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RESEARCH ARTICLE

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Precision contact of the fingertip reduces postural sway of individuals with bilateral vestibular loss

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Abstract Contact of the hand with a stationary surface attenuates postural sway in normal individuals even when the level of force applied is mechanically inadequate to dampen body motion. We studied whether subjects without vestibular function would be able to substitute contact cues from the hand for their lost labyrinthine function and be able to balance as well as normal subjects in the dark without finger contact. We also studied the relative contribution of sight of the test chamber to the two groups. Subjects attempted to maintain a tandem Romberg stance for 25 s under three levels of fingertip contact: no contact; light-touch contact, up to 1 N (≈100 g) force; and unrestricted contact force. Both eyes open and eyes closed conditions were evaluated. Without contact, none of the vestibular loss subjects could stand for more than a few seconds in the dark without falling; all the normals could. The vestibular loss subjects were significantly more stable in the dark with light touch of the index finger than the normal subjects in the dark without touch. They also swayed less in the dark with light touch than when permitted sight of the test chamber without touch, and less with sight and touch than just sight. The normal subjects swayed less in the dark with touch than without, and less with sight and touch than sight alone. These findings show that during quiet stance light touch of the index finger with a stationary surface can be as effective or even more so than vestibular function for minimizing postural sway.

Key words Posture · Somatosensation · Vestibular · Haptic · Proprioception

Introduction

Individuals who have lost vestibular function are greatly impaired in their ability to maintain quiet stance and to move about, especially on uneven surfaces and in darkness or low light levels (Begbie 1967). Normal subjects also show increased postural sway, about twofold, in the dark (Dichgans and Brandt 1978). Recent studies have shown that spatial information about body posture derived from fingertip contact with a stationary surface greatly attenuates the sway of normal individuals standing in the dark (Holden et al. 1987, 1994). Subjects spontaneously adopt a force level of approximately 0.4 N (about 40 g), which is far below that necessary to stabilize the body mechanically (cf. Holden et al. 1994 for a biomechanical analysis) but which corresponds to the maximal dynamic sensitivity of the somatosensory receptors in the fingertip (cf. Johansson 1991). The fingertip cues are so salient that even when individuals are allowed sight of their surroundings fingertip contact further attenuates their sway.

Changes in force at the fingertip lead changes in body sway by about 250–300 ms when only very light touch contact is maintained; by contrast, they are in phase when subjects are allowed physically supportive force levels at the fingertip (Jeka and Lackner 1994, 1995). The 300-ms time lead indicates that the changing cues at the fingertip are used to anticipate and counteract the body sway by appropriate activation of postural muscles. This feedforward muscle activation has been confirmed in studies correlating changes at the fingertip, onset of EMG activity in leg muscles countering sway, and displacements of the center of pressure and of the head (Jeka and Lackner 1995).

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The changing stimulation at the fingertip coupled with information about the configuration of the arm to the torso allows the finger to serve as a sensitive indicator of body sway (Rabin et al. 1997). Displacement detection thresholds at the fingertip are around 1 mm (Johansson et al. 1982). With the finger touching a surface 75 cm above the floor, a typical elevation used in our experiments, a sway of 1° at the ankles would displace the fingertip 1.3 cm if the arm were held rigid. Even 0.1° of body sway would be well above detection threshold at the fingertip. Consequently, the fingertip can be used to capture body displacement and motion at levels that are far below threshold for the vestibular apparatus (cf. Fitzpatrick and McCloskey 1994; Wilson and Melvill Jones 1979, for a discussion of vestibular thresholds). Fitzpatrick and McCloskey's (1994) systematic assessments of thresholds for vestibular detection of body displacement on the upright posture indicate a value of about 0.005 rad or 0.6° of body sway. Nashner (1971, 1972) using a posture platform that could be sway referenced to prevent motion at the ankle joints concluded that the otolith organs play little role in stabilizing normal upright posture but that the pitch axis semicircular canals are especially significant in detecting motion and initiating compensatory responses. He reports a threshold of approximately $0.05°/s^2$ with response elicitation occurring after body displacement exceeds 0.5°. The threshold values for vestibular contributions to postural compensation reported both by Fitzpatrick and McCloskey and by Nashner are about 6 times higher than displacements resolvable by the fingertip. Thresholds measured using oscillation of seated or recumbent subjects are not relevant to the present context.

