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Short Communication

CLOSING AN OPEN-LOOP CONTROL SYSTEM: VESTIBULAR SUBSTITUTION THROUGH THE TONGUE

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The human postural coordination mechanism is an example of a complex closed-loop control system based on multisensory integration [9, 10, 13, 14]. In models of this process, sensory data from vestibular, visual, tactile and proprioceptive systems are integrated as linearly additive inputs that drive multiple sensory-motor loops to provide effective coordination of body movement, posture and alignment [5–8, 10, 11]. In the absence of normal vestibular (such as from a toxic drug reaction) and other inputs, unstable posture occurs. This instability may be the result of noise in a functionally open-loop control system [9]. Nonetheless, after sensory loss the brain can utilize tactile information from a sensory substitution system for functional compensation [1–4, 12]. Here we have demonstrated that head-body postural coordination can be restored by means of vestibular substitution using a head-mounted accelerometer and a brain-machine interface that employs a unique pattern of electrotactile stimulation on the tongue. Moreover, postural stability persists for a period of time after removing the vestibular substitution, after which the open-loop instability reappears.

Keywords: Vestibular; sensory substitution; electrotactile stimulation; brain plasticity.

1. Introduction

Persons who have bilateral vestibular damage, such as from an adverse reaction to antibiotic medications, experience functional difficulties that include postural "wobbling" (both sitting and standing), unstable gait, and oscillopsia that make it impossible, for example, to walk in the dark without risk of falling. This condition presents the unique opportunity to: (i) study a model of an open-loop human control

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system, and (ii) to re-establish head-postural control by means of vestibular substitution using a head-mounted accelerometer and an electrotactile brain-machine interface (BMI) through the sense of touch on the tongue.

The control of normal upright posture is mediated by a complex system that relies on the integration of multiple sensory inputs (e.g., vestibular, visual, tactile, proprioceptive, and auditory) [5–8, 10, 11]. It remains unclear as to specifically how this sensory fusion acts in self-orientation. Nonetheless, the models developed to predict the effect of the various inputs have demonstrated that these systems provide convergent and redundant information about the position of body segments relative to each other and to overall body orientation in space. In particular, detection of linear and angular acceleration of the head may be used to resolve self-motion from that of the surrounding visual environment.

In the absence of a functional vestibular system, head-posture may be detected by an artificial sensor and presented to the brain through a substitute sensory channel: electrotactile stimulation on the tongue. We have previously demonstrated the merits of the tongue as a brain-machine interface (BMI) [1, 4]. For the brain to correctly interpret information from a sensory substitution device, it is not necessary that the information be presented in the same form as the natural sensory system. For example, we do not see with the eyes; the optical image does not go beyond the retina, where it is turned into spatio-temporal patterns of action potentials (AP's) along the optic nerve fibers [6]. The brain then recreates the images from analysis of the impulse patterns. Thus, for a sensory substitution event to occur, one need only to accurately entrain action potentials in an alternate information channel, which do not differ significantly for the individual senses. With training, the brain learns to appropriately interpret that information and utilize it to function as it would with data from the intact natural sense.

The use of vestibular sensory substitution produces a strong stabilization effect on head and body coordination in subjects with bilateral vestibular dysfunction (BVD). Under experimental conditions (in we which removed visual and tactile inputs: see Methods), we identified three characteristic and unique motion features (mean-position drift, sway, and periodic large-amplitude perturbations) that consistently appear in the head-postural behavior of BVD subjects (see Fig. 1). With vestibular substitution (VS) however, the magnitude of these features are greatly reduced or eliminated. Further analysis of the experimental data revealed that these perturbations are periodic (within individual) and did not occur just at the extremes of motion, which would suggest they are triggered by proprioceptive mechanisms. Specifically, we found that these postural "spikes" do not always correct for the large coincident postural excursions, but in many instances appeared to actually *cause* instability. We postulate that in the absence of the integrated inputs to a normally closed-loop multisensory control process an intrinsically unstable system becomes vulnerable to noise (from both internal and external sources), as characterized by Jeka [9]. The result of providing vestibular substitution supports this specific

