Neck muscle vibration disrupts steering of locomotion

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Bove, Marco, Manuela Diverio, Thierry Pozzo, and Marco Schieppati. Neck muscle vibration disrupts steering of locomotion. J Appl Physiol 91: 581–588, 2001.—Neck muscle vibration was applied to human subjects to assess the influences of neck abnormal proprioceptive input on the organization and execution of gait. Subjects walked blindfolded to a previously seen target, located straight ahead at ~4 m. Vibration was applied on the right side of the neck, both during and before walking. The variables measured were length, duration, and velocity of trajectory; relative and absolute frontal errors at target; and width of walking support base. Vibration applied during locomotion produced an undershoot of target and deviation of gait trajectory toward the side opposite to vibration. Vibration applied before locomotion produced no effect on length of trajectory but slowing of velocity and nonsystematic deviation. When vibration frequency was increased, the amplitude of the nonsystematic deviation increased. Vibration applied during or before stance trials had minor effects on body sway. Vibration before stance had no effect on the position of mean center of foot pressure, whereas vibration during stance displaced it to the side opposite to the vibrated muscle. We suggest that vibration during locomotion reduces length and velocity of trajectory because of a direct action on the locomotor centers and produces trajectory deviation related to its effect on stance. Vibration before locomotion causes a major, nonsystematic deviation from the planned trajectory, possibly connected to a disorientation of the internal references.

proprioception; orientation; posture

PURPOSEFUL HUMAN MOTION REQUIRES a set of conditions and capacities that allows appropriate planning, organization, and execution of a series of motor acts distributed in time and space. In voluntary movement in general, as much as in locomotion, the relative role of the central command to move and of the feedback from the evolving movement is still a matter of controversy. In principle, one can predict that the shorter the duration of a movement, the less momentous the role of the feedback, as, for instance, during a fast task of pointing to a target. On the other hand, during a slow-tracking task, such as accurately drawing a line along a predefined path, the weight of the multifarious feedback from the periphery would be paramount.

Concurrent problems of equilibrium maintenance, intermittent leg contact with the ground, and visual control of the path further complicate the case of locomotion. It might be envisaged that, in this task, the brain organizes its neural activity with respect to a frame of external and internal references for path selection and equilibrium control, respectively, and intermittently checks the accuracy of the performance using the available feedback from the periphery. The direction of the walking trajectory depends both on its representation, which relies on a reference framework, and on the updating of the activity of the pattern generator on the basis of the input from the evolving movement. In turn, the interpretation of the “straight ahead” depends on the coordinate input from visual, vestibular, and neck receptors, which allow the brain to estimate the position of the head in space and in relation to the trunk (14, 15).

During locomotion, the cephalic segment may constitute a stabilized reference (20, 21). Even though the task imposed on the subject does not require the orientation of the head in any particular direction, head stabilization made on a geocentric reference provided by the gravitational vertical has the advantage of simplifying incoming signal processing. The vestibular system provides both the allocentric reference and direct information as to the movements of the head in space (1). This information is possibly integrated with signals from the neck at many different levels of the central nervous system, including the spinal cord (18, 19), and may contribute to the definition of the spatial relationship between head and trunk. This would allow proper direction of the action of the lower limbs along a straight-ahead path of gait. Vibration of neck muscles in human subjects induces illusions of head and visual target displacement in the absence of visual reference (2, 28) and displacement of the subjective straight ahead (26). Moreover, the velocity of treadmill walking can be modulated by vibrating the dorsal neck muscles (13).
The aim of the present investigation was to assess whether ordinate input from the neck muscles is a condition for accurate performance of straight-ahead locomotion without visual cues toward a memorized target. To this aim, muscle vibration (6) was used to produce imbalance in the proprioceptive input from the neck. Vibration was applied either before or during natural walking to identify the conditions under which the trajectory of the locomotion was more disturbed. Attention was devoted to both extent of trajectory deviation and sign of this deviation on the frontal plane with respect to the side of the neck vibration. A different action of the stimulus when applied before or during locomotion would give hints as to possible selective effects on the reference framework for locomotion steering or on the spinal circuits responsible for gait generation and execution.

