Human Postural Responses to Sensory Stimulations: Measurements and Model

F. Hlavačka

Institute of Normal and Pathological Physiology, Dept. Biocybernetics,
Slovak Academy of Sciences, Bratislava, Slovakia
Email: unpffero@savba.sk

Abstract. *In the paper we examined the influence of vestibular and leg proprioceptive inputs on the human upright posture. Vestibular input was changed by applying current 1 mA between places near to left and right ear. Proprioceptive input was modified by vibrating the calf muscle. Furthermore, the vestibular stimulus was combined with the muscle vibration using five different temporal relationships between the stimuli. Body postural responses were measured by force platform as a center of foot pressure (CoP) to the support surface. With the anode on the right side, vestibular CoP body response was towards the right side. Vibration of right tibialis anterior muscle induced CoP body shift forward and to the right. With combined stimulation, responses with complex trajectory resulted, which depended on the stimulus interval and reflected a superposition of the single vestibular and proprioceptive effects.*
The results show that the body vertical is under the continuous control of leg proprioceptive and vestibular inputs. We present a simply model according to which these inputs are averaged by a summation process of several sensory inputs through a parallel sensory feedback in the human posture control system.

Key words: human posture, vestibular stimulation, muscle vibration, stabilometry.

1. Introduction

Vertical body orientation during stance is under the multisensory control from vestibular, visual and somatosensory system. Control of human upright posture with eyes closed requires an active involvement of kinesthetic information and vestibular information of body orientation relative to the gravity vector [1, 2].
We analysed CoP shifts of the body during upright stance which resulted from combined vestibular (galvanic) and somatosensory (muscle vibration) stimulation, while varying the temporal relationship between the stimuli. In particular, we interested to know the orientation of the CoP tilts for conditions where a transient vestibular stimulus is superimposed at different time intervals on a sustained proprioceptive stimulus. We interpreted results by simulation on simple 2D-model for human control of the body vertical.

2. Subject and Methods

Ten healthy subjects participated in the experiment (6 males and 4 females; mean age, 30.9 years). The center of foot pressure (CoP) in forward-backward and right-left directions were registered by force platform and recorded on PC at 50 samples/s for 10 s stimulus periods. During this period subjects stand on the platform with eyes closed.
For leg proprioceptive stimulation, a vibration stimulus to right tibialis anterior (TA) muscle was applied. Vibration frequency was 90 Hz for a stimulus period of 5 s with a vibration amplitude of 1 mm. Vibration was obtained by a small dc-motor with unbalanced load (5 grams) which was fastened to the muscle belly using a rubber strap.
For galvanic vestibular stimulation, binaural electrical current was applied to the mastoid process on either side, using silver electrodes (10 cm^2) that were enveloped in gauze and

moistened with physiological saline solution. The stimulus consisted of constant current with a cosine-bell wave form, a peak amplitude of 1 mA and a duration of 3.3 s. Anode was placed on the subject's right side, trying to obtain a rightward vestibular sway response.
Seven experimental conditions were used in separate trials: (1) right TA vibration alone, with the recording period of 10 s being partitioned into a 2 s pre-stimulus, a 5 s stimulus, and 3 s post-stimulus interval, (2) right anode galvanic stimulation, starting 2 s after recording onset, (3-7) combinations of 1 and 2 with the vestibular stimulus starting 1.5 s and 0.75 s before, at exactly the time of, and 0.75 s and 1.5 s after onset of the proprioceptive stimulus, respectively. Each trial was repeated four times in each subject in a random order. The CoP trajectories of each subject were averaged across the four trials per stimulus condition. The presented data represent group averages across all subjects.

3. Results

Fig. 1 shows group average of CoP shifts trajectories projected onto the horizontal plane in responses to vibration TA, to right anodal vestibular stimulation, and combinations thereof. Temporal characteristics of the stimuli and directions of their effects are presented in the left part in the Fig. 1.

