Biol. Cybern. 84, 475–480 (2001)

Biological Cybernetics

Enhancing human balance control with galvanic vestibular stimulation

Anthony P. Scinicariello[1], **Kenneth Eaton**[1], **J. Timothy Inglis**[2], **J. J. Collins**[1]

[1] Center for BioDynamics and Department of Biomedical Engineering, Boston University, 44 Cummington St., Boston, MA 02215, USA
[2] Schools of Human Kinetics and Rehabilitation Sciences, The University of British Columbia, Vancouver, BC V6T 1Z1, Canada

Received: 11 May 2000 / Accepted in revised form: 20 November 2000

Abstract. With galvanic vestibular stimulation (GVS), electrical current is delivered transcutaneously to the vestibular afferents through electrodes placed over the mastoid bones. This serves to modulate the continuous firing levels of the vestibular afferents, and causes a standing subject to lean in different directions depending on the polarity of the current. Our objective in this study was to test the hypothesis that the sway response elicited by GVS can be used to reduce the postural sway resulting from a mechanical perturbation. Nine subjects were tested for their postural responses to both galvanic stimuli and support-surface translations. Transfer-function models were fit to these responses and used to calculate a galvanic stimulus that would act to counteract sway induced by a support-surface translation. The subjects' responses to support-surface translations, without and with the stabilizing galvanic stimulus, were then measured. With the stabilizing galvanic stimulus, all subjects showed significant reductions in both sway amplitude and sway latency. Thus, with GVS, subjects maintained a more erect stance and followed the support-surface displacement more closely. These findings suggest that GVS could possibly form the basis for a vestibular prosthesis by providing a means through which an individual's posture can be systematically controlled.

1 Introduction

The maintenance of upright stance in humans involves a number of sensory systems, including the vestibular system. With galvanic vestibular stimulation (GVS), electrical current is delivered transcutaneously to the vestibular afferents through electrodes placed over the mastoid bones. This serves to modulate the continuous firing level of the vestibular afferents (Goldberg et al. 1984), and causes a standing subject to lean in different directions depending on the polarity of the current (Coats and Stoltz 1969; Coats 1972a,b, 1973; Honjo et al. 1976; Hlavacka and Njiokiktjien 1985, 1986; Johansson and Magnusson 1991; Iles and Pisini 1992; Fitzpatrick et al. 1994, 1996; Peterson et al. 1994, 1995; Inglis et al. 1995; Johansson et al. 1995; Cass et al. 1996; Day et al. 1997; Hlavacka et al. 1999; Pavlik et al. 1999). Specifically, anodal and cathodal currents decrease and increase, respectively, the firing rates of vestibular afferents, and standing subjects tend to sway toward the anodal stimulus and/or away from the cathodal stimulus (Coats 1972b).

It has been shown that in subjects who are facing forward, bipolar binaural stochastic GVS leads to coherent stochastic mediolateral postural sway (Pavlik et al. 1999). This result indicates that subjects can act as 'responders' to GVS. Motivated by this finding, we speculated that the sway response elicited by GVS can be used to reduce the postural sway resulting from a mechanical perturbation. Accordingly, our objective in this study was to test the hypothesis that in subjects who are facing forward, bipolar binaural GVS can be used to eliminate or reduce mechanically-induced mediolateral postural sway.

2 Methods

Nine healthy young subjects (six females and three males; age: 18–24 years, mean 22 years; height: 1.59–1.88 m, mean 1.72 m; weight: 49.9–99.8 kg, mean 64.2 kg) were included in the study. Informed consent was obtained from each subject prior to participation. This study was approved by the Boston University Charles River Campus Institutional Review Board.

