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Chapter 9
Evaluation of multimodal ground cues

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Abstract This chapter presents an array of results on the perception of ground surfaces via multiple sensory modalities,with special attention to non visual perceptual cues, notably those arising from audition and haptics, as well as interactions between them. It also reviews approaches to combining synthetic multimodal cues, from vision, haptics, and audition, in order to realize virtual experiences of walking on simulated ground surfaces or other features.

9.1 Introduction

The multisensory perception of objects and surfaces that are felt or manipulated with the hands has been extensively studied in the literature, and this has, to some extent, informed the design of new generations of complex, multimodal human-computer interfaces that utilize touch, vision, and sound to access and interact with digital information or virtual worlds. As noted in the preceding chapters, substantially less research in either human perception or human-computer interaction has been devoted to interacting via the feet.

Multimodality is an increasingly common feature of interactive systems. Whilst most studies focus on the interaction between vision and audition or between vision and touch, interaction between touch and audition is also significant because both sources of sensory information possess high temporal resolution, and thus are produced by and evidence similar mechanical properties and interactions. Prior literature has investigated many aspects of audio-tactile cross-modal interactions in perception; see [164, 141, 269, 45]. Other, more applied, studies have investigated audio-tactile effects to enhance interaction with virtual worlds [248, 77, 76, 218, 274, 20].

An overview of the different studies considered in this chapter is given in Table 9.1, listing various experiments that have been developed on top of the technologies seen in the previous chapters.

Sensory Modality	Stimuli	Hypothesis
haptic + visual	camera motion + force feedback to the hands	vection illusion
auditory + visual	camera motion + loudspeaker listening	perception of bumps and holes
haptic (tactile) + auditory	vibrations underfoot + headphone listening	perception of bumps and holes
haptic (tactile) + auditory	vibrations underfoot + loudspeaker listening	path following
haptic (tactile) + haptic (kinesthetic)	variable compliance + vibrations underfoot	perception of ground stiffness
haptic (tactile) + auditory	vibrations underfoot + loudspeaker listening	tactile illusion underfoot
haptic (tactile) + auditory	vibrations underfoot + headphone listening	ground surface recognition
haptic (tactile) + auditory	vibrations underfoot + sound underfoot	effects on gait cycle

Table 9.1: Summary of information about the experiments described in the chapter.

The following sections contain results as well as references to more detailed descriptions of such experiments.

9.2 Salience of visual cues in ground perception

Vision is the best understood of the senses, and this is reflected in the preponderance of literature on self-motion perception, which has extensively investigated visual aspects. Here, we review a few novel experiments that together confirm that vision plays a leading role in framing our perception of ground surface properties. Where relevant and consistent with the visual feedback that is received, haptic and auditory cues can further contribute realism or other perceptual effects that would otherwise not be felt as strongly by perceivers.

9.2.1 Haptic Motion: Perception of self motion with force feedback and visual motion

“Haptic Motion” is visuo-haptic paradigm for navigation in virtual worlds [217]. It allows users to feel their body being moved thanks to the application of force feedback to the hands in synergy to the projection of a scene reporting for self motion (see Figure 9.1).

We investigated the extent to which haptic forces felt through the hands can influence the perception of self motion, and how this influence compared with that of

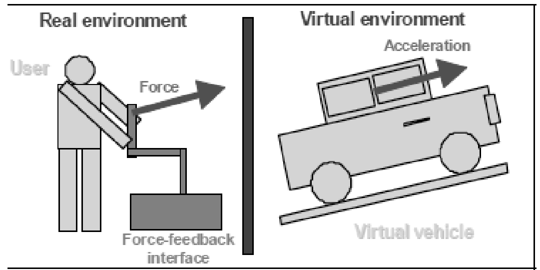

Fig. 9.1: Haptic Motion: force feedback corresponds to virtual acceleration.

visual stimulation alone. Our study involved both qualitative and quantitative measures, undertaken through two experiments. In the first, subjects were exposed to step-wise changes of *virtual acceleration*, rendered via for feedback to the hands and visual feedback, as in Figure 9.2. The visual acceleration that was supplied was

