EMG Sonification as a Tool for Functional Rehabilitation of Spinal-Cord Injury.

José Manuel Corredera.
Hospital Fundación Jiménez-Díaz.
Madrid, Spain.
jmcorredera@me.com

Atau Tanaka
Goldsmiths, University of London.
a.tanaka@gold.ac.uk

ABSTRACT
Spinal cord injury is one of the most serious causes of disability that can affect people's lives. In tetraplegia, the loss of mobility of the upper limb has a devastating effect on the quality of life and independence of these patients, so their rehabilitation is considered a crucial objective.

We present a tool for functional motor rehabilitation of the upper limb in patients with spinal cord injury, based on the use of bio-sensors and the sonification of EMG activity during the repetitive execution of a specific gesture.

During the hospital stay, the patient has a wide range of therapies available to improve motor function or compensate for loss of mobility, including execution of different maneuvers. The repetitive and continuous performance of these tasks is a key element in motor recovery. However, in many cases, these tasks do not include sufficient feedback mechanisms to help the patient or to motivate him/her during execution.

Through the sonification of movement and the design of adapted interaction strategies, our research aims to offer a new therapeutic tool that musically transforms the gesture and expands the patient's mechanisms of expression, proprioception and cognition, in order to optimize, correct and motivate movement.

Author Keywords
Electromyogram (EMG), Spinal Cord Inury, Rehabilitation, Interactive Music System, Signal Processing, Sonification, Max, AbletonLive.

CCS Concepts
• Human-centered computing • Human-centered computing ~Accessibility ~Accessibility systems and tools

1. INTRODUCTION
With an estimated global incidence between 40 and 80 new cases per year per million inhabitants, spinal cord injury is one of the most serious causes of disability that can affect people's lives [1]. In humans about 55% of spinal cord injuries occur in the cervical segments, and slightly less than 70% of them are incomplete. Cervical lesion causes chronic motor deficiencies in the upper limbs as a consequence of segmental neuronal death and disruption of the descending axons that project caudal to the lesion.

Multiple factors lead to a bad motor performance of the upper extremities: the activation and coordination of agonist and antagonist muscles is altered and discrepancies in sensory perception can considerably impair joint kinematics, which results in increased muscle fatigue and risk of muscular contractures. This implies a devastating effect on the quality of life and independence of these patients, and hampers patients during activities of daily living [2]. Therefore, the rehabilitation of arm functions is considered a primary objective.

Many of the traditional rehabilitation programs focused on improving the motor qualities of arm movement are based on the execution of active exercises with partial motor control. They are performed by continuous repetitions of the same gesture and can be considered mentally and physically very demanding [3]. Although these tasks are adapted to the patient's physical conditions, many of them do not include sufficient feedback mechanisms to provide the patient with qualitative and/or quantitative information during their execution. In addition, repetitive practice, which is essential for recovery, can lead to a lack of interest or motivation, especially in the pediatric population, requiring the constant presence of a health professional to supervise the correct performance of the movements. On the other hand, the return to everyday life is also a difficult process. The patient must incorporate all the exercises learned during the hospital regime into his or her home environment and practice them systematically, routinely and completely autonomously.

Unfortunately, in a large number of cases, the lack of accessible tools that provide the patient with adequate motivational support leads to a poor performance of the activity or directly to its definitive interruption.

2. OBJETIVES
Our ongoing research aims to develop an engaging and effective interactive musical system that can aid the rehabilitation process through the auditory feedback of electromyographic activity (EMG). EMG biofeedback provides immediate information on the pattern of muscle activation, and allows the patient to learn to control and regulate specific physiological responses, which would not be possible under normal conditions. Through the sonification of the gesture, the design of tailored interaction strategies and the creation of a suitable musical framework, the research aims to offer a new therapeutic tool with which to expand the patient's mechanisms of expression, proprioception and cognition, optimizing, correcting and promoting movement continuity.

3. RELATED WORK
The study of human physiological signals from the point of view of musical research began in the 1960s with the work of composers Alvin Lucier, Richard Teitelbaum and David Rosenboom [4]. However, it was not until the 1980s, as a result of research in the field of Human-Computer Interaction (HCI), that artists and researchers developed the BioMuse system as a tool for transforming body movement into sound [5]. Since then, several publications have appeared in the literature questioning the traditional concept of instrument, and investigating how

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gestures made with our limbs and recorded by muscle biosensors are suitable for the design of expressive interactions [6,7]. The progressive emergence of new technologies and the reduction of their costs has allowed the development of new interactive devices and has democratized their access to many more users, encouraging the production of interdisciplinary proposals and generating new models of interaction.

Within the healthcare field, there are many studies that have incorporated the use of movement sonification techniques for therapeutic purposes, mostly as rehabilitation tools. Biofeedback techniques for rehabilitation began to be developed in the United States in the 1950s with the goal of improving movement patterns after injury [8]. Over the last four decades, different publications have compared the effect of biofeedback strategies on upper and lower limb motor recovery with conventional rehabilitation therapies. Among the patients included there were those with stroke, traumatic brain injury, and cerebral palsy. At the present time, it is beyond doubt that feedback is a key component in motor control and, consequently, neurorehabilitation continues to study new types and modalities, as well as its influence in motor learning and functional recovery [9–15].

