# Integrating auditory feedback in motor rehabilitation systems

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## Abstract

*The goal of this paper is to address a topic that is rarely investigated in the literature of technology-assisted motor rehabilitation, i.e., the integration of auditory feedback in the rehabilitation device. We first review current trends and open issues in technology-assisted rehabilitation. Up-to-date uses of auditory feedback in such context are then reviewed. In particular, a comparative quantitative analysis over a large corpus of recent literature suggests that the potential of auditory feedback in rehabilitation systems is currently largely underestimated. Finally, several scenarios in which the use of auditory feedback can contribute to overcome some of the main current limitations of rehabilitation systems, in terms of user engagement, improved motor learning, acute phase rehabilitation, standardization of the rehabilitation process and development of home rehabilitation devices, are proposed.*

## 1. Introduction

Technology-assisted neurorehabilitation seeks to use advances in robotics, virtual reality, haptics, in combination with neuroscience and rehabilitation, with the goal of developing new methods for treating motor impairments caused by neurological injuries (such as stroke, spinal cord injury, and traumatic brain injury). The field is relatively new and received much attention in the last decade from researchers in the medical and engineering fields. However much work is still needed to address challenges related to hardware, software, control system designs, as well as effective approaches for delivering treatment [7].

In particular, the final goal of the rehabilitation process is to permit patients to regain the ability to independently perform activities of daily living (e.g., walking or riding a bicycle), thus facilitating their re-integration into social and domestic life. However, current rehabilitation systems lack the sophistication needed to assist patients in such complex motor tasks. Specifically, it is recognized that multimodal feedback is needed [5], and (in cases where robotic assisted therapy has to be delivered) a large number of degrees of freedom ought to be used [19].

Although several virtual rehabilitation systems which make use of multimodal virtual environments with visual and haptic feedback already exist, the consistent use of auditory feedback is far less investigated. The purpose of this paper is to address this topic, by reviewing recent related literature and by proposing potentially relevant uses of audio in this context. Section 2 discusses some of the main open issues in technology-assisted rehabilitation, and investigates the potential of audio in such context. Section 3 reviews current uses of audio in rehabilitation robotics and virtual rehabilitation, and shows that the potential of auditory feedback is largely underestimated in the literature. Finally, Section 4 proposes a few scenarios in which recent research on sound synthesis, modeling, and design can be successfully employed to overcome some of the main current limitations of rehabilitation systems.

## 2. Open Issues

In a recent work, Harwin *et al.* [7] discuss research challenges for technology-assisted neurorehabilitation, with a focus on rehabilitation robotics. In this section such challenges are reviewed, with the goal of exemplifying potentially relevant uses of auditory feedback.

**Engagement.** It is widely accepted that highly repetitive movement training can result in improved recovery and that repetition, with active engagement by the participant, promotes re-organization. How engagement and motivation can be increased in motor rehabilitation is still an open issue. The motivational aspect brought about by auditory feedback during exercise is well known and several experiments show that sound (when strictly related to movements) has benefits which include improved mood, reduced ratings of perceived exertion, and attainment of optimal arousal during physical activity (see [12] for a review).

Although much evidence supports that the use of audio increases engagement in task-oriented applications involving user movements, it is also true that a badly designed audio feedback can be counterproductive. If the sound is monotonous and little interesting, or if the sound objects are not related to what happens on the virtual scene, or again if the auditory display is little or not at all informative, users sometimes prefer to renounce the audio feedback (for instance, many users disable sound feedback in PC interfaces). Consequently, guidelines to the design of audio feedback are necessary.

**Acute phase rehabilitation.** Several studies demonstrate that traditional interventions in the acute phase make the recovery of motor activities easier and, in particular, that robotic-assisted training in the acute and sub-acute phases (i.e., patients within three months from stroke) has a greater impact on the activities of daily living of participants, if compared to robotic therapy in the chronic phase (i.e., more than three months from stroke). One of the drawbacks of many existing rehabilitation systems is that acute phase patients are often lying in bed and do not have the possibility of keeping their attention fixed on a screen. In these cases, auditory feedback can be a useful tool, replacing the visual display and integrating an haptic feedback, if any. Moreover, acute phase patients may have a limited state of consciousness and still perceive auditory stimuli.