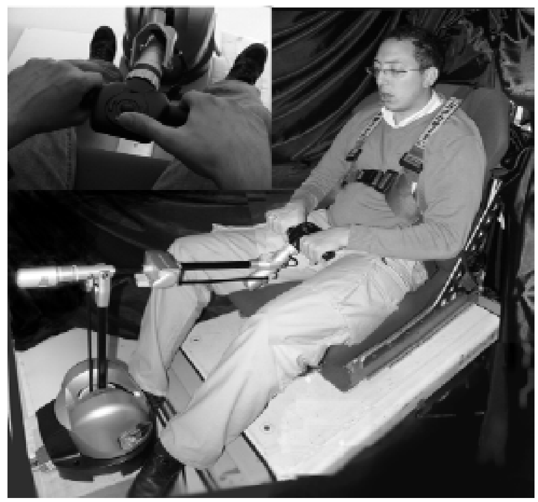

Fig. 9.2: Experimental apparatus used implementing Haptic Motion: force feedback to the user's hands is synchronized with visual feedback reporting for virtual self motion.

proportional to the haptic feedback (inertial force). Three experimental conditions were involved: haptic stimulation, visual stimulation and visuo-haptic stimulation. It was determined that the haptic force strongly influences the occurrence, onset and duration of a well-known effect in self-motion: the vection illusion.

To better understand how haptic information correlates visual information, in a second experiment we used different patterns of haptic force. It was observed that the haptic feedback evokes sensations of self motion in more complex 3D trajectories, and becomes important when subjects are exposed to force feedback that is proportional to the acceleration instead of speed.

Taken together, these results suggest that Haptic Motion could be used in various VR applications, to enhance sensation of self motion in VR and video games as well as in car driving simulators.

9.2.2 Perception of bumps and holes with camera motion and footstep sounds

Turchet et al. investigated the role of sound and vision in the recognition of different ground surface shapes, consisting of different configurations of bumps or holes along a virtual walking path [298]. Fifteen subjects participated in two within-subjects experiments. They were asked to interact with a desktop system displaying bumps, holes and flat surfaces by means of audio, visual and audio-visual cues. This display was similar to that used in purely visual experiments described in Section 6.4, allowing changes of the viewpoint in height (H), advance speed (V) and orientation (O), also simultaneously (HOV). Footstep sounds were synchronized with the vertical motion of the visual perspective rendered through the computer display, as determined by the virtual floor profile. The results of the first experiment show that participants were able to successfully identify the surface profiles in all conditions with very high success rates. The inclusion of auditory in fact did not produce higher percentages of recognition, which was already close to 100%.

In a second experiment, the dominance of vision was assessed, by presenting conflicting audio-visual stimuli. Results show that in presence of such conflicts audio is dominated by vision when H and O effects are presented. Conversely, vision is dominated by audio when V and HOV effects are presented. In particular the strongest dominance of the auditory modality was found when the visual stimuli were provided by means of the Velocity effect. Finally, a subjective questionnaire revealed a significant preference for the audio-visual stimuli compared to the unimodal condition.

9.3 Audio-haptic perception of virtual surface profiles

9.3.1 Audio-haptic walking over bumps and holes

Further to the experiments described in Section 9.2.2, simulations of auditory and haptic bumps or holes were presented to subjects as they were walking. In particular, it was investigated whether a variation of the IOI within and between footsteps, in both the auditory and haptic modality, affected the perception of surface inclination. This possibility is supported by the fact that people walking uphill tend to decelerate, while they accelerate when walking downhill.

While sitting on a chair subjects listened to footstep sounds through headphones, while feeling the corresponding vibrations through instrumented sandals. They were given a list of three different profile conditions (i.e. bump, hole, flat) presented as a forced alternative choice. The task consisted of recognizing a condition from each stimulus.

Forty-five participants were divided in three groups (n=15). These groups were composed respectively of 11 male and 4 female aged between 20 and 29 (mean =

23.6, std = 2.84), 11 men and 4 women, aged between 21 and 32 (mean = 24.86, std = 3.48) and 11 men and 4 women, aged between 20 and 28 (mean = 23.06, std = 2.40). All participants reported normal hearing conditions. They were naive with respect to the experimental setup and to the purpose of the experiment.