Probably, one of the most common approaches in most studies is to use real-time auditory feedback to help people correct and optimize technique during the execution of a specific task [16–18]. The aim of this type of sonification, therefore, focuses on informing the user about qualitative aspects (biomechanical characteristics) of the movement. However, other researchers try to explore new relationships between sound and movement and works directly on the musical characteristics and sonic properties associated with the sonification. In this way they attempt to modify the perception of movement through sound perception. An example of this is the work of Joseph W. Newbold et alii. [19] which examines the impact of musical expectation on physical activity through different cadences and harmonic properties during specific phases of movement. In a similar approach, Tajadura et alii, showed how modifying the range of sound frequencies of an individual's steps can alter their perception of the walking action [20].

Although there are very few examples in the literature describing the effects of EMG sonification in patients with spinal cord injury, its use for functional motor recovery after stroke is much better documented. Most of these studies attempt to inform the user when the maximum threshold of muscle contraction has been reached through a combination of modalities: a visual guide (usually a line moving over a cursor) and an audio guide (through amplitude modulation of a single tone by direct mapping) [21–23]. In neither case does the design of these studies aim to create a motivational framework that encourages activity and promotes continuity of movement which, as mentioned above, is of crucial importance in prolonged and repetitive tasks.

4. RESEARCH DESIGN & METHODS

Among the different gestures that are trained during the rehabilitation of patients with spinal cord injury, we consider the movement of extending the upper limb to reach a glass and bring it to the mouth to be of special relevance. The functional recovery of this task is crucial for the autonomy of these patients and must be trained repeatedly on a daily basis, so our study will focus on the sonification of this gesture. It will be carried out in collaboration with physiotherapists and rehabilitation doctors from the National Paraplegic Hospital of Spain.

By means of an individual clinical examination, patients will be selected and grouped according to similar clinical and functional characteristics. This will allow us to design a common interaction framework among the subjects in the chosen group. Although we consider it relevant whether the patient expresses an affinity for music or has previous musical knowledge such as playing an instrument, we seek to develop a system that is attractive and accessible to the general population.

4.1 Arquitecture

We acquire input data in the form of EMG signal and motion data using the EAVI EMG board, a bio-sensing device comprised of four EMG channels and 3-axis accelerometer. Unlike other systems such as the Myoband, this board provides independent skin electrodes to be placed anywhere on the body. This is of particular interest as it allows us to select the most relevant muscles for the specific patient and movement. The EAVI EMG board captures the data at a sampling rate of 16 kHz and 20-bit resolution and transmits it to a computer via USB and Bluetooth Low Energy (BLE) [24].

Many of the software tools we are using for signal acquisition, feature extraction, control processing and mapping is part of a larger project called Body Brain Digital Musical Instrument (BBDMI). The BBDMI project is being developed with the aim of creating an open source, open hardware and open science digital musical instrument using electrophysiological signals that is easy to use by artists and researchers without specialized knowledge in the fields of neuroscience and signal analysis [25]. The development of the instrument is supported by an interactive system that is composed of a series of objects created in Cycling '74 Max. It is designed to work in a modular way, and it offers multiple tools, from input signal generators to control processing algorithms such as smoothing, calibration and scaling, feature extraction and output routers. They will be reported elsewhere in this same conference.

4.2 Interaction Model

As mentioned above, previous research using EMG biofeedback as a rehabilitation tool typically relies on a very simple gesture-sound interaction design: the amplitude of the EMG input signal of a muscle group is mapped directly to the amplitude of a simple tone. This model has the main advantage of being easy for the user to understand and faithfully representing the activity of that specific muscle, although it is unlikely to be particularly engaging or motivating. Furthermore, it would not be valid for representing complex gestures, where we need simultaneous inputs from different muscle groups, as is the case in our study. As described by Schmidt R et al. too much feedback information can slow down learning in healthy individuals [26], This is why it is important to choose carefully which kinematic variables should inform the feedback system and how they will be translated into the sound domain, in a way that is intuitive for the user. In case of co-existence of several representation modalities (e.g. visual and auditory) these should be integrated into a coherent system, which does not conflict with the user's proprioceptive information [27–31].

In order to achieve this task, we have incorporated a machine learning module based on the *rapid.regression*[1] Max object, namely <bbdmi.regress> (paper is in phase of review on the same conference), which allows us to simultaneously process EMG data from different muscle groups along with other kinematic data such as acceleration, and establish a rehabilitation space based on auditory feedback. This is helping us to define at least three different states during the execution of the gesture: 1.

[1] https://github.com/mzed/rapid

Rest, 2. Extension of the elbow to reach the glass, and 3. Elevation of the arm with elbow flexion to bring the glass to the mouth (figure 1).