METHODS

Subjects

Nine healthy young subjects (2 men and 7 women, mean age: 32.5 yr., range: 26–42 yr) volunteered for these experiments. They had no history of vestibular disorders, no signs or symptoms of cervical diseases, and no discrepancies between right and left lower limbs that could affect veering of locomotion (4).

Walking

Procedure. Subjects stood on a spot, marked on the floor between their parallel feet, which were spaced 5 cm apart (starting point), and the orientation of feet, trunk, and head was aligned. They wore shoes and viewed a straight red line on the floor, which ended with a marker 4.3 m directly in front of them. This distance was empirically determined on the basis of the preliminary trials, because it permitted a comfortable execution of seven successive steps in all subjects. This distance was empirically determined on the basis of the preliminary trials, because it permitted a comfortable execution of seven successive steps in all subjects. However, because no instruction was given to the subjects as to the required number of steps, in ~10% of trials (subjects and conditions collapsed) the number of steps to reach the target was six. At the beginning of the session, they were asked to "go," they walked directly to the target along the red path with their eyes open (EO) at their own preferred velocity. Subjects started walking with their right leg and ended the trial with their feet almost parallel and together.

Control conditions. The light was dimmed, and the subjects were blindfolded. Two sets of trials were performed under this condition without vibration: the subjects simply started walking as soon as they were blindfolded (eyes closed (EC)), or, in a different session, they stood quietly for a 1-min period before starting to walk (EC1_{10s}). The two EC and EC_{10s} controls were carried out to match the two vibration conditions (see sections below). Subjects repeated each of the two walking tasks five times. At the end of each trial, the blindfold was removed, and the subjects could open their eyes and see the target.

Vibration during walking. Five blindfolded walking trials were performed. Neck vibration was applied during the walking period [vibration during walking (VDW)]. The onset of the vibration signal led the subjects to start walking. The vibrator was shut off at the end of the trial when the subjects stopped walking. Two-minute rest intervals, during which the subjects were free to move around with EO, separated the trials.

Vibration before walking. On a different day, each of the subjects who participated in the former experiment performed five additional walking trials with neck muscle vibration before walking (VBW). Trials started after 1-min vibration, during which blindfolded subjects stood quietly with their face to the target. Vibration off was the signal to start walking. Again, 2 min elapsed from the end of each trial and the onset of the next trial.

Stimulation. A direct current electric motor with an eccentric fixed on the shaft, embedded in a plastic tube, produced 5-N peak-to-peak vibration at 70 Hz or 10-N peak-to-peak vibration at 100 Hz. The vibrator was applied to the right side of the cervical column, ~4 cm from the midline along the neck circumference and ~3 cm below the tip of the mastoid bone. It was fixed with tape on that spot and secured by a large elastic band that was passed dorsally around the neck, in front of the shoulders, below the axillas, and around the back. Vibration frequency was usually 70 Hz (VBW_{70}); however, the VBW experiment was repeated in all subjects in a separate session at 100 Hz (VBW_{100}). Note that, under the VDW condition, the vibration acted for a period of ~5–7 s., i.e., much less than under the VBW condition. Under no circumstances did the subjects report sensations of head turning or tilting in response to the vibration, nor was actual head turning or tilting observed by the experimenters.