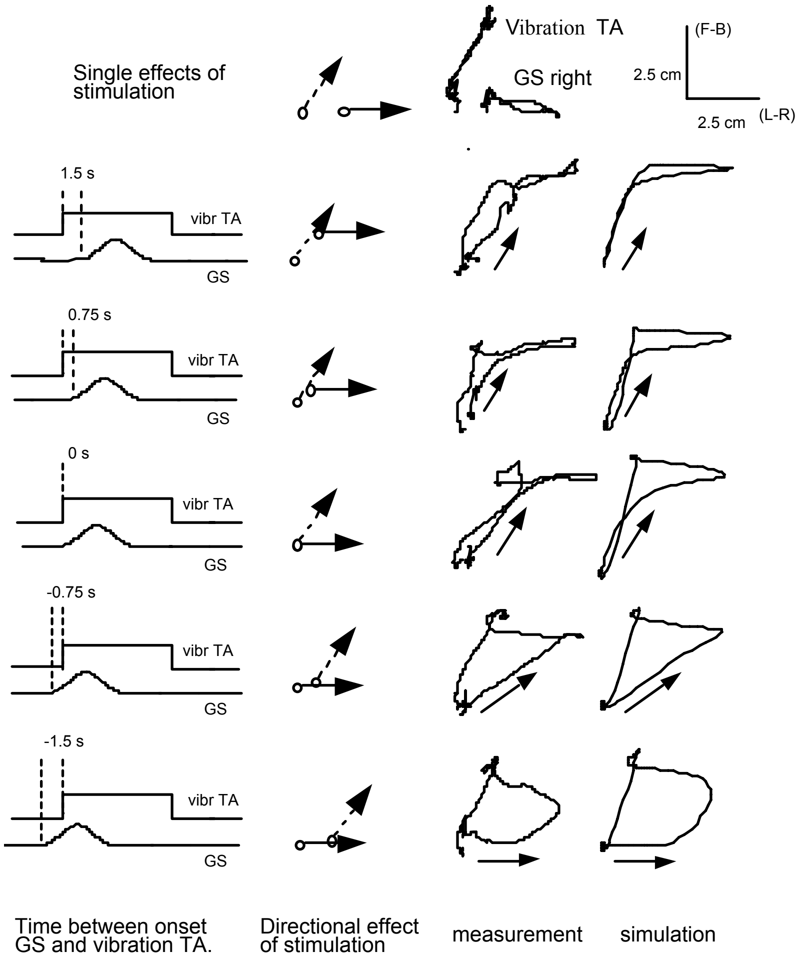

Fig1. shows in the right part "measurements" the group average of CoP shifts trajectories projected onto the horizontal plane in responses to vibration TA, right anodal vestibular stimulation, and their combinations. Temporal characteristics of the stimuli and directions of their effects are presented in the left part. Simulations of the CoP trajectories with a created posture model are in the right part of Fig.1.

The response to right vibration TA (Fig.1 upper part) was a CoP shift mainly in forward direction and, less pronounced, towards the subjects' right side. This value is essentially maintained throughout the stimulus and after stimulus end, the CoP shifts back toward baseline. The response to the right anodal vestibular stimulus (Fig.1 upper part - GS right) was CoP shift mainly towards the right side. Similar as before with the vibratory stimulus, the vestibular response follows the stimulus with a delay of approximately 1 s. Due to the different wave forms of the stimuli, the rising slope of the vestibular response is delayed with respect to that of the vibration response by about 0.7 s.

The responses to the combinations of the right vibration TA and the right anodal vestibular stimulus are presented in the Fig. 1 – "measurements", plotted as CoP shift trajectories projected onto the horizontal plane. The response to both stimuli has a more complex trajectory. When the vestibular stimulus in the combination began 1.5 s prior to the proprioceptive stimulus, the shift started with a trajectory in the rightward direction (start of vestibular effect), followed by rightward and forward direction (coincident of vestibular and proprioceptive effects), followed by leftward (end of vestibular effect) and then by a final backward shift (end of proprioceptive effect). When the vestibular stimulus in the combination began 0.75 s prior to the proprioceptive stimulus, the shift started with a rather straight trajectory in the forward-rightward direction, indicating a temporal coincidence of the vestibular and proprioceptive main effects, i.e., a rightward and forward component, respectively. This initial part is followed by a leftward shift (end of vestibular effect) and then by a backward shift (end of the proprioceptive effect). In the combination with the vestibular stimulus starting 1.5 s and 0.75 s after vibration onset, the initial part of the shift is oriented mainly forward (start of proprioceptive effect). The subsequent part is mainly rightward and, on return, leftward (start and end of vestibular effect), while the final part is backward (end of proprioceptive effect).

4. Discussion

Our results suggest that the control of a vertical orientation of the body in the upright stance is under the continuous control of vestibular and leg proprioceptive inputs. Modifying either one or the other input, or both inputs, lead to a change in CoP response orientation with respect to body. The responses can be considered functionally meaningful compensatory reorientations of the body vertical reference [1]. The experimentally observed CoP shift - body lean responses- might represent our subjects' attempts to align their bodies with the vestibular and proprioceptive vertical reference with the aim to keep the body longitudinal axis aligned with gravity [2]. From the rather long time delays between stimuli and responses (1 s), we assume that we are dealing with a slow adjustment process controlled by high level CNS mechanisms, rather than with fast, reflex like postural reactions that prevent the body from falling.

