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Technical note

Towards the enhancement of body standing balance recovery by means of a wireless audio-biofeedback system

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ABSTRACT

Human maintain their body balance by sensorimotor controls mainly based on information gathered from vision, proprioception and vestibular systems. When there is a lack of information, caused by pathologies, diseases or aging, the subject may fall. In this context, we developed a system to augment information gathering, providing the subject with warning audio-feedback signals related to his/her equilibrium. The system comprises an inertial measurement unit (IMU), a data processing unit, a headphone audio device and a software application. The IMU is a low-weight, small-size wireless instrument that, body-located between the L2 and L5 lumbar vertebrae, measures the subject's trunk kinematics. The application drives the data processing unit to feeding the headphone with electric signals related to the kinematic measures. Consequently, the user is audio-alerted, via headphone, of his/her own equilibrium, hearing a pleasant sound when in a stable equilibrium, or an increasing bothering sound when in an increasing unstable condition.

Tests were conducted on a group of six older subjects (59y-61y, SD = 2.09y) and a group of four young subjects (21y-26y, SD = 2.88y) to underline difference in effectiveness of the system, if any, related to the age of the users. For each subject, standing balance tests were performed in normal or altered conditions, such as, open or closed eyes, and on a solid or foam surface.

The system was evaluated in terms of usability, reliability, and effectiveness in improving the subject's balance in all conditions. As a result, the system successfully helped the subjects in reducing the body swaying within 10.65%-65.90%, differences depending on subjects' age and test conditions.

1. Introduction

The visual, the proprioception and the vestibular systems work to provide standing balance [1,2], so that when one or more of these systems are under sufferance (because of pathologies, diseases, or other reasons) balance capabilities can be reduce, even severely, in effectiveness.

The amount of reduction differs because of number/amount of the systems involved, and can be age-related (because of senescence).

Pathologies of the ear, brain, or sensory nerve can cause dizziness, which affects 47% of men and 61% of women over 70 years of age [3], causing the 25% of falls [4]. Fall-related injuries in older people are a major global health problem, and consequences of falling can psychological produce fear of falling again and depression, which can lead to social isolation [5]. A sedentary life style and drug usage can induce a slowdown of reflexes even in young people [4] (statistics not yet available).

When the sense of balance is reduced because of system issue(s), subjects tend to compensate by means of other systems, as it can be when information from the vestibular system increases in importance if the visual system is limited or absent. Key enabling technology (KET) can provide the subject with information no more or insufficiently supplied by the vestibular system [6–10].

Within this frame, here we propose an audio-biofeedback-based technology (ABF-T) as a KET useful to provide subjects with audio signals coded on the basis of his/her measured standing balance.

The ABF-T consists of wearable devices, or wearables, which are a belt-worn inertial measurement unit (IMU) plus a headphone, and desktop hardware, which comprises a data receiving station and a personal computer. In particular, the wearables are battery-powered low-weight, low-size, operator-independent, and low-cost

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apparatuses. The desktop hardware, wireless communicating with the wearables, provides A/D and D/A conversions, and real-time process data feeding signals to the headphone.

The overall system is validated with ten subjects, grouped in young and older people, performing four different condition tests, so to take into account of normal, and altered-visual (i.e. with closed eyes), and of altered-proprioceptive (i.e. on a foam surface) conditions.

2. State of the art

Within biofeedback systems [11–14], ABF is progressively acquiring greater relevance [15,16]. For example, ABF has been successfully exploited for motor rehabilitation after a hemiparetic stroke [17], when a patient was asked to move the hand to virtually displace an object represented on a computer screen. A cone-like surface changed in color and a sound turned into musical notes according to the right or wrong trajectory of the patient's hand. As a result, patients with sensory-motor deficits better performed compensatory movements using that system. In a recent study, Parkinson's patients enhanced their balance by using an ABF-based therapy [18]. According to Petrofsky [19], ABF was used for the therapy of five subjects with impaired walking capability and reduced muscle strength of the hip adductor (Trendelenburg's sign), caused by spinal cord injury. By means of EMG sensors, the activity of the gluteus medium muscle was measured, and the patients were provided with audio signals coded to inform of incorrect posture. The ABF was implemented successfully also by Dozza et al. [20], who performed tests on healthy subjects in standing position, with closed eyes and on foam on top of a force plate. The subjects' balance information was related to stabilogram diffusion and center of pressure analysis, from which a signal was conceived and audio-provided in a way that the subjects' postural stability increased.

Our ABS system evaluate the swaying characteristics of standing subjects on a solid surface and on a foam surface, in both conditions of open and closed eyes. Innovatively, we empirically defined different regions of swaying and audio-coding algorithms related to those regions, other from previously reported [21,22].