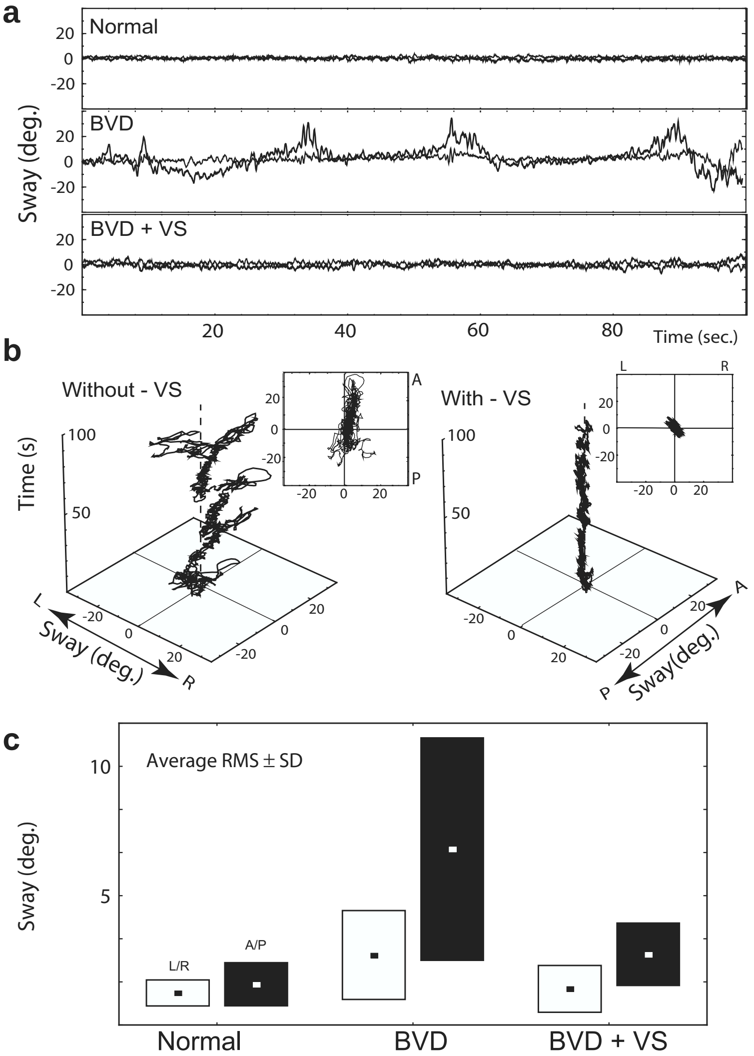

Fig. 1. Vestibular substitution stabilization effect. (a) Graph of head displacement in both anterior/posterior (A/P), and medial-lateral (M/L) directions for an adult subject with eyes closed and sitting upright without back support. Top: Typical profile for an unaffected individual. Mean amplitude: ±1.4 deg. (M/L); ±1.8 deg. (A/P), is centred about zero. Center: Subject with bilateral vestibular dysfunction (BVD). Mean amplitudes: ±3.0 deg. (M/L); ±7.6 deg. (A/P). Note the slow drift of the mean position, and occurrence of periodic (∼ 23 s.) perturbations. Bottom: The same subject while using tactile vestibular substitution (VS). Mean amplitudes of angular displacement are reduced to: ±1.4 deg. (M/L); ±3.1 deg. (A/P). (b) "Spaghetti" plots of the same displacement profiles. Left: 3-Dimensional graph showing head position as a function of time (vertical axis). Inset: 2-D projection onto horizontal plane. Right: Performance with tactile vestibular substitution (VS). (c) Box plots showing average (RMS) and Standard Deviation (SD) of angular displacement after linear regression across time to extract magnitude and direction of mean-position drift. Left pair: Overall results for eight UA subjects. Center pair: Cumulative results of eight successfully completed trials for one BVD subject. Right pair: Cumulative results of eight trials for same clinical subject using (BVD with VS). Mean M/L performance approaches that of normal head-postural behavior. Motion in A/P direction is slightly larger and more variable, but clearly superior to the unaided condition.