During the tests, subjects stood barefoot with their eyes closed and head facing forward, on a motorized platform (Fig. 1). Galvanic stimuli were applied to each subject using a bipolar binaural configuration with the anodal electrode on the subject's left mastoid and the cathodal electrode on the subject's right mastoid, so that

Correspondence to: J. J. Collins
(Tel.: +1-617-3530390, Fax: +1-617-3535462,
e-mail: jcollins@bu.edu)

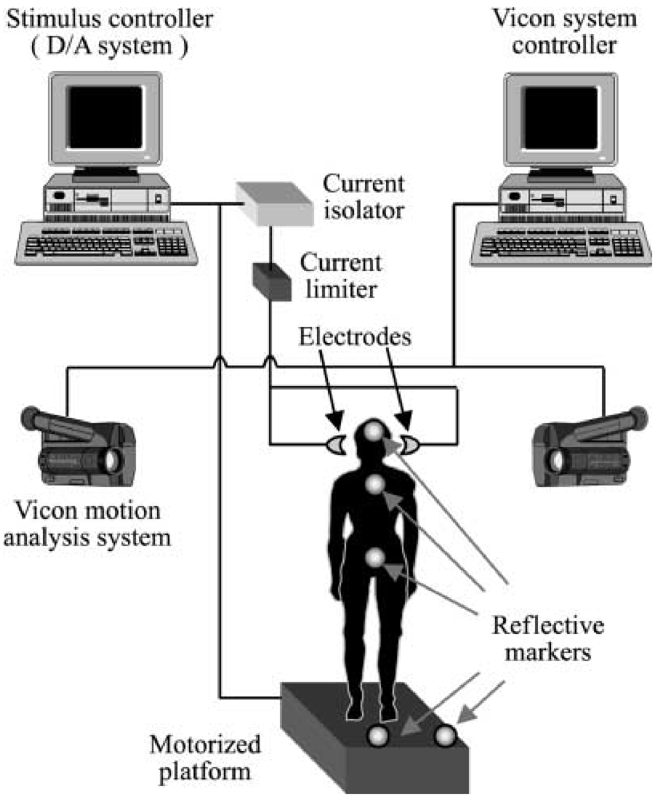

Fig. 1. A schematic representation of the experimental setup. During the tests, subjects stood on a New England Affiliated Technologies motorized x-y platform (Lawrence, Mass.). The galvanic stimuli were applied with a pair of 9 cm^2 carbon-rubber electrodes, cut to fit behind the subject's ears. Spectra 360 electrode gel (Parker Laboratories, Fairfield, N.J.) was applied to each electrode so that a complete electrical contact could be maintained between the electrodes and the skin. The electrodes were held in place by a tight headband. The electrodes were connected to an A-M Systems 2200 analog stimulus isolator (Carlsberg, Wash.) by way of a current limiter (limited to 2 mA, for subject comfort and safety). The galvanic stimulus was sent to the isolator by way of a Microstar D/A system (Bellevue, Wash.) installed on a personal computer. The mechanical stimulus was sent to the motorized platform using the same D/A system. The Vicon motion analysis system recorded the displacements of the reflective markers that were attached to the subject and the platform. The Vicon system controller also recorded the applied stimuli

positive input currents produced sway towards the left side of the subject's body. Reflective markers were attached to the subject's body: one on the forehead, one on the sternum, and one on the pelvis (Fig. 1). Two reference markers were also attached to the motorized platform. A Vicon motion analysis system (Oxford Metrics, Oxford) was used to collect lateral displacement data from these markers.

A series of 40 trials – 20 galvanic trials with a 3-s galvanic pulse of varying amplitude and polarity, and 20 perturbation trials with a 40-mm lateral platform displacement of varying direction (left or right) – was conducted at the outset of a session to estimate the subject's responses to galvanic and mechanical stimuli, respectively. In order to synchronize the inputs and the responses, the applied stimuli were recorded along with the marker displacements.

The response data were then used to find model parameters that best fit the subject's response to galvanic and mechanical stimuli, respectively. For the galvanic trials, we used the following third-order galvanic transfer-function model (Nashner and Wolfson 1974):

$$T_G(s) = \frac{\theta(s)}{I(s)} = \frac{K_G(T_N s + 1)e^{-sT}}{(T_D s + 1)[(s^2/\omega_G^2) + (2\varrho_G s/\omega_G) + 1]} \quad (1)$$