Our goal in the present experiment was to determine whether subjects with absent or severely impaired vestibular function would be able to use light touch cues from the fingertip to control their body orientation in darkness so that their body sway would be equivalent to or less than that of normal subjects tested in the dark without fingertip contact. Our prediction was that they would be able to do so. In a preliminary study, we had tested vestibular loss subjects in a semitandem Romberg stance with one foot in front of the other, and the feet about 15 cm apart horizontally. Fingertip contact attenuated the sway of the vestibular loss subjects as much as it did the sway of normal subjects standing in a heel-to-toe, tandem Romberg stance. We had tested the vestibular loss subjects in the "semitandem" stance because in this posture they can maintain balance for 25 s without falling. These pilot observations indicated that for subjects with and without vestibular function in roughly equally stable postures fingertip cues about sway stabilized posture equivalently. In the present study, we tested vestibular loss subjects in the highly demanding tandem Romberg stance to see if they would perform as well as age-matched control subjects when both groups were allowed fingertip contact with a stable surface.

None of our vestibular loss subjects could maintain balance in this stance in the dark without hand contact and most could only do so briefly (less than 5 s) when allowed normal vision in the absence of touch. Nevertheless, because of the great contribution of fingertip cues to postural stability we thought such contact might enable the vestibular loss subjects to balance as well in the dark as normal subjects who were denied fingertip contact. Individuals without vestibular function often show different patterns of head and body control than normal subjects. Consequently, we also measured both head and center of foot pressure displacements and examined their temporal relationships to force changes at the fingertip.

Materials and methods

Subjects

Five vestibular loss patients, two women and three men (ages 70, 62, 52, 54, and 57 years; mean 59 years), participated They had earlier taken part in the Massachusetts General Hospital's vestibular rehabilitation program. All had severe bilateral loss of vestibular function: several from streptomyocin poisoning, one from an autoimmune disease, and one from progressive neural degeneration of unknown etiology. Impairment was confirmed by semicircular canal, otolith, vestibulo-ocular, visual-vestibular interaction and dynamic posturography evaluations conducted at the Vestibular Testing Laboratory of the Massachusetts Eye and Ear Infirmary. The diagnostic procedures are described by Krebs et al. (1993) and Gill-Body and Krebs (1994). The patients fell within the vestibular loss category of performance on all of these tests. Five age-matched control subjects, two women and three men (mean age 58.8 years), were recruited from the staff of Brandeis University. They were without physical or neurological deficits that could have affected their balance ability. All were within normal ranges on tests of vestibular function involving rotational assessments of canals and otoliths. Table 1 summarizes the characteristics of the vestibular loss and normal subjects. Each subject

Table 1 Characteristics of the vestibular loss (*VL*) and control (*C*) subjects. SVAR is a sinusoidal angular rotation test carried out at 0.05 Hz. Step gain refers to the peak angular velocity response after sudden deceleration from constant velocity rotation. Calorics refer to both hot and cold irrigation of the external auditory meatus (*VL* vestibular loss, *C* control, *NT* not tested)

Group	Age (years)	Height (m)	Weight (kg)	SVAR (0.05 Hz)	Step gain	Calorics
VL	70	1.74	90.9	0.029	NT	Absent
VL	52	1.87	73.5	0.169	NT	Absent
VL	62	1.57	72.7	0.05	NT	Absent
VL	54	1.63	50.9	0.019	NT	Absent
VL	47	1.76	72.7	0.017	NT	Absent
C	71	1.62	70.4	0.47	0.6	NT
C	52	1.64	65.7	0.64	0.5	NT
C	52	1.67	54.5	0.53	0.6	NT
C	54	1.57	63.7	0.56	0.5	NT
C	60	1.70	90.9	0.61	0.7	NT

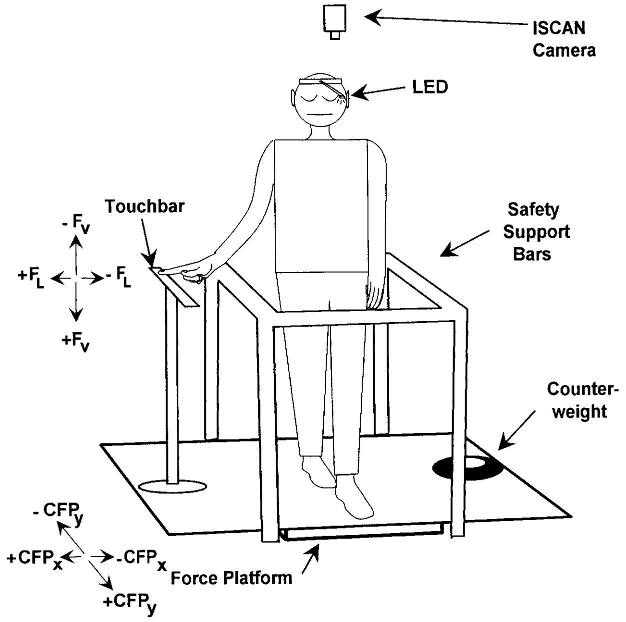

Fig. 1 Schematic illustration of the experimental apparatus with a subject in the tandem Romberg stance

signed an informed consent statement that had been approved by the Brandeis University Committee for the Protection of Human Subjects.

