Galvanic Vestibular Stimulation Elicits Consistent Head–Neck Motion in Seated Subjects

Farzad Ehtemam, Patrick A. Forbes*, Alfred C. Schouten, Frans C.T. van der Helm, and Riender Happee

***Abstract*—Humans actively stabilize the head–neck system based on vestibular, proprioceptive and visual information. Galvanic vestibular stimulation (GVS) has been used previously to demonstrate the role of vestibular feedback in standing balance. This study explores the effect of GVS on head–neck kinematics and evaluates the approach to investigate the vestibular contribution to head–neck stabilization. GVS was applied to 11 seated subjects using seven different stimuli (single sinusoids and multisines) at amplitudes of 0.5–2 mA and frequencies of 0.4–5.2 Hz using a bilateral bipolar configuration while 3-D head and torso kinematics were recorded using motion capture. System identification techniques were used evaluating coherence and frequency response functions (FRFs). GVS resulted in significant coherence in roll, yaw and lateral translation, consistent with effects of GVS while standing as reported in the literature. The gain of the FRFs varied with frequency and no modulation was observed across the stimulus amplitudes, indicating a linear system response for the stimulations considered. Compared to single sine stimulation, equivalent FRFs were observed during unpredictable multisine stimulation, suggesting the responses during both stimuli to be of a reflexive nature. These results demonstrate the potential of GVS to investigate the vestibular contribution to head–neck stabilization.**

***Index Terms*—Galvanic vestibular stimulation (GVS), head stabilization, neck reflexes and system identification.**

Manuscript received February 22, 2012; revised April 6, 2012; accepted April 7, 2012. Date of publication April 18, 2012; date of current version June 20, 2012. This work was supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO) and partly funded by the Ministry of Economic Affairs, Agriculture and Innovation. *Asterisk indicates corresponding author.*

F. Ehtemam was with the Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: f.ehtemam@gmail.com).

*P. A. Forbes is with the Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: p.a.forbes@tudelft.nl).

A. C. Schouten is with the Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands, and also with the Laboratory of Biomechanical Engineering, Institute for Biomedical Technology and Technical Medicine (MIRA), University of Twente, 7500 AE Enschede, The Netherlands (e-mail: a.c.schouten@tudelft.nl).

F. C. T. van der Helm is with the Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands, with the Laboratory of Biomechanical Engineering, Institute for Biomedical Technology and Technical Medicine (MIRA), University of Twente, 7500 AE Enschede, The Netherlands, and also with Northwestern University in Chicago, Chicago, IL 60611 USA (e-mail: f.c.t.vanderhelm@tudelft.nl).

R. Happee is with the Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: r.happee@tudelft.nl).

Digital Object Identifier 10.1109/TBME.2012.2195178

I. Introduction

Humans actively stabilize the head–neck system against the pull of gravity and external perturbations using vestibular, proprioceptive, and visual sensory information. Head–neck stabilization is typically investigated via mechanical perturbations to either the head or the torso. Early work [1] used sinusoidal and impulsive forces applied directly to the head and suggested that the active modulation of muscle properties could be used to minimize head motion in space. More recent studies, applying unpredictable perturbations to the trunk of seated subjects, hypothesized that the involvement of the different mechanisms in the control of head and neck depends on the frequency of the perturbation [2], [3]. The mechanical stimuli used in these studies not only excite the vestibular organs but also evoke responses from proprioception [4]. Thereby it is difficult in such experiments to uniquely identify vestibular and proprioceptive contributions to head–neck stabilization.

Galvanic vestibular stimulation (GVS) is a technique that stimulates the vestibular afferents directly by applying small electric currents using surface electrodes to artificially alter the vestibular information from the organs. GVS evokes a sensation of motion and consequently elicits vestibulo-myogenic responses to counteract the perceived motion. Although GVS has no natural equivalent, extensive animal recordings demonstrated that this type of stimulation has the same frequency modulating effect on the vestibular afferents as natural motion [5], [6]. Previous studies applied GVS to investigate bipedal stance, eliciting coherent stimulation-to-muscle responses in the lower limbs [7]. Observed motions were modulated with amplitude and frequency of the stochastic GVS signal [8], [9]. Similar studies indicated that the short and medium latency muscle responses due to GVS are a composition of all stimulated frequencies [10]. Furthermore, the literature suggests that the left and right labyrinths independently estimate head motion and that the motor output results from a vector summation and nonlinear transformation of these estimates [11].

Short duration transient GVS pulses have been applied to elicit vestibulocollic reflexes in neck muscles and to investigate vestibulopathy [12]. Electromyographic responses were observed in the sternocleidomastoid muscles when subjects lay in a supine position activating their muscles tonically. However, these approaches do not assess the vestibular contribution to head–neck stabilization, nor have any publications been found using GVS in such an effort. The application of GVS to the isolated head–neck system is expected to elicit small movements as compared to those reported in standing balance, making it a challenge to correlate head–neck motion to GVS. The perceived kinetic equivalent of GVS at 1 mA was shown to be 2–3 degree/s^2 [13], well below head rotational accelerations due to kinetic stimuli measured during voluntary motions ($>$500 degree/s^2) and imposed stimuli via the torso ($>$2000 degree/s^2) [14].