Results show that IOI variations between subsequent footsteps allow for successful recognition of bumps, holes, and flat surfaces especially thanks to the auditory modality. Furthermore, the inclusion of haptic cues significantly improves the recognition.

9.3.2 Walking on a virtual rope

An exploration on the role of auditory and haptic feedback in facilitating task performance was performed. The authors investigated whether these kinds of feedback facilitates the task of walking on a virtual rope, i.e. a particular case of path following. Subjects wearing instrumented sandals were blindfolded, and then asked to avoid falling from a virtual plank during an augmented walking task. Figure 9.3 shows a subject performing the experiment. Specifically, each subject was given the

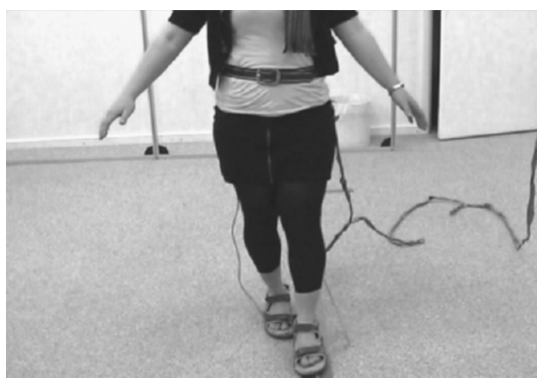

Fig. 9.3: Subject performing a walk on a virtual rope.

following instructions: "Imagine you are walking on a wooden plank. Your task is to walk from one side to the other. Walk slowly and pay attention to the feedback you receive. If your feet are outside of the plank you will fall." The auditory stimulation was designed in ways to simulate creaking wood when a user, whose position was detected by a motion capture system (Naturalpoint by Optitrack), was walking on top of the virtual plank.

The experiment was performed by 15 participants, 14 male and 1 female, aged between 22 and 28 (mean = 23.8, std = 1.97). All participants reported normal hearing. They were naive with respect to the experimental setup and to the purpose of the experiment. The results of the experiment did not provide clear indications on the role of the feedback to facilitate the task. Haptic cues appeared to be more salient, but differences with respect to the auditory feedback were not significant.

9.4 Nonvisual contribution to the perception of real and virtual ground material properties

The haptic perception of ground surface mechanical properties, such as softness or friction, or material types is essential in order to assure the stable regulation of dynamic posture and the control of locomotion in diverse environments. It is widely (often implicitly) assumed that kinesthetic (force-displacement) and visual perceptual cues dominate the sensorimotor control of locomotion over natural ground surfaces. However, a number of recent studies suggest that auditory and tactile cues acquired through the sole of the foot also contribute significantly to these perceptual processes.

9.4.1 Audio-haptic perception of virtual ground materials

Giordano et al. [110, 111] studied walkers' abilities to identify a variety of different walked-upon ground surfaces, comprising both solid materials (e.g., marble, wood) and granular media (e.g., gravel, sand) in different experimental conditions in which auditory, haptic, or audio-haptic information was available, and in a kinesthetic condition, where, during walking, tactile information was perturbed via vibromechanical noise to the sole of the foot. (Kinesthesia refers to the sense of movement and forces on the body.) Tactile masking was achieved using a novel shoe sole with integrated vibrotactile actuation (as described in Chapter 2).

The authors found haptic and audio-haptic discrimination abilities to be equally accurate, and determined that auditory and kinesthetic abilities to discriminate the ground surfaces studied are much less accurate. When walking on granular materials, which can shift underfoot, participants also appeared to focus preferentially on relatively inaccurate kinesthetic information when identifying the materials. The authors hypothesized that, although sub-optimal for the purpose of material identification, a focus on kinesthetic sensory channels indicates that attention was given preferentially to information that would most promptly signal postural instabilities.

9.4.2 Effect of plantar vibrotactile feedback on perceived ground stiffness

Visell et al. [311] investigated how the perception of ground surface compliance is altered by plantar vibration feedback. They conducted experiments in which 60 subjects walked in shoes over a rigid floor plate that provided supra- or near-threshold vibration feedback, and responded indicating how compliant it felt, either in subjective magnitude or via pairwise comparisons. In one experiment, the effect of plantar vibration feedback on ground compliance perception was measured through the use of a novel apparatus that allowed both the mechanical stiffness of a floor plate and vibration feedback presented through it to be manipulated (see Figure 9.4).