**Home rehabilitation.** The use of robotic systems in motor rehabilitation has many advantages, but the customization of these systems and their high costs make it difficult to continue therapy after hospital discharge. Home rehabilitation requires low-cost devices and hardware-independent virtual environments. In this context, the auditory modality offers interesting opportunities. Audio is usually a low-cost resource with minimal hardware requirements: a medium quality headphone or a commercial home theater system is enough for almost all the applications. Furthermore, audio can be used to integrate or even to substitute other modalities, such as haptic feedback, which require more expensive devices.

**Activities of daily living.** Motor skills that need to be learned by patients after neurological injuries include those related to the performance of Activities of Daily Living (ADLs). This is an essential requirement to facilitate the reintegration of patients into social and domestic life. These functional movements typically use a large number of degrees of freedom of the arm and hand, thus requiring the development of sophisticated, multiple degree-of-freedom robotic therapy devices. Moreover, due to the complexity of the involved motor tasks, their representation to the patient is more challenging.

During ADLs, our interaction with the world is essentially continuous. Complex tasks, such as walking or riding a bycicle, or even relatively simpler jobs, such as reach and grasp, rely on a mixture of visual, kinestetic and auditory cues, that continuously provide information about the surrounding environment. To this respect, auditory feedback can be a very powerful tool.

## 3. Auditory feedback in technology-assisted rehabilitation systems

### 3.1. Examples of auditory feedback in existing systems

Auditory feedback is used in technology assisted rehabilitation under multiple disguises, both in the context of rehabilitation robotics and that of virtual rehabilitation systems. At a very first level, simple prerecorded samples of environmental sounds or speech are used in many rehabilitation systems to improve the patient's involvement in motor tasks. A very straightforward example is given by the system for neurological rehabilitation developed by Cameirao *et al.* [1], where audio has a rewarding function in the context of a vision-based motion capture system with gaming technologies: each time the patient accomplishes the goal of a specific game, a "positive sound" is triggered. Similarly, speech and sounds as a feedback modality are used also by Louriero *et al.* [15], to give encouraging words and sounds while the user is trying to perform a task and congratulatory or consolatory words on task completion.

Complementarily, audio feedback can be used to guide the execution of the task. For instance, Masiero *et al.* [17] developed a robotic device which provides auditory feedback during treatment in the form of a sound whose intensity is increased to signal the start and the end phase of the exercise. The authors report that this feedback is very useful in maintaining a high level of patient attention; nevertheless, it is not correlated with how the patient is performing. An analog kind of feedback is exploited in the wrist and elbow-shoulder manipulators designed by Colombo *et al.* [2].

Another exemplary application is GenVirtual [3], an augmented reality musical game designed for people with learning disabilities: the game requires patients to imitate sound or color sequences in a virtual environment, and audio feedback (again by means of triggered pre-recorded sounds) is used to help memorization of sequences. Similar approaches are adopted in [14], [13], and [6]. Still, even though sounds are more correlated to user movements with respect to the previous examples, no realistic interaction between user and environment is provided.

Audio feedback is otherwise used to reinforce the verisimilitude of a virtual reality environment; as in the car, boat or airplane driving scenes discussed in [11] and [5], so in the simulation of more complex ADLs proposed in [19] and [9]. For instance, the latter (by Hilton *et al.*) sketches a system which offers a method of rehearsing activities such as preparing a hot drink: in this case audio feedback has to render as realistically as possible the sound of virtual objects, e.g. the kettle, that are manipulated by the patient. However, the non-continuous relation between user movements and audio feedback makes the interaction not realistic.

Regrettably, not many of the above-quoted studies do strongly assess the effectiveness of auditory feedback in rehabilitation systems. One of the few that does is due to Schaufelberger *et al.* [27], who evaluated the use of short tonal sequences in the context of an obstacle scenario: if different distances from the obstacle and obstacle heights are associated to different repetition rates and pitches of the tonal sequence respectively, then healthy subjects walk faster and hit fewer obstacles when acoustic feedback is present in addition to the visual one.

### 3.2. Comparative analysis of auditory displays in rehabilitation robotics

In order to investigate the importance given so far to audio feedback in rehabilitation systems, we have analyzed in detail a number of robot-assisted rehabilitation systems that report some use of auditory feedback. The analysis includes all the papers referenced in the two recent review articles [28] and [10], all the papers that appeared in a related special issue of the Proceedings of the IEEE (Vol. 94(9), 2006), and the proceedings of two relevant international conferences (ICORR - Int. Conf. on Rehabilitation Robotics, and the Virtual Rehabilitation Int. Conf.) from 2006 to 2008.

