12 Designing Interactive Sound for Motor Rehabilitation Tasks

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Technology-assisted motor rehabilitation is today one of the most potentially interesting application areas for research in SID. The strong social implications, the novelty of such a rapidly advancing field, as well as its inherently interdisciplinary nature (contents combine topics in robotics, virtual reality, and haptics as well as neuroscience and rehabilitation) are some of the aspects that consolidate its challenging and captivating character. Such prospects justify the considerable amount of attention it has received in the last decade from researchers in the fields of both medicine and engineering, the purpose of their joint effort being the development of innovative methods to treat motor disabilities occurring as a consequence of several possible traumatic (physical or neurological) injuries. The final goal of the designed rehabilitation process is to facilitate reintegration of patients into social and domestic life by helping them regain the ability to autonomously perform activities of daily living (ADLs, e.g., eating or walking). However, such activities embody complex motor tasks for which current rehabilitation systems lack the sophistication needed in order to assist patients during their performance. Much work is needed to address challenges related to hardware, software, control system design, as well as effective approaches for delivering treatment [13]. In particular, although it is understood that multimodal feedback can be used to improve the performance in complex motor tasks [9], a thorough analysis of the literature in this field shows that the potential of auditory feedback is largely underestimated.

12.1 Motivations

Strong motivations for integrating interactive sound into motor rehabilitation systems can be found by examining in some detail the most prominent current research challenges in the field of technology-assisted rehabilitation, as described by Harwin, Patton, and Edgerton [13] in a recent study.

As already mentioned above, the most important challenges are related to recovery of ADLs. The functional movements associated with ADLs typically involve very complex motor tasks and a large number of degrees of freedom of the involved limbs (e.g., arm, hand, fingers). On the one hand, this requires the use of sophisticated sensors and actuators (in particular, multiple-degrees-of-freedom robots have to be used in the case of robotic-assisted therapy). On the other hand, representing such complex motor tasks to the patient is a particularly challenging goal. The simple schematic exercises implemented in current rehabilitation systems help recovery of ADLs only to a limited extent.

ADLs rely on an essentially continuous and multimodal interaction with the world, which involves visual, kinesthetic, haptic, and auditory cues. Such cues integrate and complement each other in providing information about the environment and the interaction itself, both in complex tasks (e.g., walking) and in relatively simpler ones (e.g., a reach and grasp movement). In this regard, auditory feedback has to be used in conjunction with other modalities to continuously sonify the environment and/or the user's movements.

The engagement of the patient in the rehabilitation task is another fundamental aspect to consider. It is common sense that a bored patient may not be as motivated as an engaged patient. In the literature it is widely accepted that highly repetitive movement training in which the participant is actively engaged can result in a quicker motor recovery and in better reorganization [5]. Therefore, an open research challenge is how to increase engagement and motivation in motor rehabilitation.

Several studies have shown that auditory feedback intentionally designed to be related to physical movement can result in attainment of optimal arousal during physical activity, reduce the perceived physical effort, and improve mood during training [19]. Moreover, engagement is strictly related to the concept of presence, that is, the perception of realism and immersion in a virtual environment, commonly used in virtual reality research. In this respect it is known that faithful spatial sound rendering increases the realism of a virtual environment, even in a task-oriented context [14, 33]. Nonetheless, it must also be emphasized that auditory feedback can also be detrimental to patient engagement if not properly designed. This is a general issue in sound design: users will typically turn audio off in their PC interface if the auditory feedback is monotonous or uninteresting/uninformative.

The use of interactive sound in rehabilitation systems is also motivated by technological challenges. The qualities of virtual reality and robotic systems in motor rehabilitation are counterbalanced by their disadvantages in terms of customizability and high costs, and designing low-cost devices and hardware-independent virtual environments for home rehabilitation systems is indeed one of the current challenges for technology-assisted rehabilitation.

In this context the auditory modality can be advantageous over the visual and haptic ones in terms of hardware requirements and computational burdens. High-quality sound rendering is comparatively less computationally demanding than three-dimensional video rendering or haptic rendering and can be conveyed to the patients through headphones or through a commercial home theater system with no need for dedicated, expensive, and cumbersome equipment. In the context of home rehabilitation, auditory feedback may even be used as a sensory substitute for the visual and haptic modalities [1, 27].

