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Short communication

Effectiveness of an electro-tactile vestibular substitution system in improving upright postural control in unilateral vestibular-defective patients

Nicolas Vuillerme [a,*], Nicolas Pinsault [a], Anthony Fleury [a], Olivier Chenu [a], Jacques Demongeot [a], Yohan Payan [a], Paul Pavan [b]

[a] *Laboratoire TIMC-IMAG, UMR UJF CNRS 5525, Grenoble, France*
[b] *Cabinet de Réhabilitation Vestibulaire, Grenoble, France*

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Abstract

We investigated the effects of an electro-tactile vestibular substitution system (EVSS) on upright postural control in 12 unilateral vestibular-defective patients. The underlying principle of this system consists in supplying the user with additional information about his/her head orientation/motion with respect to gravitational vertical, normally provided by the vestibular system, through electro-tactile stimulation of his/her tongue. Subjects were asked to stand as immobile as possible with their eyes closed in two No-EVSS and EVSS conditions. Reduced centre-of-foot pressure displacements were observed in the EVSS relative to the No-EVSS condition. These results, demonstrating the effectiveness of the EVSS system in improving upright postural control in unilateral vestibular-defective patients, could have implications in clinical and rehabilitative areas.

Keywords: Balance control; Sensory substitution; Vestibular-defective patients; Tongue Display Unit; Centre-of-foot pressure

1. Introduction

One way to improve balance control, especially in contexts lacking available, accurate and reliable sensory cues, involves the use of biofeedback system. Recently, a head position-based tongue placed biofeedback system has been developed to supply the user with additional information about his/her head orientation/motion, normally provided by the vestibular system (e.g. [1,2]) through electro-tactile stimulation of his/her tongue [3–6]. Whereas previous studies have evidenced the effectiveness of this biofeedback system in improving upright postural control as a sensory supplementation for an alteration of somatosensory information from the ankles and foot soles [5,6], whether this biofeedback system could help individuals to improve their upright postural control, as a sensory substitution for loss of vestibular information, remained to be investigated. The present study was thus designed to address this issue by assessing the effects of this biofeedback system on upright postural control in unilateral vestibular-defective patients, known to constitute one of the largest groups of patients with a falling tendency (e.g., [7]).

2. Methods

2.1. Subjects

Twelve unilateral vestibular-defective patients (age = 70 ± 15 - years; body weight = 68 ± 10 kg; height = 164 ± 6 cm) voluntarily participated in the experiment. They gave their informed consent to the experimental procedure as required by the Helsinki declaration (1964) and the local Ethics Committee. Unilateral vestibular deficit was assessed using a battery of clinical tests. On the whole, a vestibular deficit was considered as unilateral if

* Corresponding author at: Laboratoire TIMC-IMAG, UMR UJF CNRS 5525, Faculté de Médecine, 38706 La Tronche cédex, France.
Fax: +33 4 76 51 86 67.
E-mail address: nicolas.vuillerme@imag.fr (N. Vuillerme).

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results of these tests showed an asymmetry larger than 20%. To assess vestibular dysfunction, we first used a caloric test, during which bithermal caloric irrigation with cold (30 °C) and warm (44 °C) water was induced in the two ears. All patients exhibited a difference in the velocity of slow phases of nystagmus between the two ears larger than 20%. To assess dynamic nonlinearities in vestibular function, we examined head-shaking nystagmus. During this test, patient shook their head vigorously about 30 times from side to side. All patients demonstrated nystagmus following head shaking. Two rotational tests under videonystagmoscopy also have been conducted: (1) the Rotatory Impulsion Test (RIT) at 0.05 Hz and (2) the High Speed Rotational Test (HSRT) at 1 Hz. All patients exhibited a difference in number of saccades to the RIT between clockwise and counter-clockwise way larger than 20%. They also showed a difference in the velocity of slow phases of nystagmus to the HSRT between clockwise and counter-clockwise way larger than 20%. Hearing loss averaged 45 ± 19 dB (range 5–70 dB) in the affected ear. The history of the symptoms ranged from 1 to 22 years (mean 6 ± 6 years).

