The purpose of this study was to assess the influence of electrotactile feedback on postural control performance during binaural galvanic vestibular stimulation (GVS). Postural equilibrium was measured with a computerized hydraulic platform in 10 healthy adults (6M, 4F, 24–65 y). Feedback of anterior–posterior (AP) and mediolateral (ML) body sway was derived from a 2-axis linear accelerometer mounted on a torso belt and displayed on a 144-point electrotactile array held against the anterior dorsal tongue. Subjects were trained to use the tongue electrotactile feedback (TEF) by voluntarily swaying to draw figures on their tongue, both with and without GVS. Subjects performed 24 randomized trials (20-s duration with eyes closed, 2 trials per condition), including 4 support surface conditions (fixed, rotational sway-referenced, translating the support surface proportional to AP sway, and combined rotational–translational support-platform sway referencing), and 3 feedback conditions (baseline, GVS, and GVS with TEF). Postural performance was assessed using deviations from upright (peak-to-peak and root-mean-square sway) and convergence toward stability limits (time and distance to limit of support boundaries). Postural stability was impaired (with respect to baseline) during GVS in all platform conditions, with larger decrements in performance during trials with rotation sway-referencing. Electrotactile feedback improved performance with GVS toward non-GVS levels, especially during trials with rotation sway-referencing. These results demonstrate the effectiveness of TEF in providing sensory substitution to maintain postural stability during vestibular disturbances.

**Key words:** posturography; translation; biofeedback

**Introduction**

Integration of multisensory inputs to detect tilts relative to gravity is critical for sensorimotor control of upright orientation. Bilateral vestibular loss leads to difficulty in reliably making judgments of perceived verticality, and adversely affects the stabilization of head and body posture. MacDougall and colleagues recently demonstrated that unpredictably varying binaural galvanic vestibular stimulation (GVS) induces postural instability that is similar to profound bilateral loss, especially during conditions where visual and proprioceptive feedback are altered. Hlavacka and
Horak\textsuperscript{5} also demonstrated that binaural GVS compromises postural stability during translations of the support surface.

One advantage of GVS is the transient nature of the impairment. MacDougall, Moore, and colleagues have observed that short exposures to GVS can temporarily cause postural\textsuperscript{4} and locomotor\textsuperscript{6} dysfunction without any evidence of aftereffects when the GVS is turned off. Thus, GVS can be employed as a technique to briefly disrupt vestibular-mediated responses while allowing comparison to baseline measures, and/or can be used to evaluate promising treatments such as sensory substitution aids.

Rehabilitating patients with bilateral vestibular loss typically involves training to utilize vision, proprioception, and peripheral sensation to substitute for the missing vestibular input.\textsuperscript{7,8} However, compensation is limited in some patients.\textsuperscript{9} Retraining proprioceptive function is often incomplete due to the strong reliance on visual mechanisms to compensate for vestibular loss. Electrotactile feedback to the tongue was developed by Bach-y-Rita and colleagues as a sensory aid to display orientation cues on the heavily innervated and highly sensitive dorsal anterior tongue surface.\textsuperscript{10} Initially devised to examine sensory substitution in the blind, this technique has recently been extended to provide a substitute body-orientation reference to subjects with vestibular dysfunction.\textsuperscript{11} The purpose of this study was to assess the influence of tongue electrotactile feedback (TEF) on postural control performance during binaural GVS as previously developed by MacDougall and colleagues.\textsuperscript{4} Trials were conducted with eyes closed and altered somatosensory feedback to accentuate reliance on the electrotactile feedback in the presence of the disrupted vestibular function associated with GVS.

