Fingertip Contact Suppresses the Destabilizing Influence of Leg Muscle Vibration

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Lackner, James R., Ely Rabin, and Paul DiZio. Fingertip contact suppresses the destabilizing influence of leg muscle vibration. J Neurophysiol 84: 2217–2224, 2000. Touch of the hand with a stationary surface at nonmechanically supportive force levels (<1 N) greatly attenuates postural sway during quiet stance. We predicted such haptic contact would also suppress the postural destabilization caused by vibrating the right peroneus brevis and longus muscles of subjects standing heel-to-toe with eyes closed. In experiment 1, ten subjects were tested under four conditions: no-vibration, no-touch; no-vibration, touch; vibration, no-touch; and vibration, touch. A hand-held physiotherapy vibrator (120 Hz) was applied ~5 cm above the malleolous to stimulate the peroneus longus and brevis tendons. Touch conditions involved contact of the right index finger with a laterally positioned surface (<1 N of force) at waist height. Vibration in the absence of finger contact greatly increased the mean sway amplitude of the center of pressure and of the head relative to the no-vibration, no-touch control condition \((P < 0.001)\). The touch, no-vibration and touch–vibration conditions were not significantly different \((P > 0.05)\) from each other and both had significantly less mean sway amplitude of head and of center of pressure than the other conditions \((P < 0.01)\). In experiment 2, eight subjects stood heel-to-toe under touch and no-touch conditions involving 40-s duration trials of peroneus tendon vibration at different duty cycles: 1-, 2-, 3-, and 4-s ON and OFF periods. The vibrator was attached to the subject’s leg and remotely activated. In the no-touch conditions, subjects showed periodic postural disruptions contingent on the duty cycle and mirror image rebounds with the offset of vibration. In the touch conditions, subjects were much less disrupted and showed compensation occurring within 500 ms of vibration onset and mirror image rebounds with vibration offset. Subjects were able to suppress almost completely the destabilizing influence of the vibration in the 3- and 4-s duty cycle trials. These experiments show that haptic contact of the hand with a stable surface can suppress abnormal proprioceptive and motor signals in leg muscles.

INTRODUCTION

Vibrating the Achilles tendons of a standing subject elicits backward sway and loss of balance (Eklund 1972). Vibration circa 100-Hz stimulates the spindle receptors of the soleus-gastrocnemius muscles thereby evoking a tonic vibration reflex causing the muscles to shorten (Hagbarth and Eklund 1966). In addition to a reflexive contraction of the muscles, there is a misinterpretation of their length with the vibrated muscles being centrally represented as longer than they actually are and the increased length being reflected in misrepresentations of the angles of the controlled joints (Goodwin et al. 1972; Matthews 1988). For example, with bilateral vibration of the Achilles tendons, a standing subject restrained in position will experience forward body tilt pivoting at the ankles (Lackner and Levine 1979). In total darkness, such subjects, although physically stationary, will exhibit nystagmoid eye movements with slow phase compensatory for the apparent body motion. The sensed pivot point of the body can also be influenced by somatosensory cues: if the subject has a bite plate, the axis of apparent body rotation can shift from the ankles to the head.

Somatosensory stimulation influences orientation in other situations as well. Subjects who are free floating with eyes closed in the weightless phase of parabolic flight maneuvers often lose all sense of body orientation in relation to the aircraft. However, tactile stimulation will restore a sense of orientation, e.g., pressure on their feet will make them feel upright (Lackner and Graybiel 1983). Moving tactile stimulation of the soles of the feet or the palms of the hands can induce illusions of self movement in stationary, seated subjects (Brandt et al. 1977; Lackner and DiZio 1984). Other evidence indicates that contact of the hand with the rest of the body is an important element in calibrating the spatial dimensions of the body schema (Lackner 1988).

Somatosensory stimulation can also be used to enhance accurate spatial localization and stabilize postural control. The oculogyral and the autokinetic illusions are suppressed if the fixation target is attached to the subject’s hand (Evanoff and Lackner 1987; Lackner and Zackar 1977). Illusions of torsional rotation induced by sinusoidally rotating the head of a stationary subject can be suppressed if the subject is allowed to grasp a spatially fixed handle (Gurfinkel and Levik 1993). Standing subjects become much more stable if they are allowed to touch a stationary surface with their index finger at mechanically nonsupportive force levels (Holden et al. 1987, 1994; Jeka and Lackner 1994). Such touch contact is more effective than
visual cues in stabilizing balance and even allows subjects with absent labyrinthine function to balance as stably in the dark as normal subjects (Lackner et al. 1999). If the finger contact reference is unstable, for example, a flexible filament, it can only serve as a regional spatial reference and attenuates sway a limited amount (unpublished data).

