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RESEARCH ARTICLE

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Vestibular contribution to combined arm and trunk motion

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Abstract Recent studies have shown that the hand-pointing movements within arm's reach remain invariant whether the trunk is recruited or not or its motion is unexpectedly prevented. This suggests the presence of compensatory arm-trunk coordination minimizing the deflections of the hand from the intended trajectory. It has been postulated that vestibular signals elicited by the trunk motion and transmitted to the arm motor system play a major role in the compensation. One prediction of this hypothesis is that vestibular stimulation should influence arm posture and movement during reaching. It has been demonstrated that galvanic vestibular stimulation (GVS) can influence the direction of pointing movements when body motion is restrained. In the present study, we analyzed the effects of GVS on trunk-assisted pointing movements. Subjects either moved the hand to a target or maintained a steady-state posture near the target, while moving the trunk forward with the eyes closed. When GVS was applied, the final position of the hand was deviated in the lateral and sagittal direction in both tasks. This was the result of two independent effects: a deviation of the trunk trajectory and a modification of the arm position relative to the trunk. Thus, the vestibular system might be directly involved not only in the control of trunk motion but also in the arm-trunk coordination during trunk-assisted reaching movements.

Keywords Motor control · Pointing · Reaching · Galvanic vestibular stimulation · Interjoint coordination

Introduction

In studies of whole-body reaching movements, it has been demonstrated that the hand trajectory remained invariant whether the trunk was involved or not, with or without vision of the hand (Kaminski et al. 1995; Ma and Feldman 1995; Pigeon and Feldman 1998; Pigeon et al. 2000). This supports the hypothesis that arm-trunk coordination during reaching is achieved by combining two functionally different synergies: the transport synergy moving the hand along a trajectory to the target and the compensatory synergy that determines the relative contribution of the trunk to the direction and extent of hand movement.

The hand trajectory invariance was still observed when the trunk motion was unexpectedly prevented by a mechanical perturbation (the trunk-arrest paradigm, Adamovich et al. 2001; Ghafouri et al. 2002; Rossi et al. 2002). This was achieved by appropriate changes in interjoint coordination at a latency of about 40–50 ms. It has also been shown that the hand trajectory remained invariant when the body was unexpectedly rotated about the subject's vertical axis (Bresciani et al. 2002b). These results suggested that while the arm transport synergy may be essentially the result of central commands, the compensatory synergy may be driven on-line by afferent signals associated with trunk motion. In addition to proprioceptive feedback resulting from motion at the hip joint, Adamovich et al. (2001) postulated the involvement of vestibular signals, transmitted to the spinal cord by descending pathways and influencing motoneurons of arm muscles. This hypothesis has been supported by the observation that subjects proprioceptively deafferented below the neck managed to compensate without vision for the influence of the trunk arrest on the hand trajectory, at the same latency as that of healthy subjects, implying that the compensation was based on vestibular signals (Tunik et al. 2001).

In order to test the hypothesis of a vestibular contribution to arm-trunk coordination, the present study examined the effects of galvanic vestibular stimulation (GVS) on trunk-assisted reaching movements. GVS is

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achieved by applying direct current of moderate intensity between the mastoid processes, which increases (cathode) or decreases (anode) the spontaneous firing of the otolith and semicircular canal afferents (Goldberg et al. 1984). GVS is an artificial way of altering the vestibular information and acts on the perceptual and motor systems in a way that has not been completely understood (Wardman and Fitzpatrick 2002). However, this technique provides controlled and reversible perturbations to vestibular signals, allowing one to probe their influence on motor tasks. Effects of GVS have been shown to influence various sensorimotor functions, such as the control of eye movements (Watson et al. 1998), posture (Inglis et al. 1995), walking (Fitzpatrick et al. 1999) or spatial orientation (Mars et al. 2001). In particular, GVS resulted in a systematic deviation of trunk trajectory in the direction of the anode when subjects took a forward step (Bent et al. 2002a, 2002b) or were walking along a predetermined trajectory (Bent et al. 2000c; Fitzpatrick et al. 1999). Recently, Bresciani et al. (2002a) also demonstrated that pointing movements, performed by standing subjects whose body movement was restrained, were significantly deviated by GVS.