2.2. Experimental procedure

Subjects stood barefoot, feet 10 cm apart, their hands hanging at the sides, with their eyes closed, on a plantar pressure data acquisition system (FSA Orthotest Mat, Vista Medical Ltd.). They were asked to sway as little as possible in two No-EVSS and EVSS experimental conditions. The No-EVSS condition served as a control condition. In the EVSS condition, subjects performed the postural task using a vestibular-based tongue-placed electro-tactile biofeedback system (BrainPort Balance Device, Wicab Inc.). The underlying principle of this biofeedback system consists in supplying the user with additional information about his/her head orientation with respect to gravitational vertical through electro-tactile stimulation of his/her tongue. The BrainPort Balance Device system comprises two principal components: (1) the intraoral device (IOD) and (2) the controller.

On the one hand, the IOD is made up of an electro-tactile array, a tether, and a micro-electro mechanical system (MEMS) 3-axis, ±2 g, digital output accelerometer (manufactured by ST Microelectronics). Electro-tactile stimuli are delivered to the dorsum of the tongue by the electrode array (Tongue Display Unit, TDU), which is fabricated using industry-standard photolithographic techniques for flexible circuit technology and employs a polyimide substrate. All 100 electrodes (1.5 mm diameter, on 2.32 mm centers) on the 24 mm × 24 mm array are electroplated with a 1.5-μm-thick layer of gold. The tether (12 mm wide × 2 mm thick) connects the electro-tactile array and accelerometer to the controller. The MEMS accelerometer, mounted on the superior surface of the electrode array, senses head position along both the anteroposterior and medioateral directions. Both the accelerometer and associated flex circuit are encapsulated in a silicone material to ensure electrical isolation for the user.

On the other hand, the controller contains an embedded computer (ColdFire MCF5249C, 120-MHz, 32-bit microprocessor), stimulation circuits, user controls, and battery power supply. Custom software operating on the controller converts head-tilt signals from the accelerometer in the IOD into a dynamic 2 × 2 electrodes pattern of electro-tactile stimulation. The stimulation is created by a sequence of three 25-μs wide pulses presented at a rate of 200 Hz. The amplitude value of the pulse sequence or 'burst' is updated at 50 Hz. Output coupling capacitors in series with each electrode assure zero net DC current to minimize the potential for tissue irritation. This waveform produces a tactile stimulus that is perceived by users as a continuous 'buzzing' or 'tingling' sensation, with minimal sensory adaptation.

In the current implementation, mapping the 12-bit data to the 10 × 10 oral tactile array causes 'binning' of the output signal into 2.8° increments (both mediolateral and anteroposterior) to individual tactor rows or columns, to a maximum range of ±14° in each direction. Note that a pilot study with kinematic data showed that the use of a linear accelerometer alone is sufficient to provide directional information to the subject, when the device is used in the relatively static training environment. Rate sensor data coupled with linear accelerometer data could offer a more precise measure of angular and linear displacement; however, in this application, it is not necessary, as long as the stimulus displacement is in the correct direction (the direction of tilt).

Subjects kept the IOD in their mouth all over the duration of the experiment (i.e. in both the No-EVSS and EVSS conditions). In the EVSS condition, subjects continuously perceived both position and motion of an activated electrode on the TDU, corresponding to head orientation with respect to gravitational vertical (Fig. 1). Specifically, when the subject's head sways on the left, right, forwards and backwards, the electro-tactile stimulation on the tongue continuously moves to the left, right, forward and backward, respectively. Subjects were then asked to adjust head orientation and to maintain the stimulus pattern at the centre of the TDU. Several practice runs were performed prior to the test to ensure that subjects had mastered the relationship between the different head positions and tongue stimulations.

Three 30-s trials for each experimental condition were performed. The order of presentation of the two experimental conditions was randomized.

2.3. Data analysis

Three dependent variables were used to describe subject's postural behavior:

(1) The surface area (mm^2) covered by the trajectory of the CoP with a 85.35% confidence interval [8] as a measure of the CoP spatial variability;
(2) The range of the CoP displacements (mm) representing the difference between the maximum and minimum values of the CoP; and
(3) The mean velocity of the CoP displacements (mm/s) representing the total distance covered by the CoP (total sway path) divided by the duration of the sampled period and constituting a good index of the amount of activity [9].

2.4. Statistical analysis

The means of the three trials performed in each of the No-EVSS and EVSS conditions were compared using paired *t*-tests. Level of significance was set at 0.05.

3. Results

Analysis of the surface area covered by the trajectory of the CoP showed a smaller value in the EVSS than No-EVSS condition ($t = 3.23$, $P < 0.01$, Fig. 2A).