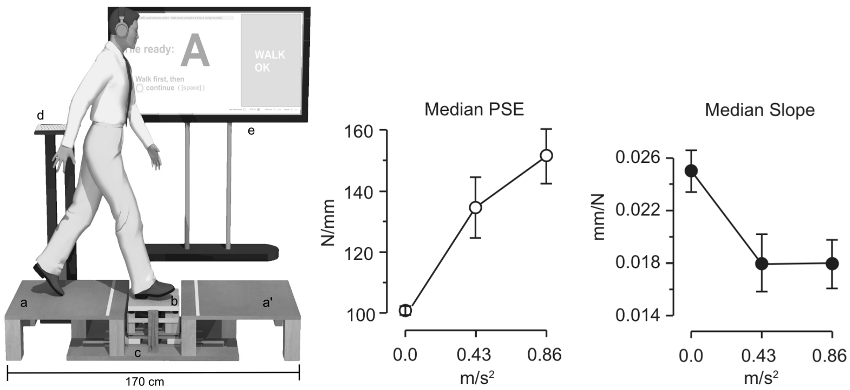

Fig. 9.4: Left: Vibrotactile floor interface from the experiment of Visell et al. [311]. Right: Point of subjective equality and psychometric curve slope for stiffness perception vs. vibration amplitude, based on fits to the experimental data.

Results showed that perceived compliance of the plate increased monotonically with vibration feedback intensity, and depended to a lesser extent on the temporal or frequency distribution of the feedback. When both plate stiffness (inverse compliance) and vibration amplitude were manipulated, the effect persisted, with both factors contributing to compliance perception. A significant influence of vibration was observed at low amplitudes (< 0.5 m/s^2) that were close to psychophysical detection thresholds for the stimuli. Taken together, the results of these experiments demonstrate that the perceived haptic compliance of a walking surface is increased in the presence of plantar cutaneous vibration feedback. The authors also found that an increased perception of compliance could be achieved with types of vibration feedback that differed in waveform, amplitude envelope, or the frequency distribution of their energy. None of the experiments involved training, and the effects observed did not require awareness that vibration feedback was being provided.

It was concluded that vibration felt during stepping on a rigid surface is combined with the mechanical stiffness of the surface in the haptic perception of compliance. In addition, the results show that the variation of vibration feedback alone is sufficient to elicit a percept of compliance. One hypothesis consistent with the observations is that plantar vibration feedback simulated the effect of increased displacement during stepping. This interpretation is also consistent with a basic mechanical description of the mechanics of material deformation underfoot during stepping. These findings show that vibrotactile sensory channels are highly salient to the perception of ground surface compliance, and suggest that correlations between vibrotactile sensory information and motor activity may be of broader significance for the control of human locomotion than has been previously acknowledged.

9.4.3 Tactile illusion induced by low frequency auditory cues

Making use of the sandals described in Chapter 2, Papetti et al. investigated the influence of low-frequency auditory cues on the perception of underfoot vibration during a walking task. The results indicated that tactile perception is influenced by such cues. However, further experiments including more robust control conditions should be performed to add significance to such results. In this sense, they must be considered still preliminary.

Walking sounds from each shoe were routed to mini-speakers mounted on the shoes and to the vibrotactile transducers (haptuators) embedded in the respective sandals. Only their low frequency component was routed to four larger loudspeakers located at the corners of the experiment room, to avoid loss of footstep sound localization due to the auditory precedence effect. Finally, in order to enhance the sense of presence and the sound localization itself, environmental sounds of a forest (representing wind in the trees, birds singing and a river flowing) were superimposed to the auditory feedback from the loudspeakers.