The goal of the present paper was to determine the influence of finger contact on balance in subjects being exposed to destabilizing vibration of their leg muscles. We tested subjects in a highly demanding posture, the heel-to-toe, tandem Romberg stance, which increases lateral instability. To maintain balance in this posture, subjects have to keep the vertical projection of their center of mass within the support area defined by the width of their feet, ~10 cm. In this stance, balance is controlled primarily by ankle evertor muscles, the peroneal group, which can exert a maximum moment of ~10 Nm before the edge of the foot will lift up from the support surface and make it impossible to exert further torque on the body (Winter et al. 1993). We predicted that fingertip contact would stabilize balance during vibration because by maintaining “precision touch” and keeping the forces at their fingertip nearly constant, subjects would automatically attenuate their sway.

METHODS

Experiment 1: continuous leg muscle vibration

SUBJECTS. Ten right-handed college students took part after giving informed consent. They were without neurological or skeletomuscular disorders that could have influenced their balance. They ranged in age from 19 to 26 yr and in height from 162 to 185 cm.

APPARATUS. The test situation and apparatus are illustrated schematically in Fig. 1. A Kistler force platform (model 9261A) was used to measure the reaction forces generated by the feet. An ISCAN video monitoring system tracked a light-emitting diode (LED) attached to a head band worn by the subject. The “touch bar” measured the lateral ($T_L$) and vertical forces ($T_V$) generated by the fingertip when the subject made contact with the bar. All data were digitally sampled at 60 Hz.

![FIG. 1. Schematic illustration of the test situation.](Image)
ANALYSIS. The heel-to-toe stance was employed to enhance mediolateral sway. In other experiments, we have shown that in this stance anterior-posterior sway is small and unrelated to stimulation of the fingertip (Holden et al. 1994; Jeka and Lackner 1994, 1995). Therefore, we have concentrated our analyses on mediolateral head and center of pressure sway measures. For each trial, the time series of \( CP_X \) and \( H_X \) were reduced to mean sway amplitudes (MSAs) as follows

\[
\text{MSA} = \frac{1}{N} \sum_{i=1}^{N} x_i - \bar{x}
\]

where

\[
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i
\]

and \( x_i = CP_X \) or \( H_X \).

The same computation was used to derive an average absolute mediolateral touch bar reaction force for each trial. Vertical touch bar reaction forces are unipolar (up only), so the average absolute value was computed.

Cross-correlations were calculated between forces at the fingertip and center of pressure and head positions at 16.67 ms/steps over ±1,500 ms to identify where the maximum correlations occurred.

Initial statistical treatment involved 2 \( \times \) 2 \( \times \) 5 ANOVAs to evaluate the effects of vibration (NV, PV), contact (NT, T), and trial (1–5) on \( CP_X \) MSA, and \( H_X \) MSA. Trial order was not significant in either ANOVA, but the interaction between the other two factors was significant, so the data were averaged across trials for each subject, and further analyses were based on Tukey, pairwise comparisons among the four experimental conditions.

Experiment 2: leg muscle vibration with different duty cycles

This experiment evaluated the role of finger contact in attenuating sway when the peroneal muscle tendons were vibrated at different on and off duty cycles. Subjects were again tested in the demanding heel-to-toe posture and had their eyes closed throughout each trial. The use of multiple periods of vibration in a single trial creates multiple perturbations of posture in each trial including a disturbance when the vibrator is turned on and a rebound when it is switched off. Horak and Nashner (1986) have shown that if subjects are exposed to repeated translations or rotations of a platform on which they are standing, then they soon come to anticipate the perturbation and can attenuate its disrupting influence. We predicted that finger contact with a stable reference would enhance subjects’ ability to compensate for the periodic muscle vibration so that in subsequent vibration cycles within the same trial they would be more stable.