Measurements. At the back of each of the subject’s shoes, two felt pens (red: right; blue: left) were secured, which produced a clear-cut mark on the floor, which was covered by a white paper layer. The location of the foot placements was manually measured on the paper with reference to a coordinate system centered on the starting spot (x = 0 m, y = 0 m). The errors at the target were measured with reference to the target itself (x = 0 m, y = 4.3 m). For each trial, the following variables were measured (Fig. 1): 1) the straight line joining the start to the end point of the walk trajectory; 2) the time from the start to the end of the walk by means of a chronometer; 3) the mean velocity; 4) the relative distance between the end point and the target with respect to the frontal plane (x) and the sagittal plane (y) (overshoot and undershoot were considered positive and negative, respectively; right-hand and left-hand shifts were considered positive and negative, respectively); 5) the same distances were also taken as absolute values (independent of right or left deviation) to get an index of the global mismatch between the intended and the performed path (the absolute error); 6) the width of the support base, which was the horizontal (x) distance between one marker produced by one heel and the straight segment connecting the markers produced by the preceding and successive strokes of the heel of the other foot; and 7) the successive positions of the right foot allowed the check of the linearity of the path.

Quiet Upright Stance

The subjects who participated in the walking sessions also stood upright on a dynamometric platform (QFP Systèmes, Mougin, France) on a different day. The sampling frequency of the force exerted on three strain gauges was set at 10 Hz. The subjects were asked to stand still with their bare feet on a patterned surface at an angle of 30° and with the heels separated by 10 cm. The arms were by the subjects’ sides, with EC or with EO gazing at a target placed at eye level at 1-m distance. Postural performance was measured under the following six conditions: stance with J) EO or 2) EC without vibration; stance with 3) EO or 4) EC after 1-min vibration of the neck muscle [vibration before stance (VBS) (EO-VBS and EC-VBS, respectively); and stance with 5) EO or 6) EC...
Statistical Analysis

The effects of vibration on walking were assessed by ANOVA. Before ANOVA, a test on the homogeneity of the variances of the data was done (Levene’s test). Two different procedures based on ANOVA were then used. Because the EO condition was represented by one trial only, the comparison of the conditions (EO, EC, EC1fp) was made by means of ANOVA for repeated measures. The differences among all EC conditions were assessed by the ANOVA, applied to all single data gathered under the EC conditions, with or without vibration, in all subjects. The post hoc Newman-Keuls test was employed to assess significant differences among EC, EC1fp, VDW, VBW70, and VBW100.

The effects of vibration on stance were assessed by a two-way ANOVA for repeated measures, where the factors were represented by the visual condition (EO, EC) and by the vibration parameters (control, VBS, VDS). The post hoc Newman-Keuls test was employed to assess significant differences among the six conditions.

RESULTS

Walking

Length and velocity. There were considerable differences across subjects in the kinematics of walking under all experimental conditions. On the average, the mean total path lengths were not different between EO and EC (1 trial per subject in the EO condition against the average of the means of 5 trials per subject per condition). The EC total path length was shorter, although not significantly so, with EC1fp. Figure 2A summarizes the effect of the vibration on the length of the straight line traced from the starting to the end point, as averaged on the basis of all individual EC trials with and without vibration. Length was different when all conditions were compared (ANOVA, $F = 2.868; \text{df} = 4, 220; P = 0.0242$). The post hoc test showed that, when vibration was applied during walking (VDW), path length decreased significantly with respect to both the control condition (EC) and the conditions with VBW (VBW70 and VBW100).

The walk duration was significantly longer with EC than EO (ANOVA for repeated measures, $F = 4.397; \text{df} = 1, 16; P = 0.03$). The mean duration was similar between EC and EC1fp. Figure 2B shows that VDW70 increased walk duration but not significantly so. Walking velocity was significantly higher with EO than EC or EC1fp (ANOVA for repeated measures, $F = 3.14; \text{df} = 1, 16; P = 0.007$). No significant differences in walking velocity were observed (Fig. 2C) among the conditions with EC, whether or not vibration was used. If anything, velocity was the least when vibration was administered during walk (VDW), as a consequence of the maximum duration and minimum length observed under this condition.