where s is a complex variable, $\theta(s)$ is the Laplace transform of the body angle relative to vertical, $I(s)$ is the Laplace transform of the current input stimulus, T_N is the lead time constant, T_D is the lag time constant, K_G is the gain, ω_G is the natural frequency of the body, ϱ_G is the damping ratio of the body, and T is the delay. For the mechanical perturbation trials, we used the following third-order mechanical transfer-function model (Nashner and Wolfson 1974):

$$T_M(s) = \frac{\theta(s)}{V(s)} = \frac{K_M(T_N s + 1)}{(T_D s + 1)[(s^2/\omega_M^2) + (2\varrho_M s/\omega_M) + 1]} \quad (2)$$

where $V(s)$ is the Laplace transform of the induced sway rate, $\theta(s)$, T_N, and T_D are as described above for (1), and K_M, ω_M, and ϱ_M are as described above, but for mechanical stimuli. In both models (Eqs. 1 and 2), the values of T_N and T_D are 0.3 s and 1 s, respectively, as reported in a previous modeling study (Nashner and Wolfson 1974). With GVS, there is a slight delay between the application of the current stimulus and the sway response, which gives rise to the delay term T in the galvanic model. For mechanical stimuli, the sway response occurs at the onset of the stimulus; therefore, there is no delay term in the mechanical model.

The head-marker and platform displacement time series were used to determine the body angle relative to vertical and the sway rate induced by the platform movement. In order to calculate these quantities, the body was assumed to act as an inverted pendulum with one degree of freedom at its base. Body angle was calculated as the angle formed between the head marker and one of the reference markers (on the platform) in the coronal plane. Induced sway rate was calculated as the angular velocity achieved by displacing the base of the pendulum.

A nonlinear, least-squared fit was performed to find the unknown model parameters for the respective trials. Note that there are four parameters – K_G, ω_G, ϱ_G, and T – that must be determined for the galvanic transfer-function model, and three parameters – K_M, ω_M, and ϱ_M – that must be determined for the mechanical transfer-function model. The parameters for the galvanic and mechanical transfer-function models were averaged across the trials for each subject to obtain a subject-specific set of parameters for each model. (Any asymmetry in the subject's sway responses to the left and right was assumed to be negligible.) These parameters were then used in the control scheme depicted in Fig. 2 to calculate the galvanic stimulus needed to counteract a