SUBJECTS. Eight Brandeis undergraduate and graduate students participated after giving informed consent. All were in their 20s, and they ranged in height from 158 to 191 cm. They were without neurological or skeletomuscular abnormalities that could have affected their performance.

PROCEDURE. The experimental details and methods of data analysis were the same as in experiment 1. Eight conditions were run. All involved vibration of the right peroneal muscle tendons. Four were control conditions not involving physical contact of the index finger and four involved fingertip touch. The vibrator was held over the peroneal group by elastic tensor bandages and could be cycled for 1-, 2-, 3-, or 4-s on and off duty periods (i.e., 1 s on and 1 s off, etc.) by a timing circuit that gated the vibrator starting 5 s into a trial. Trials were 40 s in duration. In touch trials, a subject attempted to keep his or her finger in the same place on the touch bar without sounding the alarm set at a threshold of 1 N. Three trials were run per condition in a randomized order.

RESULTS

Experiment 1

Figure 2 presents representative trials from one subject for the four experimental conditions. All subjects showed the same patterns. \( CP_X \) MSA was greatest in the vibration condition without touch (NT-PV). The next least stable condition was that without either vibration or finger contact (NT-NV). The conditions involving touch (T-NV, T-PV) were the most stable. They were not different from each other (\( P > 0.05 \)); but both were significantly different from the no-touch conditions (\( P < 0.01 \), both comparisons). This means that subjects were as stable with touch and vibration (T-PV) as they were with touch without vibration (T-NV).

Head (\( H_X \)) MSAs showed precisely the same patterns and significance levels for comparisons between conditions. In the two conditions involving fingertip contact, subjects kept the lateral and vertical contact forces well below 1 N and did not trigger the alarm signal, finger force levels were not significantly different between these two conditions (\( P > 0.05 \)). Figure 3, B and C, presents the results for the different conditions.

The temporal relationships between the lateral forces at the...
fingertip ($T_L$) and center of pressure and head sway are summarized in Fig. 3D. $T_L$ led both $CP_X$ and $H_X$ by $\approx 250$ ms in the T-NV condition. These values did not significantly change during leg muscle vibration (condition T-PV) although the lead of $T_L$ increased somewhat relative to $H_X$. Leg muscle vibration did not affect the strength of the relationship between finger touch force and sway as can be seen from the cross-correlations of $CP_X$ and $H_X$ with $T_L$ (Fig. 3D).

The subjective reports of the participants mirror and extend the quantitative findings. In the absence of finger contact (NT-PV), subjects found the peroneal vibration extremely destabilizing. However, in the vibration condition involving finger contact (T-PV), the vibration was no longer felt to be destabilizing. Subjects could sense the vibrator against their leg but no longer felt unsteady nor as if they were moving. On average, subjects lost balance and grasped the safety railing once per trial in the no-touch, vibration condition and once every five trials in the no touch, no vibration condition (Fig. 3A). In touch conditions, there was only one instance of a subject using the safety rails in the entire experiment. When subjects held onto the safety railing this decreased their body motion and led to an underestimate of $CP_X$ MSA, especially for the no-touch, vibration condition.

Experiment 2

Figure 4 provides representative trials from a single subject for the eight experimental conditions. Figure 5 presents the mean sway amplitudes of $CP_X$ and $H_X$ across subjects within conditions. The no-touch conditions all have two to three times the MSAs of their touch counterparts and much greater standard deviations, $P < 0.001$ for all comparisons. All no-touch conditions have roughly comparable MSAs regardless of vibration duty cycle. In the touch conditions, the subjects were always able to maintain the finger contact force well under the 1 N level allowed.

The reduction of each time series to a MSA actually conceals large differences in the postural responses to vibration within and across touch and no-touch conditions. These differences can be seen in Fig. 6, which presents $CP_X$ MSAs averaged across subjects and trials separately by condition for ON and OFF periods. For example, for the 1 s ON and OFF cycles, 20 1-s periods of ON and 20 1-s periods of OFF were averaged across the three trials for each of the eight subjects.