**Methods**

Postural performance was measured with a computerized hydraulic platform in 10 healthy adults (6M, 4F, 24–65 y). Each subject reported no history of balance or vestibular abnormal-
Galvanic Vestibular Stimulation

GVS was achieved using a system previously described.4 Bilateral bipolar current (max 3.5 mA) was delivered to the surface of the subject’s skin via leads and large electrodes placed over the mastoid processes. An elastic headband was utilized to maintain consistent surface contact of the electrodes throughout the session. The large size of the electrodes and use of electrode gel ensured that the stimulus amplitude did not cause discomfort, and the lead cables were arranged so they did not restrict movements. The galvanic stimulus was a modified sum-of-sines that was delivered in bilateral and bipolar fashion. The dominant frequencies were at 0.16, 0.33, 0.43, and 0.61 Hz. The GVS stimulus was initiated just prior to the start of a trial by a stand-alone laptop computer, and turned off at the end of each trial (typically 25- to 30-s periods of constant exposure). Motion-sickness symptoms, if any were noted, were recorded in between trials.

Tongue Electrotactile Feedback

Electrotactile feedback of AP and ML body orientation was derived from a two-axis linear accelerometer mounted on a torso belt. The linear accelerometer package was mounted at approximately 55% of subject height to be near the COM, thus the feedback closely corresponded to body-sway position that was used for the rotational and translation sway-referencing. The display consisted of a 144-point electrotactile array held against the anterior dorsal tongue (BrainPort, Wicab, Inc., Middleton, Wisconsin, USA). The signals were scaled so that instantaneous feedback of sway was continuously provided within the limits of stability. The intensity of the electrotactile feedback was adjusted as needed throughout the session to optimize resolution while minimizing discomfort. Subjects were trained to use TEF at the beginning of each session by voluntarily swaying to draw figures on their tongue, including a cross, circle, figure 8, and letters. The training trials were then repeated using both TEF and GVS. In order to minimize stabilizing influences of TEF cables connected to the control unit, the cables from the tongue array were secured to the torso belt and thus moved with the subject. Subjects were required to keep the intraoral display in their mouths on all trials, including those where TEF was not used.

Data Analysis

Postural performance was assessed using deviations from upright (peak-to-peak and root-mean-square [RMS] sway) and convergence toward stability limits (minimum time and distance to limit of support boundaries). The limit of support (LOS) in the AP plane was defined by the foot boundary.15 AP sway was differentiated to compute sway velocity, and both minimum time and distance to LOS took into account the direction of COM, for example, the distance or time to the LOS boundary was computed relative to either edge of toes or heel, depending on which the COM was moving toward. A maximum value of 5 s for the time to LOS was allowed. Using an alpha error of 0.05 as the decision rule, the null hypothesis that there was no difference across conditions was tested for each of these measures using a paired Wilcoxon signed-rank statistic.

Results

The GVS was well tolerated by all subjects. Two subjects reported mild flushing and sweating, and one subject noted mild stomach awareness. During quiet stance without sway-referencing, most subjects perceived more unsteadiness during GVS laterally than in the AP direction. However, the most striking differences occurred in the direction of the sway-referencing, so all remaining results refer to AP measures.

No falls were observed during baseline testing of each condition, nor during GVS testing.
with a fixed or translation-SR support surface. However, two falls occurred during GVS testing for each condition where there was rotation-SR support surface. The peak-to-peak sway was generally twice as large during conditions involving rotation-SR as compared to conditions that did not involve rotations (compare Fig. 1C and 1D with Fig. 1A and 1B).

Consistent with the results of MacDougall and colleagues, GVS significantly increased peak-to-peak sway relative to baseline for both fixed and rotation-SR conditions (Fig. 1A and 1C). The same finding was present for RMS sway (e.g., increase from $1.8^\circ \pm 0.1$ to $2.0^\circ \pm 0.1$ for rotation-SR, mean $\pm$ SEM). GVS also significantly decreased the minimum time to LOS for both conditions (Fig. 2A and 1C), indicating that during trials with GVS, subjects came closer to stability margins. This was also true for the minimum distance to LOS, for example, decreasing from $4.0^\circ \pm 0.2$ to $2.9^\circ \pm 0.3$ for rotation-SR. The same trend for GVS to impair postural performance was present during the conditions involving translation-SR, although this was only significant for peak-to-peak and RMS sway during rotation--translation SR (Fig. 1D).

Most notable to this investigation, electrotactile feedback during GVS successfully improved peak-to-peak and RMS sway to baseline levels for all conditions (Fig. 1). There was a significant improvement between GVS without TEF and GVS with TEF for both rotation-SR and translation-SR conditions. Interestingly, TEF did not significantly alter measures of minimum time or distance to LOS during GVS.