Finally, auditory feedback may be in certain cases the only modality accessible to the patient, whereas other modalities (and especially the visual one) are not. A notable example is found in neurorehabilitation treatment following a traumatic brain injury such a stroke: in this case, it has been demonstrated by many studies [10, 22, 35] that it is essential to start the rehabilitation process within the acute phase (typically less than 3 months from the trauma) in order to improve the recovery of ADLs. However, this is not always possible because the acute-phase patient has extremely limited motor and attentional capabilities and, in some cases, may have a limited state of consciousness. Auditory feedback may be successfully used in such situations because it can still be perceived without requiring patients to keep their attention focused on a screen and can be processed with relatively little cognitive effort.

12.2 Auditory Feedback for Continuous Interaction

We now examine a few scenarios, methods, and technologies from recent research on sound modeling and on sonic interaction design, which can be employed and applied in the context of motor rehabilitation tasks.

In order to realize a fully interactive auditory feedback, suitable synthesis models that allow continuous control of audio rendering in relation to user gestures need to be used. One interesting scenario is provided by the PhysioSonic [40] system, which presents a generic model for movement sonification as auditory feedback, in which target movement patterns produce motivating sounds and negatively defined sounds are triggered by evasive movement patterns. Sonification is applied to intuitive attributes of bodily movements and comes in the form of metaphorical sounds (e.g., the sound of a spinning wheel is associated to velocity). Furthermore, sounds can be chosen by each subject and change over time, thus reducing fatigue or annoyance. In an example the authors implement a system for the treatment of shoulder injuries, providing two different training scenarios for the abduction movement in which the arm elevation and velocity are sonified into environmental sounds and reproduction rate of a sound file, respectively. In both cases, all evasive movements add noise or creaking to the audio feedback proportionally to their displacement.

One second relevant example of continuous and interactive sonic feedback related to user gesture is the Ballancer [32], a simple interface composed by a track (approximately 1 m long) and an accelerometer that measures acceleration in the direction of the track's length and thus makes it possible to estimate the track's tilt angle. The movement of a virtual ball, which rolls on the track and stops or bounces back when it reaches the extremities, is rendered in real time both visually on a monitor and sonically through a physically based sound synthesis model that uses the state of the ball and the tilt angle as input controls. The task of the user of this interface is to balance and tilt the track in order to move the virtual ball to a target position on the track and to stop it there. The experimental tests presented [32] demonstrate that the presence of continuous auditory feedback (the rolling sound of the virtual ball) shortens the completion time for this task with respect to the case where no sound is provided. Therefore, the auditory feedback effectively conveys information about such a complex gesture as tilting and balancing. Although the Ballancer is not conceived as an interface for motor rehabilitation, it highlights the potential of continuous auditory feedback in supporting motor learning in complex tasks.

Despite the abundance of literature on the use of human-computer interaction (HCI) methods in the design and evaluation of input devices and interfaces [24], sound started to play a significant role in HCI research only in recent years, and yet few studies [36] were devoted to the application of HCI methods to the design and the evaluation of "new interfaces for musical expression." Orio, Schnell, and Wanderley [30] started the investigation in this direction in 2001, focusing on the evaluation of controllers for interactive systems. The authors mention a target acquisition task that could be compared with the acquisition of a given pitch as well as a given loudness or timbre [39], proposing interesting analogies with HCI studies.

These works inspired a thread of research in the field of sound and music computing, focused on the analysis of simple HCI tasks (e.g., target acquisition) in the auditory domain [31]. Here the aim is not the comparison of different input devices but rather the evaluation of the influence of different kinds of feedback on the user's performance. As an example, de Götzen and Rocchesso [8] performed various tests to evaluate pointing/tuning tasks with multimodal feedback. Their results suggest that when the interaction involves any sort of kinesthetic feedback, the performance is distinctly better with respect to free gesture interfaces, and that these improvements in performance are especially significant with high speeds of the target, that is, when the target should be more difficult to hit. Furthermore, redundant feedback is needed when the task is difficult. These results support the idea of applying predictive HCI laws, along with multimodal feedback, in the field of technology-assisted motor rehabilitation with the purpose of improving patients' performance during the rehabilitation task.

