A New Audio Bio-feedback System for Postural Stability Enhancement

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Abstract: - In this paper, we describe a bio-feedback system for rehabilitation based on an accelerometric sensor, a processing unit and an output unit. The sensory unit, which incorporates a cell with three uni-axial accelerometers and three rate gyroscopes, is mounted on the subject’s back (L5 level) using a velcro belt and allows to evaluate the trunk accelerations in the anterior-posterior (AP) and medial-lateral (ML) directions. The processing unit is composed by a laptop with Arduino board, able to acquire in real time data coming from sensory unit through the data acquisition module of Max/MSP, and to produce an audio output. The output unit is a pair of headphones which produce a kind of sound whose activation level is proportional to the magnitude of patient’s displacement.

A set of experiments have been carried out in order to measure the performance of this system, and results show that it can significantly improve rehabilitation times.

Key-Words: - Bio-feedback, postural stability, sensor interface, audio feedback, e-rehabilitation.

1 Introduction

In motor rehabilitation, biofeedback is a therapeutic tool able to compensate sensory and motor deficit through the activation of alternative sensory channels. This activation is stimulated by different types of biofeedback (visual, vibro-tactile, audio), coming from real time processing of a physiological control signal, chosen as the most significant in reference to the therapy required by patients [1-6].

In the last decade, research on biofeedback systems for motor rehabilitation, with particular regard to audio biofeedback experimentation, has had two main objectives:

- design of inexpensive, small and portable devices, which can be used by patients even without a therapist or outside the standardized clinical environment;
- comparison between different types of coding of the physiological control parameter, looking for the one that cab to give the most effective sensory compensation depending on biofeedback type and goals of the rehabilitation.

Starting from results reached till now by scientific experimentation, a new system is proposed, capable of coding an audio signal.

The biofeedback system here described can be an effective instrument for comparing Central Nervous System’s response and reaction times to different kind of coding; furthermore, the processing unit could be replaced with a palmtop to send in real time, or anyway periodically, the biomechanical parameters of patient's exercises to a doctor or a therapist: this would make the device a potential instrument of support for rehabilitation therapies from a distance (e-rehabilitation), nowadays an expanding field of research.

The paper is structured as follows: in the second section we present the state of art in the field of audio bio-feedback. In particular, we describe three systems that we took as reference. In the third section we describe our system: first we describe the hardware structure, and then the audio algorithms to produce the output. On the fourth section we describe the experimentation which allowed us to test the system. Finally, the last section is dedicated to the conclusions.

2 Audio Biofeedback

Biofeedback systems that use audio signals are among the most important ones. This kind of biofeedback is known as Audio Bio-Feedback (ABF) [7-19]. J. Petrofsky describes in [7] the use of ABF for the recover ten subjects with injury in the spinal cord with the walking capacity compromised by a reduction in the muscle strength of the hip adductor (Trendelenburg's sign). The adopted therapy used for every subject, in addition to the usual training aimed at strengthening the muscles, was EMG biofeedback sessions lasting 30 minutes, performed in clinic 5 days a week. 5 of 10 subjects had also been equipped with an ABF device that allowed them to continue the rehabilitation process at home, independently e continuously.

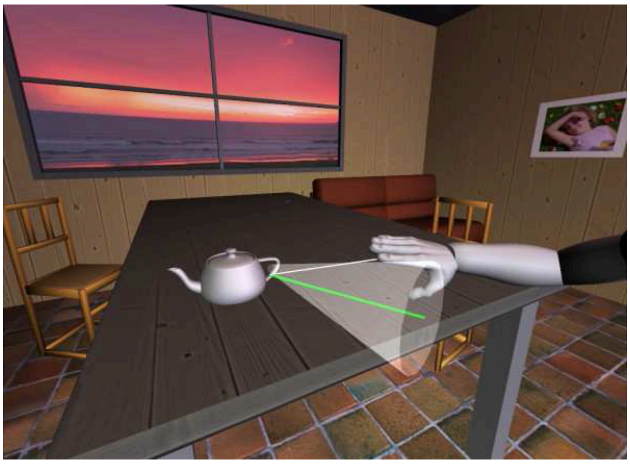

Figure 1: virtual environment created in the study of ASU regarding multimodal biofeedback (note the body-object trajectory signaled by the cone).

This device used the activity of gluteus medius muscle detected by EMG sensors as physiologic control parameter and emitted an audio signal if the position of the subject was not correct, advising this way to modify it. The emission of the signal could only be of two kinds: one tone was associated to a low muscular activity, and another to a too slow gait.

More recent studies, carried out by Anat Mirelman et al. [8] found enhancements on the posture and balance of patient affects by Parkinson disease when using an ABF therapy.

