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Audio-Haptic Simulation of Walking on Virtual Ground Surfaces to Enhance Realism

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Abstract. In this paper we describe two experiments whose goal is to investigate the role of physics-based auditory and haptic feedback provided at feet level to enhance realism in a virtual environment. To achieve this goal, we designed a multimodal virtual environment where subjects could walk on a platform overlooking a canyon. Subjects were asked to visit the environment wearing an head-mounted display and a custom made pair of sandals enhanced with sensors and actuators. A 12-channels surround sound system delivered a soundscape which was consistent with the visual environment. In the first experiment, passive haptics was provided by having a physical wooden platform present in the laboratory. In the second experiment, no passive haptics was present. In both experiments, subjects reported of having a more realistic experience while auditory and haptic feedback are present. However, measured physiological data and post-experimental presence questionnaire do not show significant differences when audio-haptic feedback is provided.

1 Introduction

When navigating in a physical place by walking, several nonvisual cues are provided, such as the feel of the surface a person is stumpling upon, the sound of footsteps and the soundscape of the environment. In order to create realistic simulations of walking in a virtual place, it is desirable to reproduce such cues in a virtual environment.

In this paper, we are interested in investigating one's awareness of auditory and haptic feedback in foot based devices, topic which is still rather unexplored in the virtual reality community. Virtual augmented footwear has interesting applications in different fields related to virtual reality. As an example, auditory and haptic feedback in foot-based interaction can assist rehabilitation. Moreover, feet-based interfaces has started to appear in the entertainment industry, in the form of platforms such as the Wii fit from Nintendo, which is connected to the Wii console.[1] Having the possibility to provide auditory and haptic feedback has the potential of providing interesting applications in the field of navigation, especially for visually impaired people, rehabilitation and entertainment.

[1] www.nintendo.com

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2 Previous Work

In the academic community, foot-based interactions have mostly been concerned with the engineering of locomotion interfaces for virtual environments [8]. A notable exception is the work of Paradiso and coworkers, who pioneered the development of shoes enhanced with sensors, able to capture 16 different parameters such as pressure, orientation, acceleration [7]. Such shoes were used for entertainment purpose as well as for rehabilitation studies [1]. The company Nike has also developed an accelerometer which can be attached to running shoes and connected to an iPod, in such a way that, when a person runs, the iPod tracks and reports different information. Shoes enhanced with sensors and actuators were presented in [6], and an experiment was run in order to evaluate ability of subjects to recognize the virtual simulated surfaces driven by such shoes. Results showed that subjects were able to recognize simulated surfaces when rendered both using auditory and haptic at feet level.

However, to our knowledge the use of footwear augmented with sensors and actuators has not been investigated yet when combined with visual feedback in a virtual reality experience. While active haptic feedback at feet level has not been investigated yet in a virtual reality environment, passive haptics is known to significantly enhance presence [3]. Passive haptics has also been combined with redirected walking in [4].

In this paper, we are interested in investigating whether realism in a virtual reality environment is increased by enhancing the simulation with interactive auditory and haptic feedback provided at the feet. To achieve this goal, we engineered a pair of shoes enhanced with sensors and actuators. While wearing the shoes, subjects are able to hear and feel the surfaces they are stumpling upon. Our hypothesis is that this enhanced simulation has an impact on the perceived realism of the simulation and also sense of presence reported by the subjects in the environment.

To validate our hypotheses, as done in [5], we measured both physiological data while the subjects performed the experiments, and we also asked subjects to fill a post-experimental presence questionnaire. Measuring physiological data is essentially based on the assumption that a user, experiencing an intense sense of presence in a virtual environment, will exhibit physiological and behavioral responses comparable to those produced while experiencing a similar real world environment [9].

Moreover, after completing the experiment we asked subjects whether they were able to notice any difference among the experimental conditions they were exposed to.

We start by briefly describing the technology developed, and we then present two experiments whose goal is to evaluate the ability of auditory and haptic feedback to enhance realism and presence in the simulated virtual environment.

3 A Multimodal Architecture

We have developed a multimodal architecture with the goal of creating audio-haptic-visual simulations of walking-based interactions. The system requires users to walk around a space wearing a pair of shoes enhanced with sensors and actuators.

The architecture consists of a pair of custom made shoes enhanced with sensors and actuators. On top of the shoes, markers are place to track the position of the feet by using an Optitrack motion capture system by Naturalpoint. Auditory feedback is provided using a surround sound system composed by 12 Dynaudio BM5A speakers, and visual feedback is provided by a nVisor SX head-mounted display (HMD), with 1280x1024 resolution in each eye and a diagonal FOV of 60 degrees.

