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Can an electro-tactile vestibular substitution system improve balance in patients with unilateral vestibular loss under altered somatosensory conditions from the foot and ankle?

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Abstract— **This pilot study aimed at assessing the feasibility and the effectiveness of an electro Electro-tactile Vestibular Substitution System (EVSS) in patients with unilateral vestibular loss under normal and altered somatosensory conditions from the foot and ankle.**

Four unilateral vestibular-defective patients voluntarily participated in the experiment. They were asked to stand upright as still as possible with their eyes closed in two *Normal* and *Altered* foot and ankle sensory conditions. In the *Normal* condition, the postural task was executed on a firm support surface constituted by the force platform. In the *Altered* condition, a 2-cm thick foam support surface was placed under the participants' feet. These two foot and ankle sensory conditions were executed under two *No EVSS* and *EVSS* experimental conditions. The *No EVSS* condition served as a control condition. In the *EVSS* condition, participants executed the postural task using a biofeedback system whose underlying principle consisted of supplying them with additional information about their head orientation/motion with respect to gravitational vertical through electro-tactile stimulation of their tongue. Centre of foot pressure displacements (CoP) were recorded using the force platform.

Results showed that, relative to the *No EVSS* condition, the *EVSS* condition decreased CoP displacements in both the *Normal* and the *Altered* foot and ankle sensory conditions. Interestingly, the stabilizing effect was more pronounced in the *Altered* than in the *Normal* foot and ankle sensory condition.

These preliminary results suggest that patients with unilateral vestibular loss were able to take advantage to a head position-based electro-tactile tongue biofeedback to mitigate the postural perturbation induced by alteration of somatosensory input from the foot and the ankle.

I. INTRODUCTION

THE concept of "sensory substitution" that refers to the translation of sensory information that is normally available via one sense to another was pioneered by Paul Bach-y-Rita during the late 1960's [1]. Initially applied to provide distal spatial information to blind people through a tactile display [1-3], this concept has been extended to provide a substitute body-orientation reference to individuals with vestibular dysfunction, by delivering them head-position information/motion - normally provided by the vestibular system (e.g. [11, 20]) - via electro-tactile stimulation of the tongue [21]. Previous studies using this so called "electro-tactile vestibular substitution system" (EVSS) have reported that sensory substitution via electro-tactile stimulation of the tongue was effective at improving balance control in both healthy and balance-impaired individuals [6, 7, 21-24, 27]. However, while the effectiveness of this EVSS in improving postural control during bipedal quiet standing has recently been reported in unilateral vestibular-defective patients under reliable somatosensory conditions from the foot and ankle [24], whether these patients could benefit from EVSS when subjected to challenging foot and ankle somatosensory condition remains to be investigated.

The present experiment was designed to address this issue by assessing the feasibility and the effectiveness of an electro-tactile vestibular substitution system in patients with unilateral vestibular loss under normal and altered somatosensory conditions from the foot and ankle.

II. METHODS

A. *Participants*

Four unilateral vestibular-defective patients 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 [24]. On the whole, a vestibular deficit was considered as unilateral if results of these tests showed an asymmetry larger than 20 %. To assess vestibular dysfunction, we first used a caloric test, during which

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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 ways larger than 20 %. They also showed a difference in the velocity of slow phases of nystagmus to the HSRT between clockwise and counter-clockwise ways larger than 20 %. Hearing loss averaged 43 ± 12 dB in the affected ear. The history of the symptoms ranged from 6 to 10 years.

B. Experimental procedure

Participants stood barefoot on a force platform (sampling frequency: 40 Hz) in a natural but standardized position (feet abducted at 30°, heels 3 cm apart), their arms hanging loosely by their sides and their eyes closed.

They were asked to stand upright as still as possible in two *Normal* and *Altered* foot and ankle sensory conditions and two conditions of *No EVSS* and *EVSS*.

In the *Normal* condition, the postural task was executed on a firm support surface constituted by the force platform. In the *Altered* condition, a 2-cm thick foam support surface was placed under the subjects' feet.

The *No EVSS* condition served as a control condition. In the *EVSS* condition, subjects executed the postural task using an electro-tactile vestibular substitution system (BrainPort Balance Device, Wicab Inc.). This system comprises two principal components: (1) the intraoral device (IOD) and (2) the controller. On the one hand, the intraoral device is made up of an electro-tactile array, a tether, and a micro-electro mechanical system (MEMS) 3-Axis, ±2 g, digital output accelerometer. 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 polyiamide 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 antero-posterior and medio-lateral 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 electrode pattern of electro-tactile stimulation. The target position (x_n,y_n) of the stimulation at time n is calculated from the head-tilt data as the difference between the values of the position vector at t_n and t_0, by:

$$x_n = c \sin(\Theta_{x|n} - \Theta_{x|0})$$

$$y_n = c \sin(\Theta_{y|n} - \Theta_{y|0})$$

where 'c' is a linear scaling factor used to adjust the stimulus pattern range of motion on the electrode array to match the subject's maximum anticipated head-tilt or sway and values for $\Theta_{x|n}$, $\Theta_{x|0}$, $\Theta_{y|n}$, $\Theta_{y|0}$ are the instantaneous and initial tilt angles in x and y, respectively [6].