Subjects wore the augmented sandals and walked at a regular pace along a predefined path. Halfway along the path, the intensity of the low frequency signal at the loudspeakers could be varied by ± 6 dB or ± 12 dB in the range [0,12] dB, or conversely left unchanged, with 0 dB corresponding to a loudspeaker loudness producing about 46 dB(A) in the room. Before the experiment, subjects were informed that this could occur, however they were not aware that only the audio feedback, and not the vibration, was altered. The experiment lasted about 45 minutes and consisted of twelve experimental configurations corresponding to all possible (both varied and unvaried) couples of low frequency levels. Each condition was repeated four times in balanced randomized order, for a total of 48 trials. After each trial, subjects had to write down whether they had felt any change in the vibrotactile feedback under their feet (answer: yes/no). For each participant, the percentages of "yes" responses were calculated for the twelve experimental conditions. The difference from random percentage (50%) was tested using one-proportion (two-tailed) z tests, and we used two-proportion (two-tailed) z-tests in order to check the differences between the experimental conditions.

The experimenters considered the percentages of "yes" responses for each couple of stimuli. The results are presented in Figure 9.5. As expected, the largest low frequency variation (amounting to ± 12 dB) corresponded to the strongest illusion. On the other hand, it was found that couples introducing a variation of ± 6 dB resulted in considerably different effects, indicating that the corresponding intensity changes are possibly too small to firmly overcome the existing thresholds of illusory tactile detection underfoot. In absence of a further experiment including a more robust con-

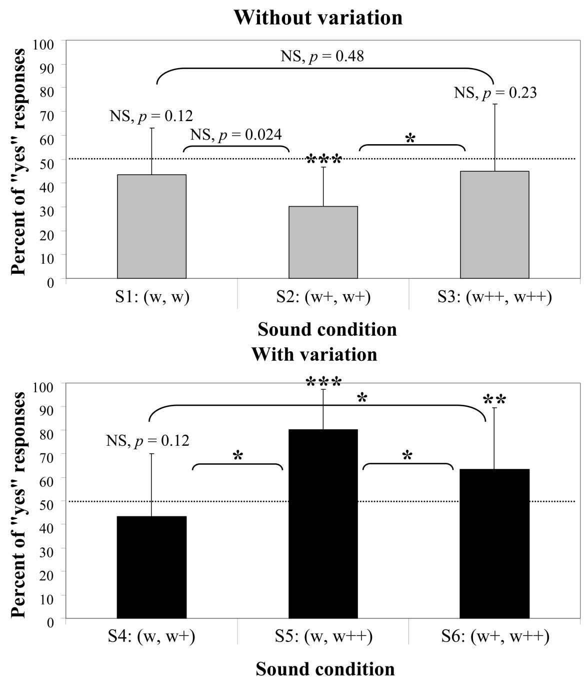

Fig. 9.5: (Above) Mean percentage of "yes" responses (bars represent std) for the unvaried couples as a function of the sound configurations S1: (w,w), S2: (w+,w+), S3: (w++,w++), with w=0 dB, w+=±6 dB, w++=±12 dB. The difference from random (line at 50%) was tested using one-proportion (two-tailed) z-tests. The differences between the three sound conditions were tested with two-proportion z-tests (two-tailed and Bonferroni-adjusted alpha-level with p = 0.05/3 = 0.0167). (Below) Mean percentage of "yes" responses (bars represent std) for the varied couples as a function of the sound configurations S4: (w,w+), S5: (w,w++), S6: (w+,w++), with w=0 dB, w+=±6 dB, w++=±12 dB. The difference from random (line at 50%) was tested using one-proportion (two-tailed) z-tests. The differences between the three sound conditions were tested with two-proportion z-tests (two-tailed and Bonferroni-adjusted alpha-level with p = 0.05/3 = 0.0167). Legend: *:$p < 0.05$, **: $p < 0.01$, ***:$p < 0.001$, NS: not significant.

trol test, these results suggest that a cross-modal effect is present which manifests itself as an audio-tactile illusion, where audio low frequency influences vibrotactile perception.

9.4.4 Audio-haptic identification of ground surfaces

This section overviews experiments whose goal was to investigate the subjective ability to recognize auditory and haptic ground surface simulations. All these experiments were carried out in an acoustically isolated laboratory sized approximately

18 square meters, allowing subjects to walk with the instrumented sandals (Chapter 2) while wearing a pair of Sennheiser HD 650 headphones.

In the auditory conditions, the haptic actuators of the sandals were not used. The pressure sensors inside the sandals were used to drive the audio synthesis engine. In the haptic conditions, participants wore earplugs and sound protection headsets instead of headphones, to minimize any external sound interference.