In order to provide auditory and haptic feedback during the act of walking, a pair of custom made shoes with sensors and actuators has been recently developed. The technology is described in [11].

4 Simulation Software

We developed a multimodal physics-based synthesis engine able to reproduce auditory and haptic feedback at feet level, to simulate the act of walking on different surfaces. An interesting characteristic of this engine is its ability to physically simulate both auditory and haptic feedback. The footstep synthesis engine, is able to render the sounds of footsteps both on solid and aggregate surfaces. Several different materials have been simulated, in particular wood, creaking wood, and metal as concerns the solid surfaces, and gravel, snow, sand, dirt, forest underbrush, dry leaves, and high grass as regards the aggregate surfaces. A complete description of such engine in terms of sound design, implementation and control systems is presented in [12].

In this particular experiment, the engine was tuned in order to simulate the audio and haptic sensation of walking on a creaking wooden plank. This particular material was chosen to match the visual feedback provided to the subjects. The synthesis engine works in realtime and is driven by the shoes described in the previous section.

4.1 Visual Feedback

The goal of the visual feedback is to render, through the use of a commercial game engine, the visual sensation of exploring a canyon. In particular, in our simulation the Unity3D game engine has been used (http://unity3d.com/). This engine was used for its ability to render realistic visual environments without being skilled visual designers. This choice was ideal for us, since our main interest is a physically based audio-haptic engine, so the visual feedback is used only for supporting it, without being the main goal. Figure 1 shows one view of the visual feedback provided to the users and one user performing the experiment. As can be seen in the left side of Figure 1, subjects are able to see a representation of their own feet when looking down in the virtual environment. This feature was implemented since it has been demonstrated that when using an HMD presence is enhanced when visual body feedback is provided [2].

5 Experiment Design

We designed two experiments whose goal was to investigate the role of auditory and haptic feedback in enhancing presence and realism in the simulated virtual environment. As can be seen in Figure 1, in the first experiment subjects were asked to stand on a physical wooden plank while experiencing the environment. Such plank was not present in the second experiment. The reason was to investigate whether passive haptic had an effect in the results.

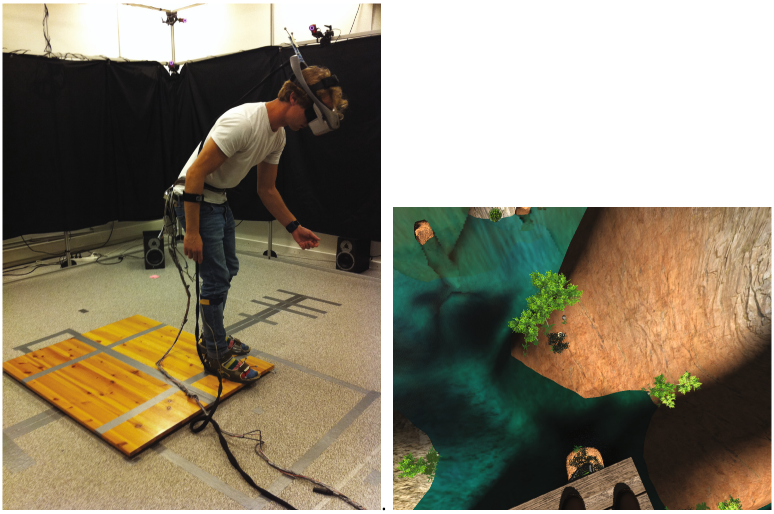

Fig. 1. One participant performing the test (left) and a view of the environment (right)

Both experiments were designed as within-subjects experiments, where half of the subjects experienced the condition without audio-haptic feedback (named NF in the following) first and the one with audio-haptic feedback (named F in the following) afterwards, while the other half experienced the condition with audio-haptic feedback first and the one without audio-haptic feedback afterwards.

5.1 Equipment and Task

Before starting the experiment, each participant was asked to wear the HMD and haptic shoes previously described, together with a wireless Q sensor device developed by Affectiva (www.affectiva.com), which, placed around the wrist, allows to measure skin conductance and temperature. Subjects were instructed that their task was to find three objects in the environment: a backpack, a camera and a hat. Subjects were also asked to wear a wireless device able to measure heart beat (Scosche mytrek wireless pulse monitor). After being ready to start the experiment, subjects were taken on the wooden platform, for those subjects exposed to the condition with passive feedback. For about a minute, subjects were allowed to freely explore the visual environment. In addition to allowing the participants to become familiar with the equipment, the hope was that this would minimize the effects of the orienting effect, that is, individuals usually elicit a stronger physiological response the first time they are exposed to a given stimulus event [5].