In the present study, we investigated the arm and trunk responses to GVS in two distinct tasks. In one task, subjects pointed to a memorized lateral target while leaning the trunk forward. In everyday life, a similar movement can be made when a person takes a cup from a table while simultaneously leaning the trunk forward to hear a person on the opposite side of the table better. In another task, subjects initially positioned the hand above the final target and were asked to move the trunk forward while maintaining the hand position. Thus, subjects were required to modify the inter-joint coordination to minimize the influence of the trunk motion on the hand trajectory, including the final hand position, in the first task or on the hand steady-state position in the second task. The second task thus required subjects to make pure compensatory modification of the coordination without producing an arm-transport component of movement. This gave us the opportunity to investigate the effects of GVS on different components of the trunk-assisted reaching. The results of this study have been reported in abstract form (Mars et al. 2002).

Materials and methods

Nine right-handed subjects (four women and five men, aged 21–32 years) with no known vestibular or neurological problems were included in the study, which was approved by the local ethics committee. The subjects gave their informed consent after being briefed about the experiment.

Subjects sat on a stool and held their right (dominant) arm so that the forearm was parallel to the surface of a semicircular table. In the *pointing task* (PT, Fig. 1A), subjects were asked to place the tip of their finger above the starting position, located at a distance of 35 cm from the midline of the chest in front of the subject. Then, a light-emitting target was illuminated at a distance of 40 cm on the right of the starting position, 85° to the sagittal plane. In response to an auditory signal, subjects moved the hand to the lateral target in combination with a forward trunk motion produced by a hip flexion. The *stable-hand task* (SH, Fig. 1B) was similar to the pointing task, except that subjects placed the tip of their finger above the lateral target at the beginning of the trial. Subjects had to maintain the hand at this position while they were moving the trunk forward. In both tasks, subjects were instructed to hold the final posture of the arm and trunk momentarily before moving back to the initial position (476±218 ms in PT; 452±200 in SH). Subjects wore liquid crystal glasses (Translucent Technologies, Plato S2 Spectacles) that became opaque simultaneously with the signal so that vision of the target and the hand was blocked during the task. Arm movements were performed approximately 5 cm above the surface of the table, thus excluding haptic feedback during each trial. Before each task, subjects were trained to perform stereotyped movements of the arm and trunk. Performance was judged as satisfactory by the experimenter when arm and trunk movements were initiated simultaneously and when the amplitude of the trunk movement was consistent from trial to trial (about 20 cm). Subjects were instructed to move the trunk by the same extent in both tasks. This training session was performed with visual feedback and did not last more than 10 trials for most subjects. The two tasks were counterbalanced for order of presentation.

Each task consisted of 15 trials. Five of them were performed without stimulation (condition 0). In a random 10 trials, bipolar GVS was delivered using 6 cm^2 carbon-rubber electrodes tapped over the mastoid processes. Conductive gel insured minimal resistance between the skin and the electrodes. At the beginning of the trial, simultaneously with the auditory signal that prompted the subject to initiate the movement, a stimulator (Grass S88) delivered a 1.5-mA square-wave pulse lasting 1.5 s through a constant current stimulus isolation unit (Grass SIU5). In half of the trials with GVS, the anode (+) was on the right mastoid and the cathode (-) on the left (R condition). In the other half, the polarity was inverted (L condition). GVS was accompanied by mild cutaneous sensation. Rest periods of 20 s were made between trials. After the first and second stimulations, the experimenter asked about sensations associated with the stimulation. No pain was reported. The subject was also asked to report whether they had the

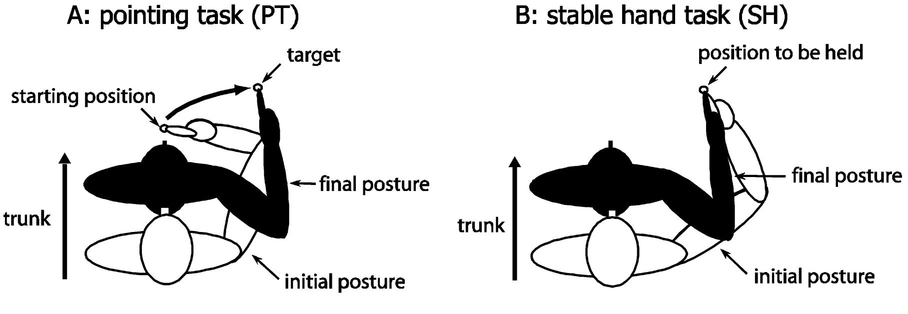

Fig. 1A, B Schematic diagram of the pointing (**A**) and stable hand (**B**) tasks. **A** Subject moved the hand from an initial position to a lateral target while simultaneously leaning the trunk forward. **B** Subject moved the trunk forward while maintaining the hand above the lateral target feeling that the GVS influenced their movement direction or amplitude. The same questions were repeated at the end of the experiment, and the subject was offered the opportunity to make additional comments.