Apparatus and Measures

Figure 1 depicts the test situation with a subject standing in the tandem Romberg position (heel-to-toe) on a force platform, touching a device used to measure the forces applied by the fingertip. The force platform (Kistler Model 9261A) measured the ground reaction forces at the feet.

Center of foot pressure

Medial-lateral (CFP$_x$) and anterior-posterior (CFP$_y$) coordinates of foot pressure were computed from the force components registered by piezoelectric crystals in the corners of the force platform.

Head motion

The subject wore a head band that had a light-emitting diode (LED) attached at the midline of the forehead. An ISCAN video camera system detected medial-lateral (Head$_x$) and anterior-posterior (Head$_y$) head displacements by tracking the position of the LED. The ISCAN system measures two-dimensional movement in a field of view of 512 pixels (Head$_x$) × 256 pixels (Head$_y$). The camera was mounted to the ceiling of the test chamber. We normalized the field of view across subjects of different heights by measuring the distance between the camera and the LED on the head band when each subject was standing on the test platform; this allowed us to compute a calibration factor for each subject. The average resolution across subjects was 0.48 mm (Head$_x$) and 0.96 mm (Head$_y$).

Fingertip contact forces

The "touch device" that the subject contacted with his or her index finger consisted of a horizontal metal bar (46 cm×1 cm×2 cm) attached at either end to a metal stand (see Holden et al. 1994). The stand rested on a rigid wooden platform (155 cm× 70 cm) that overlay the force plate and extended beyond its lateral edges. The touch device apparatus on one side of the platform was balanced by a comparable mass on the other side (see Fig. 1). This arrangement ensured that the Kistler force platform detected all forces applied to the touch device as well as all forces generated by the subject's feet and that it did not interpret forces at the fingertip as changes in CFP$_x$ or CFP$_y$. In this circumstance, the force applied by the finger to the touchbar and transmitted to the platform by the touchbar's base will be exactly balanced by the resulting reaction force generated at the subject's feet; consequently, there will be no spurious change in CFP$_x$ or CFP$_y$ as a result of the force at the fingertip. The horizontal bar was adjusted in height to allow individual subjects to assume a comfortable lateral arm position while touching the contact plate with their index finger. Two, dual-element, temperature-compensated strain gauges (Kulite Semiconductor, Type M(12) DGP-350-500) mounted on the metal bar transduced the lateral (Finger$_L$) and vertical (Finger$_V$) forces applied by the finger. The strain gauge signals were amplified and calibrated in units of force (newtons). A comparator could trigger an auditory tone when a specified threshold force was reached.

Procedure

The subject stood with right foot behind left along the center of the anterior-posterior axis of the force platform. Adhesive tape was used to mark the position of the subject's feet on the platform so that the same foot position could be repeated for the different conditions of the experiment. The touch bar was adjusted to a comfortable height (approximately waist level) and lateral distance for the subject to make contact with the right INDEX fingertip.

The experimental conditions varied in terms of allowing vision (Vision) or having eyes closed (Dark) and type of fingertip contact: no contact (NoTouch) in which the subject's arms hung passively, touch contact (Touch) in which the subject was limited to 1 N of applied force on the touch apparatus, and force contact (Force) during which the alarm was turned off and subjects could apply as much force as desired. One newton of applied force at the fingertip is mechanically inadequate to attenuate sway amplitude by more than 2.3% (Holden et al. 1994). The six experimental conditions included: Vision-NoTouch, Vision-Touch, Vision-Force, Dark-NoTouch, Dark-Touch, and Dark-Force.

One practice trial was given for each condition before the experiment began. Subjects started a trial by getting on the platform and looking straight ahead at a fixation target on a wall 2 m away that was covered with a black cloth. The subject's peripheral visual field beyond 30° provided a rich, complex visual environment with many horizontal and vertical features. Subjects were told to let go of the safety railing surrounding them and take as much time as desired to assume a comfortable stance with their fingertip on or off the touch bar and with eyes open or closed, depending upon the condition. Once they felt ready, subjects said "go" and the experimenter initiated data acquisition. When a vestibular loss subject was tested, one experimenter stood near the subject to assist in case they began to fall.

The experimental trials were run in four blocks of six trials (one trial of each condition per block) for a total of 24 trials. Conditions were randomized within a block. Trial duration was 25 s. All signals were collected in real time at 60 Hz. After each trial, the subject stepped off the platform and sat comfortably for at least 1 min. The experiment lasted approximately 1 h.