Therefore, the goal of this study was to assess whether GVS is suitable to investigate the role of the vestibular system in upright head–neck stabilization. We aim to quantify the contribution of vestibular feedback, as well as other sensory feedback components, in order to develop models predicting head–neck control. Such models could provide insight into natural head stabilization and the physiological origin of neck related movement disorders.

Applying GVS to seated subjects we tested three hypotheses: 1) GVS elicits consistent head–neck motion that has significant coherence with the stimulation in the conditions considered, 2) the observed responses originate from the stimulation of vestibular afferents, and 3) the head–neck system behaves linearly across the bandwidth and amplitude considered. Nonparametric system identification techniques were applied to obtain coherence and frequency response functions (FRF) (gain and phase) characterizing the input–output relationship of the GVS signals and the associated head kinematics. Nonvestibular (NV) stimulation tests were included in a limited subject set to evaluate the second hypothesis. Sinusoidal GVS signals of different frequencies and amplitudes, as well as a sum of sinusoids, were used to evaluate the first and third hypotheses.

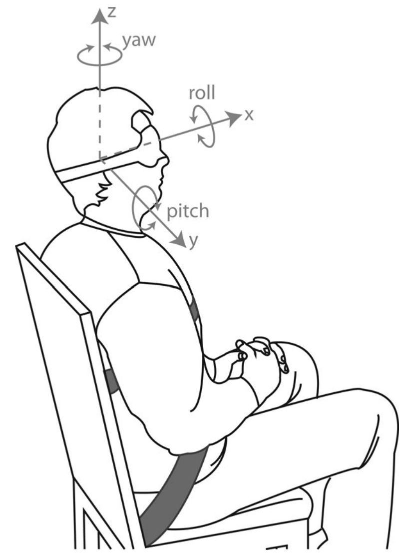

Fig. 1. Experimental setup showing a subject seated on a chair restrained by two torso belts. The head local coordinate system is depicted, defining translation directions (x = anterior–posterior, y = lateral, and z = vertical) and rotation directions (roll, pitch, and yaw).

II. Methods

A. Subjects

Eleven healthy subjects (six male) between the ages of 18 and 42 with no history of vestibular or neck disorders participated in this study. The testing procedure was explained to the participants and their written informed consent was obtained prior to the experiments. The experimental protocol was in accordance with the Declaration of Helsinki and was approved by the Human Research Ethics Committee at the Delft University of Technology.

B. Apparatus and Measurement

The vestibular stimuli were applied with a custom made current controlled analog galvanic stimulator [15]. The analog stimulator input signal was generated on a computer using custom made software (MATLAB, Mathworks Inc., Natick, MA) and delivered to the stimulator using a DA board (dSpace, Paderborn, Germany). The stimulator provided an additional output signal measuring the applied stimulus current.

The vestibular stimulation was applied to the subjects using carbon rubber electrodes (3.8 cm $\times$ 4.4 cm) coated with Spectra 360 electrode gel (Parker Laboratories, Fairfield, NJ). Electrodes were fixed in place using a swimming cap and adhesive tape. The stimuli were applied in a binaural bipolar configuration, where electrodes were placed on the left and right mastoid processes. This configuration was preferred over monopolar configurations as it generates stronger responses and results in higher coherences [16], [17]. In addition, an NV configuration was applied with one electrode placed on the forehead and the other one on the seventh cervical vertebra (C7) [9]. The NV configuration was included to confirm the vestibular origin of GVS responses and to rule out the possibility that responses were due to stimulation of cutaneous afferents.

Head and torso kinematics were recorded using a motion capture system (Qualisys, Gothenburg, Sweden), along with the input signal to and the output current signal from the stimulator with an analog board (Qualisys, Gothenburg, Sweden). Six infrared cameras (Oqus) captured all motions using reflective passive markers. Head motion was recorded using five markers, four attached to a helmet worn by the subjects and one directly on the head close to the tragion. The marker positions together with the head breadth were used to define the head as a rigid body with a local coordinate system at the estimated center of gravity [18] oriented along the Frankfurt plane. Fig. 1 presents the local coordinate system and the directions of translation and rotation used to derive the 6-degree of freedom (DOF) motion (rotations and translations). Looking in the direction of the axes, positive roll and pitch were defined clockwise and positive yaw was defined counterclockwise. In this coordinate system, if the negative (cathodal) and positive (anodal) currents are placed on the right and left mastoids, respectively, the observed response will be negative roll and yaw toward the anode (left side) [19]. Accordingly a change of polarity will result in positive roll and yaw towards the right side. Torso motion was recorded with three markers: two attached to the sternum and one attached to the spinous process of T1. The root-mean-square motion of the torso was compared to the responses recorded in the natural sway tests (i.e., no stimulation, see Protocol) for all stimulation conditions and results confirmed the assumption that the torso was effectively restrained by the seat belts.

C. Stimuli

Seven different signals (six single sinusoids and one multisine) were applied as GVS.