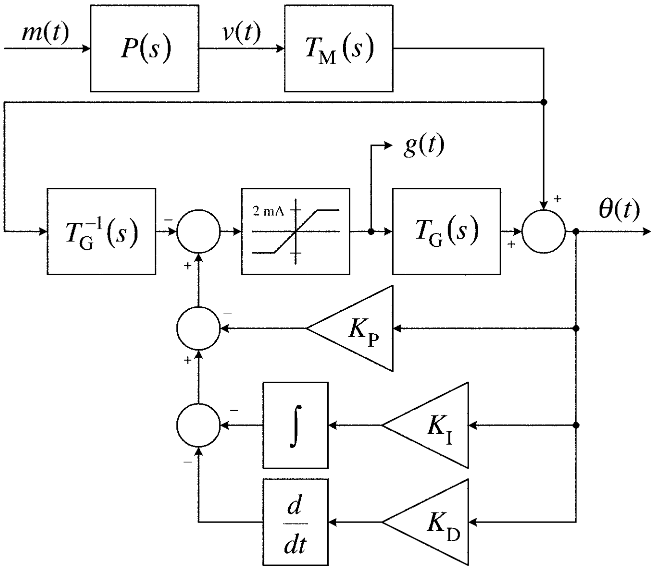

Fig. 2. A schematic representation of the procedure used to calculate a galvanic stimulus that would act to counteract sway induced by a support-surface translation. Here $m(t)$ represents the mechanical stimulus, $v(t)$ represents the induced sway rate, $g(t)$ represents the stabilizing galvanic stimulus, $\theta(t)$ represents the predicted body angle, $P(s)$ represents the platform model which converts the mechanical stimulus into induced sway rate, $T_M(s)$ represents the mechanical transfer-function model (see Eq. 2), $T_G(s)$ represents the galvanic transfer-function model (see Eq. 1) with zero delay, and K_P, K_I, and K_D represent gain coefficients corresponding to proportional-integral-derivative (PID) feedback control. The stabilizing galvanic stimulus is found by using the mechanical transfer-function model to predict a sway pattern. This sway pattern is then input to the inverse of the galvanic transfer-function model, and the polarity of the resulting signal is reversed. The output of this procedure is a first-order estimate of the stabilizing galvanic stimulus. A PID feedback loop was used to increase the efficacy of the stabilizing galvanic stimulus. This feedback loop was introduced because the imposed 2-mA limit (see Fig. 1 caption) on the amplitude of the galvanic stimulus reduced the effectiveness of the stimulus. Note that in the subject trials, the delay in the galvanic transfer-function model was taken into account by advancing the stabilizing galvanic stimulus in time with respect to the platform displacement by an amount equal to the delay term T from the galvanic transfer-function model (see Eq. 1)

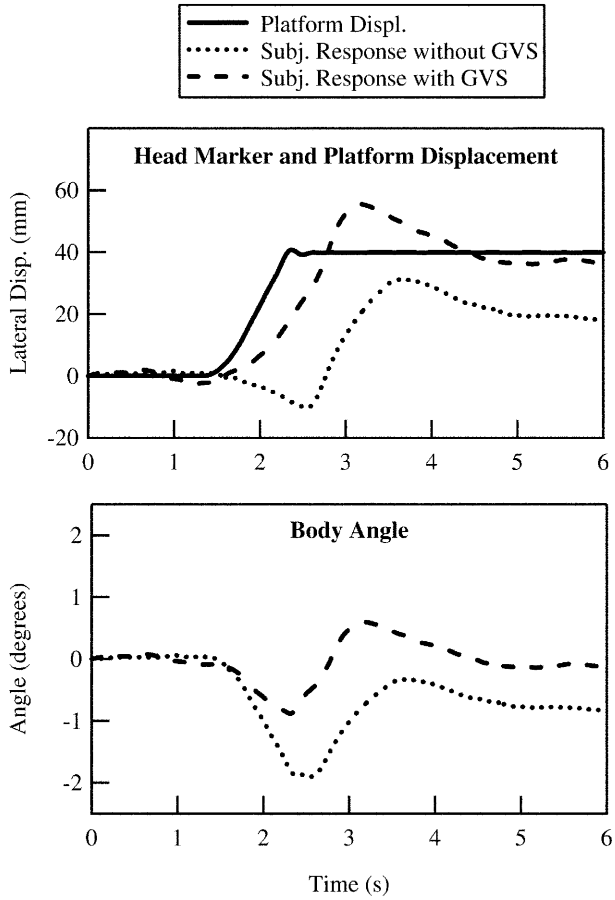

Fig. 3. Normalized platform and head-marker displacement time series (*top panel*) and body angle data (*bottom panel*) for a representative subject. The marker displacement time series was shifted so that the initial position of the respective marker at the beginning of a trial ($t = 0$) was equal to 0. Data are shown for trials without (*dotted lines*) and with (*dashed lines*) the stabilizing galvanic stimulus. For the GVS trial, the stabilizing galvanic stimulus was applied from $t = 1.0$ s onwards

given mechanical stimulus. For these analyses and the posture tests described below, the mechanical perturbation (see top panel of Fig. 3) was the same as that used for the aforementioned parameter-estimation trials.

Subjects were then tested under two conditions: mechanical perturbation only, and mechanical perturbation plus the stabilizing galvanic stimulus. Ten trials were conducted for each condition: five trials with platform translations to the right and five trials with platform translations to the left. The presentation order of the 20 trials was randomized for each subject.

The two test conditions were also simulated for each subject by using the averaged model parameters in the mechanical and galvanic models. The mechanical response was computed as the output of the mechanical model (2) driven by the induced sway rate (determined as described above), and the galvanic response was computed as the output of the galvanic model (1) driven by the stabilizing galvanic stimulus. For these analyses, the mechanical response served as a simulation for the condition of mechanical perturbation only, while the sum of the mechanical response and the galvanic response served as a simulation for the condition of mechanical perturbation plus the stabilizing galvanic stimulus.