Analysis

The first and last 4 s of data were excluded from analysis to minimize anticipation effects associated with the beginning and end of a trial, leaving 17 s of data for each trial. The experimental posture, tandem Romberg (heel-to-toe), had been chosen to enhance medial-lateral body sway. In our earlier work, we had found that the horizontal and vertical contact forces at the fingertip on a laterally positioned touch bar were not strongly correlated with anterior-posterior body sway in the tandem Romberg stance (Jeka and Lackner 1994). Consequently, we report here only measures related to medial-lateral body and head sway (i.e., CFP_x and $Head_x$ displacement). Drift was estimated from the coefficients of a first-order polynomial fit by least squares to the raw data. Subtracting this straight line resulted in a time series with a mean equal to zero and no linear trend. The mean sway amplitude (MSA) of CFP_x within a trial was determined by subtracting the average position of CFP_x from each data point and then taking the root mean square of the normalized CFP_X time series. The same technique was used to determine $Head_x$ mean displacement. Mean horizontal and vertical forces applied by the fingertip were calculated for the conditions involving touch or force contact.

Cross-correlations between CFP_x displacement and lateral and vertical fingertip contact forces ($Finger_L$ and $Finger_V$) and between CFP_x and $Head_x$ displacements were carried out in each of 200 periods (±16.07 ms/period) to determine whether correlations were strongest at times other than $t=0$ (i.e., in-phase). Because correlations do not have a normal distribution, they were transformed to Fisher's Z_r prior to statistical analysis (Senders 1958). In our terminology, positive time delays mean that changes in the second variable of a pair occur ahead of changes in the first, and follow changes in the first for negative time delays. For example, a positive time delay of 100 ms for a CFP_x–$Finger_L$ correlation would mean that changes in $Finger_L$ occurred 100 ms ahead of changes in CFP_x.

Results

The control subjects were able to maintain their balance throughout all trials of all conditions without ever contacting the safety railing. By contrast, the vestibular loss subjects lost balance within 5 s in all Dark-NoTouch trials, and in Vision-NoTouch trials they tapped the safety railing at least 2 or 3 times per trial with their arms to keep themselves from falling. The movement was generally a bilateral push of the arms against the safety railings. Such temporary mechanical stabilizations diminish the CFP_x and $Head_x$ displacements in the Vision-NoTouch trials of the vestibular loss subjects; without these contacts these subjects would have fallen before the trial was over. In trials involving touch or force contact of the index finger, the vestibular loss subjects were able to complete all trials of all conditions without losing their balance.

A repeated measures (2×2×3×4) MANOVA was conducted to evaluate the influence of Subject group (Control, Vestibular Loss), Vision (Vision, Dark), Contact (NoTouch, Touch, Force) and Trial (1–4) factors on CFP_x and $Head_x$ mean displacements, as well as CFP_x-$Head_x$ cross-correlations and time lags. Because fingertip contact forces were zero in the NoTouch condition, a separate MANOVA for measures involving contact forces (mean absolute $Finger_L$ and $Finger_V$, cross-correlations, and time lags for CFP_x-$Finger_L$ and CFP_x-$Finger_V$) used only the Touch and Force levels of the Contact factor.

The effect of trial order was not significant in either MANOVA ($P>0.5$); therefore we averaged data across trials for each subject. The results of the first MANOVA showed significant effects for the Vision×Contact interaction ($P<0.0001$) and a main effect for Subject group ($P<0.001$). The second MANOVA showed a significant Subject group×Contact interaction ($P<0.001$). Univariate ANOVAs and pairwise comparisons were carried out to explore the origins of these differences.

Center of foot pressure (CFP) and head mean sway amplitude (MSA)

Control subjects

Both vision and light touch of the index finger diminished CFP_x and $Head_x$ MSA relative to the Dark-NoTouch condition by more than 50%. MSA was actually significantly less in the Dark-Touch condition than the Vision-NoTouch condition for both CFP_x and $Head_x$. The Vision-Touch condition was associated with significantly smaller MSAs than the Vision-NoTouch condition. These results show the powerful benefit of light touch of the fingertip in attenuating head and body sway in the normal individual during quiet stance. The conditions allowing unlimited force at the finger (Dark-Force, Vision-Force) showed precisely the same patterns as the light touch conditions (Dark-Touch, Vision-Touch). The findings are presented in Fig. 2.

Vestibular loss subjects

None of these subjects could maintain balance for more than a few seconds in the dark without hand contact (Dark-NoTouch condition); however, when touch was allowed (Dark-Touch condition) their CFP_x sway was significantly less than when they were standing with eyes open (Vision-NoTouch), and MSA of $Head_x$ was equivalent for the Dark-Touch and Vision-NoTouch conditions. Allowing touch and vision (Vision-Touch) significantly attenuated CFP_x sway relative to vision alone (Vision-NoTouch). There was no difference in CFP_x or $Head_x$ MSA between the Dark-Touch and Vision-Touch conditions. The force conditions (Dark-Force, Vision-Force) showed the same pattern as the touch conditions (Dark-Touch, Vision-Touch).