1) A multisine containing four frequencies being 0.4, 1.2, 2.0, and 5.2 Hz and having a peak of 2.0 mA.
2) Sinusoids at 0.4, 1.2, 2.0, and 5.2 Hz with an amplitude of 2.0 mA.
3) Sinusoids at 1.2 Hz with reduced amplitudes of 0.5 and 1.0 mA.

Single sinusoids and multisine stimuli were chosen to ensure subject comfort and to avoid extravestibular cutaneous triggers observed with pulse train stimuli [20]. Single sinusoids applied all available power at one frequency resulting in an optimal signal-to-noise ratio (SNR). The multisine excites the system at four frequencies simultaneously in a pseudorandom fashion. The unpredictable nature of the multisine minimized voluntary contributions that was more likely to occur in predictable single sinusoids. Additionally, multisines are deterministic and thereby avoid spectral leakage, which is an advantage over white noise stimuli [21].

The amplitudes and frequencies of these stimuli were based on the GVS literature and on the dynamics of the head–neck system. Previous studies on bipedal human stance reported high GVS-to-motion coherences in the frequency ranges of 1–5 Hz [22] and 1–2 Hz [16]. Furthermore, the natural frequency of the head and neck system ranges between 1.5 and 2.5 Hz in pitch [23] and approximately 2 Hz in yaw [24]. Amplitudes of 0.5–2 mA were similar to previous studies on bipedal human stance [9], [16], [20] and avoid discomfort.

D. Protocol

Subjects sat on a chair and were instructed to maintain their head in an upright position while staying relaxed during the tests. Horizontal seatbelts across the chest minimized torso motion and confined kinematic responses to the head and neck. During the tests subjects were blindfolded to exclude vision and were asked to listen to a science podcast (Quirks & Quarks, CBC Radio, Canada) to distract them from the stimulus. Subjects were told that the stimuli may cause a tingling sensation behind their ears but were given no further information regarding the nature of the experiments.

Each test had a duration of 80 s and the six single sinusoid tests were applied twice in a randomized order followed by two repetitions of the multisine tests. Previous studies with GVS during stance control indicated that a stimulus of 60 s is sufficient to reveal the characteristics of the human response [16]. Natural head sway tests (i.e., no stimulation) were performed before and after all stimulations as a control condition, resulting in a total of 16 trials of 80 s per subject. The NV configuration was applied on two subjects after all aforementioned test conditions. Subjects were asked to comment on the sensation of the stimuli following each test to ensure safety and comfort.

E. Analysis

The two realizations of each condition were divided into 32 segments of 5 s, providing a frequency resolution of 0.2 Hz. The head rotations and translations had considerable drift. The drift did not follow any pattern and was of no interest for the analysis. To remove drift, each segment was detrended before further analysis. All calculations were performed using MATLAB (Mathworks Inc., Natick, MA).

1) Nonparametric System Identification: System identification techniques were used to establish relationships between the stimulus and the 6-DOF head motion. The data were transformed to the frequency domain and power spectra were averaged over the 32 disjoint time segments D:

$$\hat{S}_{yy}(f) = \frac{1}{DN_d}\sum_{d=1}^{D} Y_d^*(f)Y_d(f) \tag{1}$$

$$\hat{S}_{xy}(f) = \frac{1}{DN_d}\sum_{d=1}^{D} X_d^*(f)Y_d(f) \tag{2}$$

where $Y_d(f)$ and $X_d(f)$ are the Fourier transforms of segment d of the output motion and input stimulus, respectively, f is the frequency vector and $*$ represents the complex conjugate [25]. Linearity was evaluated with the (magnitude-squared) coherence:

$$\gamma_{xy}^2(f) = \frac{\left|\hat{S}_{xy}(f)\right|^2}{\hat{S}_{xx}(f).\hat{S}_{yy}(f)}. \tag{3}$$

Coherence varies between 0 and 1, where 1 indicates a linear and noise free system. In the presence of noise (uncorrelated to the input), coherence represents the linear fraction of the response variance due to the input stimulus [26]. The significance of the estimated coherence was assessed by comparing the values to a 95% confidence limit derived from the number of disjoint segments D [27]:

$$1 - (0.05)^{\frac{1}{D-1}}. \tag{4}$$

FRF using the input stimuli and the output motion were estimated to provide a measure of their relationship:

$$\hat{H}_{xy} = \frac{\hat{S}_{xy}}{\hat{S}_{xx}}. \tag{5}$$

The FRF gain indicates the magnitude of the output relative to the input as a function of frequency. The FRF phase indicates the timing of the output relative to the input. It should be noted that the FRF is a linear construct that is meaningful only when there is significant coherence.

2) Statistics: The effects of amplitude and frequency were investigated using repeated measure ANOVAs—where frequencies were evaluated at 2 mA and amplitudes at 1.2 Hz—on the FRF gain, FRF phase and coherence of the system as dependent variables. Additionally, a paired Student's t-test was performed to determine the effect of repeating each stimulus. Any adaptation to the stimulus should be revealed as a significant difference between the two repetitions. A significance of $P = 0.05$ was used for all analyses.

In order to meet the assumptions of ANOVA (normality and homogeneity), the FRF gains were log transformed. This reduced the deviations from the normal distribution [28].