Three parameters were extracted from the posture data to characterize a subject's sway response quantitatively. The first parameter, the magnitude of the first peak in the body angle, is the extent of the initial sway of the subject's body in the direction opposite to that of the platform displacement. The second parameter is the average body angle during the platform displacement. The third parameter is the latency between the platform displacement and the motion of the respective body markers in the same direction as the platform, which was determined as the lag time corresponding to the peak in the cross-correlation function formed between the platform displacement and the respective body-marker displacement time series. (Note that although the sway response occurs at the onset of the mechanical stimulus, the initial body sway is in the direction opposite to that of the platform, e.g., see Fig. 3.)

For each subject, a two-tailed, paired *t*-test was used to compare the parameters from the trials with and without the stabilizing galvanic stimulus.

3 Results

Head-marker and platform displacement data and body angle data for a representative subject are shown in Fig. 3. It can be seen that with the stabilizing galvanic stimulus, the subject's body swayed substantially less and followed the movement of the platform more closely. Also, during the platform displacement, the subject's head movement was correlated with that of the platform for the trial with GVS, in contrast to the clearly anti-correlated movement of the head for the trial without GVS. The data in Fig. 3 also demonstrate a reduction in the three parameters mentioned above. The magnitude of the first peak in body angle for the trial with GVS is less than half that for the trial without GVS, and the average body angle during the platform displacement is also clearly less for the trial with GVS than that for the trial without GVS. In addition, the head marker moved in the same direction as the platform much sooner for the trial with GVS than for the trial without GVS, indicating a decrease in our latency measure with GVS.

The model predictions for a representative subject are compared to measured data in Fig. 4. It can be seen that the model predictions fit the observed data quite well, but there are two discrepancies worth noting. Firstly, in the top panel of Fig. 4 it appears that the subject did not return to his or her original orientation after the platform displacement, as was predicted by the model. One possible explanation for this effect is that subjects can maintain several different stable positions during quiet standing. Since the platform displacement alters quiet-standing posture, it is possible for subjects to return to a different stable orientation following a perturbation. Among all subjects, this behavior was observed in approximately one-third of the trials without GVS and in half of the trials with GVS. Secondly, in the bottom panel of Fig. 4 it can be seen that after the platform displacement, the subject returned to vertical while the model prediction oscillated and overshot the vertical orientation. This prediction error could be due to the fact that there is no postural response to galvanic stimuli that are below a subject-specific threshold (Pavlik et al. 1999). In the trial shown in Fig. 4, the galvanic stimulus became sub-threshold for the subject near the time that the subject returned to vertical. The galvanic model, however, does not account for this threshold phenomenon, and therefore predicts a postural response for even the weakest of galvanic currents.

Experimental results for the first peak, average angle, and latency for the nine subjects are shown in Fig. 5. With the stabilizing galvanic stimulus, all subjects exhibited statistically significant decreases in the magnitude of the first peak in body angle and the latency between the platform displacement and the displacement of the respective body markers in the same direction as the platform. (Latency results similar to those shown in Fig. 5 for the head marker were obtained for both the sternum marker and the pelvis marker.) In addition, with the stabilizing galvanic stimulus eight of the nine subjects exhibited statistically significant decreases in average body angle during the platform displacement. The ninth subject exhibited a marginally significant reduction ($p = 0.053$).

An analysis of the model predictions confirmed that the aforementioned sway parameters should decrease with the stabilizing galvanic stimulus. A two-tailed, paired *t*-test confirmed that there were no significant differences between the model predictions and the subject means for the first peak, average angle, and latency (averaged over the trials for each subject). Across all subjects, the model slightly overestimated the decreases in the magnitude of the first peak and average angle. Specifically, a 35% decrease in the magnitude of the first peak was observed, while the model predicted a 54% decrease. For average angle a 35% decrease was observed, while a 44% decrease was predicted. In contrast, the model slightly underestimated the decrease in latency: a 58% decrease was observed while a 48% decrease was predicted.