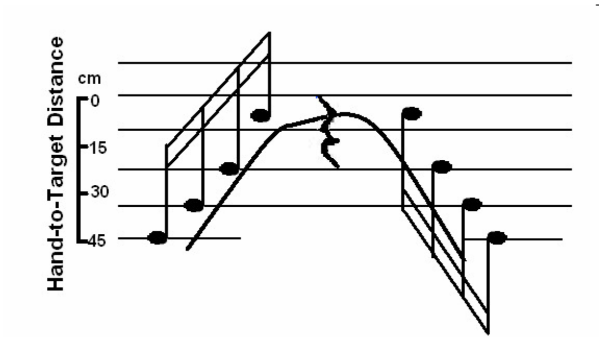

Figure 2: auditory feedback of the path to the object.

Another study on the use of ABF has been carried out by the Arizona State University by He Huang et al. [9], regarding multimodal ABF for motor rehabilitation of hemiparetic patients.

The rehabilitative exercise given to the patients was the movement of a round trip of their hand towards an object in the disabled side. In this case the patient had both a visual and an auditory feedback. The visual feedback was a virtual representation of a room where an object, placed on a table, had to be reached by the hand, following a pre-definite trajectory (see Fig. 1). The trajectory was defined by a cone whose surface became more opaque as long as the hand was departing from the correct trajectory. The auditory feedback consisted on a set of musical notes associated with different points of the path of the round trip to the object.

When the hand reached a given position (1/3 or 2/3 of the total length of the body-object path) a specific note was emitted, whose length depended on the speed of the movement. If the patient correctly completed the gesture (complete movement of round trip e correct trajectory) he was gratified by the listening of a correctly execution of a familiar melody. Otherwise (for example in case of spastic movement, where the musical phrase was distorted by the repetition of a note) he was stimulated to retry the exercise until the correct result was achieved.

In patients with sensory-motor deficits, it is very common to do compensatory movements as, in this case, bending their trunk forward to bring near the hand. So, another feedback was provided to let him control the position of the shoulders, monitored by means of the movements of the ipsilateral acromion of the moving hand. When the shift of the acromion was considered excessive (indicating the presence of some compensatory activity) the patient listened a set of notes that was dissonant with the ones used to escort the movement of the hand, advising to correct the position of the trunk.

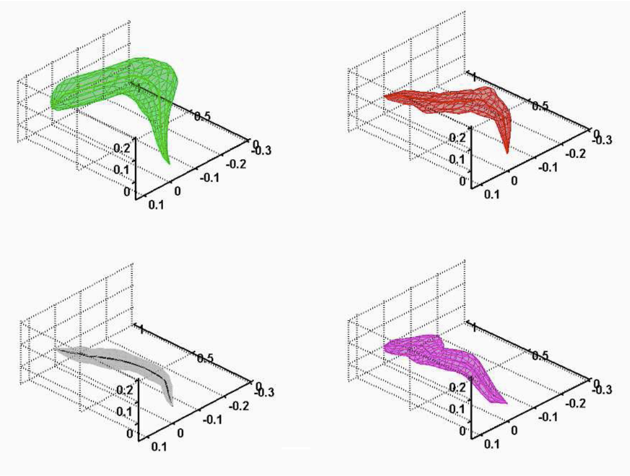

Figure 3. Normalized trajectory body-object: axis *z* shows the correct direction, while opaque area represents the standard deviations with respect to axis *x* and *y*: the solid line represent the mean value. Results for simple visual feedback is shown in the image at top left. Results for visual feedback with trajectory shown is at top right. Visual and auditory feedback is at down left. Movement with the healthy arm is at down right.

Results are reported in Fig. 3. As it is apparent, we can see a progressive reduction of the spatial error when switching from simple visual feedback (Fig. 3 top left) to the feedback in which the patient is given an ideal trajectory delimited by a cone (Fig. 3 top right). In presence of visual and auditory feedback further enhanced results (Fig. 3 bottom left) up to make the movement of the injured limb comparable with the one of the healthy limb (Fig. 3 bottom right).

Finally, we can mention the work by Dozza et al. [11]. In this case, the experiment regarded eight healthy subjects, which were asked to stand with closed eyes over a dynamometric platform covered with Temper^{TM} foam (see Fig. 4), while the following set of measures was taken:

- position of center of pressure of the patient (measurable by means of reactions, forces and momentums applied on the dynamometric platform).
- trunk accelerations (obtained by means of an accelerometer applied at the fifth lumbar vertebra of the patient);
- level of muscular activity of the legs (evaluated by an EMG sensor), with particular reference to the muscle gastrocnemius, soleus, and tibialis muscles.