A total of 47 papers have been reviewed, describing altogether 36 different robot-assisted rehabilitation systems. All of the analyzed systems have been split into different typologies according to what auditory display among the following four [18] is implemented:

- *auditory icons* – pre-recorded everyday sounds mapped to computer events;
- *earcons* – short pieces of music which characterize individual events;

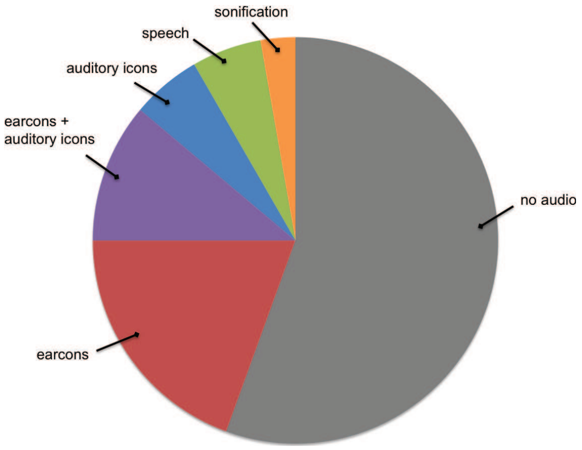

Figure 1: Pie chart representing the distribution of auditory feedback techniques for all the 36 reviewed systems.

- *sonification* – the mapping of multidimensional datasets into an acoustic domain;
- *synthetic speech*.

Figure 1 sketches this subdivision: it can be noticed that the majority of the considered systems does not report any use of auditory feedback. Moreover, speech and sonification are rarely exploited. As a matter of fact, almost all of the systems use a very simple control of the sound, that is, pre-recorded samples or sounds triggered by a single event (for instance, a falling glass).

The results of this analysis show that the potential of auditory feedback in rehabilitation systems is largely underestimated in the current literature. We are convinced instead that technology-assisted rehabilitation systems could draw advantage from a more knowledgeable use of audio feedback, and this is why in the next Section we suggest more effective ways to employ auditory feedback, specifically using continuous sonification of user movements.

## 4. Auditory feedback for continuous interaction

### 4.1. Physically-based sound models for ADLs

As reported in Section 3, current virtual systems for ADLs training mainly use triggered pre–recorded sounds. This approach does not allow to simulate a continuous feedback analogous to the real world. In order to realize a full interactive sound feedback, suitable synthesis models which allow a continuous control of audio rendering related to user gestures have to be used. An example of continuous, reactive sonic feedback in natural surroundings is represented by the Ballancer [24], a

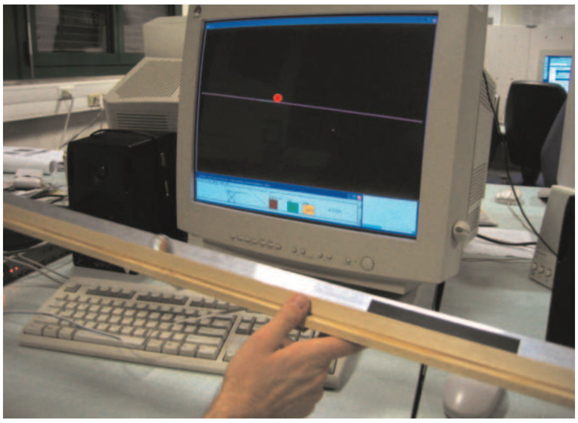

Figure 2: Balancing a virtual glass marble on an aluminum track (figure reproduced from [24]).

tangible device composed by a 1 meter long track, a position sensor, and a sonification technique that simulates the movement of a ball on the track. The user has to balance the ball by tilting the rectilinear track (see Figure 2). Feedback is provided by a physical model-based algorithm (see [22] for an introduction to this topic) that synthesizes in real–time the sound of the ball rolling over the surface of the track starting from the state of the ball and the angular tilt of the bar. The ball is free to move along one axis over the length of the track, stopping or bouncing back when reaching the extremities. Experimental tests show that the presence of continuous audio feedback decreases the time necessary for reaching the balancing of the ball. Furthermore, it is important to notice that the synthesized sound provides a unitary feedback that is able to cope with the information given by such a complex gesture. Although not explicitly designed for a rehabilitative scenario, this application highlights the potential of continuous sound feedback in supporting motor task learning in ADLs.