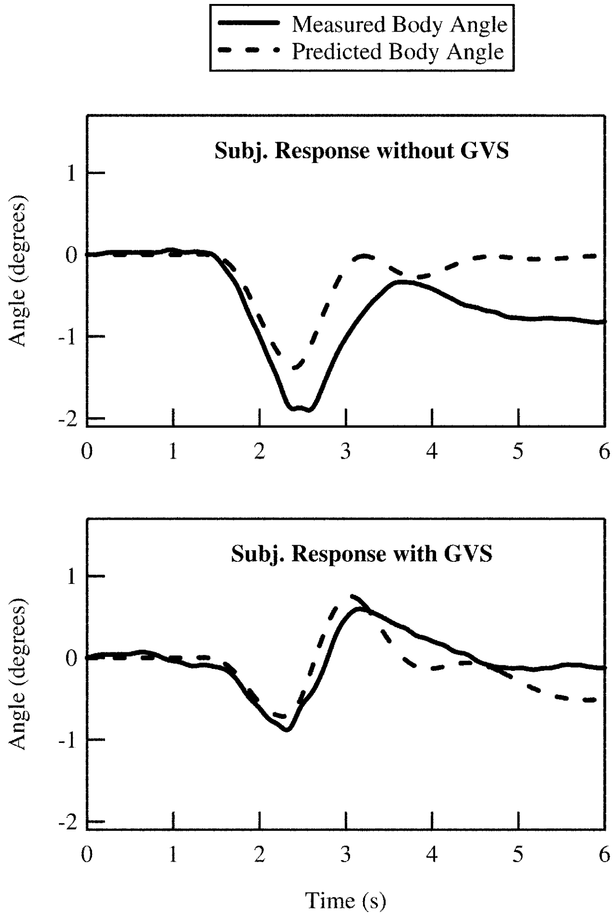

Fig. 4. Body angle data (*solid lines*) and model predictions (*dashed lines*) for the representative subject of Fig. 3. Data are shown for trials without (*top panel*) and with (*bottom panel*) the stabilizing galvanic stimulus. These trials are the same as those included in Fig. 3