Comparison of subject groups

The vestibular loss subjects showed significantly less CFP_x sway in their Dark-Touch condition than the control subjects in their Dark-NoTouch condition, $P<0.01$; $Head_x$ sway was comparable. The CFP_x and $Head_x$ MSAs of the vestibular loss subjects in the Vision-NoTouch condition were equivalent to that of the control subjects' Dark-NoTouch condition. The contribution of touch and force were striking for both groups in attenuat-

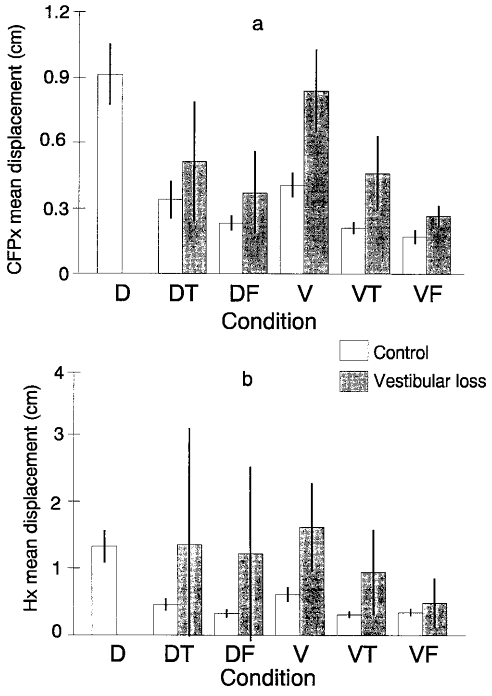

Fig. 2a, b Lateral mean sway amplitude of center of foot pressure (*CFP$_x$*) **(a)** and of head (*H$_x$*) **(b)**. *Error bars* in this and subsequent figures represent standard errors (*D* eyes closed, no touch, *DT* eyes closed, touch contact force less than 1 N, *DF* eyes closed, unlimited contact force, *V* normal vision, no touch, *VT* normal vision, touch contact force less than 1 N, *VF* normal vision, unlimited contact force). The vestibular loss subjects were unable to perform the D condition

ing CFP$_x$ MSA, but the control group showed a more pronounced overall influence on Head$_x$ MSA than the vestibular loss group. However, one of the vestibular loss subjects (WB) had very large Head×MSAs in his Dark-Touch and Dark-Force conditions. The remaining vestibular loss subjects actually had comparable MSAs in Dark-Touch and Dark-Force conditions to the control group.

Fingertip contact forces

Both groups of subjects were able to keep the applied force in their touch conditions (Dark-Touch, Vision-Touch) below the 1 N value that would have triggered the alarm; see Fig. 3. The lateral forces were in the 0.3–0.6 N range as were the vertical forces. In the force conditions (Dark-Force, Vision-Force), the control subjects exerted 3.5–4 N vertical force; by contrast, the average vertical force was only about 0.8 N for the vestibular loss subjects in these conditions. The lateral forces were below 1 N for both groups in both conditions. There was no significant difference between the two groups in applied lateral or vertical force at the fingertip in the Dark-Touch and Vision-Touch conditions; but the vestibular loss subjects exerted significantly less vertical force in Dark-Force and Vision-Force conditions; $P<0.01$.

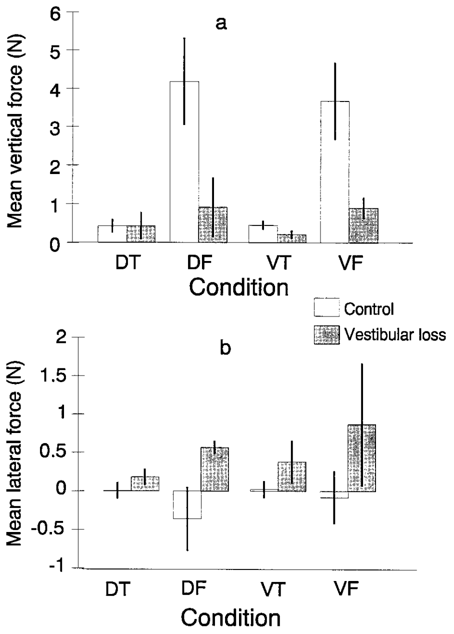

Fig. 3a, b Mean vertical **(a)** and lateral **(b)** forces applied to the touch bar by the fingertip in conditions involving contact

Center of foot pressure–head displacement correlations

The mean CFP$_x$ and Head$_x$ correlations were slightly higher across conditions for the control subjects than for the vestibular loss group, correlations being in the 0.7 and 0.6 ranges for the two groups, respectively. The maximum CFP$_x$–Head$_x$ correlation occurred in the Vision-NoTouch condition for both groups. Mean CFP$_x$–Head$_x$ time lags tended to be less in the touch conditions (Dark-Touch, Vision-Touch) for the vestibular loss subjects, with CFP$_x$ sway leading Head$_x$ by about 10–30 ms. The head lagged the torso for both groups for all conditions, never exceeding 70 ms in the touch conditions, or 100 ms in the force conditions.