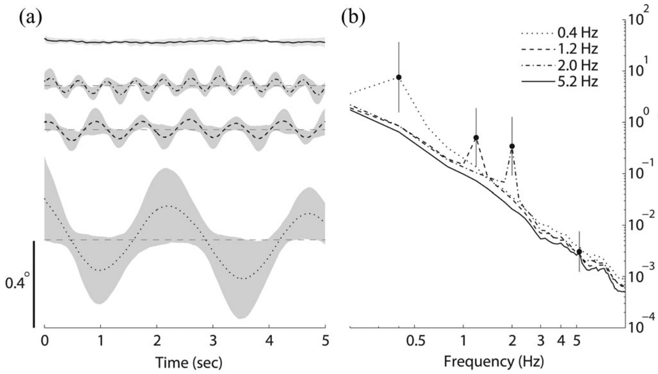

Fig. 2. Head roll responses for the four stimulation frequencies at 2 mA averaged over all subjects ($n = 11$) in (a) time domain and (b) frequency domain. In (a) from top-to-bottom: 5.2, 2.0, 1.2, and 0.4 Hz stimulation. Lines represent means and shaded areas represent the standard deviation of all subjects ($n = 11$). In (b) peak values in the power spectra at 0.4, 1.2, 2.0, and 5.2 Hz indicate dominant power at the stimulus frequency. The spectra are log transformed before calculating the subject average and standard deviation (indicated by the dots and error bars at the stimulated frequencies).

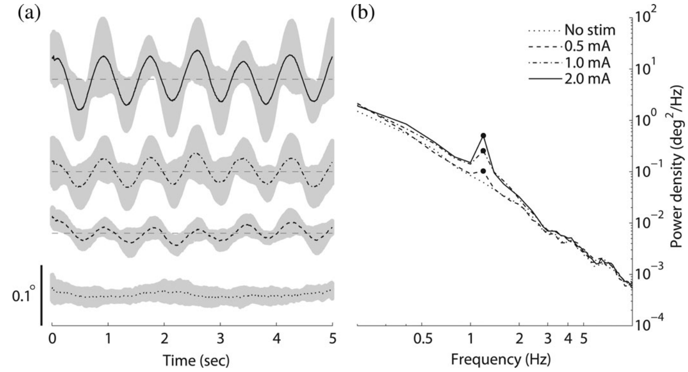

Fig. 3. Head roll responses for the three stimulus amplitudes at 1.2 Hz averaged over all subjects ($n = 11$) in (a) time domain and (b) frequency domain. In (a) at 1.2 Hz from top-to-bottom: 2.0, 1.0, 0.5 mA stimulation, the lowest trace is the control condition (no stimulation). Lines represent means and shaded areas represent the standard deviation over all subjects ($n = 11$). In (b) peak values at 1.2 Hz in the power spectra indicate the dominant power at the stimulus frequency. The spectra are log transformed before calculating the subject average (dots). Standard deviations (not shown) are comparable to Fig. 2.

Since ANOVA results violated the homogeneity assumption Greenhouse–Geisser and Huynh–Feldt corrections were applied. Since Greenhouse–Geisser underestimates and Huynh–Feldt overestimates sphericity, *P*-values were calculated averaging both adjustments.

III. Results

Subjects primarily commented on the cutaneous sensations of the stimuli, remarking them to induce a "tickling" feeling. Several subjects indicated that the low-frequency stimuli (0.4 and 1.2 Hz) caused a sensation of ambiguous motion occurring at either the head or body that was difficult to separate. At higher frequencies several subjects reported the perception of head movement and some subjects commented on a "tapping" sensation behind their ears during the 5.2-Hz single sinusoid and multisine tests.

Figs. 2 and 3 demonstrate that, after averaging over 32 time segments, GVS resulted in clear head movements in roll at the stimulated frequencies and amplitudes. Response magnitude decreased with frequency and increased with stimulation amplitude [see Figs. 2(a) and 3(a)]. The response variance decreased with stimulation frequency and increased with stimulation amplitude. Peak values in the power spectra at the stimulated frequencies exhibit substantially higher power than adjacent nonstimulated frequencies reflecting the single sinusoidal input [see Figs. 2(b) and 3(b)]. The decreasing power with increasing frequency was attributed to head–neck inertial effects that dominate kinematic responses at higher frequencies.

Similarly, during multisine stimulation substantially higher peak values at the stimulated frequencies were observed (not presented), although these were noted as being lower than the peak values obtained from single sinusoids. The control condition (no stimulation) did not have a specific response pattern or dominant power at any specific frequency [see Fig. 3(b)].

Fig. 4 presents the coherence and FRFs for head roll, yaw and lateral translation averaged over subjects for both single sine and multisine stimulation conditions. Coherence was above the 0.95 confidence limit for roll, yaw and lateral translation at the stimulated frequencies for all single and multisine stimuli, indicating a significant kinematic response due to the input GVS. Multisine responses had lower coherences, most likely due to the fact that multisines divide power over multiple frequencies thereby lowering the SNR. Frequency had a significant effect on the coherence for roll and lateral translation in single sinusoids ($P < 0.001$) and multisines ($P < 0.01$), where the coherence at 5.2 Hz was substantially lower relative to all other frequency points. For yaw, no significant effect of frequency on coherence was found. The pitch, anterior–posterior translation and vertical translation had coherence below the 0.95 confidence limit at all stimulus frequencies and are, therefore, not presented.