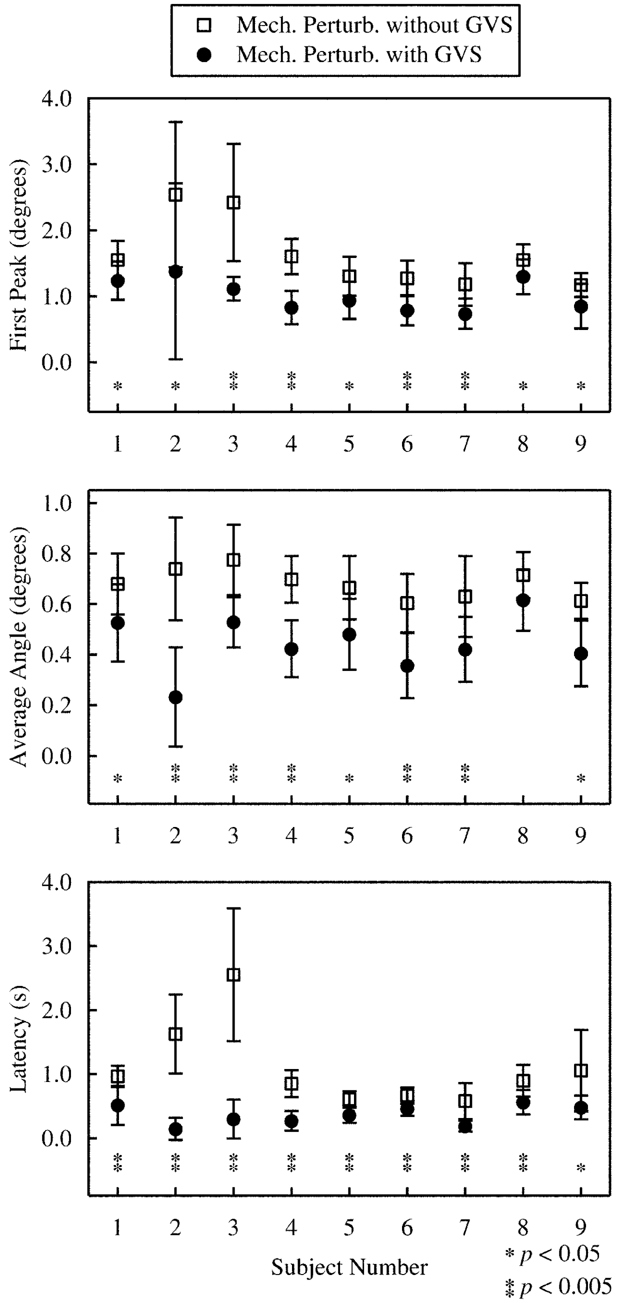

Fig. 5. Means and standard deviations of the first peak in the body angle (*top panel*), the average body angle during the platform displacement (*middle panel*), and the latency between the platform displacement and the displacement of the head marker in the same direction as the platform (*bottom panel*), for each of the nine subjects. Results are shown for perturbation trials without (*open squares*) and with (*solid circles*) the stabilizing galvanic stimulus. The symbols * and $\ast\atop\ast$ denote statistically significant differences at $p < 0.05$ and $p < 0.005$ levels, respectively

4 Discussion

These findings demonstrate that the sway response elicited by GVS can be used to significantly reduce postural sway resulting from a mechanical perturbation. Specifically, we showed that with the application of an appropriately determined galvanic stimulus, mechanically-perturbed subjects maintained a more erect stance and followed the movements of the perturbing platform more closely. The decrease in the magnitude of the first peak indicated that immediately following the introduction of the perturbation, subjects remained in a more upright orientation. The decrease in average angle indicated that subjects did not sway as much while the platform was moving. Finally, the decrease in the latency between the platform displacement and movement of the body-markers in the same direction as the platform indicated that the stabilizing galvanic stimulus caused the subjects to move more closely with the platform.

In spite of the simplicity of the models we used for calculating the stabilizing galvanic stimulus, we were able to achieve the desired effect of reducing postural sway caused by a mechanical perturbation. Further development of the modeling techniques could, however, lead to a greater reduction in postural sway than is reported here. For example, the galvanic model could be expanded to incorporate the threshold phenomenon discussed earlier. In addition, the use of a real-time proportional-integral-derivative (PID) feedback loop could serve to further reduce the aforementioned sway parameters. Our current system (see Fig. 2) used PID feedback during simulations to calculate the stabilizing galvanic stimulus. Such an approach, however, cannot account for unpredictable components of the experiment that change from trial to trial. As an example, consider the situation we discussed earlier in which subjects have a tendency to shift between stable orientations during a trial. Using real-time control would customize the stabilizing galvanic stimulus for each trial, and could help reduce this effect and possibly other unanticipated effects. These issues will be considered in a future study.

The present work focused on mediolateral sway. It has been shown, however, that in subjects who are facing forward, monopolar binaural GVS can be used to induce a sway response in the anteroposterior direction (Magnusson et al. 1990; Severac Cauquil et al. 1998). Thus, it is possible that the present GVS techniques could be extended to monopolar stimulus protocols and used to reduce or eliminate anteroposterior sway. Similarly, it is likely that combinations of monopolar and bipolar stimulus protocols could be used to counteract sway in arbitrary directions.

Our results suggest that GVS could possibly form the basis for a vestibular prosthesis for balance control by providing the means through which a subject's posture can be systematically controlled. A GVS-based control system could consist of accelerometers or rate sensors that would monitor an individual's postural sway and provide feedback for calculating an appropriate galvanic stimulus in real-time. Since support-surface translation during quiet standing represents only a small portion of possible situations that could occur during normal daily activity, the system would need to be able to calculate appropriate galvanic stimuli for a number of different situations and body positions. Further work needs to be done in order to determine how these different situations would impact the efficacy of using GVS in such a system. Another complication is the delay between the application of the galvanic stimulus and the elicited sway response. In the present study, the perturbation was known ahead of time, and the galvanic stimulus was shifted in time appropriately. If this delay cannot be diminished or eliminated, a GVS-based control system will need a predictive component to deal with the dynamics of normal daily activity.

Acknowledgements. This work was supported by the US National Institutes of Health (grant DC03484-01) and National Science Foundation.