Motion of the arm and trunk was monitored by a 3D Optotrak system (Northen Digital, Waterloo, Canada). Five infrared light-emitting markers were placed on bony landmarks: the tip of the index finger, elbow, right and left shoulders, and sternum. The coordinates of the fingertip and sternal markers were used to compute, respectively, the hand and trunk trajectories. Movement onsets and offsets were computed using the time at which tangential velocity rose above and fell below 5% of its peak value, respectively. For SH, since the hand was quasi-static, movement time was determined by onsets and offsets of trunk motion. The hand and trunk deviation relative to their starting position in the lateral (x), foreaft (y) and vertical (z) direction were computed, as well as shoulder orientation in the frontal (roll) and horizontal (yaw) planes. The analysis of arm joints coordination focused on the elbow flexion/extension and shoulder horizontal adduction/abduction angles. The effects of the task (PT/SH) and stimulus (L/0/R) on these variables were assessed by repeated measure ANOVAs. Newman-Keuls tests were used for post-hoc comparisons. The level of significance of $P<0.05$ was used in all tests.

Results

In PT, subjects simultaneously started to move the hand and trunk after the auditory signal (reaction times: 279±63 ms for the hand, 282±69 ms for the trunk). Motion of the trunk outlasted motion of the hand (duration of movements: 744±191 ms for the hand, 821±167 ms for the trunk; $P<0.001$), as reported in previous studies (Kaminski et al. 1995; Ma and Feldman 1995). Time values for trunk motion in SH did not differ significantly from those in PT: the trunk started to move 305±192 ms after the "go" signal and lasted 868±194 ms.

Figure 2 illustrates the average endpoint and trunk trajectories of a representative subject for the different tasks and GVS conditions. Figure 3 shows the deviations of the trunk and hand, the shoulder orientation and the forearm orientation relative to the trunk at the end of the movement, averaged across subjects. The main effect of GVS on trunk motion was in the lateral direction, always toward the anode (1.3 cm in both task; $F(2,16) = 25.5$, $P<0.001$; Fig. 3D). Subjects also moved the trunk further ahead when GVS was applied compared to the control condition (0.8 cm in PT, 0.4 cm in SH; $P<0.05$; Fig. 3E). Post-hoc comparisons revealed that this effect was only significant in PT ($P<0.01$). GVS did not influence the final vertical position of the trunk (Fig. 3F). GVS also induced a rotation of the shoulders in the frontal plane toward the anode (1.6° in both tasks; $P<0.001$; Fig. 3G). No effect on yaw orientation was observed (Fig. 3H).

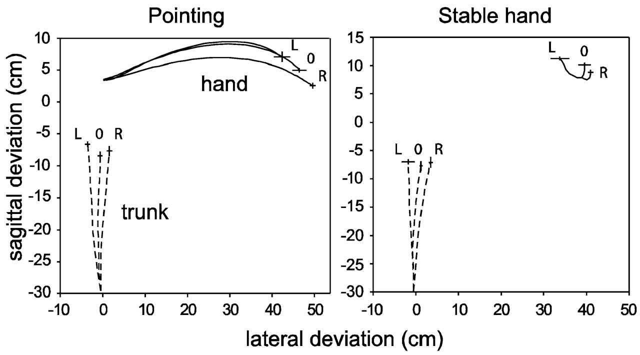

Fig. 2 Mean endpoint and trunk trajectories for the pointing task and the hand stabilization task, for one subject (*L* anode left, *0* no stimulation, *R* anode right). Crosses on final positions represent SD

The main effect of GVS on the final position of the hand was also in the lateral direction, toward the anode (2.3 cm in PT, 2 cm in SH; $P<0.001$; Fig. 3A). A supplementary ANOVA including the marker (trunk vs endpoint) as an additional variable revealed that the endpoint deviation was larger than the trunk deviation ($P<0.001$). GVS also changed the endpoint position in the sagittal direction (1.1 cm in both tasks; $P<0.001$; Fig. 3B). The effect was in the same direction (forward) as the one observed on the trunk when the anode was on the left, but it was significantly larger ($P<0.001$). When the anode was on the right, the endpoint was displaced backward, that is, in the opposite direction to the trunk displacement ($P<0.001$). Additional effects were observed in the vertical direction (1.1 cm in PT, 0.6 cm in SH; $P<0.001$; Fig. 3C), with the endpoint moving upward when the anode was on the left and downward when the anode was on the right.