Recent research on novel musical interfaces provides a number of systems and approaches that could be directly applied to rehabilitative applications [28, 34]. Work in mobile sensor performance technology is particularly interesting in this respect. Small sensors (including microphones, accelerometers, and so on) are already being used to detect various kinds of movements and gestures that can affect the produced auditory feedback such as by changing the tempo of a musical accompaniment or by controlling some expressive effects added according to input gesture [3, 4].

The application of all these results to the design of audio feedback for motor rehabilitation systems must take into account the specificities of people involved, which can often be affected by various perceptual deficits. In particular, extensive experimental work is needed in order to assess the influence of audio feedback on motor learning processes; to understand the effect of the combination of auditory feedback with other modalities, such as the visual and haptic ones; and to define criteria and guidelines for the design of the feedback, depending on the required motor task.

12.3 Current Uses of Auditory Feedback in Technology-Assisted Rehabilitation Systems

In recent years auditory feedback has been used in various systems for technology-assisted rehabilitation. The simplest possible use, which can be found in many systems discussed in the literature, consists in employing nonprocessed, prerecorded samples of vocal or environmental sounds in order to improve the involvement of the patient in the task. As an example, Cameirao et al. [2] developed a neurorehabilitation system, composed by a vision-based motion capture device augmented with gaming technologies. In this case audio has a rewarding function: in particular, a "positive sound" is triggered whenever the patient accomplishes the goal of a specific game. In a similar way, speech and nonverbal sound are used by Louriero et al. [23] as a feedback modality, with the role of providing encouraging words and sounds during task execution and congratulatory or consolatory words at the end of the exercise. Despite its simplicity, such use of sound has positive effects on the patient's emotions and involvement.

One second approach to the use of auditory feedback is to actively guide the execution of a motor task, rather than simply triggering it as a response to the patient performance. As an example, Masiero et al. [25] present a robotic device that includes simple auditory feedback: a sound signal is delivered to the patient, and its intensity is increased at the start and the end phase of the rehabilitation exercise in order to signal to the patient the occurrence of these phases. According to the authors, this kind of feedback retains the power of maintaining a high level of attention in the patient. On the other hand, the feedback has no correlation with the quality of a patient's performance. Colombo et al. [6] used a similar type of feedback to guide the user's movement in wrist and elbow-shoulder manipulators.

A more interactive use of sound can be found in the GenVirtual application [7]. This augmented reality musical game is designed as an aiding tool for patients with learning disabilities. Users of this system are instructed to imitate sound or color sequences in the GenVirtual environment, and auditory feedback is provided to help a user memorizing the sequences. Similar approaches can be found elsewhere [12, 20, 21]. However, it has to be noted that no realistic interaction is provided between user and environment, even though sounds are more closely correlated to user movements with respect to the former examples. Moreover, auditory feedback is still realized in the form of triggered prerecorded sounds.

In many systems, auditory feedback is intended to provide generation of soundscapes that can reinforce the verisimilitude and realism of a virtual environment, thus addressing aspects of sound design that are closer to SID research topics and in particular to aesthetic quality issues. To date, a plethora of environments have been developed, ranging from relatively simple driving scenarios (such as car, boat, or airplane [9, 17]) to more complex ADLs [15, 29]. The latter work describes a system that allows patients to practice various everyday activities, such as preparing a hot drink: here the role of audio feedback is to render as realistically as possible the sounds of the virtual objects involved in the activity and manipulated by the patient (e.g., the kettle, the cup). However, a fully realistic sonic interaction is not achieved because of the unidirectional and noncontinuous nature of the relation between user movements and sound generation.

Despite the great variety of uses assigned to auditory feedback, the studies discussed above do not generally provide a quantitative assessment of the effectiveness of sound regarding a patient's performance in the rehabilitation task. Schaufelberger, Zitzewitz, and Riener [37] are among the few authors who have provided such an assessment, although they used healthy subjects. In their work the use of short tonal sequences is experimentally evaluated in the context of an obstacle scenario. In particular, different distances from the obstacle and different obstacle heights are sonically rendered using different repetition rates and different pitches of a tonal sequence. Experimental results provide quantitative indications that, when acoustic feedback is added to the visual one, subjects perform better both in terms of completion time and in terms of fewer obstacles hit.