The overall patterns are presented in Fig. 4.

Correlations between center of foot pressure and fingertip contact forces

The control and vestibular loss subjects showed remarkably similar correlations between CFP$_x$ displacement and lateral and vertical fingertip contact forces. The lateral force correlations averaged about 0.6 in Dark-Touch and Vision-Touch conditions, and about 0.8 in Dark-Force and Vision-Force conditions. The overall correlations were lower for the vertical force, about 0.4 for Dark-Touch and 0.25 for Vision-Touch, and about 0.6 for Dark-Force and Vision-Force. The mean time lags also showed similar patterns for the two groups. For Dark-Touch and

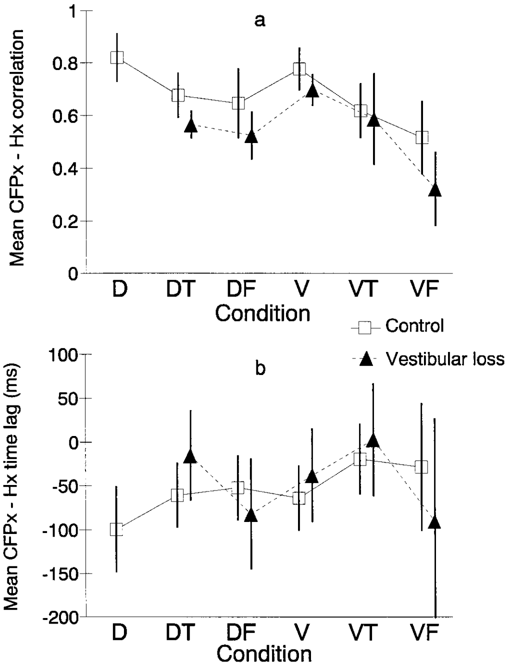

Fig. 4a, b Mean correlations between center of foot pressure (*CFP_x*) and head (*H_x*) sway **(a)** and mean time lag between CFP_x and H_x **(b)**. Negative value means CFP_x leads H_x

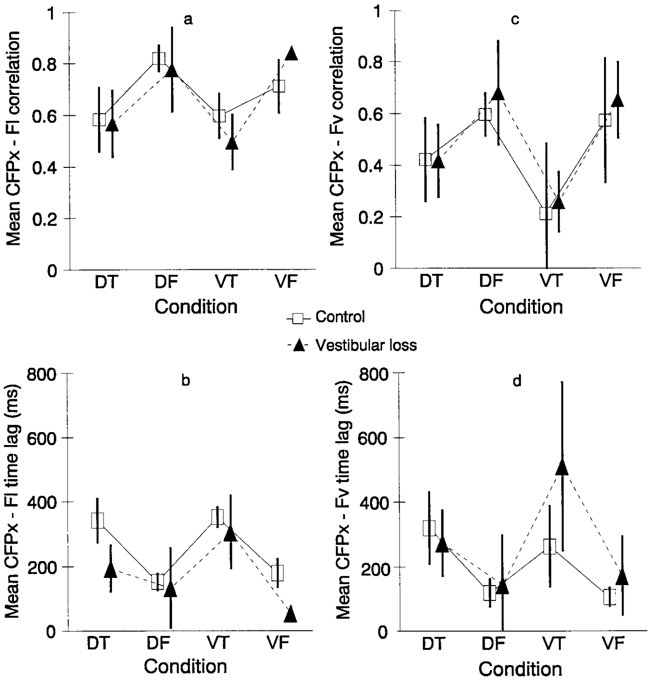

Fig. 5a–d Mean correlations between center of foot pressure (*CFP_x*) and lateral (*F_L*) and vertical (*F_v*) fingertip forces **(a, c)** and mean time lags between CFP_x and F_L and CFP_x and F_v **(b, d)**

Vision-Touch, lateral force changes at the fingertip led CFP_x by about 200–350 ms, and tended to be shorter for the vestibular loss subjects. The time lags were shorter for the force conditions. The CFP_x-vertical, fingertip force time lags showed the same overall pattern for the four conditions. The results are presented in Fig. 5.