3. Materials and methods

The ABF system is based upon three logical components: a *sensor unit* (consisting of an inertial measurement unit, IMU, device) that measures the subject's movements, a *processing unit* (consisting of an electronic device and a personal computer) that codes the sensory information in real time (routines written in Max/MSP, a Max Software Tools for Media, by Cycling '74, San Francisco, USA), and an *output unit* (consisting of a headphone) that provides the subject an acoustic representation of the physiological parameters.

3.1. Hardware

The sensor unit is a belt-worn low-size (4.77 × 4.12 × 1.76 cm), low-weight (20 g), scientifically validated [23] IMU, termed Movit (Fig. 1(a), by Captiks Srl, Rome, Italy), which provides inertial data related to the movements of the subject. The Movit is operated by a 40 MHz clock microcontroller (AT32UC3A4256 by Atmel, San Jose, California, US) and includes a 3D gyroscope, a 3D accelerometer, a 3D compass (each sensors integrated in a MEMS MPU-9150 by Invensense, San Jose, California, US), and a barometer (BMP-180 by Bosch Sensortec, Reutlingen, Germany). The Atmel microcontroller wireless sends data via 802.15.4 protocol, and a built-in Li-Po battery provides up to 8-hour supply, thus allowing no interruptions during tests (of only few minutes in our case).

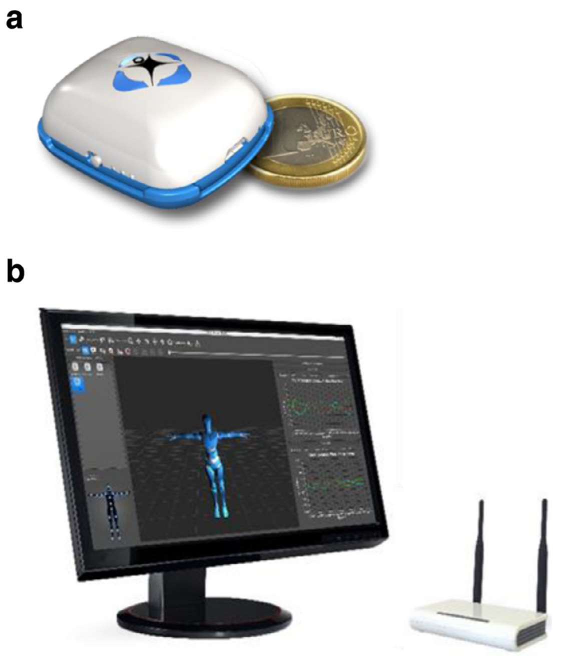

Fig. 1. (a) The Movit unit, dressed by the subject, which integrates a 3D gyroscope, a 3D accelerometer, a 3D compass, a barometer, and a Li–Po battery, (b) the receiving unit, and the software termed "Captiks Motion Studio SDK, CMS".

The Movit unit (which can be networked with up to 15 other units if necessary), wireless sends data to a receiving device (the *receiver*) connected to a personal computer. Specifically, we acquired data from the internal 3-axis digital-output accelerometer, which has a programmable full-scale range of ±2 g, ±4 g, ±8 g and ±16 g, and integrates a 16-bit A/D converter, enabling simultaneous sampling of accelerometers without requiring an external multiplexer. Data rate can range within 4 Hz–1000 Hz. We operated the unit in low-power mode, at an operating current of 140 μA with a 50 Hz updating rate. The Movit was housed in a belt and located at the subject's spine level, between the second and the fifth lumbar vertebra (L2 and L5, Fig. 2). We used a subset of two (out of three) parameters of the accelerometer, as useful for our purposes, in particular the pitch angle (x coordinate, known as AP: Anterior/Posterior), and the roll angle (y coordinate, known as ML: Medial/Lateral).

A personal computer (i5 processor by Intel, 4GB Ram), connected to the receiver component, converts data into coded sounds furnished to the subject by means of headphone (model K701 by AKG) with large-band frequency response (10Hz-39.800 Hz) and high dynamics (105 dB SPL/V). The headphone is an "open-type", which allows the subject hearing the voice of an assistant, if necessary.

3.2. Software

The personal computer runs proprietary software (termed Captiks Motion Studio SDK, CMS, by Captiks Srl) for motion analysis (Fig. 1(b)), so that pitch (x) and roll (y) signals (Fig. 3) are A/D converted and further normalized, within 0–1 range. Output data are converted into proper sound signals by means of routines based on Max/MSP (which is a graphical dataflow programming environments for audio, by Cycling '74, San Francisco, USA) [24].

3.3. Regions and ranges of swaying

We modelled the body of the subject as an inverted pendulum, so that pitch (x) and roll (y) of the trunk motion shaped a

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