References

Cass SP, Redfern MS, Furman JM, DiPasquale JJ (1996) Galvanic-induced postural movements as a test of vestibular function in humans. Laryngoscope 106: 423–430

Coats AC (1972a) Limit of normal of the galvanic body-sway test. Ann Otol Rhinol Laryngol 81: 410–416

Coats AC (1972b) The sinusoidal galvanic body-sway response. Acta Otolaryngol 74: 155–162

Coats AC (1973) Effect of varying stimulus parameters on the galvanic body-sway response. Ann Otol Rhinol Laryngol 82: 96–102

Coats AC, Stoltz MS (1969) The recorded body-sway response to galvanic stimulation of the labyrinth: a preliminary study. Laryngoscope 79: 85–103

Day BL, Severac Cauquil A, Bartolomei L, Pastor MA, Lyon IN (1997) Human body-segment tilts induced by galvanic stimulation: a vestibularly driven balance protection mechanism. J Physiol (Lond) 500: 661–672

Fitzpatrick R, Burke D, Gandevia SC (1994) Task-dependent reflex responses and movement illusions evoked by galvanic vestibular stimulation in standing humans. J Physiol (Lond) 478: 363–372

Fitzpatrick R, Burke D, Gandevia SC (1996) Loop gain of reflexes controlling human standing measured with the use of postural and vestibular disturbances. J Neurophysiol 76: 3994–4008

Goldberg JM, Smith CE, Fernandez C (1984) Relation between discharge regularity and responses to externally applied galvanic currents in vestibular nerve afferents of the squirrel monkey. J Neurophysiol 51: 1236–1256

Hlavacka F, Njiokiktjien CH (1985) Postural responses evoked by sinusoidal galvanic stimulation of the labyrinth. Acta Otolaryngol 99: 107–112

Hlavacka F, Njiokiktjien CH (1986) Sinusoidal galvanic stimulation of the labyrinths and postural responses. Physiol Bohemoslov 35: 63–70

Hlavacka F, Shupert CL, Horak FB (1999) The timing of galvanic vestibular stimulation affects responses to platform translation. Brain Res 821: 8–16

Honjo S, Tanaka M, Sekitani T (1976) Body-sway induced by galvanic stimulation. Agressologie 17A: 77–84

Iles JF, Pisini JV (1992) Vestibular-evoked postural reactions in man and modulation of transmission in spinal reflex pathways. J Physiol (Lond) 455: 407–424

Inglis JT, Shupert CL, Hlavacka F, Horak FB (1995) Effect of galvanic vestibular stimulation on human postural responses during support surface translations. J Neurophysiol 73: 896–901

Johansson R, Magnusson M (1991) Lateral posture stability during galvanic stimulation. Acta Otolaryngol Suppl 481: 585–588

Johansson R, Magnusson M, Fransson PA (1995) Galvanic vestibular stimulation for analysis of postural adaptation and stability. IEEE Trans Biomed Eng 42: 282–292

Magnusson M, Johansson R, Wiklund J (1990) Galvanically induced body sway in the anterior-posterior plane. Acta Otolaryngol 110: 11–17

Nashner LM, Wolfson P (1974) Influence of head position and proprioceptive cues on short latency postural reflexes evoked by galvanic stimulation of the human labyrinth. Brain Res 67: 255–268

Pavlik A, Inglis JT, Lauk M, Oddsson L, Collins JJ (1999) The effects of stochastic galvanic vestibular stimulation on human postural sway. Exp Brain Res 124: 273–280

Petersen H, Magnusson M, Fransson PA, Johansson R (1994) Vestibular disturbance at frequencies above 1 Hz affects human postural control. Acta Otolaryngol 114: 225–230

Petersen H, Magnusson M, Fransson PA, Johansson R (1995) Vestibular stimulation perturbs human stance also at higher frequencies. Acta Otolaryngol 520: 443–446

Severac Cauquil A, Tardy Gervet MF, Ouaknine M (1998) Body response to binaural monopolar galvanic vestibular stimulation in humans. Neurosci Lett 245: 37–40