation. Other preferred the gravel or wood conditions because evaluated their sound qualities as more realistic.

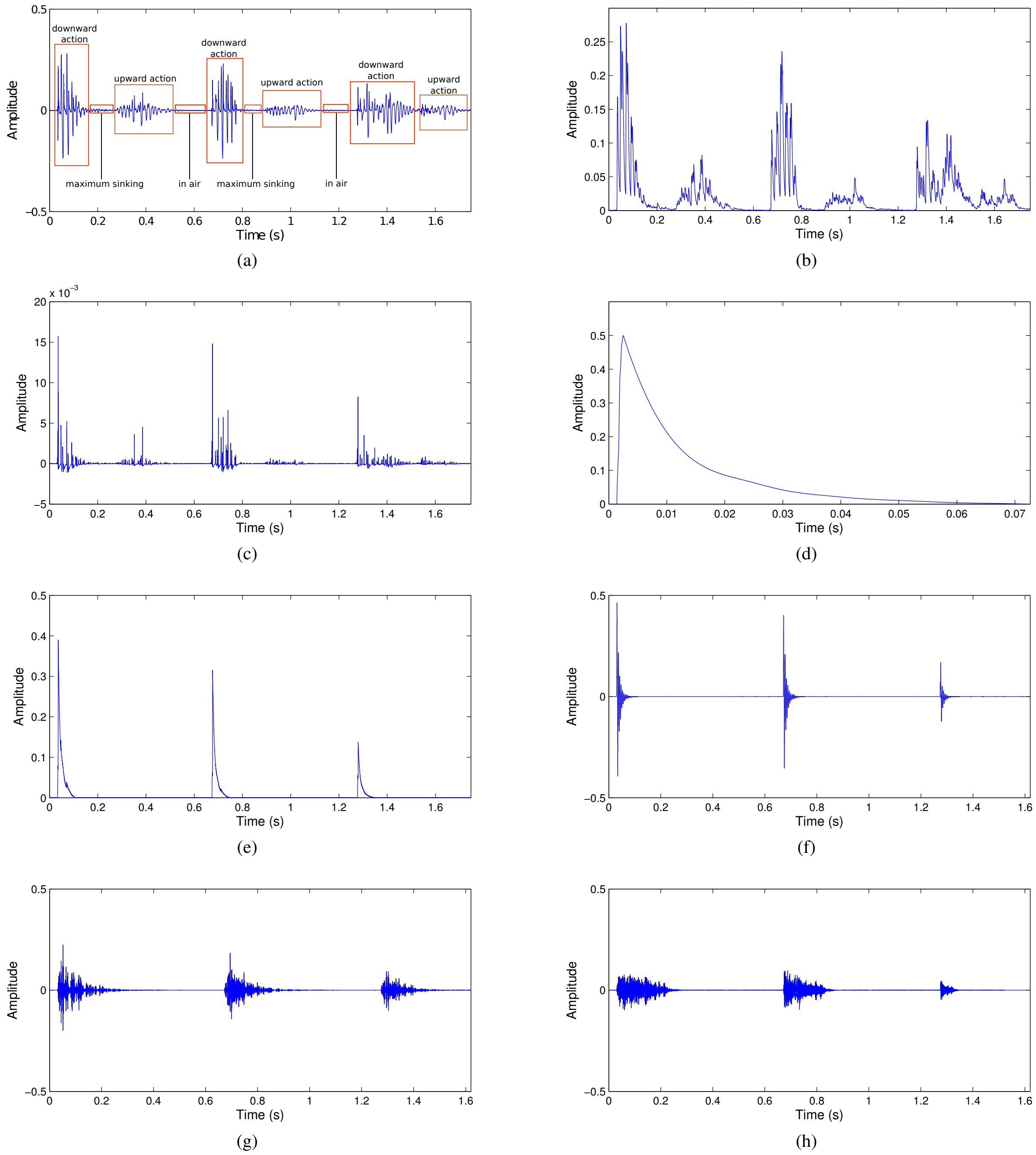


Figure 2: Sonification process: from the signal captured by the contact microphone to the synthesis of jumping sounds on different surfaces. Figure 2(a) shows the waveform of the signal detected by the microphone corresponding to three jumps with different dynamics. Figure 2(b) illustrates the corresponding rectified and low-pass filtered waveform and Figure 2(c) its derivative. Figure 2(d) shows the signal utilized as an exciter simulating the dynamics of a typical foot-floor interaction corresponding to a jump, while Figure 2(e) illustrates the same exciter modulated in amplitude by the maximum value of the envelope derivative of each of the three jumps. The differences in the exciters amplitude are reflected in the corresponding synthesized sound as shown in Figures 2(f) for wood, 2(g) for gravel, and 2(h) for a puddle of water.