Different patterns are apparent for the touch and no-touch conditions as vibration period is lengthened. For the 1 s duty period, the ON period of the touch condition shows a rapid leftward shift in $CP_X$, reversing at $\approx 0.5$ s into the vibration
period after peaking at ~1 cm, and then returning to the start position. The OFF period is a virtually exact mirror image of the ON period. The ON period of the no-touch condition shows a similar leftward movement of CPX, but it persists in the same direction albeit decelerating ~0.5 s into the period, peaking at ~2.5 cm of displacement as the period ends. The OFF period is a mirror image of the ON period.

For the 2-s duty cycles, the touch condition shows about a 1-cm leftward shift, reversing at 0.5 s with mirror image return to start position and maintenance near that position for the next 1 s until the period is over. The OFF period is a virtual mirror image of the ON period with a small peak sway displacement. The no-touch, ON period shows about a 2.5-cm leftward displacement peaking and reversing at ~1.5 s, with a hitch in the displacement ~0.5 s into the period. The OFF period is mirror image to the ON period.

The 3- and 4-s vibration periods are very similar for the touch conditions. The changes in medial-lateral, CPX position characteristic of the 1- and 2-s periods are greatly suppressed and only relatively small drifts from baseline are apparent with direction reversals occurring at 0.5 s and sometimes at multiples thereof. The ON and OFF periods are mirror images. The no-touch conditions show large shifts of CPX, nearly 2.5 cm, during the ON periods that reverse after ~1.5 s and then reverse again after another 1.5 s. The OFF periods are roughly mirror images of the ON periods.

Figure 7 shows the mean power frequency of CPX for the different conditions. Power peaks are present at each of the ON-OFF frequencies. The difference in sway power between the touch and no-touch conditions is huge.

In summary, as vibration duration is increased, touch allows subjects to maintain balance without significant disruptions or changes in CPX, they remain stable throughout the ON and OFF periods. In the no-touch conditions, the subjects continue to be disrupted by the vibration at about comparable levels regardless of vibration period. The mirror image patterns exhibited in the touch conditions for the OFF periods indicate that finger contact enables active compensation for the vibration. Active compensation is clear because the CPX patterns in the touch conditions with 1- and 2-s vibration periods involve movement first in one direction then the opposite within a period. By contrast, the rebound effects in the no touch, 1- and 2-s conditions involve unidirectional shifts consistent with a passive release effect. In the ON period, there is a progressive leftward CPX shift followed by a comparable rightward shift in the OFF period. The direction reversals that are first really prominent 1.5 and 3.0 s into the 3- and 4-s no-touch, vibration conditions point to active compensations occurring although they are not as effective as the compensations achieved with finger contact in stabilizing the body.

DISCUSSION

Experiment 1

Vibration of the peroneus muscles in the absence of finger contact was very destabilizing (NT-PV > NT-NV). Our prediction that fingertip contact would counteract vibration was borne out: when subjects were allowed finger contact, they were as stable with peroneal muscle vibration as they were with no vibration (T-PV = T-NV). This is a remarkable effect further accentuated by the subjects’ reports that the vibrator no
longer had any influence on their sway so long as they concentrated on keeping their finger stationary. They also did not experience any tilt or unusual body motion when touching. The 250-ms time lead of $T_L$ relative to $CP_X$ has been observed in all our touch stabilization experiments (e.g. Jeka and Lackner 1994, 1995).

**Experiment 2**

Our expectation that finger contact would suppress the destabilizing effects of intermittent vibration was supported. When allowed contact, subjects were able, especially during the 3- and 4-s vibration periods, to suppress almost completely the debilitating influence of vibration. Only a modicum of improvement was apparent in the no-touch conditions: the subjects were unable to develop anticipatory compensations to counteract either the primary effects of vibration or the mirror image release effects.

**General discussion**

Our first experiment demonstrated that finger contact could completely suppress the instability induced by continuous vibration of the peroneal muscles and the illusory motion induced by such vibration. Subjects were as stable during vibration when allowed finger contact as when allowed touch in the absence of vibration. They were more stable in both of these conditions than in the control condition in which there was neither finger contact nor vibration. The extent of instability in the no-touch vibration conditions is underestimated because periodically the subjects had to push against the safety railing to regain balance. In the touch trials, subjects were always able to keep their finger contact force below the 1 N level permitted. Under optimal conditions, 1 N of force at the fingertip would be able to absorb at most 3% of the sway energy. The actual sway reduction in our touch conditions was $\sim 70\%$. Detailed experimental and modeling data for sway attenuation by finger contact are presented in Holden et al. (1994) and Rabin et al. (1999).