The elbow angle and the shoulder horizontal abduction angles increased when the anode was on the right and decreased when the anode was on the left, consistently with the endpoint deviation (elbow: 1.3° in SH, 1.7° in PT; shoulder: 0.8° in SH, 2.2° in PT). However, the effects were not statistically significant when each angle was considered independently, because of the large variability in the mean position of each joint. However, when the orientation of the forearm relative to the trunk was computed (i.e. by summation of the shoulder and elbow angles), the effect of GVS was significant ($P<0.05$, Fig. 3I).

Most of the subjects reported a kind of dizziness in the first trials with GVS, but could not tell if the stimulation had any effect on their movement. Only two subjects reported that they perceived a deviation of trunk motion in the direction of the anode, i.e. in the direction of the actual deviation of trunk trajectory, only during the first trials with GVS. No illusion of body motion in the opposite direction to the anode was reported.

Discussion

This study revealed that GVS could significantly modify the final position of pointing movements to a remembered target while moving the trunk forward. The endpoint was deviated to the right, forward and downward with the anode on the right side, and to the left, backward and upward with the anode on the left. Thus, the effects of GVS depended on the stimulus polarity, as has also been observed in studies using GVS to perturb other movements (Bent et al. 2000c; Bresciani et al. 2002a; Inglis et