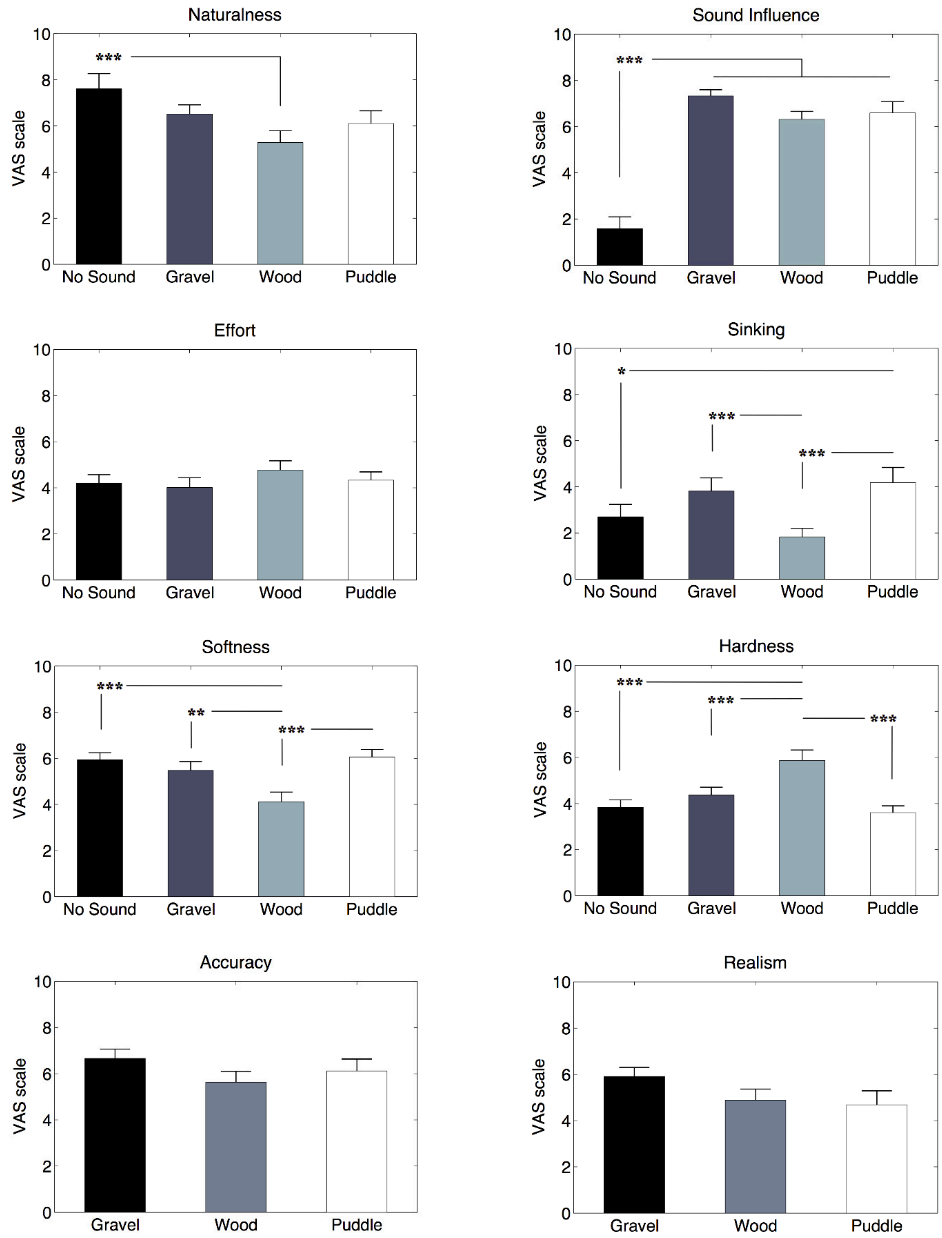


Figure 3: Graphical representation of the mean and the standard error for participants' answers to the questionnaire items Q1, Q2, Q3, Q4, Q5, Q6, Q7, and Q8 expressed on a VAS. Legend: * represents $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

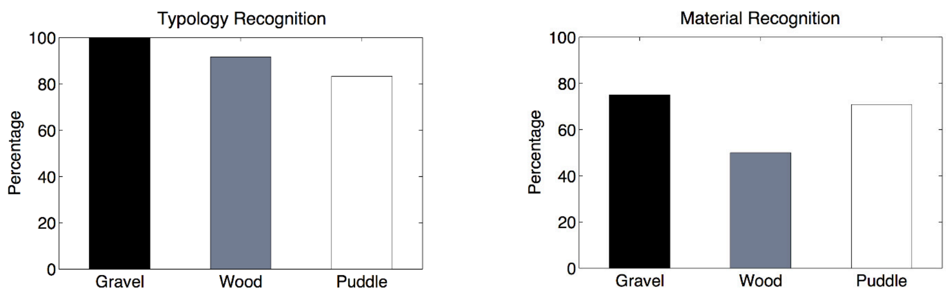


Figure 4: Graphical representation of the percentages of surface typology (questionnaire item Q9) and material recognition (Q10).