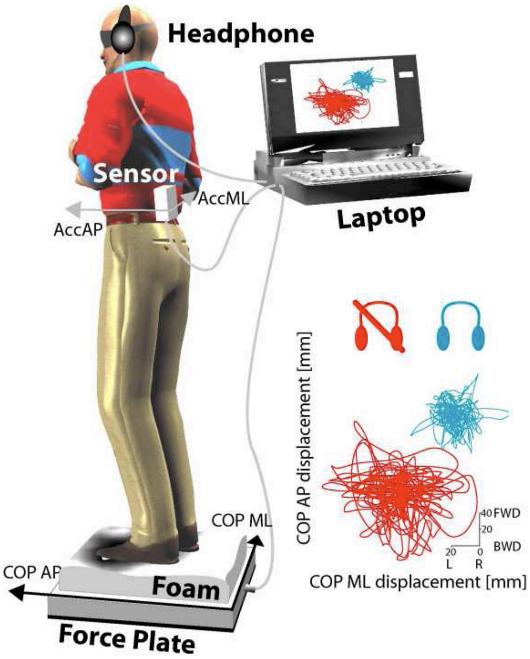

Figure 4. ABF and experimental protocol.

A Stabilogram Diffusion Analysis (SDA) has been carried out over the data regarding the center of pressure (COP). Every subject has performed ten tests lasting one minute each one; in half of the sessions, in random order, an audio feedback was also present.

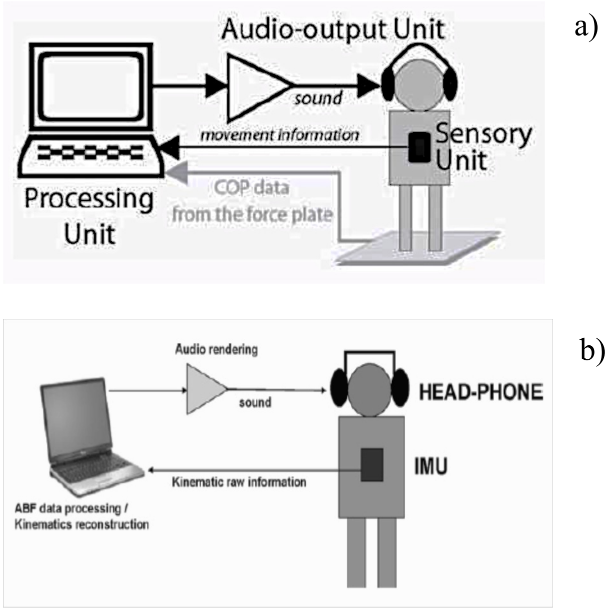

Figure 5. Audio-biofeedback with (a) and without (b) dynamometric platform.

Results showed that in presence of ABF, and in direction front/back, a significant reduction of the RMS of COP shifts and of the trunk accelerations, respectively of 10.7% and 17.2%. In addiction, an increment of the F95% (frequency of oscillation that includes 95% of total power) of 6%, showing a postural correction more frequent but of a lower amount. Measures from the EMG, on the other hand, showed the action of the ABF on the determination of the balance strategy of the patient. The reduction of postural oscillations can be achieved, in general, by means of three different strategies:

1) greater hardening due to muscular co-activation
2) the “inverse pendulum” or “ankle strategy”, where the patient moves as one rigid body, hinged at the ankles;
3) hip strategy, where the body behaves as it was composed by many rigid bodies, whose reciprocal position is given by the different articulations.

Results of the experiment, with particular reference to the EMG data, showed that ABF doesn’t determine a major increment in the muscular rigidity and doesn’t modify in a significant way the co-activation of different muscle of the leg. Hence, its use modifies the balance control strategy adopted by the CNS, yielding to an increment of feedback control.

Chiari et al. in [12] and Dozza et al. in [15] have shown that the RMS value of the shifts of the COP and the RMS value of the trunk accelerations are characterized by high correlation coefficients. The mutual dependence of these two parameters, the first of which (COP shifts) can be obtained only by means of a dynamometric platform and the second one (trunk accelerations) valuable by means of a sensor. Moreover they suggested to avoid the presence of the platform in the next sessions. In fact, accelerometric data are equally significant and reliable, but can be obtained with a simpler and less expansive instrumentation. Hence, in the experiments the ABF system shown in Fig. 5(a) has been replaced by the system in Fig. 5(b).

The possibility to avoid the platform has allowed to use cheap and portable devices as sensor units; the next introduction of a wireless *body network* has represented another step forward in the realization of devices that could be used daily by the patients and not only in clinic, but also domestic environments.

3 The New ABF system

In this paragraph we describe our proposed audio-biofeedback system, which can be useful to grant a faster and effective enhancement of postural stability with respect to the usual physiotherapy without feedback. This is possible due to the execution of repeated exercises finalized to teach a correct and stable posture, enforcing, thanks to the progressive memorization of such balance positions acquired during the training, the autonomous capacity to remain in balanced even when there is no feedback.