It has also to be noted that, despite the substantial amount of research, there are very few cases in which technology-assisted rehabilitation systems have made the step from research prototype to a real-world application in a medical context. A relevant example is vibroacoustic sound therapy (VAST), initially conceived for children with profound and multiple learning difficulties and recently developed with frail and mentally infirm elderly people in the context of an interactive multisensory environment (iMUSE) [11].

To conclude this section, we provide a quantitative analysis of current uses of auditory feedback in technology-assisted rehabilitation systems. A detailed review of a large number of systems has been carried out by the authors. Specifically, the systems taken into account for this analysis have been collected based on the works referenced in two recent review articles [16, 38], on a related journal special issue [18], and on the 2006–2008 proceedings of two relevant international conferences: the ICORR (International Conference on Rehabilitation Robotics) and the ICVR (the International Conference on Virtual Rehabilitation). A total of thirty-six systems, described in forty-seven reports have been selected. These systems have been grouped into four different clusters, representing four different macrocategories of auditory feedback: *auditory icons*, *earcons*, *sonification*, and *synthetic speech* (figure 12.1). These categories correspond to those identified by McGookin and Brewster [26].

Such analysis pitilessly reveals that most of the systems do not make any use of auditory feedback. In addition, speech and sonification, despite being the two most attractive alternatives for SID, are used only in a small number of cases. On the other hand, the vast majority of the systems that employ sound use it in the simplest possibly way; that is, they use prerecorded samples triggered by a single event. As a result, it emerges clearly that, although several systems exist that make use of multimodal virtual environments, the consistent use of auditory feedback is very little investigated, and thus its potential is largely underestimated.

12.4 Conclusions

Although current technology-assisted rehabilitation systems exploit only a limited set of possibilities from SID research, several studies show that properly designed auditory

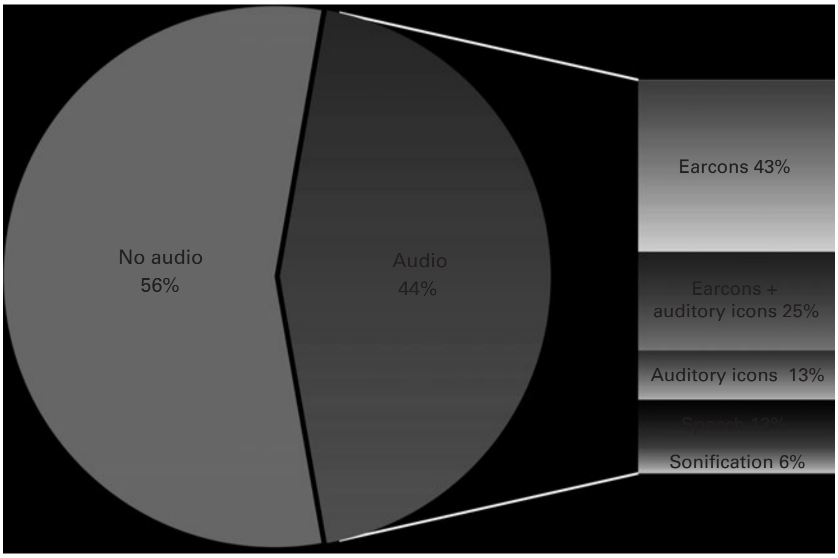

Figure 12.1
Pie chart representing the distribution of auditory feedback techniques for all of the thirty-six reviewed systems.

feedback, able to provide temporal and spatial information, can improve engagement and performance of patients in the execution of motor tasks, can improve the motor learning process, and can possibly substitute for other modalities (as with visually impaired users). Moreover, the relatively limited computational requirements of audio rendering and the low costs of related hardware make it attractive to use auditory feedback in the context of home rehabilitation systems. In light of this, the authors strongly believe that research in technology-assisted rehabilitation may only take advantage from a wary use of the know-how in sonic interaction design.

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