The objects were sufficiently hard to see in such a way to encourage subjects to explore the environment. After two minutes, subjects were asked to stop their search and to complete a presence questionnaire described later. Once subjects were done with the questionnaire, they were asked to repeat the experiment with the other condition. After two minutes, subjects were again asked to stop the experience of visiting the environment and asked to fill the same presence questionnaire. At the end of the experiment, subjects were asked questions to assess their ability of recognizing the feedback provided.

5.2 Participants

Forty participants were divided in two groups (n=20) to perform the two experiments. The two groups were composed respectively of 15 men and 5 women, aged between 20 and 34 (mean=23.05, standard deviation=3.13), and of 15 men and 5 women, aged between 20 and 32 (mean=23.5, standard deviation=3.17). Participants were primarily recruited from the campus of the Media Technology Department of the Aalborg University Copenhagen; however no restrictions on background were imposed. All participants reported normal, or corrected to normal, hearing. Participants were primarily recruited from the campus of the Media Technology Department of the Aalborg University Copenhagen; however no restrictions on background were imposed.

Participants were not awarded after the completion of the study. They were provided an informed consent form discussing the possible effects of participation in the study. Additionally, participants were informed that they could stop at any time during the experiment.

6 Results

In this section we present the results of both experiments, discussing the importance of feedback by examining both the case with passive haptics and the case without passive haptics.

6.1 Physiological Measures of Presence

Table 1 and Table 2 show the results pertaining to the measures of skin conductance and skin temperature.

The skin temperature and skin conductance measures used during the experiment including passive haptic feedback did generally not suggest an increase in presence as a consequence of the added feedback. It is possible that the skin temperature measure have been corrupted by the orienting effect, individuals usually elicit a stronger physiological response the first time they are exposed to a given stimulus event. The results suggest that the participants in average experienced an increase in skin temperature between the first and the second trial, regardless of what condition was experienced first.

Table 1. Mean and standard deviation skin temperature (degrees celsius) for the two condition-orders NF-F and F-NF

	NF-F		F-NF	
Condition	NF	F	NF	F
With PH	29.46 ± 0.80	30.27 ± 1.09	$30,51 \pm 0,95$	$29,92 \pm 0,79$
Without PH	31.19 ± 0.63	30.71 ± 0.62	30.42 ± 0.70	31.01 ± 0.69

Table 2. Mean skin conductance (microSiemens) for the two condition-orders NF-F and F-NF

	NF-F		F-NF	
Condition	NF	F	NF	F
With PH	1,69 ± 2,15	1,71 ± 1,68	1,54 ± 1,87	1,29 ± 1,37
Without PH	5.79 ± 8.18	4.80 ± 8.41	2.07 ± 2.43	2.30 ± 2.35

Note that these differences were statistically significant (p(19) = -5,4930, $p \leq 0.05$). Similarly, significant difference was found between the averages pertaining to the skin temperature in case of both condition orders (NF-F: t(9) = 7945, p = ≤ 0.05 and F-NF: t(9) = -4.1416, $p \leq 0.05$). It is possible to offer at least two explanations for this set of results, one being that the participants generally found the first exposure to the VE the scariest and therefore had a lower skin temperature during the first trial. A second explanation is that the high temperature within the laboratory caused their temperature to rise gradually for the duration of the experiment. Notably, the one explanation does not preclude the other. The results obtained from the skin conductance measure are inconclusive at best since no meaningful tendencies are present. The measures of skin temperature and skin conductance applied during the experiment where passive haptic feedback yielded similar results. It is worth noting that there is a significant difference between the averages pertaining to the skin temperature in case of both condition orders for the experiment without passive haptic feedback. (NF-F: t(9) = 4.6577, p = $\leq$ 0.05 and F-NF: t(9) = -5,0466, $p \leq 0.05$). As was the case with the experiment including passive haptic feedback, it seems possible that the participants have experienced less stress or fear during the second condition or simply have gotten gradually warmer due to the high temperature in the lab. Moreover, there was a significant difference between the mean skin conductance during condition order NF-F (t(9) = 2,5008, p $\leq$0.05). However, the corresponding means related to condition order F-NF did not differ significantly. With this being said, it should be stressed that a significant difference would not have changed the fact that these results do not suggest that the participants experienced a higher level of presence during the condition with added feedback. Regardless of the condition order the participants seem to have experienced an increase in skin conduction from the first to the second condition, which suggests a higher degree of skin perspiration. Notably a comparison by means of paired sample t-test revealed that there is a significant difference between the first and second trial, both in case of skin temperature (p(19) = -6,946, $p \leq 0.05$) and skin conductance (p(19) = -2,4511, $\leq$0.05).