Orientation of the walked trajectory. Figure 3 shows examples of the gait patterns of one subject, for five trials, obtained under four conditions (EO, EC, VBW100, and VDW). The scatter of the actual end point of the trajectories on the frontal plane relative to the target was measured for each trial for each subject (the end position was evaluated as the center of the feet support base). The scatter was negligible with EO but was somewhat larger under the EC and EC1fp conditions. There was ample variability in the orientation of the trajectories in the VBW100 condition: across trials...
and subjects, it could lie either on the right or on the left of the target. As a consequence, the grand means of the scatter of the final position in the frontal plane were not different from the EO or EC control conditions. A minor variability in the orientation of the trajectories was present under the VDW condition, where a systematic deviation to the left was nevertheless observed.

Figure 4A shows the averages of these relative frontal deviations under all of the EC and vibration conditions. The variance of the data recorded under the VBW\textsubscript{100} condition proved to be different from all other conditions (Levene's test, $F = 9.669$; df = 4, 220; $P < 0.0001$). This was enough for stating that the VBW\textsubscript{100} condition produced a different pattern of trajectory deviations from all other conditions. This pattern consisted of an ample deviation of the trajectory that was nonsystematic from trial to trial and from subject to subject. The data related to the VBW\textsubscript{100} condition were then excluded from further analysis, and ANOVA was applied to the other conditions. A significant effect on the trajectories was detected when all EC and vibration conditions were compared (ANOVA, $F = 5.3985$; df = 3, 176; $P = 0.014$). The post hoc test showed that a significant deviation was present under the VDW condition only. This systematic deviation to the left (opposite to the vibration side) was common to all subjects except two, for whom the deviation to the left was limited to one trial. With VBW\textsubscript{70}, much like with VBW\textsubscript{100}, there was no systematic deviation from the straight-ahead line. In this case, there was just a slight tendency to deviate to the right (same side of the vibration) except for one subject who drifted to the left.

Figure 4B shows the averages of the absolute errors from the straight-ahead path. An increase in the absolute error with respect to the other conditions was evident in the VBW\textsubscript{100} condition. This error was more than double with respect to the EC\textsubscript{1fp} control condition, indicating that the 1-min vibration before start made the subjects’ walk uncertain. This finding underscores the nonhomogeneity of the variance in the VBW\textsubscript{100} condition mentioned above. As a result, the hypothesis that continuous VBV can disrupt the possible “calibration” between cephalic and body segments appears to be tenable. In four subjects, we repeated the VBV test by using a stimulus duration of 7 s (similar to the duration used under the VDW condition) to check the relevance of the duration of the vibration on the orientation of the walked trajectory. The frequency of vibration was 100 Hz. It turned out that a deviation of the path was indeed produced, despite the short duration of the stimulus. This deviation was nonsystematic, like with the longer stimulus duration. The range of the errors on the frontal plane was larger than under control conditions but reduced (by \textasciitilde 50\%) compared with the longer stimulus duration. Levene’s test indicated nonhomogeneity of variances between the conditions (EC variance < 7-s VBV variance < 1-min VBV variance). As far as the nonsystematic deviation on the frontal plane under the VDW condition is concerned, the absolute error was larger, although not significantly so (Friedman’s ANOVA, $P = 0.18$), compared with EC control walks.

Support base. The horizontal ($x$) distance (see segment $D$ in Fig. 1) between the markers produced by the heel strokes was an index of the width of the dynamic support base. The mean width of the support base was not significantly influenced by vibration, either VBV or VDW, with respect to that under the EC control conditions. Furthermore, no significant differences
were found among the mean widths either across all steps or between the first and the last steps.

To assess whether the VDW produced a cumulative effect or subjects started in the wrong direction but then continued in a relatively straight path, we measured the deviation of each step as the difference between the position of the right foot at one step and that at the preceding step, for three successive steps. As a matter of fact, however, the various differences against the successive steps, subjects, and trials collapsed, showing no consistent pattern, nor was the slope of the regression line through the data points significant.