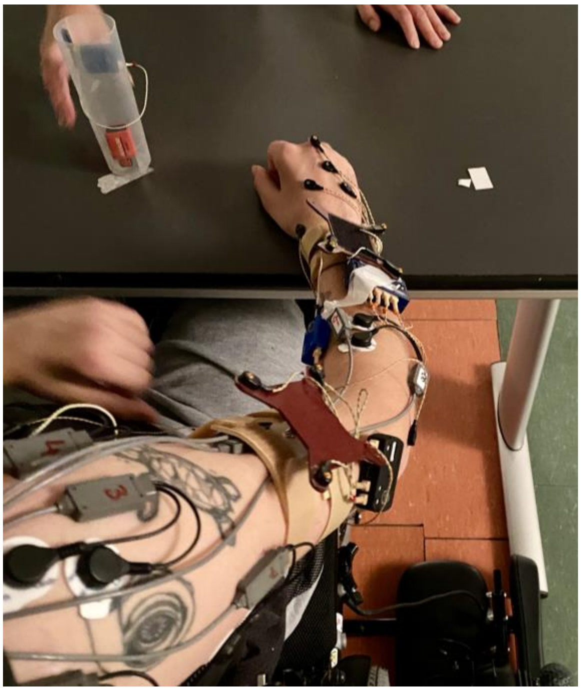

Figure 1. Maneuver of reaching a glass of water.

The machine learning component uses a regression algorithm that enables the user to associate gestures with sounds by combining multiple dimensions of input and target output. The model is trained on a set of pre-recorded examples, allowing the prediction of output values based on new input data. This results in a smooth transition between motion states, as the user can listen to the sound representation designed during the mapping process. This provides the user with qualitative feedback about the activity and can act as a sonic guide to assist with the trajectory of movement. It would also be possible to use sonification to alert the user about the activation of antagonistic muscles, whose co-contraction is undesirable.

In addition, the ability to define and identify the different phases in the execution of the gesture allows us to quantify the number of times the user has successfully performed a complete a full cycle of movement (Figure 2). This not only provides us with a clinical tool to assess the patient's functional progression, but also serves as a basis for building a reward system based on target acquisition and an interactive musical framework, aimed at promoting continuity of movement.

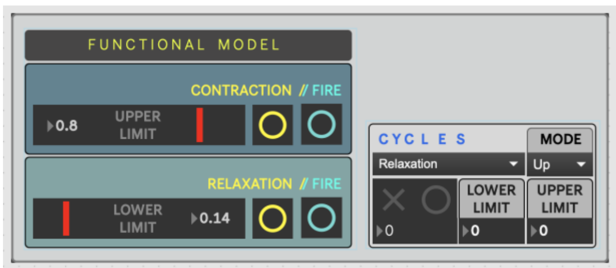

Figure 2. Threshold detection system (left) and movement cycle counter (right).

4.3 Movement Continuity

If we want the movement sonification to be attractive to the user, its transformation into a musical gesture should be accompanied by a certain sense of progression. This would seem easier to achieve in the free practice of a movement, where the mere curiosity of the user would make him/her progress through the sonification, listening to its result and exploring again other postures and movements. Unfortunately, in the case of our study this is not possible as the maneuver to be rehabilitated is always the same and the patient's own disability limits the range of his movements.

Movement continuity is a crucial aspect of the proposed interaction model. In an attempt to promote and encourage continuous movements we have tried to change its context, making the user feel that, with his/her performance, he/she is part of a larger musical composition. We have used Ableton Live to create several midi and audio clips with multiple tracks and instruments, following a western harmonic and rhythmic structure, to form a small musical composition. The Ableton Live software allows us to organize the clips in numbered scenes, which we will use to define the different parts of the composition (introduction, verses, chorus, etc...). Simultaneously, we have built a max object that allows us to monitor and count how many times the user reaches the turning point of the movement, and when the user has returned to neutral or rest position. This will act as a trigger for Ableton to play a scene in synchronization with the desired phase of the movement. As the user repeats the gesture, the musical scenes will play consecutively throughout the composition, giving the user the perception of musical progression through the execution of the activity (figure 3).

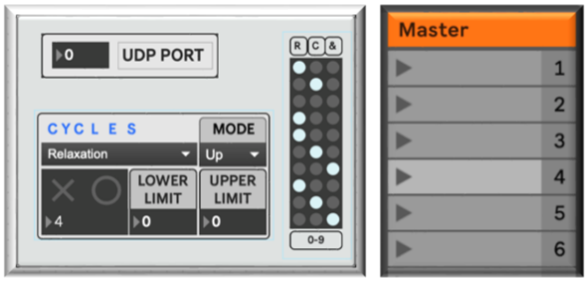

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Figure 3. The motion cycle counter (left) triggers the selected scene in Ableton (right), which jumps forward when a new full cycle of movement is completed.

We believe that the combination of all of these elements described above will establish a positive feedback loop that rewards the user for maintaining smooth and continuous motion.

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