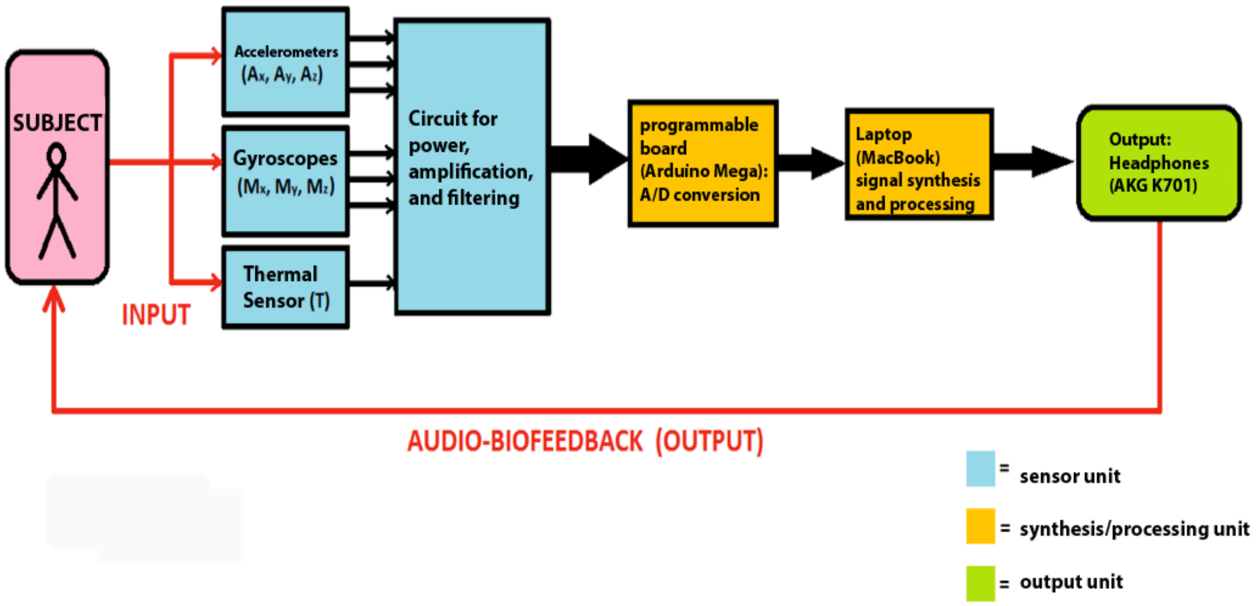

Figure 6. Architecture of the audio-biofeedback system.

2.1 Architecture of the audio-biofeedback system

Like all previous biofeedback (BF) systems examined in this paper, even in this case we can see the presence of three components:

- *sensor unit*: used to detect the control physiological parameter.
- *processing unit*: used to code in real time the sensor information by means of specific algorithms.
- *output unit*: used to give the patient an auditory representation of the control physiological parameter. The architecture of the system is shown in Fig. 6.

The sensor unit is constituted by three accelerometers (3031-Euro Sensor, US), three gyroscopes (Gyrostar ENC-03J-Murata, Japan), assembled together according to an orthogonal reference, and a temperature sensor. All sensors, including their circuits are inside a black box of dimensions 4x5x2 cm and a total weight of about 250g, as shown in Fig. 7.

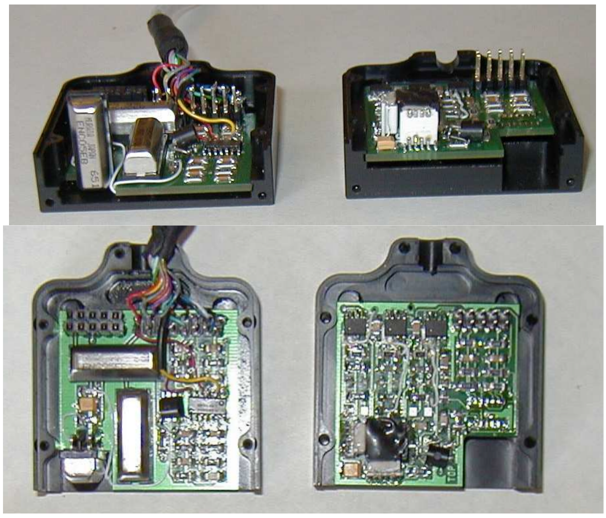

Figure 7. Sensory unit circuits.

These characteristics allow the user to comfortably wear this module, which must be applied at the spine, at the height between the second and the fifth lombar vertebra (between L2 and L5). We used only two accelerometers of seven sensors: one to measure the pitch angle (also known as AP: Anterior/Posterior), and the other one to measure the roll angle (known as ML: Medial/Lateral) [20-26].