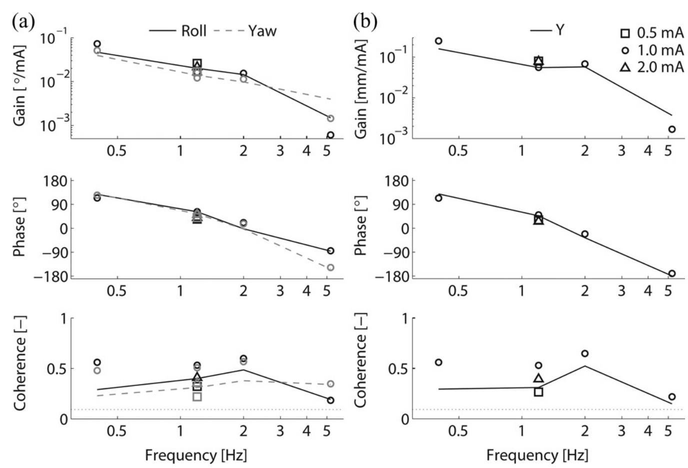

Fig. 4. FRFs (gain and phase) and coherences for (a) head rotations and (b) translations averaged over all subjects ($n = 11$). The gain was log transformed before calculating the subject average. Lines represent multisine (2.0 mA) and markers represent single sine responses at respective amplitudes and frequencies. Circles represent the four different frequencies at 2.0 mA, squares represent 0.5 mA at 1.2 Hz, and triangles represent 1.0 mA at 1.2 Hz. On the left roll and yaw motions are plotted in black and gray, respectively. On the right lateral translation is plotted in black. The dotted lines in the coherence plots indicate the significance threshold.

Roll and yaw rotation as well as lateral translation group averaged FRF responses show similar behavior: the gain ($P < 0.001$) and phase ($P < 0.001$) decrease significantly with stimulation frequency (see Fig. 4). This was the case for both single sinusoids and multisines. The gain fell off after 2.0 Hz, i.e., after the estimated eigenfrequency of the system. At the lowest frequency, the phase was 90° and degraded toward −180° at the highest frequency. The decreasing gain and increasing phase lag as a function of frequency is expected due to the inertia of the musculoskeletal system.

The effect of stimulus amplitude on the group response is depicted in Fig. 4 by the different markers at 1.2 Hz. Coherence increased significantly with stimulus amplitude (roll: $P < 0.05$, yaw: $P < 0.001$, and lateral translation: $P < 0.01$), which can be attributed to the increasing SNR. No significant effects of stimulus amplitude were present for either the FRF gain or phase. This suggests a linear input–output relationship for the amplitudes tested.

Consistent with the effect of GVS while standing reported in the literature, the gain for roll was higher than that of yaw at all frequency points with the exception of 5.2 Hz where the gain for yaw was higher than roll. These response characteristics were consistent for both single sinusoids and multisines. Finally, no significant difference between the first and second repetition could be found for any of the tested responses.

Confirming that the responses originate from vestibular afferents and not from cutaneous cues, additional stimuli were applied to the forehead and C7 (i.e., the NV condition) where estimated coherence of the two subjects tested did not exceed the 0.95 confidence limit in any movement direction for both single sine and multisine stimulation.

IV. Discussion

The primary aim of this study was to determine whether GVS is suitable to identify the vestibular contribution of head–neck stabilization. Three hypotheses were tested: 1) the coherence estimates for GVS-to-head–neck motion are significant in the tests considered, 2) these responses are due to the stimulation of vestibular afferents, and 3) the system behaves linearly across the bandwidth and amplitude range considered.

A. Coherent Motion

In this study, head motion in roll, yaw, and lateral translation was observed in both single sine and multisine stimulation conditions for all amplitudes and frequencies considered. Although the magnitude of observed motions was at most five times larger than natural sway, the motions were significantly coherent (i.e., exceeding the 0.95 confidence limit) with the stimuli. These findings support our hypothesis that GVS elicits consistent motion of the head–neck system in seated subjects.

Binaural bipolar GVS is known to primarily affect the semicircular canals, inducing a sensation of roll and yaw rotation. Consistent with the effect of GVS while standing reported in the literature [19], in seated subjects higher gains in roll compared to yaw were observed in all stimulations except for 5.2 Hz. The higher yaw gain at this frequency can be attributed to the lower rotational inertia of the head in yaw [18] when compared to pitch or roll.

The directionality of the motions in response to the vestibular stimuli suggests a vestibular origin in reaction to the electrical stimulation and not cutaneous cues (i.e., via electrodes being placed left and right). This was further confirmed via the NV stimulation condition, where electrodes were placed on the forehead and C7 and GVS-to-motion coherence was below the 0.95 confidence limit. Similar to [9], this suggests that the coherence originates from the modulation of the firing frequency of vestibular afferents.