Table 3 shows the results for the heart-rate measurements in the two experiments. As it is possible to notice, the average values in both the conditions and in both the experiments are always higher for the typology of stimuli presented first. In particular the statistical analysis conducted by means of a paired t-test revealed that such differences are significant for the heart-rate mean and maximum of the condition F-NF in the first experiment (t(9) = 4.7555, $p \leq 0.5$ and t(9) = 3.0251, $p \leq 0.5$ respectively), and for the heart-rate mean and maximum of the condition NF-F in the second experiment (t(9) = 3.4804, $p \leq 0.5$ and t(9) = 5.0558, $p \leq 0.5$ respectively).

Note there is a significant difference between the averages pertaining to the skin temperature in case of both condition orders. This can be interpreted in two different, albeit

Table 3. Heart-rate results of the experiment with passive haptics. Legenda: NF-F: trials in which the no feedback condition was presented first and the feedback condition afterwards; F-NF: trials in which the feedback condition was presented first and the no feedback condition afterwards.

	Trials NF-F			**Trials F-NF**		
WITH PH	**Mean**	**Max.**	**Min.**	**Mean**	**Max.**	**Min.**
NF	90±13.96	99.2±14.92	81.9±14.45	89.2±15	97.2±14.28	83.7±15.83
F	87.5±11.17	96.9±8.68	78.6±11.89	93.3±14.17	101.6±14.71	86.2±15.12
WITHOUT PH	**Mean**	**Max.**	**Min.**	**Mean**	**Max.**	**Min.**
NF	92.2±9.54	103.3±10.97	84.1±9.38	86.1±10.21	95.8±11.79	77.6±8.07
F	88.1±8.19	94.4±10.04	82.2±9.24	89.6±14.45	99.3±19.04	79.5±10.69

not necessary mutually exclusive, ways. First, the participants may have experienced less stress or fear during the second condition. Secondly, it is possible that the participants got gradually warmer as due to the hight temperature in the lab. Moreover, there was a significant difference between the mean skin conductance during condition order NF-F. The corresponding means related to condition order F-NF were not significantly different ($p = 0.2$).

6.2 Self-reported Measures of Presence

The participants experience of presence was assessed by means of the Slater-Usoh-Steed (SUS) questionnaire [10], [13], which is a questionnaire intended to evaluate the experience after exposures to a virtual environment (VE). The SUS questionnaire contains six items that evaluate the experience of presence in terms of, the participants sense of being in the VE, the extent to which the participant experienced the VE as the dominant reality, and the extent to which the VE is remembered as a place. All items are answered on scales ranging from 1 to 7 where the highest scores would be indicative of presence [13]:

Q1: Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.
Q2: To what extent were there times during the experience when the virtual environment was the reality for you?
Q3: When you think back to the experience, do you think of the virtual environment more as images that you saw or more as somewhere that you visited?
Q4: During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?
Q5: Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today?
Q6: During the time of your experience, did you often think to yourself that you were actually in the virtual environment?

The general level of presence experienced by the participants may be determined by summarizing the data obtained from the all of the questionnaire items in two ways.

First, one may present the central tendency as the mean of all ratings to all items and the variability may thus be presented as the corresponding standard deviation. Secondly, it is possible to present the general experience of presence across participants (SUS count), as the mean of the individual presence scores. The presence score is taken as the sum of scores of 6 and 7 out of the number of questions posed [13].

Tables 4 illustrates the questionnaire's evaluations for the two experiments.