Discussion

The vestibular loss subjects in this study were unable to stand in the tandem Romberg stance for more than a few seconds with their eyes closed without falling to one side or the other. Even with eyes open and sight of a rich visual environment they had great difficulty standing and had to push against the safety railing several times during a trial in order not to fall over. Consequently, the quantitative measurements of posture presented in the figures for the Vision-NoTouch condition overestimate the balance ability of the vestibular loss subjects with eyes open. If they had not touched the safety railing, their trials would have ended with a loss of balance within 5–10 s.

When allowed light touch of the index finger with a stationary surface, all of the vestibular loss subjects could stand for the full trial duration in the dark. The difference in performance was stunning: the vestibular loss subjects went from teetering out of control without touch to being able to stand more stably than the control subjects could in the dark without touch. The vestibular loss subjects in their Dark-Touch condition had half the CFP_x MSA of the control subjects in their Dark-NoTouch condition. This means that the light touch cues at the fingertip, which are much too low in magnitude to provide mechanical support, are more effective for the vestibular loss subjects than vestibular cues are for the normal subjects in subserving static balance.

It is notable that the vestibular loss subjects when denied touch contact but permitted sight of their surroundings showed CFP_x and $Head_x$ MSAs comparable to the control subjects standing in the dark. The visual cues contributed about as much to the vestibular loss subjects as the vestibular cues did to the control subjects standing with eyes closed. Allowing the vestibular loss subjects vision as well as touch greatly attenuated CFP_x and $Head_x$ MSAs relative to their vision alone condition but was not more effective than touch with eyes closed. These findings emphasize the preeminent importance of the haptic cues about body orientation provided by fingertip contact for the vestibular loss subjects when they are attempting to maintain static balance.

Light touch of the index finger also significantly enhanced the postural control of the control subjects. Both their CFP_x and $Head_x$ MSAs were significantly less with light touch in the dark than their dark or vision conditions without touch. Their relative benefit from touch was not as great as that of the vestibular loss subjects. The findings do emphasize, however, that the control subjects as well as the vestibular loss subjects benefit more from light touch of the finger than they do from vision during quiet stance. For both subject groups, their performance in the conditions in which force contact of the finger was allowed was basically the same as in their corresponding touch conditions, but with somewhat smaller MSAs, Dark-Touch vs Dark-Force, and Vision-Touch vs Dark-Force. There was one exception: the Vision-Force condition showed comparable Head_x MSA with the Vision-Touch condition for the control subjects; this likely represents a “floor effect” because Head_x MSA is only about 0.3 cm in these conditions.

Holden et al. (1994) have presented a quantitative analysis of the physical stabilization potentially conferred by lateral contact of the fingertip with a stationary surface. The applied force in the touch conditions (Dark-Touch, Vision-Touch) could have attenuated CFP_x MSA at most several percent relative to the Dark-NoTouch condition. In the force conditions, the maximum possible attenuation of sway by the forces at the fingertip would have been about 40%. The difference between the touch and force conditions is further emphasized by the time lags between changes at the fingertip and the associated changes in CFP_x or Head_x sway for both groups. This points to the sensorimotor coupling provided by the touch contact (and in part by the force contact, too, because the applied force in the force conditions, Dark-Force and Vision-Force, could not by its magnitude account for the full attenuation of sway observed). Sensory changes at the fingertip coupled with information about ongoing arm configuration signal direction and velocity of body sway allowing corrective maneuvers to be employed. The time lags in these correlations in the Dark-Touch condition were shorter for subjects with labyrinthine loss, and CFP_x MSA was lower.

Both groups of subjects showed relatively close coupling of CFP_x and Head_x with correlations on the order of 0.6–0.7. In addition, in their touch conditions (Dark-Touch, Vision-Touch) the vestibular loss subjects showed near synchronous CFP_x and Head_x sway, with CFP_x leading Head_x by 0–15 ms. In other studies, we have measured both center of pressure and torso movements of normal subjects allowed light touch of the fingertip and found them to be correlated at ≈0.8 with ±20-ms time lags for the fingertip contact conditions studied in the current experiments (Jeka and Lackner 1995). These subjects swayed essentially as inverted pendula and, in this circumstance, the pattern of fingertip contact coupled with knowledge of arm configuration to the torso provided a very precise indication of body motion. We did not measure enough body segments in the present study to determine whether the vestibular loss subjects swayed as inverted pendula when allowed light touch of the fingertip. The correlations and time lags observed would be consistent with this but in principle could be associated with multilink motion, as well.