In spite of the small motions and low power density of multisines in comparison to the amplitude equivalent single sinusoids, the coherence values were as high as 0.5. An advantage of multisines is the unpredictable nature they have for human subjects. Since GVS is known to elicit vestibulocollic reflexes in the neck [12] one can assume the observed motion is due to stimulation of the vestibular afferents. Therefore, as the single sine gain and phase results matched those of the multisines, it is reasonable to assume that single sine GVS responses are of a similar vestibular afferent stimulation origin generating muscle activity via the vestibular reflex pathways, as opposed to voluntary motion adapting to the predictability of sinusoidal stimuli.

The literature [29] indicates that the muscular drive of small head motions such as during small gaze shifts originates from the activation of the suboccipital muscles. Experiments on monkeys [30], [31] indicated that for small low velocity yaw head movements from center, only deep suboccipital muscles (obliquus capitis inferior and rectus capitis posterior major) were active while the more superficial muscles (sternocleidomastoid and splenius capitis) were inactive. It is likely that these deep suboccipital muscles are also involved in small low velocity yaw and roll head movements as recorded here.

B. Response Characteristics

The coherence and FRFs provide valuable information on the vestibular contribution to head–neck stabilization. High values of coherence were observed at 0.4, 1.2, and 2 Hz. The degradation of coherence at 5.2 Hz was attributed to the filtering caused by inertial effects that minimized movement resulting in low SNRs. Coherence values increased with stimulation amplitude up to 0.5 during the 2-mA stimulations. This indicates a high SNR at 2 mA while the reduced coherence at lower stimulus amplitudes presumably originates from noise in the system and not from system nonlinearity. The values obtained for coherences in this study were higher than those reported in stance control kinematics ($\sim$0.2) [7] using stochastic stimuli of a similar root mean square (1 mA) as the multisine used in this study. Considering the small motions observed in the head–neck, this suggests that the multisine vestibular stimulation is a more viable approach to galvanically perturb the vestibular system during head–neck stabilization. Furthermore, multisines provide additional signal design flexibility allowing for targeted stimulation of desired frequencies rather than an entire bandwidth.

For both head rotation and translation, modulation of FRF gain and phase was observed with frequency. The lowest frequency had a phase advance of $\sim 90^\circ$ that decreased toward -180 degrees at the highest frequency. The 90° phase lead indicates differentiation action that is consistent to prior knowledge on semicircular canals; a damped second-order system that acts as velocity sensor [32], [33]. The gain and phase (see Fig. 4) resemble behavior of an overdamped second-order system. These results are also consistent with previous findings suggesting that the head and neck constitute a quasi-linear second-order system [1].

No significant modulation of gain and phase with the stimulus amplitude was found. Next to the high coherence values, this is another indication of the linear characteristics of the combined vestibular and head–neck system, i.e., twofold increase in input results in twofold increase in output. In addition, the mechanics of the vestibular system are established to act linearly in the range of frequencies from 0.01 to 30 Hz [34]. Although stronger stimuli would improve SNR, stimuli above 2 mA were omitted due to possible discomfort for the subjects.

V. Conclusion

In seated subjects GVS resulted in significantly coherent GVS-to-head–neck motions consistent with responses observed in during bipedal stance, which result from stimulation of the vestibular afferents. No modulation was observed across the stimulus amplitudes, indicating a linear system response for the stimulations applied. These results demonstrate that GVS together with system identification techniques form a valuable toolset to investigate the vestibular contribution to head–neck stabilization. Combined with measurements of neck muscle activity further investigations could quantify the vestibular contribution and explore characteristics of the vestibular projections to different neck muscles. Such results are essential for the development of models predicting head–neck control, in an effort to quantify the vestibular contribution in both healthy controls as well as patients suffering from neck movement disorders.

Acknowledgment

The authors would like to thank Professor H. Kingma at the University Hospital Maastricht for providing facilities and GVS expertise, as well as M. Mailhiot for drawing Fig. 1. F. Ehtemam and P. A. Forbes contributed equally to this work.

References

[1] P. Viviani and A. Berthoz, "Dynamics of head-neck system in response to small perturbations—Analysis and modeling in frequency domain," *Biol. Cybern.*, vol. 19, no. 1, pp. 19–37, Aug. 1975.

[2] E. A. Keshner, R. L. Cromwell, and B. W. Peterson, "Mechanisms controlling human head stabilization—II. Head-neck dynamics during random rotations in the vertical plane," *J. Neurophysiol.*, vol. 73, no. 6, pp. 2302–2312, Jun. 1995.

[3] E. A. Keshner and B. W. Peterson, "Mechanisms controlling human head stabilization—I. Head-neck dynamics during random rotations in the horizontal plane," *J. Neurophysiol.*, vol. 73, no. 6, pp. 2293–2301, Jun. 1995.

[4] B. L. Day and R. C. Fitzpatrick, "The vestibular system," *Curr. Biol.*, vol. 15, no. 15, pp. R583–R586, Aug. 9, 2005.

[5] J. M. Goldberg and C. Fernandez, "Physiology of peripheral neurons innervating semicircular canals of squirrel monkey—1. Resting discharge and response to constant angular accelerations," *J. Neurophysiol.*, vol. 34, no. 4, pp. 635–660, Jul. 1971.