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 degree increments (both medio-lateral and antero-posterior) to individual tactor rows or columns, to a maximum range of ± 14 degrees 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).

Participants were asked to keep the IOD in their mouth all over the duration of the experiment, i.e. in both *No EVSS* and *EVSS* conditions. In the *EVSS* condition, subjects continuously perceived both position and motion of a small "target" stimulus on the tongue display, corresponding to head orientation/motion with respect to gravitational vertical. Specifically, as illustrated in Figure 1, when the participant's head sways on the left, right, forwards and backwards, the electro-tactile stimulation on the tongue moves to the left, right, forward and backward, respectively. Participants were then asked to continuously adjust their head orientation and to maintain the stimulus pattern at the centre of the display [6, 7, 21-24].

Prior to the experiment, participants performed practice trials with eyes closed on the firm and on the foam support surfaces, with and without the provision of *EVSS*, by voluntarily swaying in different directions. The purpose of these practice trials was for the participants to ensure that they had become familiar with standing with the foot and ankle sensory conditions and they had mastered the relationship between the different head positions and lingual electro-tactile stimulations. Data from these practice trials were not considered in the analyses.

Three 25.6-s trials for each condition were executed. The order of presentation of the two *Normal* and *Altered* foot and ankle sensory conditions and two conditions of *No EVSS* and *EVSS* was randomized. Participants were not given feedback about their postural performance.

III. RESULTS AND DISCUSSION

Our initial data analysis was based on the surface area (mm²) covered by the trajectory of the CoP, which provides a measure of the size of the CoP over the support surface.

Results showed that, relative to the *No EVSS* condition, the *EVSS* condition yielded a 29 % CoP surface area reduction in the *Normal* foot and ankle sensory condition and a 43 % CoP surface area reduction in the *Altered* foot and ankle sensory condition.

Results first confirm that patients with unilateral vestibular loss were able to efficiently take advantage of a head orientation/motion information delivered through electro-tactile stimulation of the tongue to improve their postural control during quiet standing under *Normal* foot and ankle sensory conditions [24]. This was also the case in the *Altered* foot and ankle sensory condition. More importantly, results further showed that the provision of the EVSS allowed them to mitigate the destabilizing effect induced by the alteration of somatosensory information at the foot and the ankle. At this point, these results extend those previously obtained in young healthy adults to a population of unilateral vestibular loss patients [23].

Although an extended study including a larger number of participants is needed to confirm these preliminary data, the larger CoP surface area reduction observed in the *Normal* than in the *Altered* foot and ankle sensory conditions suggest that the effectiveness of the EVSS in improving postural control during bipedal standing depends on the somatosensory context. Along these lines, these results are in accordance with a previous study reporting a greater stabilizing effect provided by the EVSS observed when ankle proprioception was altered through Achilles tendon vibration than when ankle proprioception was normal [22]. Interestingly, our results obtained with vestibular-defective patients under normal and altered somatosensory from the foot and the ankle are also consistent with those recently reported in healthy subjects during vestibular disturbances induced by binaural galvanic vestibular stimulation in normal and altered support-surface conditions [27]. Indeed, EVSS has been shown to improve the control of bipedal posture during GVS toward baseline levels, again with the greatest postural improvement occurring during trials with rotation sway-referencing, i.e., in conditions of altered somatosensory conditions.

More largely, with regard to the effectiveness of a biofeedback-based intervention for improving balance control during quiet stance, the present findings are in line with previous studies reporting that the availability of a biofeedback - visual [13], vibro-tactile [10, 16, 25, 26], electro-tactile [6, 7, 21, 24] or auditory [4, 8, 9, 12] - improves upright postural control in patients with vestibular disorders. They also support recent findings of Dozza et al. who reported that augmenting sensory information for balance control by providing audio-biofeedback related to trunk acceleration to individuals with bilateral vestibular loss yielded the largest stabilizing effect when the environment provided limited somatosensory and visual information [9].

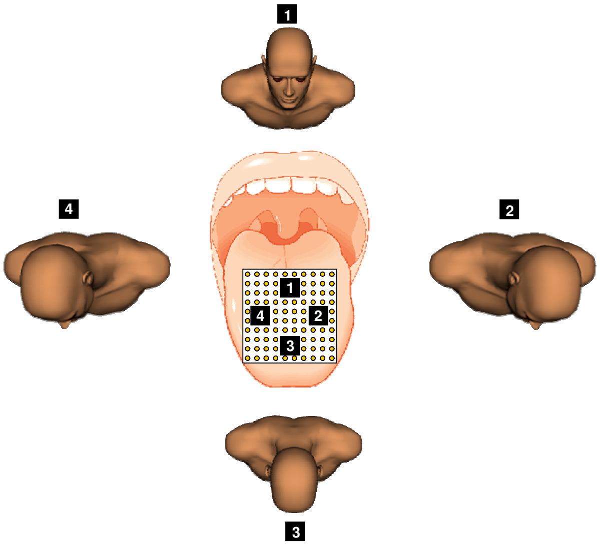

Fig. 1. Sensory coding schemes for the Tongue Display Unit as a function of the head orientation with respect to gravitational vertical: (1) extended head posture, (2) left-side-tilted posture, (3) flexed posture and (4) right-side-tilted posture

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