**Stance.** On the average, body oscillation (sway path length) was larger during EC than EO trials under all conditions (control, VBS, VDS). A two-way ANOVA showed in fact a significant effect of visual conditions on the length of the sway path (EO vs. EC: $F = 29.19; \text{df} = 1, 24; P < 0.0001$). The vibratory stimulus, under both VBS and VDS conditions, did produce an increase in the sway path. The VDS condition was more effective than the VBS condition. Neither effect, however, reached significance with respect to control conditions ($F = 2.11; \text{df} = 2, 24; P = 0.14$). There was no interaction between visual and vibratory conditions. Figure 5A shows the summary of the mean sway path lengths obtained under the six conditions tested.

Neck muscle vibration produced a significant shift to the left (opposite to the vibrated side) of the mean CP, when it was applied during (VDS) but not before (VBS) stance trials (2-way ANOVA; EO vs. EC: $F = 0.09; \text{df} = 1, 24; P = 0.75$; vibration effect: $F = 4.27; \text{df} = 2, 24; P = 0.02$) (Fig. 5B). The visual condition had no significant effect on the displacement of the CP, nor was the interaction between vision and vibration significant. Vibration produced no significant shift in the antero-posterior direction either, regardless of the visual conditions.

**DISCUSSION**

Neck muscle vibration produced perturbation of quiet stance, confirming previous results from the literature (22, 25). In particular, right-side vibration applied during the maintenance of stance (VDS) produced both an increase in sway and a deviation of the CP toward the side opposite to the vibration. Vibration applied before the acquisition of the stance data (VBS) had a smaller effect on sway path but no effect on mean position of the CP on the platform. The visual conditions did not obviously interfere with the vibration effects: the known effect of closing the eyes on body oscillations or position of CP (24) was not specifically changed by the neck vibration. The results observed under quiet stance condition give evidence of the effectiveness of the neck vibration procedure used in the present investigation.
Neck muscle vibration produced perturbation of gait. Vibration was effective both during (VDW) and before walking (VBW). However, the effects were different, depending on the timing of vibration. VDW induced a significant undershoot of the planned distance, with slowing of the velocity of walk, without affecting the width of the dynamic support base. VDW also produced a significant deviation of the path trajectory toward the side opposite to the neck vibration site, thus indicating a systematic effect on the orientation of the intended trajectory. Notably, the vibratory stimulation applied during walk was effective despite the relatively short stimulus duration (5–7 s, corresponding to the trial duration).

The selective side deviation induced by neck vibration administered during gait (VDW) is reminiscent of the findings obtained with VDS. Therefore, a left-side shift of the CP seems to be associated with a left-side deviation of the trajectory, perhaps as a consequence of the asymmetric neck input to brain stem or spinal centers that control balance. Preliminary findings of an investigation in which vibration was applied for a longer period during stepping in place (3) allow us to suggest that VDW did not produce an initial misdirection on the trajectory, possibly connected to the transient effect of vibration on, but a steady and systematic influence on locomotion steering. The reduction of the path length during walking with vibration (VDW) might instead be interpreted as the effect of a depressing action of the neck muscle vibration on the gait generator. The effects could be mediated either by short central circuits connecting the neck muscle afferent fibers with the mesencephalic locomotor region (17) or by direct influences on the spinal generator of locomotor pattern (11). The target undershoot, the trajectory deviation, and the (minor) velocity decrease could be the result of difficulty in integrating the conflicting sensory input and updating the ongoing motor program. During upper limb movements, tendon vibration produced under- or overshoot of a target defined in terms of elbow joint angles (7). The effects observed during gait might be the consequence of an intrusion of the abnormal neck proprioceptive input in the alter-

![Graph A](image1)

**Fig. 4.** Deviation of the path trajectories under the EC and vibration conditions. Grand averages (±SE) are shown for all trials for all subjects. A: relative frontal deviation (positive values: deviation to the right; negative values: deviation to the left) from the straight-ahead path to the intended target. It was negligible with EC and EC1fp. A significant deviation to the left (opposite to the vibration side) was observed with VDW only. The VBW70 and VBW100 conditions were characterized by a slight tendency to deviate to the right (same side of the vibration). B: absolute frontal error from the straight-ahead path to the intended target. With respect to EO (absolute error = 0, not shown), there was a sizeable error with EC, EC1fp, and vibration conditions. It was greatest for VBW100.