A major aim of the present study was to elucidate the way in which vestibular and leg proprioceptive inputs interact when establishing the internal reference for the body vertical. The obtained results essentially reflected a superposition of the individual vestibular and proprioceptive effects. In order to explain our results, let us consider that during stance with eyes closed there are two sources of sensory inflow to inform them on body lean, one being the vestibular signal on (head in space) body orientation relative to the gravitational vector, the other being the proprioceptive signal on leg-to-foot angle (body relative to foot support surface), each. During a spontaneous body sway, the two systems signalize the same angle values. Why should these two values be summed, rather than averaged, for instance? We assume that they are, indeed, averaged by a summation process of several sensory inputs through a parallel sensory feedback in the stance control system.

For an interpretation of vestibular and leg proprioceptive inputs integration, we created a simple model (Fig. 2). The overall dynamics of the feedback system, including those of body, muscles, and central processing, are put in a second order transfer function identified by measurement of the body sway to galvanic stimulation [2]. For the vestibular input we assumed a single otoliths influence and second order linear model [3], while the proprioceptive input, for simplicity, was considered to have ideal transfer characteristics.

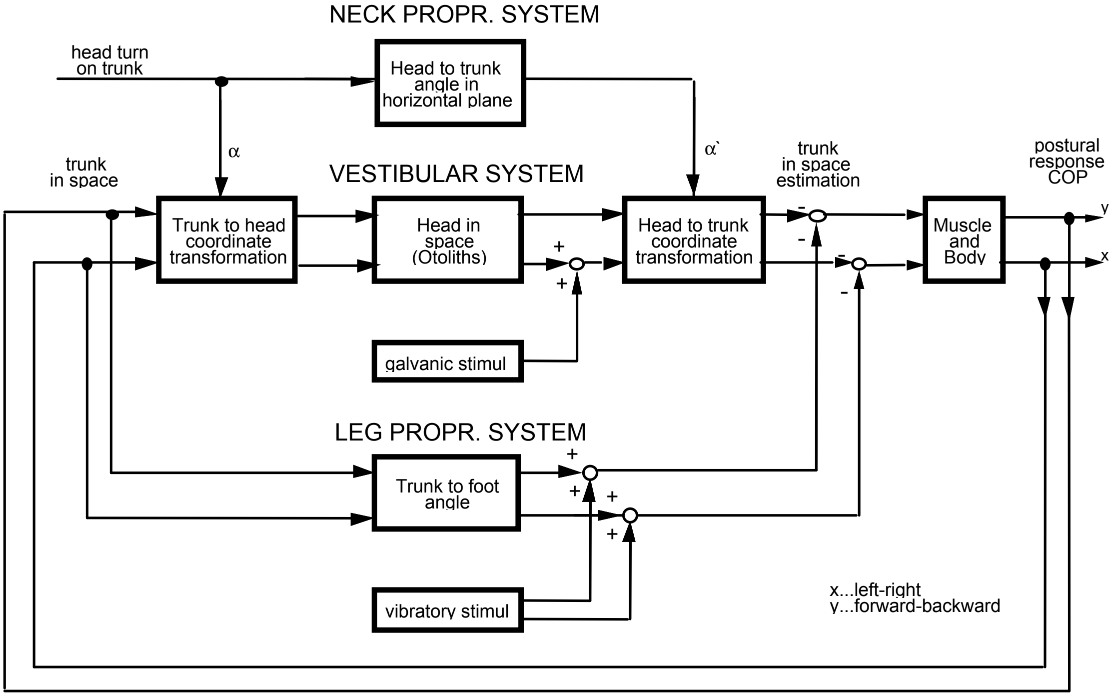

Fig. 2. Simple model of vestibulo-proprioceptive interaction in human postural control

In the model, the two dimensions of body lean in the right-left and in the forward-backward are considered in two separate loop. For interaction, a simple summation was assumed and incorporated in feedback control system. Gain and time delay were adjusted to match the experimentally obtained values. The results were simulated while applying the same "vestibular" and "leg proprioceptive" stimuli as in experiments and the model was created by program Matlab Simulink. The results of the simulation are shown in Fig. 1 (simulation). Note that the simulated data show a high degree of correspondence with the measured CoP responses.

Acknowledgements

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