The processing unit is constituted by a MacBook and a programmable board Arduino Mega (see Fig. 8). Arduino board uses two of its analog inputs to get the signals coming from the two sensors of acceleration on axis x and y (in our case we used pins 5 and 8). The second step is the transmission of binary code according to a serial communications form Arduino board o the laptop (a MacBook in our case), by means of an USB (universal Serial Bus) cable. This code is read by a Max/MSP patch available on the web site of Max/MSP [27], developed to interface with the various models of Arduino board and called “maxuino” (ref. http://www.maxuino.org). This communications is possible thanks to the OSC-Route objects loaded on Max/MSP. Finally, Arduino software has been used to program Arduino hardware, writing on it the code which made it functional to our needs, making active, among other things, its analog inputs.

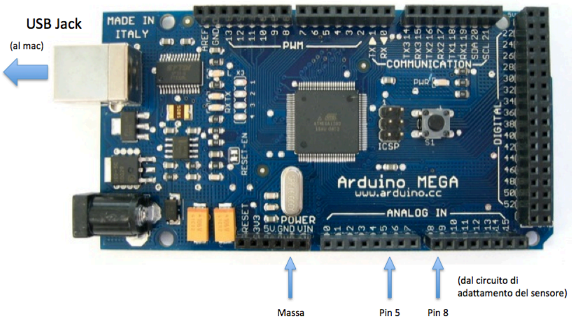

Figure 8. Arduino board with used pins indicated.

The signals for every channel (angles of pitch and roll) after being converted in digital and processed to be read by Max/MSP, are in the form of numbers between 0 and 1, values that correspond to maximum detectable acceleration and deceleration.

For practical reasons we decided to use, to detect the leaning of the body along the two angles of pitch and roll, the accelerometers in spite of the gyroscopes. Even if one could think that gyroscopes would be better for our purposes, we found that accelerometers had a better performance and precision.

The output unit is a pair of earphones. In this case we used a pair of open earphones (AKG K701) having an excellent frequency response, precision and dynamics. Being of open type, we can hear well even sounds coming from outer world, allowing the communication with an assistant possibly present.

2.1 Audio coding algorithm

The audio coding algorithm generates sounds in function of two numeric signals x and y, which will be sent to the soundboard. These sounds will be heard in the earphones of the patient, giving him an audio-biofeedback that represents the information useful to correct his own posture. We will now examine in detail the structure and function of the system that synthesize such sounds.

To understand the algorithm, it is useful to draw the two signals on a graph: the first value (ML angle) is on the *x* axis and the second one (AP angle) on the *y* axis, imaging to watch the position of the sensor from the top. For every instant *t* we will have a point in this plane, defined by a couple (*x,y*) in input to the Max/MSP patch, this point can be, with an acceptable approximation of little angles (<7°), as the projection of the position of the sensor on the plane *x-y.* This graph is very useful to understand how the sound synthesis is performed, according to the region where this point lays on each instant.

The signal is stereophonic, and its amplitude is unbalanced on the two channels left and right: for $x<0$ (leaning left) the amplitude of left channel increases with a given gain $g(x)$ while the amplitude of the right channel decreases by the same amount; when $x>0$ (leaning right) the amplitude of the right channel will increase and the amplitude of the left channel will decreases.

The kind of sound that is generated depends on the region where the point is: when the point is inside the region 1, which is shown with light green color, in Fig. 9 and represents a right posture, pink noise is generated, with low volume, slightly over the hearing threshold. Volume is adjustable, because the right level depends on the single subject. The shape of this region is a circle with radius 1, and it is centered the origin: this means that every posture with a leaning, in module, less than 1° is considered correct.

In the second region, pink noise is filtered by a band-pass filter from 128 Hz to 14263 Hz and has volume higher than the first region. Volume in this region can be adjusted as well. This region is shown with green colour in Fig. 9, and represents a slight leaning that can easily be tolerated. As Fig. 9 shows, this region is not circular, but elliptical, and is not centered in the origin. This is because frontal leaning is more tolerable than back and lateral leaning. The region is analytically defined as the area inside the following ellipse:

$$(y-0.5)^2/2.25^2 + (x^2/1.5^2) = 1$$

In the third region (yellow), another pink noise is generated, but the band is narrower: 415 Hz to 4390 Hz, and volume is higher than the second region: this region represents a position where leaning is becoming more serious. The shape of this region is another ellipse, larger then region 2, and it is defined as the area inside the following ellipse:

$$(y-0.5)^2/3^2 + (x^2/2^2) = 1$$

In the fourth region (orange) the noise has a very narrow band, around 800 Hz, lower bound of the band varies exponentially in function of *y* ($f_{inf} = 2^y$) so that the perception is that the variation of the pitch of the sound is proportional to the angle. The upper bound of the band will be $f_{sup} = f_{inf} + 800$ in order to keep the same bandwidth. Being the pass band very narrow, we will have the perception to hear almost a pure sinusoidal wave and when the frequency increases, this perception will be heard stronger because human perception of the pitch is logarithmic. Value of f_{inf} is $f_{inf} = 2^8$ when $y = -20$ to $f_{inf} = 2^8$ when $y = 20$, which means from 256 Hz to 4896 Hz. We generated sounds from 250 Hz to 5 KHz to be sure that every subject could hear it those frequencies. Region 4 is defined as the area outside region 3 and with $-2 < x < 2$.