Offline experiments were conducted by having subjects sit and experience feedback provided to the shoes or to the ears. Conversely, online experiments were conducted by allowing subjects to walk across the laboratory, hence enabling the interactive features of the sandals (see Figure 9.6).

Fig. 9.6: A person wearing the sandals enhanced with pressure sensors and actuators.

9.4.4.1 Offline audio-haptic identification of virtual grounds

The goal of this experiment was to assess whether subjects are able to recognize virtual ground surfaces from offline audio or haptic cues. More details on the experiment are described in [209].

All participants were asked to wear a pair of instrumented sandals and headphones, and then to sit on a chair. The task consisted of recognizing a ground surface from passively felt audio-haptic stimuli. They were given a list of sixteen materials: wood, creaking wood, underbrush, snow, frozen snow, beach sand, gravel, metal, high grass, dry leaves, concrete, dirt, puddles, water, carpet and ‘I don’t know’. Each material was presented twice in a random sequence. Participants had to match every stimulus to an item in the list, furthermore to rated the realism and quality of the simulations. to debrief.

Forty five volunteers (students and faculty members of the Engineering college in Copenhagen; 31 male and 14 female; average age = 24.5, std = 4.6) were randomly assigned to one of these three groups: audio, haptic, audio-haptic. None reported hearing problems or other sensory impairments. The results indicated that haptic cues alone enabled poor discrimination of ground surfaces. Though, solid surfaces were not confused with aggregate, and vice-versa. Furthermore, the combination of auditory and haptic cues did not result in better recognition performance.

9.4.4.2 Online audio-haptic identification of virtual grounds

The goal of this experiment was to assess whether subjects were able to recognize virtual ground surfaces from online audio and haptic cues.

Thirty participants were divided in three groups (n = 10) to perform a between-subjects experiment. The three groups were composed respectively of 7 male and 3 female aged between 20 and 35 (mean = 24.6, std = 4.67), 9 male and 1 female aged between 20 and 31 (mean = 23.4, std = 3.23), and 7 male and 3 female aged between 21 and 25 (mean = 22.7, std = 1.07). All participants reported normal hearing.

Groups 1 and 3 wore the instrumented sandals and headphones. Group 2 wore the same sandals, along with earplugs and sound protection headsets. All groups then performed a walking task across the laboratory.

Eight stimuli were presented twice in randomized order. The stimuli consisted of audio and haptic simulations of footstep sounds on the following surfaces: beach sand, gravel, deep snow, forest underbrush, dry leaves, wood, creaking wood, metal. Participants were given a list of ground surfaces in form of a non-forced alternate choice, included also materials which were not present in the set of stimuli.

Subjects simultaneously perceived footsteps sounds and/or vibrations during spontaneous walking tasks. The results confirm that recognition was more successful compared to the previous experiment. As in the offline case, the combination of auditory and haptic stimuli did not significantly enhance the recognition. More details on the experiment are described in [267].

9.4.4.3 Audio-haptic matching of ground categories

A between-subjects experiment was conducted, whose goal was to investigate possible dominance of the audio or haptic modality during an augmented walking task. Subjects were asked to recognize surface material sounds and vibrations during the task. Both coherent and incoherent stimuli were presented in form of audio-haptic couples of surface materials. Incoherent couples contained materials belonging to different categories: if the auditory feedback reported for a solid surface, the simultaneous haptic feedback was of an aggregate surface and vice-versa. The hypothesis was that the audio modality dominates over the haptic one. Another was that the recognition would have slightly improved using coherent rather than incoherent stimuli.

As previously described, participants were asked to wear a pair of instrumented sandals and headphones, then to walk across the laboratory. During walking they simultaneously perceived footstep sounds and vibrations. The task consisted of recognizing the surfaces they were exposed to. As opposed to the previous experiments, participants were not provided with a forced list of possible choices.

Participants were exposed to 12 trials consisting of 4 coherent stimuli and 8 incoherent stimuli. The 12 audio-haptic stimuli were presented once in randomized order. The modeled surfaces were 4 (2 solid and 2 aggregate): wood, metal, snow and gravel. All possible material incoherences existing between the two categories were accounted for by the 8 stimuli, for both modalities.