## 4.2. Sound design and presence

In Section 2 we emphasized the importance of active engagement by the participant to promote his re–organization. Besides the motivational aspect, auditory feedback in a VR system can improve therapeutic effects: it is known, for instance, that engagement is increased when the sense of presence, i.e., the perception that the virtual environment is “real”, gets higher. Sound feedback which provides a faithful spatial representation of audio events in the real world increases the naturalness, realism, and richness of a mediated environment [8, 25].

In this context sonic interaction design becomes a crucial aspect in the exploitation of a successful device, as for a rehabilitation system, so for a generic interface. Applications such as the Gamelunch [23] provide a useful scenario of sonic interaction design: here the authors apply the basic design method to the new content of interactive artifacts by means of a series of prototypical kinds of interaction primitives [1], that are summarized by

- *multistage yet continuous coupling* – continuous non-symbolic feedback, immediate to catch, divisible into clear stages;
- *cyclic interaction* – continuous and rhythmic feedback, giving a sense of progress to emphasize the coordination and the expressiveness of gestures;
- *counter-interaction* – contradictory feedback to mislead the perceptual experience.

All of the three scenarios investigated in this work can be easily transposed in the technology-assisted rehabilitation context, suggesting specific design for different kinds of therapy that could include multistage movements and cyclic interaction or could benefit from the use of contradictory feedback.

## 4.3. Movement Evaluation through HCI laws

Predictive HCI methods have been extensively used to design and evaluate input devices and interfaces [16]. However, sound started to play a significant role in the Human–Computer Interaction community in the last two decades only. The literature on input devices evaluation was already extended while a few studies [26] were devoted to the application of HCI knowledge to the design and evaluation of “new interfaces for musical expression”. Wanderley and Orio [20] started research in this direction in 2001, focusing into the evaluation of controllers for interactive systems. The authors, trying to define parallels with HCI studies, mention the target acquisition task that could be compared with the acquisition of a given pitch as well as a given loudness or timbre [29]. Moving from these observations, a research thread on sound and music computing focuses on the analysis of simple HCI tasks, like target acquisition, in the auditory domain [21]. The aim is not the evaluation and comparison of different input devices but rather the influence of different feedbacks on the user’s performance. In [4] the authors performed different tests to evaluate pointing/tuning tasks with multimodal feedback, finding out that:

- redundant feedback is needed when the task is difficult;

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[1] http://www.soundobject.org/BasicSID/basicSID/BasicSID_Home.html

- results obtained when the interaction involves a kinesthetic feedback are distinctly better when compared with the free gesture interfaces;
- the results are mostly better at higher speeds, that is, when the target should be more difficult to hit.

These studies also suggest further investigation in technology-assisted rehabilitation, where predictive HCI laws can be used alongside with multimodal feedback in order to improve the performance of the user. Obviously, in order to apply the results to the Auditory Display field of technology-assisted rehabilitation systems, specific customization and an intense experimental work are required: it is necessary to verify the influence of audio feedback on the motor learning process, and what happens when it is combined with other modalities, such as the visual and haptic ones. Moreover, design criteria have to be defined in order to choose the suitable audio cues in relation to a given task.

## 5. Conclusions

We strongly believe that technology-assisted rehabilitation systems may take advantage from an aware use of auditory feedback. Many studies show that, if properly designed, auditory feedback can motivate users to perform repetitive and hard tasks, represent temporal and spatial information, improve the motor learning process, and eventually substitute absent feedback modalities (as with visually impaired users). Moreover, the high availability of low-cost devices to implement auditory feedback makes it suitable for domestic rehabilitation.

In spite of this, very little attention to auditory feedback is paid in the robotic rehabilitation community. The majority of the reviewed systems do not utilize any auditory feedback, whereas the others exploit only a limited set of possibilities, such as earcons or auditory icons. Auditory feedback is mostly implemented in a virtual reality context, to reproduce realistic environmental sounds with the aim of increasing the user's sense of presence. Only in very few cases it is utilized to support the motor learning process, providing an augmented feedback to the user.

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