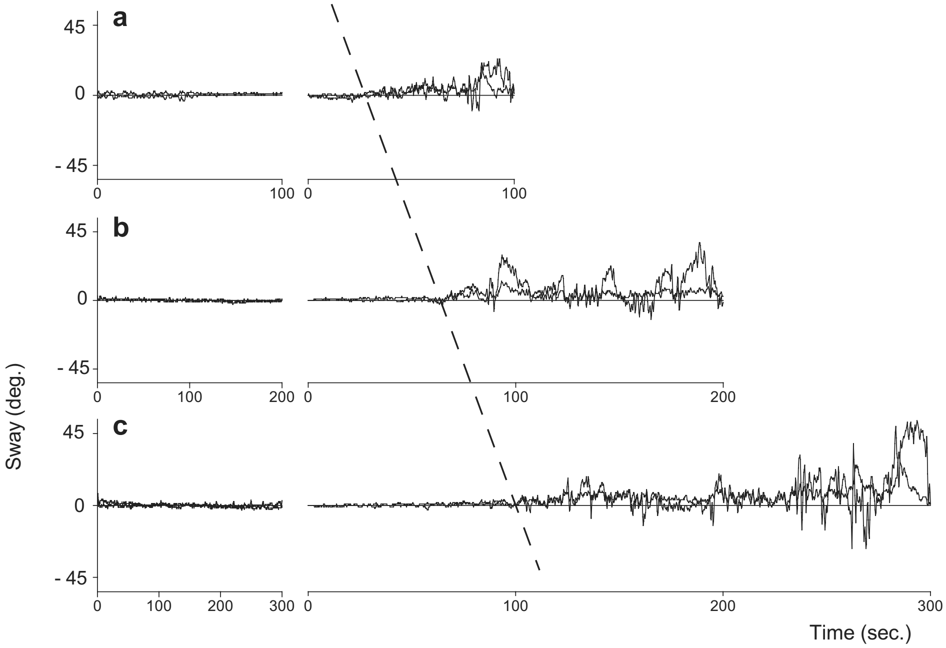

Fig. 2. Vestibular substitution after-effect. Results of the second experiment (EC-VS → EC). Left half of each row is with VS, right half is the post-VS period. A consistent proportionality of relative head-postural stability without VS to the period with VS exists across the three test durations (a: 100, b: 200 and c: 300 sec. for each phase). Oscillations consistently begin with small A/P motion at the head at approximately 30% into the non-VS period, while the torso remains initially stable. Head-movement gradually increases in amplitude, and at approximately 70% of the post-VS (EC) period motion begins to involve the torso, again growing in amplitude over time until the subject is unable to maintain stability.

characterization of the head-postural control system, and demonstrates that vestibular information plays a crucial role in the overall control postural process.

During these experiments the BVD subjects reported feeling "normal", "stable", or having reduced perceptual "noise" while using VS and for short periods after removing the stimulation. This "after-effect" was specifically explored in a second experiment involving a single BVD subject by recording head position during prescribed periods of VS, followed without interruption by equal periods without tactile or other feedback. As can be seen in Fig. 2, there is an initial period of relative quiet after removal of VS. Then at about 30% into the non-VS period, small amplitude anterior-posterior (A/P) oscillations begin to appear at the head, progressively increasing in amplitude with time. At approximately 60% into this period torso A/P motion becomes evident, and increases with time until finally the entire upper body reaches instability and the experiment is terminated. The duration of the post-VS instability appears to be linearly related to the duration of VS period (within the ranges tested). These results again provide evidence that the presence of meaningful substitutive input to the multisensory postural control process is sufficient to produce stability approaching that of unaffected individuals [cf. Fig. 1(c)]. Conversely, in the absence of valid data from vestibular, visual and tactile sources, the system appears inherently noisy and unstable.

The results presented here support the concept of developing practical tactile sensory substitution and augmentation systems based on brain plasticity [2]. The technology may also be applicable to vestibular stress situations such as for astronauts and pilots who are subject to spatial disorientation [10]. The tongue BMI may also be applied to other sensory substitution systems such as for blindness, deafness or diabetic insensate feet, and to augmentation systems such as for urban search and rescue (with an infrared camera) or for underwater orientation and navigation [1–4, 12]. Finally, the BMI also offers a tool for studies of brain reorganization, some of which have already been reported [2, 4].

2. Methods

A miniature 2-axis accelerometer (Analog Devices ADXL202) was mounted on a low-mass plastic hard hat. Anterior-posterior and medial-lateral angular displacement data (derived by double integration of the acceleration data) were fed to a previously developed tongue display unit (TDU) that generates a patterned stimulus on a 144-point electrotactile array (12×12 matrix of 1.8 mm diameter gold-plated electrodes on 2.3 mm centers) held against the superior, anterior surface of the tongue [1]. Subjects readily perceived both position and motion of a small “target” stimulus on the tongue display, and interpreted this information to make corrective postural adjustments, causing the target stimulus to become centered.

Four subjects with bilateral vestibular dysfunction (BVD: 2 M, 2 F: mean age 49.8 yr., SD = 9.7 yr.) and eight unimpaired subjects (5 M, mean age = 40.6 yr., SD = 15.5 yr.; 4 F, mean age = 41 yr., SD = 9.8 yr.) were studied using repeated measures in two basic conditions. Subjects were seated in a modified Romberg position (elbows lightly cupped in opposite hands): Eyes Closed (EC), and Eyes Closed with Vestibular Substitution (EC-VS) for trials of 100 seconds duration. In a second experiment, a single BVD subject was tested in the EC-VS mode for 100, 200, or 300 seconds, followed without interruption by the EC condition for an equal period (EC-VS → EC).

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