Ten participants, 7 male and 3 female, aged between 20 and 38 (mean = 25.81, std = 5.77), were involved in the experiment. All participants reported normal hearing conditions and all of them were naive with respect to the experimental setup and to the purpose of the experiment.

Results show that the auditory modality dominates over the haptic one: in both coherent and incoherent conditions, subjects tend to classify the floor surface category by listening. Furthermore, coherent audio-haptic presentations of a surface material do not result in significantly improved subjective performance. More details on the experiment are described in [301].

9.5 Effects of ecological auditory and vibrotactile underfoot feedback on human gait: a preliminary investigation

A pilot experiment was carried out [226] in which individual IOIs were measured while subjects were asked to walk along a predefined path while wearing the audio-tactile instrumented sandals of Chapter 2. The experimental hypothesis was that human gait can be influenced by providing ecological audio-tactile feedback through the feet. Virtual snow and mud were presented based on the physics-based models of Chapter 7, along with one neutral (i.e. control) condition presenting no artificial feedback. Eight subjects, seven males and one female, participated in the experiment. Their average age was 22.3 years. Six subjects were right-handed and also considered their right foot as dominant. One subject was left-handed and one ambidextrous, also with regard to the use of his feet. None of them reported locomotion disorders.

The participants were asked to wear the instrumented sandals and included backpack, and walked along an eight-shaped trajectory in the experiment room. They were informed that a change in the multimodal feedback could occur at each trial, and no other instructions were given. In order to avoid biases due to the room configuration, half of the participants started walking from one of the shorter sides of the rectangular room and the other half from the other side. The experiment considered 8 trials for each condition, resulting in 24 trials in balanced randomized order for each experimental session, which lasted about 15 minutes.

The following IOIs were analyzed starting from measured ground reaction force thresholds: within-foot heel-to-toe intervals for both the left and right foot; heel-to-heel intervals; between-feet heel-to-toe intervals. A one-way repeated measures ANOVA (RM-ANOVA) was first performed on the data recorded in the neutral condition, in order to verify whether the subjects walked with a regular pace when no stimuli were present. The different trials in this condition were considered as repeated measures for each subject, and the mean IOIs in each trial were used for the analysis. The obtained p-values are very high, meaning that the subjects walked with a regular gait in the neutral condition. In particular, the heel-to-toe IOI for the right foot appeared to be extremely regular and was chosen as reference.

The same IOI under conditions of virtual snow and mud was analyzed using a RM-ANOVA, again considering the mean IOI over all trials under each condition. Results show that the subjects' gait was slightly affected by the virtual feedback: the IOIs in fact are more irregular compared to the neutral condition.

Indeed, the results are close to statistical significance. However, the relatively high p-values indicate that the effects need further investigation. In particular, the experiment should be repeated with a larger number of subjects. In a broader perspective, the lack of a clear statistical significance in the obtained results may have an alternative interpretation. In fact the ability to provide salient non-visual cues underfoot, which do not significantly alter one's walking style, may enable the design of foot interfaces supplying informative, meanwhile non-intrusive messages for guiding users across spaces otherwise difficult to navigate.

9.6 Conclusions

This chapter presented an overview of multimodal experiments performed in the context of foot-floor interactions. The experiments were performed with the goal of evaluating different simulation technologies, while at the same time achieving a better understanding of the role of the sensory modalities in the discrimination of surface textures and ground properties, also in the context of cross-modal illusions.

In the limits of the (often debatable) statistical significances, some general rules can be learned from these experiments:

- subjects can recognize simulated surfaces using both auditory and haptic cues;
- the combination of auditory and haptic information does not significantly enhance the recognition;
- subjects are able to recognize simulated surface profiles that are reproduced visually, auditorily and haptically;
- auditory and haptic feedback slightly modifies a subject's gait, although not significantly.

Using auditory and haptic feedback also allows to recreate some illusions, such as a sensation of stronger tactile cues when only auditory feedback is boosted. Moreover, auditory and haptic feedback can be used to signal to subjects to walk on a given path, such as a straight line.

Taken together, these experiments provide some evidence of the importance of floor feedback in simulated environments, furthermore they call for more research on a topic which has been rather unexplored in the virtual reality community.