![Graph B](image2)

![Graph C](image3)

![Graph D](image4)

**Fig. 5.** Body sway (A) and mean position of center of foot pressure (CP; B) during quiet stance, without (control) and with vibration before (VBS) and during stance (VDS). Grand averages (±SE) are shown for all trials for all subjects. A: slight and moderate increases in sway path were induced by VBS and VDS, respectively, regardless of the visual condition. Closing the eyes (EC) further increased the sway path under all conditions. B: VDS induced a displacement of the body’s CP to the side opposite to the vibration. VBS had no effect.
nate switching from the head to foot stable frame of reference, which normally resets the pattern generator on the basis of the intermittent proprioceptive and tactile information from gait (10). A clear systematic departure of the path from the planned trajectory when directional galvanic vestibular stimulation was applied during gait has been recently reported by Fitzpatrick et al. (9). Galvanic stimulation promptly and markedly affects equilibrium maintenance during stance (8), and neck vibration produces weak but nonnegligible effects on the position of the CP. These effects might entrain balance corrections that, if operating during walk, produce some deviation of the trajectory. However, to explain the relative modesty of the side deviation shown here, it could be considered that lateralized neck muscle vibration might produce, at least in part, bilateral effects, because of the propagation through tissues and bone of the mechanical wave, much as what happens with the simple tendon tap (5).

VBW did not affect velocity of locomotion or distance walked, despite the clear-cut disorientation of gait, as shown by the large absolute error on the frontal plane (with VBW100), in the absence of a systematic deviation. A set of trials under the VBW100 condition with a shorter period of stimulus administration, similar to that used in the VDW condition, showed that some effect on the path could indeed be produced. This was a nonsystematic deviation, like with the longer stimulus duration, but the range of the errors on the frontal plane was reduced compared with the longer stimulus duration (VBW100). This finding shows that a rather brief, abnormal proprioceptive input from the neck can derange the calibration between cephalic and body segments. In passing, this finding explains why the nonsystematic error, associated with the systematic deviation produced by VDW, was larger than that observed during the control trials, thus possibly indicating an additional effect on the straight-ahead identification. Presumably, the reference framework for walking needs to be updated during, as well as before, the start of the walk. Because a few seconds are enough, some disturbance in updating can take place within a very short walk and sum up with the action producing the systematic trajectory deviation.

The absence of systematic walk deviation by VBW was consistent with the findings obtained when the vibration was administered before stance (VBS). It can be assumed that neck muscle VBW interferes with the correct reproduction of the straight-ahead direction (16) rather than with the execution of the locomotor movement. It would prevent the rehearsal of the direction of travel or induce a loss of the internal straight-ahead reference so that, from trial to trial, the direction of the blindfolded gait would be set almost randomly. Under this condition, the head would no longer be used as a stable frame of reference, possibly because of the discrepancy between the abnormal neck proprioceptive information and otolithic input. The variable error (the ample nonsystematic path deviation) indicates that neck vibration altered the whole body orienting system, which seems to be an integrating system rather than a simple relay of a proprioceptive input. One might, therefore, speculate that neck muscle vibration, administered immediately preceding the onset of walk, prevented the correct updating of the spatial reference system on the basis of the input from the vestibulum and neck proprioceptors. Otherwise, vibration would have prevented a correct “reading” of the reference parameters before planning of gait direction or would have produced a faulty integration of the inputs from the relevant receptors, thereby giving rise to an unknown reference. In this view(s), it can be suggested that planning of the gait direction implies scanning of the reference parameters immediately before the start of walking. Further investigation, during which vibration would be applied at different body levels, would confirm the specific role of the head-trunk linkage on dynamic body orientation.

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REFERENCES