[6] J. M. Goldberg, C. E. Smith, and C. Fernandez, "Relation between discharge regularity and responses to externally applied galvanic currents in vestibular nerve afferents of the squirrel-monkey," *J. Neurophysiol.*, vol. 51, no. 6, pp. 1236–1256, Jun. 1984.

[7] R. Fitzpatrick, D. Burke, and S. C. Gandevia, "Loop gain of reflexes controlling human standing measured with the use of postural and vestibular disturbances," *J. Neurophysiol.*, vol. 76, no. 6, pp. 3994–4008, Dec. 1996.

[8] C. J. Dakin, B. L. Luu, K. van den Doel, J. T. Inglis, and J. S. Blouin, "Frequency-specific modulation of vestibular-evoked sway responses in humans," *J. Neurophysiol.*, vol. 103, no. 2, pp. 1048–1056, Feb. 2010.

[9] C. J. Dakin, G. M. L. Son, J. T. Inglis, and J. S. Blouin, "Frequency response of human vestibular reflexes characterized by stochastic stimuli," *J. Physiol.-London*, vol. 583, no. 3, pp. 1117–1127, Sep. 2007.

[10] C. J. Dakin, J. T. Inglis, and J.-S. Blouin, "Short and medium latency muscle responses evoked by electrical vestibular stimulation are a composite of all stimulus frequencies," *Exp. Brain Res.*, vol. 209, no. 3, pp. 345–354, Mar. 2011.

[11] B. L. Day, J. F. Marsden, E. Ramsay, O. S. Mian, and R. C. Fitzpatrick, "Non-linear vector summation of left and right vestibular signals for human balance," *J. Physiol.-London*, vol. 588, no. 4, pp. 671–682, Feb. 2010.

[12] S. M. Rosengren, M. S. Welgampola, and J. G. Colebatch, "Vestibular evoked myogenic potentials: Past, present and future," *Clin. Neurophysiol.*, vol. 121, no. 5, pp. 636–651, May 2010.

[13] R. C. Fitzpatrick, J. Marsden, S. R. Lord, and B. L. Day, "Galvanic vestibular stimulation evokes sensations of body rotation," *Neuroreport*, vol. 13, no. 18, pp. 2379–2383, Dec. 2002.

[14] G. P. Siegmund, J. S. Blouin, J. R. Brault, S. Hedenstierna, and J. T. Inglis, "Electromyography of superficial and deep neck muscles during isometric, voluntary, and reflex contractions," *J. Biomech. Eng.-Trans. ASME*, vol. 129, no. 1, pp. 66–77, Feb. 2007.

[15] S. G. T. Balter, R. J. Stokroos, I. De Jong, R. Boumans, M. Van de Laar, and H. Kingma, "Background on methods of stimulation in galvanic-induced body sway in young healthy adults," *Acta Oto-Laryngologica*, vol. 124, no. 3, pp. 262–271, Mar. 2004.

[16] A. E. Pavlik, J. T. Inglis, M. Lauk, L. Oddsson, and J. J. Collins, "The effects of stochastic galvanic vestibular stimulation on human postural sway," *Exp. Brain Res.*, vol. 124, no. 3, pp. 273–280, Feb. 1999.

[17] A. P. Scinicariello, J. T. Inglis, and J. J. Collins, "The effects of stochastic monopolar galvanic vestibular stimulation on human postural sway," *J. Vestib. Res., Equilib. Orientat.*, vol. 12, no. 2–3, pp. 77–85, 2002.

[18] N. Yoganandan, F. A. Pintar, J. Zhang, and J. L. Baisden, "Physical properties of the human head: Mass, center of gravity and moment of inertia," *J. Biomech.*, vol. 42, no. 9, pp. 1177–1192, Jun. 2009.

[19] R. C. Fitzpatrick and B. L. Day, "Probing the human vestibular system with galvanic stimulation," *J. Appl. Physiol.*, vol. 96, no. 6, pp. 2301–2316, Jun. 2004.

[20] L. D. Latt, P. J. Sparto, J. M. Furman, and M. S. Redfern, "The steady-state postural response to continuous sinusoidal galvanic vestibular stimulation," *Gait Posture*, vol. 18, no. 2, pp. 64–72, Oct. 2003.

[21] R. Pintelon and J. Schoukens, *System Identification: A Frequency Domain Approach*. New York: IEEE Press, 2001.

[22] R. Johansson, M. Magnusson, and P. A. Fransson, "Galvanic vestibular stimulation for analysis of postural adaptation and stability," *IEEE Trans. Biomed. Eng.*, vol. 42, no. 3, pp. 282–292, Mar. 1995.

[23] G. C. Y. Peng, *Dynamics and Control of Head, Neck and Eye Stabilization: Neuromechanical and Experimental Models.* Northwestern University, Evanston, IL, 1996.

[24] J. L. Tangorra, L. A. Jones, and I. W. Hunter, "Dynamics of the human head-neck system in the horizontal plane: Joint properties with respect to a static torque," *Ann. Biomed. Eng.*, vol. 31, no. 5, pp. 606–620, May 2003.

[25] A. V. Oppenheim, R. W. Schafer, and J. R. Buck, *Discrete-Time Signal Processing*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 1999.