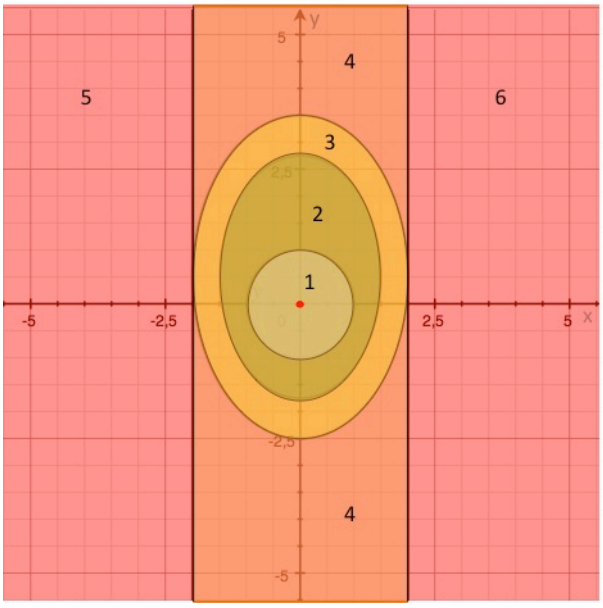

Figure 9. Shape and position of the six regions considered for the sound synthesis.

On regions 5 and 6 (red) we have the same sound as in 4, but with a variation: the signal in one of the two channels is multiplied by a square wave: left channel if $x \leq -2$ and right channel if $x \geq 2$. The square wave is from 0 to 1 with a duty cycle of 50%, the period *T* decreases exponentially in function of the module of *x*: $T = 8^h$, with $h(|x| = 0) = 2.5$, $h(|x| = 20) = 2$, so $T_{min} = 82$ ms, $T_{max} = 82.5$ ms; *h* goes linearly from 2.5 to 2 when $|x|$ goes from 0 to 20). So, as soon as we enter in this region (when $x = -2$ or $x = 2$) we will have on a channel the sound described for the fourth region, and on the other channel the same sound but it is intermittent. This kind of train of pulses has a frequency of about 15.6 Hz when $|x| = 20$ which is the maximum angle that we considered. Region 5 is defined as $x \leq -2$ and region 6 is defined as $x \geq 2$.

4 Experimental Results

An experimental test was executed with six healthy subjects. Numerical data for x and y were registered and accurately examined and compared. Tests consisted on maintaining a standing position for 60 seconds trying to remain balanced, oscillating as less as possible and not changing the posture. Every subject performed a set of trials in different experimental conditions. By means of the acquisition and processing of data from Arduino, we could write numerical values of these samples on a text file. We used Matlab to extract these values from files and plotting them on a graph, and to get some necessary parameters to evaluate the performance of the new system, such as the standard deviation, variance, mean value and range.

Acquisitions have been performed on the following experimental conditions:

- with or without a layer of foam rubber
- with open eyes or closed eyes
- with or without the help of audio-feedback

Hence the experiment was composed of 2×2×2 = 8 sessions.

Considering the 4 cases that don’t use ABF, the best case is the one with open eyes and without foam rubber under the feet, because the subject can have most information from its somatosensory system. The worst case is the one with closed eyes, because total absence of visual information and somatosensory reduction. There will also be two intermediate situations: open eyes with foam rubber and closed eyes without foam rubber. All these experiments were compared with the corresponding experiments in presence of ABF, to show both graphically and numerically its helping effect. As we will see, the worst case (closed eyes with foam rubber) is the one where the helping effect is greater, this fact gave us more confidence in the performance of this system mostly for subjects affected by diseases or in rehabilitation, because for those patients the amount of sensorial information necessary for postural balance is reduced.

Every session lasts 60 seconds and data is sampled at a sampling rate of 20 Hz. Hence, we have 1201 samples (we include the sample in time 0 as well as time 60 s), both for AP angle (y) and ML angle (x). With Matlab, we use the function *textscan* to read these values and put them in a matrix 1×1201 (row vector). For every couple of matrices of measures of the angles AP and ML (one for every session), a phase and modulus matrix have been generated by means of the function *cart2pol*.