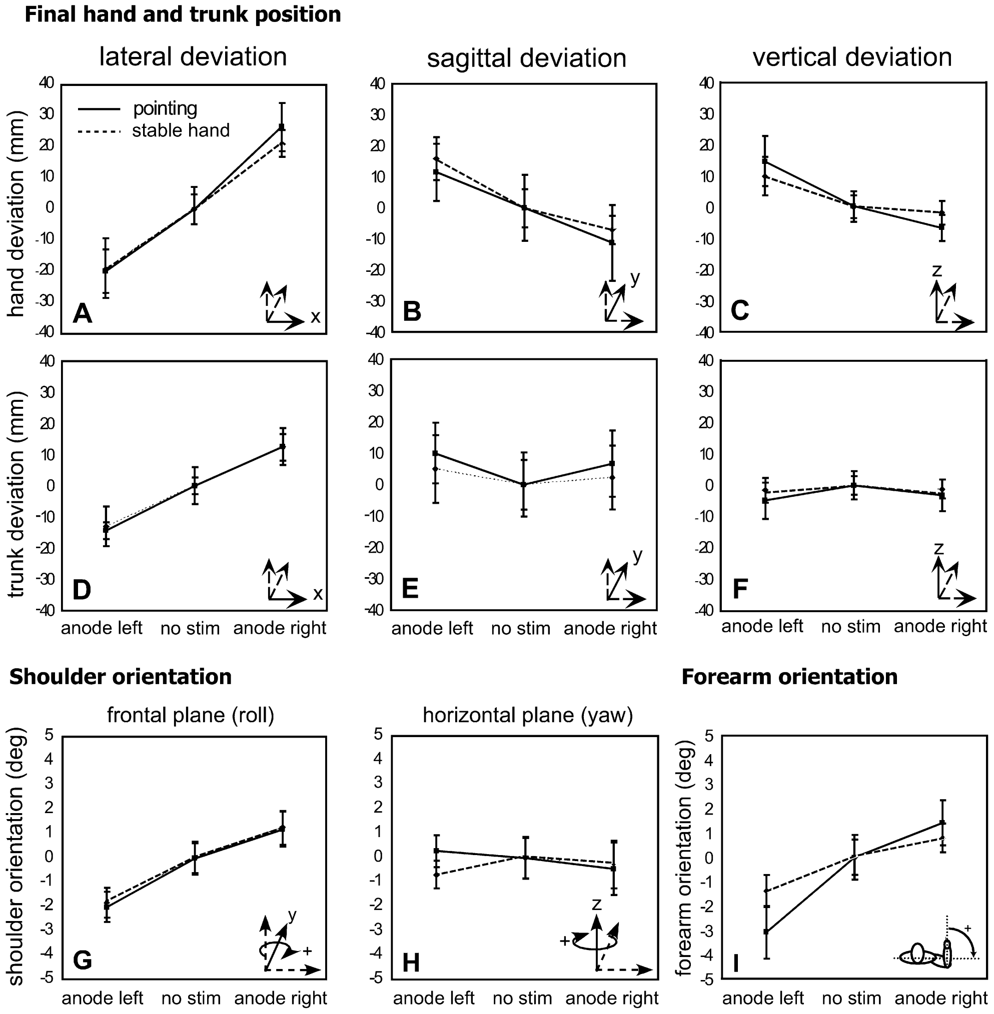

Fig. 3A–I Mean effects of GVS and task. **A–F** Final hand and trunk position in the lateral, sagittal and vertical directions; **G–H** shoulders orientation in the frontal and horizontal plane; **I** forearm orientation relative to the trunk. Positive values correspond to a deviation in the direction indicated by the diagrams in the lower right part of each graph. All figures were centered on the position obtained without GVS in order to compare the magnitude of the effects. Error bars represent standard errors of the means

al. 1995). It is possible that these effects can be graded in a continuous way by changing the intensity of GVS, an assumption that can be verified in future studies.

The change in position of the endpoint in the vertical direction can be explained by a postural effect, since GVS also yielded a tilt of the shoulder in the frontal plane (1.5°), which corresponds to the elevation or lowering of the endpoint (about 1 cm). However, neither lateral nor sagittal deviation of the endpoint can be explained by a modification of the trunk trajectory or its orientation in the horizontal plane. Indeed, although the trunk trajectory was laterally deviated in the same direction as the endpoint, it could be responsible for only 60% of the endpoint deviation. Similarly, the final position of the hand was deflected forward when the anode was on the left and backward when the anode was on the right, which contrasted with the tendency of subjects to move the trunk slightly more forward when GVS was applied, whatever the side of stimulation. The deviation of the final hand position was actually the consequence of a modification of the elbow and/or shoulder angles, which yielded a change of the arm posture relative to the trunk. Very similar effects were obtained when the task required holding the hand stationary in space. The only task-related difference resided in the amplitude of the effect of GVS on the final trunk position in the sagittal direction. The forward deviation observed in PT was not significant in SH.

Thus, GVS had two distinct consequences: an alteration of the trunk trajectory and a modification of the arm posture relative to the trunk. Considering the similarity of the effects of GVS in the pointing and stable hand tasks, it seems that GVS predominantly influenced compensatory mechanisms involved in arm-trunk coordination rather than the transport component of hand movement. This supports the idea that vestibular signals are functional in compensatory synergies involved in whole-body reaching movements. In normal conditions, the influence of trunk motion on the hand trajectory is fully compensated. We propose that GVS disrupted this compensatory mechanism by artificially altering afferent vestibular signals evoked by the trunk motion.

Vestibular signals may influence arm muscles via vestibulo- and vestibulo-reticulospinal pathways (i.e., Büttner-Ennever 1999). The question arises as to whether these pathways are fast enough to ensure the short latency (40–50 ms) of compensatory responses underlying the hand trajectory invariance (Adamovich et al. 2001; Ghafouri et al. 2002; Rossi et al. 2002). Indeed, several studies have shown that GVS elicits short (60 ms)- and medium (100 ms)-latency EMG responses in leg muscles, presumably mediated by vestibulospinal and reticulospinal pathways, respectively (Britton et al. 1993; Fitzpatrick et al. 1994; Rosengren and Colebatch 2002; Welgampola and Colebatch 2001). On the other hand, the latency of EMG responses to GVS has been shown to decrease with shortening the distance from the brain stem to the recording site. For example, if the medium-latency responses can be detected in leg muscles after about 100 ms, then they can be detected in back muscles (erector spinae at level L3–4) after 60 ms (Ali et al. 2003). These authors estimated that the medium-latency response was the sum of a 26 ms central delay (including the time of conduction of the signal in the vestibular nerves and processing in the brain stem) and the time of signal transmission, at a speed of about 13 m/s, from the brain stem to the target muscle. This suggests that vestibulo- and vestibulo-reticulospinal reflexes in arm muscles may be markedly shorter than in leg muscles. In support of this idea, Baldissera et al. (1990) reported EMG responses in the triceps brachii with a latency of 30–40 ms, which resembles that measured for the onset compensatory arm-trunk movements (Adamovich et al. 2001).

Thus we showed that when the arm and trunk participated in a common task, GVS elicited systematic deviations of trunk motion in combination with a modification of the arm position relative to the trunk. These results support the hypothesis of a vestibular contribution to the arm-trunk coordination. In future studies, this hypothesis might further be verified, for example, by analyzing trunk-assisted reaching in individuals with vestibular neuropathy.

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