[26] D. T. Westwick and R. E. Kearney, *Identification of Nonlinear Physiological Systems*. New York: Wiley-IEEE Press, 2003.

[27] D. M. Halliday, J. R. Rosenberg, A. M. Amjad, P. Breeze, B. A. Conway, and S. F. Farmer, "A framework for the analysis of mixed time series/point process data—Theory and application to the study of physiological tremor, single motor unit discharges and electromyograms," *Prog. Biophys. Mol. Biol.*, vol. 64, no. 2–3, pp. 237–278, 1995.

[28] G. Gamst, L. S. Meyers, and A. J. Guarino, *Analysis of Variance Designs: A Conceptual and Computational Approach With SPSS and SAS*. Cambridge, U.K.: Cambridge Univ. Press, 2008.

[29] I. A. Kapandji, *The Physiology of Joints. III. The Trunk and the Vertebral Column*. New York: Churchill Livingstone Press, 1974.

[30] F. G. Lestienne, B. Legoff, and P. A. Liverneaux, "Head movement trajectory in 3-dimensional space during orienting behavior toward visual targets in rhesus-monkeys," *Exp. Brain Res.*, vol. 102, no. 3, pp. 393–406, Jan. 1995.

[31] B. D. Corneil, E. Olivier, F. J. R. Richmond, G. E. Loeb, and D. P. Munoz, "Neck muscles in the rhesus monkey—II. Electromyographic patterns of activation underlying postures and movements," *J. Neurophysiol.*, vol. 86, no. 4, pp. 1729–1749, Oct. 2001.

[32] W. C. Vanbuskirk, R. G. Watts, and Y. K. Liu, "Fluid-mechanics of semicircular canals," *J. Fluid Mech.*, vol. 78, no. 5, pp. 87–98, 1976.

[33] D. Obrist, "Fluidmechanics of semicircular canals—Revisited," *Z. Angew. Math. Phys.*, vol. 59, no. 3, pp. 475–497, May 2008.

[34] J. W. Grant, "Vestibular mechanics," *Biomedical Engineering Handbook* J. D. Bronzino, Ed. Boca Raton, FL: CRC Press, 2000.

Farzad Ehtemam received the M.Sc. degree in biomedical engineering from the Delft University of Technology, Delft, The Netherlands, in 2011.

His research interests include in the fields of sensorimotor control and system identification.

Patrick A. Forbes received the B.A.Sc. and M.A.Sc. degrees in mechanical engineering from the University of Waterloo, Waterloo, Canada, in 2003 and 2005, respectively, and is currently working toward the Ph.D. degree at the Delft University of Technology, Delft, The Netherlands.

His current research interests include neuromuscular control of the head–neck system and techniques to separate vestibular and proprioceptive afferent feedback, neuromuscular modeling and system identification. His research focuses on understanding head–neck stabilization in healthy individuals and those suffering from neck movement disorders.

Alfred C. Schouten received the M.Sc. and Ph.D. degrees in mechanical engineering from the Delft University of Technology, Delft, The Netherlands, in 1999 and 2004, respectively.

He is currently an Assistant Professor at the Delft University of Technology and University of Twente, AE Enschede, The Netherlands. He is Co-Founder of the Delft Laboratory for Neuromuscular Control. His research interests include the field of neuromuscular control and techniques to quantify the functional contribution of afferent feedback, neuromuscular modeling, haptic manipulators, and system identification. His research focuses on both able-bodied individuals and individuals suffering from movement disorders.

Frans C. T. van der Helm received the M.Sc. degree in human movement science from VU University Amsterdam, Amsterdam, The Netherlands, in 1985, and the Ph.D. degree in mechanical engineering from the Delft University of Technology, Delft, The Netherlands, in 1991.

He is currently a Professor in Biomechatronics and Biorobotics, Delft University of Technology, and also an Adjunct Professor at the University of Twente, AE Enschede, The Netherlands, and at the Northwestern University in Chicago, Chicago, IL. He was the Chair in the Department of Biomechanical Engineering from 2005 to 2010. He was member of the board of the International Society of Biomechanics from 2005 to 2009, and participates in the board of the Technical Group of Computer Simulation and the International Shoulder Group. He is one of Programme Leaders in the Medical Delta, the collaboration between Leiden Unversity Medical Center, Erasmus Medical Center Rotterdam and TU Delft. He is a Principal Investigator in the TREND research consortium, investigating Complex Regional Pain Syndrome as a neurological disorder, the NeuroSIPE program and H-Haptics program. He has published more than 100 papers in international journals on topics as biomechanics of the upper and lower extremity, neuromuscular control, eye biomechanics, pelvic floor biomechanics, human motion control, and posture stability.

Riender Happee received the M.Sc. and Ph.D. degrees in mechanical engineering from the Delft University of Technology, Delft, The Netherlands, in 1986 and 1992, respectively.

He is currently an Assistant Professor at the Delft University of Technology and he is investigating neuromuscular stabilization focusing on the neck and the lumbar spine and human control as related to automotive human factors. His expertise is in biomechanical human modeling for impact simulation, posture maintenance, driver modeling, and driver observation.