Our second experiment showed for a range of vibration duty periods that finger contact can greatly suppress the consequences of vibration. This effect is dramatic at the longer vibration periods. It indicates that the nervous system is able to anticipate what the consequences of vibration will be and to

![FIG. 6. Mean sway amplitudes of center of pressure ($CP_X$) averaged across subjects and trials separately for on and off periods within trials for the conditions of experiment 2, $n = 8$.](image-url)
implement compensations that nearly cancel these effects. These compensations apparently cannot be fully implemented when finger contact is absent because the no-touch conditions show disruptions at all duty cycles though partial compensation is present for the 3- and 4-s on-and-off periods.

In the touch trials, the extent of compensation increased with period duration even though the order of conditions was randomized. This is likely because after the subjects had received several trials, they recognized that all on vibration and off vibration periods within that trial would be identical to the first ones in the trial and that all trials were the same length. This allowed them to anticipate the consequences of subsequent vibration periods and subsequent off periods within a trial. Touch contact enabled subjects to model very effectively the 3- and 4-s on-and-off periods. These compensations apparently cannot be fully implemented when finger contact is absent because the no-touch conditions show disruptions at all duty cycles though partial compensation is present for the 3- and 4-s on-and-off periods.

The touch conditions thus implicate a potential role for internal models, both inverse and forward (cf. Miall and Wolpert 1996), involving detailed monitoring of arm configuration and fingertip force patterns and anticipated consequences of vibration and compensatory motor innervations on body position. Limb position must be monitored quite precisely for finger contact to have such strong stabilizing effects on posture or it would not be possible for the nervous system to distinguish between changes in fingertip contact forces resulting from postural shifts and from shifts in arm configuration relative to the torso (cf. Rabin et al. 1999).

A natural way to interpret our findings is in terms of “precision touch,” in analogy to the concept of “precision grip” introduced by Johansson and Westling (1987). They showed that the nervous system is extremely sensitive to micro-displacements at the fingertips. When an object being held between the thumb and index finger starts to slip, changes in grip strength just adequate to suppress slip occur “automatically” (Johansson 1991). Our results indicate that one finger can make precision contact with a surface and that whole-body, postural musculature can be automatically marshaled to preserve that contact. This is a nonconscious mobilization in which the task goal of maintaining light contact is conscious but the details of implementation are not. It is likely that the nervous system can automatically modulate the postural apparatus to achieve precision contact or grip with any mobile part or combination of parts of the body.

Control is dependent on regulating the somatosensory input at the fingertip, which under the experimental conditions, is the relevant receptor region. Adjustments of arm and leg muscles are made as appropriate to minimize changes at the fingertip, and the configuration of body segments between the fixed points of the feet and fingertip is monitored. Vibrating the ankle muscles alters balance and finger contact, but automatic adjustments are made to alleviate alterations in force thereby stabilizing posture. That this would be the case should not be surprising because tool use and manipulation are a quintessential human activity. In every day life, we constantly reach for and manipulate objects and tools while adjusting our postural muscles to maintain precise control at the relevant effector surface, be it the fingertips or the tip of a screwdriver blade. Attention is attuned to the hand or the tool, not the postural musculature involved in achieving the control.

An important feature of our experiments is that the hand has representational priority in control of spatial orientation. For example, in other studies we have shown that if a blindfolded subject is standing and maintaining precision touch with a surface, then if unbeknownst to the subject the surface is oscillated at low amplitude, he or she will become entrained and sway at the same frequency as the surface. The subject will perceive the finger contact surface to be stationary and not perceive his or her body sway even though it would be suprathreshold in the absence of finger contact (Jeka et al. 1997, 1998). In yet other studies, we have shown that the hand has representational priority in affecting the perceptual representation of both body orientation and body configuration (Lackner 1988). The present experiments show the importance of the hand in allowing the CNS to monitor and model the destabilizing effect of leg muscle vibration on postural control in order both to regain stability and to prevent destabilization. These observations have obvious significance for developing rehabilitation paradigms for individuals with balance deficits. The importance of the hand in spatial control may relate to the enormous amount of cortex devoted to the sensory and motor aspects of hand function relative to that assigned to the other parts of the body.
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