**Discussion**

The first main finding in this study was that postural stability was impaired with GVS in all platform conditions, with larger decrements in performance during trials with rotation sway-referencing. This is consistent with the findings of MacDougall and colleagues, who utilized a larger stimulus current (5 mA versus 3.5 mA). In addition, this study also demonstrates that
GVS compromises postural stability as determined by convergence to stability limits. The minimum time to LOS reflects control of both COM position and velocity, and therefore may better account for fall risk during dynamic motions. The observation that subjects were more at risk of exceeding their stability limits is consistent with MacDougall’s conclusion that higher levels of GVS distort vestibular input to balance centers in the cerebellum.

The second main finding of this study was that electrotactile feedback improved performance during GVS toward baseline levels, again with the greatest improvement during trials with rotation sway-referencing. This is consistent with Vuillerme and colleagues, who recently demonstrated that tongue electrotactile feedback reduced sway in normals on both fixed and unstable (foam block) support surfaces. Our laboratory has also noted improvements using TEF with BVL patients (unpublished data). Anecdotally, TEF training appeared to have retention effects that appear promising. Figure 3 provides preliminary data for one of our BVL patients during the eyes-closed rotation-SR condition, commonly referred to as Sensory Organization Test 5. Prior to TEF training, this subject exhibited a fall pattern that is typical of bilateral loss of vestibular function. The subject was then exposed to four consecutive days of TEF training with both morning and afternoon sessions. Following the training, retention effects were monitored with measurements immediately after the last training, and then at +12 h and +1, 2, 3, and 5 days. After the first day of training, although improvements were noted, the subject still tended to fall on SOT-5. However, by the end of the second day the median SOT-5 score was already within clinical normal limits, with further improvements after
Figure 3. Sample of training and retention effects of tongue electrotactile feedback (TEF) on one bilateral vestibular loss (BVL) patient during the rotation sway-referenced (SR) condition. Each bar represents the equilibrium (EQ) score (median of three trials) derived from peak-to-peak anterior–posterior (AP) sway. An EQ of 0 represents a fall, while EQ of 100 represents absence of sway. The line at 45 represents the age-adjusted clinical normal limits.

a third day of testing. Performance appeared to plateau by the fourth day, and remained within clinical normal limits throughout the posttraining period (through at least 5 days). It is interesting to note that other tactile feedback methods have shown similar retention effects.

Given the high correlation between postural performance in normals during GVS and postural performance in BVL patients, the ability to reduce sway in both groups using electrotactile feedback further confirms the utility of GVS as a model for functional impairment of vestibular origin. However, the use of sensory substitution for balance control depends on the environmental context and individual sensory weighting, as well as on the nature of the feedback provided. It is interesting to note that TEF did not significantly improve stability measures that account for COM position and velocity control toward stability margins based on both sway position and velocity, and then evaluate the influence of this feedback on minimum time to LOS during GVS.

Our study introduced a novel method of sway-referencing involving translations of the support surface in response to sway from upright. Hlavacka and Horak observed that bilateral GVS resulted in greater forward displacements during backward platform translations. The increase in these displacements relative to a given increase in GVS current (0.5- to 1-mA range) was interpreted as vestibulospinal sensitivity, which correlated to the severity of somatosensory loss in the feet due to diabetic neuropathy. The polarity of our translations (e.g., backward acceleration during backward lean) would have the tendency to counteract body sway. This explains why the sway measures during translation SR were similar to the fixed support condition. We propose that changing the gain of the translation sway-referencing, or even the polarity of the displacements, will provide additional insight into the use of somatosensory feedback for posture control.

In summary, these results demonstrate the effectiveness of TEF in providing sensory substitution to maintain postural stability with distorted vestibular input. The improvements in postural performance reflect the support surface conditions and the specific information displayed to the subject. GVS provides a useful mechanism to optimize and validate sensory substitution feedback strategies targeted toward rehabilitating vestibular-mediated function.

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Conflicts of Interest

The authors declare no conflicts of interest.

References