Table 4. Questionnaire results of both experiments

	Trials NF-F		**Trials F-NF**	
WITH PH	**NF**	**F**	**NF**	**F**
Q1	5.3±1.49	6±1.15	5.63±1.2	5.45±1.12
Q2	5.5±1.08	5.6±1.26	5.45±1.36	5.45±1.12
Q3	3.9±1.79	5.1±1.59	5.09±1.57	5.81±0.98
Q4	5.9±0.99	6.1±0.56	5.18±1.53	6.18±0.87
Q5	3.5±1.5	4.7±1.63	4.72±1.79	4.54±0.93
Q6	4.9±1.72	5.3±1.7	5.09±2.02	6.18±1.16
SUS count	0.38±2.13	0.65±2.16	0.6±0.89	0.6±2.52
WITHOUT PH	**NF**	**F**	**NF**	**F**
Q1	4.7±1.15	5.4±1.26	5.3±1.56	5.6±0.96
Q2	4.±1.15	5.±1.33	4.8±1.22	5.3±0.94
Q3	4.5±1.77	4.7±1.56	4.8±1.68	4.8±1.68
Q4	5.4±1.07	5.3±1.15	5.5±0.97	5.3±1.15
Q5	3.9±2.55	4.3±2.49	4.1±1.79	4.2±2.14
Q6	3.6±1.57	5.2±1.68	5.7±1.25	4.9±1.37
SUS count	0.28±1.17	0.5±1.41	0.46±1.75	0.41±0.75

As outlined in [13], to check if the differences found in the questionnaire results for the two typologies of stimuli F and NF are statistically significant, one should not compare the means of the questionnaire items results, but rather the number of answers having a score of 6 or 7. Following this approach we found statistical significance in both the experiments (with and without passive haptics) for the trials in which the no feedback condition was presented first and the feedback condition afterwards ($\chi^2(1) = 5.0364$, p-value = 0.02482 and $\chi^2(1) = 7.5083$, p-value = 0.006141 respectively). Conversely, no significance was found in none of the two experiments for the trials in which the feedback condition was presented first and the no feedback condition afterwards. While the choice of the SUS-presence questionnaire was motivated by the fact that it is extensively validated and used in the VR community, it can be questioned whether it is the most suitable for examining the relationship between feedback and presence.

6.3 Realism and Audio-Haptic Feedback

As a final analysis of the experiments' results, it is interesting to discuss the observations provided by the subjects when the experiments were completed. Specifically, we asked subjects if they had noticed any difference on the two conditions and, in affermative case, if they could elaborate on the differences noticed and how they affected their experience.

During the first experiment, when asked whether they had noticed a difference between the two trials, 13 of the participants mentioned that they had noticed the change in the haptic and/or auditory feedback provided by the shoes. Precisely, 5 subjects noticed a difference in both auditory and haptic feedback, 7 only noticed the difference in auditory feedback, while 1 only noticed the difference in haptic feedback. All of the participants who noticed the difference expressed a preference towards the added feedback. When asked to elaborate, 11 of the 13 stated that it added realism, 5 felt that it made the experience more scary or intensified the sensation of vertigo, while 1 explicitly stated that it increased the sensation of presence in the virtual environment.

During the second experiment, out of the 20 participants, 16 noticed the additional feedback, 5 participants noticed both the auditory and haptic feedback while 7 just noticed the sound and 4 only noticed the haptic feedback. With one exception, all of the participants who noticed the difference preferred the additional feedback. The one participant who did not, described that he did like the haptic feedback, but he had found it too intense. Out of the 16 who noticed the feedback 13 thought that it added realism, 2 described that it made it more scary and 2 explicitly stated that it intensified the sensation of being there.

Such observations show that subjects indeed were able to notice and appreciate the provided feedback in both experimentals' conditions. The lack of the same evidence while analyzing physiological data or presence questionnaire can be due to the fact that the provided feedback does not necessarily elicit a higher physiological response or sense of presence.

7 Conclusion and Future Work

In this paper, we have described two experiments whose goal was to assess the role of auditory and haptic feedback delivered at feet level to enhance sense of presence and realism in a multimodal virtual environments. The first experiment was performed with passive haptics, while subjects were experiencing the environment with and without auditory and haptic feedback. The second experiment was performed without passive haptics. While quantitative results obtained while measuring physiological data and performing a post-experimental presence questionnaire do not show significant differences among the two conditions, subjects were actually able to perceive the differences among the experiences. As discussed in the paper, indeed several subjects noticed the auditory and haptic feedback and reported on appreciating it and experiencing it as a way to simulate realism and sense of "being there".

In the future, we are interested in further investigating the role of auditory and haptic feedback provided at feet-level, also as a mean to provide useful information such as indications for navigation in virtual environments or feedback for actions in computer games.

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