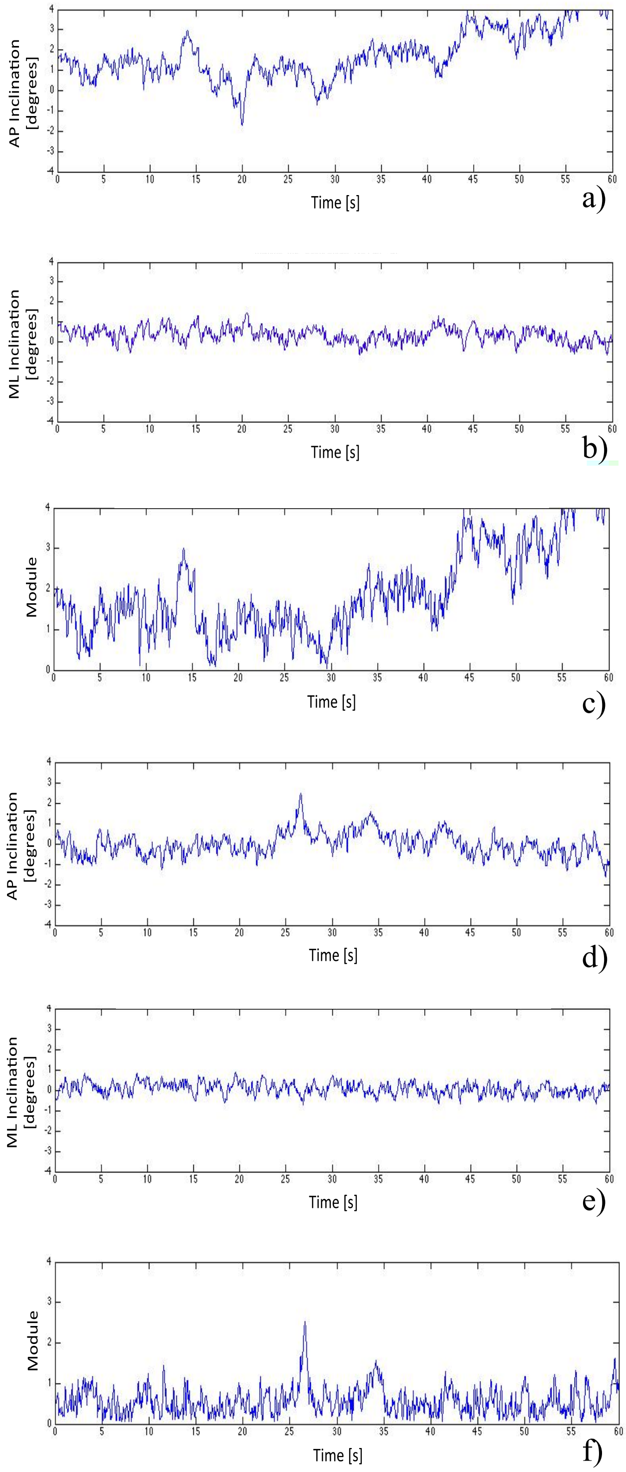

Figure 10. Graphs of (a) x axis, (b) y axis, and (c) module for subject 2, with closed eyes, foam rubber and no ABF. The same measurements with ABF (d,e,f).

The modulus, which means the distance from origin, gives us a measure of the joint effect of the two angles, that is the magnitude of the leaning, but without information about the direction, while the phase give us how much the point rotated around the origin, giving us an indication of how often we changed the direction of leaning.