## 5. DISCUSSION

With the exception of the sonification effect on the perceived effort, the results well supported our hypotheses (see Figure 3). The most relevant result was that participants clearly reported that the provided auditory feedback was effective in modulating the act of jumping compared to the case in which only the original sound of the membrane of the trampoline could be heard, as shown in the results of questionnaire item Q2. In this regard, some participants reported to have jumped at different heights, and to have exerted different forces to the trampoline membrane when presented with different sound materials.

Also, results indicated that the provided sounds were effective in altering the haptic perception of the elasticity of the membrane of the trampoline. On the one hand, higher sinking impressions were reported for gravel condition compared to both the no-sound and wood conditions, as well as for no-sound condition compared to wood condition. On the other hand, higher values of hardness and lower values of softness were reported for wood condition compared to the other three conditions. In addition, higher sinking impressions were found for gravel condition compared to both no-sound and wood conditions, as well as for no-sound condition compared to wood condition. In general, gravel and water puddle conditions received quite similar ratings for all the investigated parameters.

In accordance with all these results, participants reported that the interaction with the system was less natural in presence of the wood condition compared to other ones. As far as the accuracy and the realism of the simulated sounds are concerned, results showed that participants did not express high ratings in either the cases. However, how it can be noticed in Figure 3, the average scores were not low, and all above the half of the VAS scale. This in an indication of the quality of the sonification algorithms and their control. The lack of high ratings concerning the accuracy could be attributed to the fact the system was not fully capable of detecting specific foot-membrane events such as swinging motion or very fast jumping. Also the system did not allow for the sonification of swinging motion on the trampoline due to the deliberate choice of limiting the interactive sonification to the impact event only. The lack of high ratings concerning the realism could be due to both the sound quality and to the mismatch between the appearance of the trampoline, the foot-haptic sensation, and the delivered feedback. Also, no reverberation was added to the simulations. The reverberation could have improved the realism of the provided sounds, as reported in the comments by some of the participants.

As far as the recognition of the simulated materials is concerned, better than chance percentages were reported for gravel and water puddle, while wood was recognized the 50% of the times (see Figure 4, right). In addition, the three simulations were correctly classified on the corresponding surface typologies aggregate, liquid and solid with very high accuracy (see Figure 4, left). These results perfectly parallels those reported in [22] for walking interactions.

The developed architecture allowed to accomplish an ecologically valid human-system interaction. Users were allowed to wear their own footwear as well as jump unconstrained. The latency between action and auditory feedback was not perceivable and the dynamics of each jump were correctly mapped into the corresponding simulated sounds. In addition, on average the involved synthetic auditory stimuli were correctly recognized and classified in the corresponding surface typologies. In addition, the use of a contact microphone attached to the rear of the trampoline's membrane overcame potential feedback loop issues between an external microphone and the speakers. This allowed to place the speakers very close to the original feet-membrane impact point. This resulted in the impression that the sounds came from the ground. More importantly, in this way the use of headphones was avoided.

Finally, the proposed sonification process can be achieved using different kinds of trampolines. Since the elasticity and the diameter of the trampoline's membrane affects the dynamics of the act of jumping, the minimum time delay constraint between subsequent jumps (in our case 600 ms) needs to be calibrated.

## 6. CONCLUSION

In this paper we presented a custom-made locomotion interface capable of interactively sonifying the foot-floor contacts resulting from jumping on an elastic trampoline. The interface was a wireless, non intrusive, shoe-independent system which allowed the user to jump unconstrained. The solution was evaluated by means of a usability experiment which revealed the success of the proposed algorithms and their control.

Taken together the evaluation results provided indications that ecological auditory feedback can modulate the perception of the foot-haptic sensations of the surface utilized when jumping.

The system is ready to be integrated with visual feedback to simulate different multimodal environments and can find application in several augmented reality contexts for sport and entertainment. It is already able to provide interactive control over a variety of different surface materials sounds but can also accommodate other sonic interaction design strategies without substantial modification. Moreover, it is suitable for studies on multi-sensory perception, especially those investigating the relation between the foot-haptic and the auditory channel, as well as between action and auditory perception.

Future works will focus on the research question concerning the role of the developed auditory feedback in affecting the jumping kinematics, similarly to the findings reported in [24]. Also, we plan to conduct a more extensive investigation on the alteration of the foot-haptic perception arisen in presence of auditory feedback simulating a larger palette of surface materials. Furthermore, we plan to evaluate the sense of engagement which can be induced by the proposed auditory feedback.

## 7. ACKNOWLEDGEMENTS

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