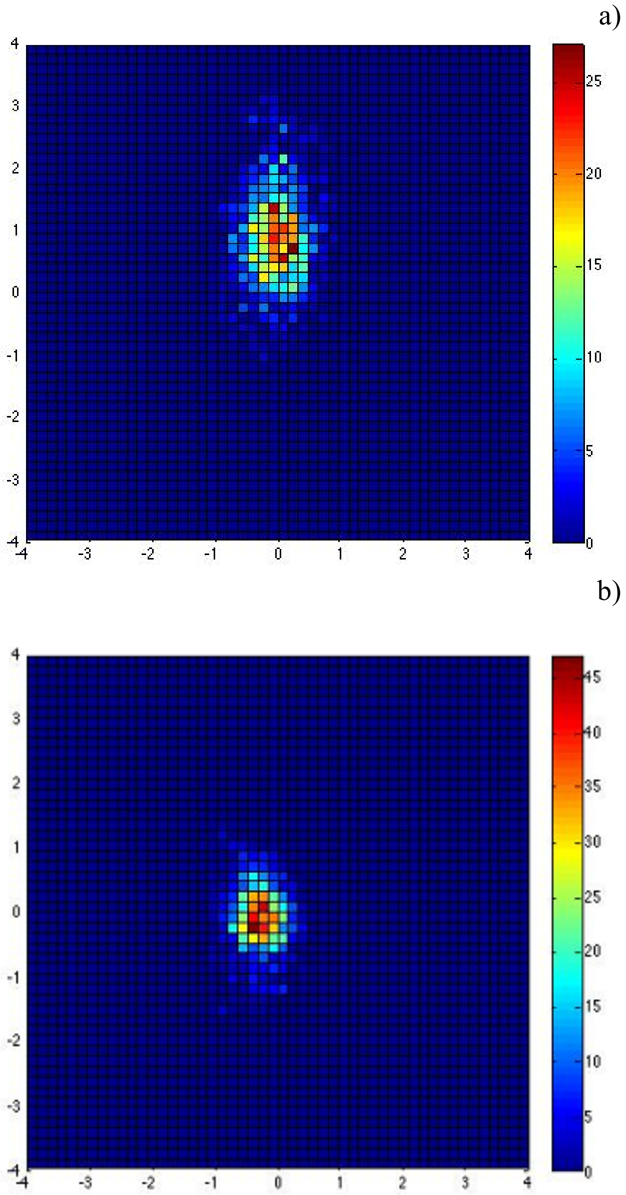

Figure 11. Example of density distribution of values for *x* and *y*. Data is from subject 1 with closed eyes, foam rubber, without ABF (a) and with ABF (b).

Starting from these four matrices, we generated their corresponding four graphs. In order to do this, we first had to create a vector that contained the time values (*nT*) where *n* is the index of the *n*-st sample ($1 \leq n \leq 1201$ including time "zero") and *T* is the sampling period: so, we generated a vector *t* from 0 to 60 with step *T* expressed in seconds ($T = 0.005$) and we have a list of all sampled times in 60 seconds, expressed in seconds ($t = 0$, 0,05, 0.1, 0.15, …, 59.9, 59.95, 60). Now we can use the function plot to create the graphs. We show in Fig. 10 one those graphs.

Finally we traced the histogram in two and three dimensions, by means of the function *histmat*: these graphs express the distribution of the values of the two angles, that is the number of samples insidy the different intervals. An example is in Fig. 11.

For every session, we calculated the following parameters:

- maximum value
- minimim value
- range
- mean value
- standard deviation
- variance

we compared, for every subject, the parameters calculated in the four session without ABF and the ones calculated int rhe four session with ABF. If we call v_{ABF} the variance calculated with ABF in a given case and v_{noABF} the variance calculated without ABF, the relative variation of the variance, in percent is

$$p_v = (v_{ABF} - v_{noABF}) / v_{ABF} = (v_{ABF} / v_{noABF} - 1)\cdot 100$$

the same formula is used for the range *r*:

$$p_r = (r_{ABF} - r_{noABF}) / r_{ABF} = (r_{ABF} / r_{noABF} - 1)\cdot 100$$

In table 1 we report, for every session, the value of p_v and p_r calculated on the module.

Eyes	**Foam rubber**	**p_v**	**p_r**
open	no	-24.59%	-11.27%
closed	no	-20.42%	-12.60%
open	yes	-29.89%	-17.76%
closed	yes	-53.40%	-23.84%

Table 1. Relative variation of the variance and of the range of the module, with different combinations of open/closed eyes and presence of foam rubber. Values are an average over all nine subjects.

5 Conclusion

From an analysis of the reported graphs and results of calculations, we can see that the number and magnitude of the oscillations, the range of the values as well as the standard deviation and variance, are always less in the cases where the subject have been assisted by ABF with respect to the ones where it was not used. Mean values, on the contrary were near to zero.

Moreover, we note that the positive stabilizing effect of ABF was always more prominent in worst case sessions, where the subject has less information for the maintaining a stable posture, so mainly in the sessions with foam rubber and closed eyes.

In the future, with the use of more powerful devices and sensors or new sound synthesis algorithm, such as implemented in Texture [28], we will have the possibility to use this kind of systems in every day life, to individually carry on the rehabilitative physiotherapy even in non clinic contexts. The diffusion of wireless devices could make the use of these systems even more comfortable.

This ABF system is a useful instrument for rehabilitative therapies. It is known that often the enhancements in postural balance or mobility of the patients inside standardized clinical environments couldn’t be maintained outside them. The possibility to have a BFB system that could be used with only a pair of headphones allows to continue the therapy even in contexts of every-day life and in a semi-autonomous way.

Moreover, the substitution of the central processing unit with a palmtop, could allow to send in real-time biomechanical data about the executed exercises from the patient to a physician or a therapist: these could give indications about the correct execution without the need of the patient to go to the clinic.

In alternative, the processing unit could simply record patient’s data; these data could be periodically revised form professional staff, obtaining information about the effectiveness of the therapy and about the possible necessity of integration or substitution. The proposed biofeedback system can represent a possible support instrument for *e-rehabilitation*, a sector of the scientific research that is nowadays developing.

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