Johansson (1991) in his studies of precision grip has shown that the nervous system is exquisitely sensitive to microdisplacements (incipient slip) of an object relative to the fingertips and executes rapid (non-conscious) corrections of grip force to prevent slip of the grasped object. Our subjects are exerting a form of precision touch in their light touch contact conditions analogous to precision grip. They are using comparable fingertip information to control their whole body posture. Interestingly, subjects report that in the touch conditions they concentrate on their fingertip and their body adjusts “automatically” to keep the force level below threshold for triggering the alarm. In their non-contact conditions, they concentrate on their feet and attempt to stabilize their bodies by controlling the forces applied at the feet.

These findings are fully consistent with the broad involvement in the control of precision grip of “...distributed processes in the CNS, engaging most areas known to be involved in sensorimotor control...” (Lemon et al. 1995). It is well known for example that the CNS in controlling balance has to make anticipatory compensations for impeding arm movements that would affect stance (Cordo and Nashner 1982; Nashner 1981). The present results show that automatic postural compensations also occur to maintain voluntary hand contact with a surface. The value of the precision touch input in our paradigm is that it provides an orientational reference that is more sensitive to change than the vestibular receptors, which have relatively high thresholds (cf. Fitzpatrick and McCloskey 1994; Nashner 1971, 1972; Peterka and Benolken 1992; Wilson and Mellvill Jones 1979) for eliciting postural reactions. Our vestibular loss subjects when allowed light touch of the finger in the dark showed less than half the CFP_x MSA of the control subjects standing without fingertip touch in the dark. The control subjects in the present study were much older than the college age students of our earlier studies and tended to have greater CFP_x and Head_x mean sway amplitudes. Nevertheless, they benefitted as much by touch contact of the finger as the younger group.

Our findings demonstrate unequivocally that precision contact of the index finger at mechanically non-supportive force levels serves as an effective substitute for labyrinthine function in subjects with vestibular loss who are attempting to maintain quiet stance. In ongoing studies, we have shown that such touch contact can totally suppress the destabilizing effects on balance that occur when tonic vibration reflexes are evoked in antigravity leg muscles (Lackner et al. 1996). Together such observations emphasize the utility of precision touch cues in enhancing postural stability in the elderly and in patients with balance problems of varying etiologies and point to an important role for precision touch of the hand in rehabilitation paradigms.

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References

Begbie JV (1967) Some problems of postural sway. In: deReuck AVS, Knight J (eds) CIBA Foundation symposium on myotactic, kinesthetic and vestibular mechanisms. Churchill, London

Cordo P, Nashner LM (1982) Properties of postural adjustments associated with rapid arm movements. J Neurophys 47: 287–302

Dichgans J, Brandt Th (1978) Visual-vestibular interaction: effects on self-motion perception and postural control. In: Held R, Leibowitz H, Teuber H-L (eds) Handbook of sensory physiology, vol. 8. Springer, Berlin Heidelberg New York, pp 755–803

Fitzpatrick R, McCloskey DI (1994) Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. J Physiol 478:173–186

Gill-Body K, Krebs D (1994) Locomotor stability problems associated with vestibulopathy: assessment and treatment. Phys Ther Pract 4:232–245

Holden M, Ventura J, Lackner JR (1987) Influence of light touch from the hand on postural sway. Soc Neurosci Abst 13:348,95.7

Holden M, Ventura J, Lackner JR (1994) Stabilization of posture by precision contact of the index finger. J Vest Res 4:285–301

Jeka JJ, Lackner JR (1994) Fingertip contact influences human postural control. Exp Brain Res 100:495–502

Jeka J, Lackner JR (1995) The role of haptic cues from rough and slippery surfaces on human postural control. Exp Brain Res 103:267–276

Johansson RS (1991) How is grasping modified by somatosensory input? In: Humphrey DR, Freund H-J (eds) Motor control: concepts and issues. John Wiley, pp 331–355

Johansson RS, Landstrom U, Landstrom R (1982) Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to sinusoidal skin displacements. Brain Res 244: 17–25

Krebs DE, Gill-Body KM, Riley PO, Parker SW (1993) Double-blind, placebo-controlled trial of rehabilitation for bilateral vestibular hypofunction: preliminary report. Otolaryngol Head Neck Surg 109:735–741

Lackner JR, DiZio P, Jeka JJ, Rabin E (1996) Fingertip contact suppresses the destabilizing effects of leg muscle vibration. Soc Neurosci Abst 22:641.8

Lemon R, Westling G, Johansson R (1995) Corticospinal control during reach, grasp, and precision lift in man. J Neurosci 15:6145–6156

Nashner LM (1971) A model describing vestibular detection of body sway motion. Acta Otolaryngol 72:429–436

Nashner LM (1972) Vestibular postural control model. Kybernetic 10:106–110

Nashner LM (1981) Analysis of stance in humans. In: Towe A, Luschei E (eds) Motor coordination. Handbook of behavioral neurobiology, vol. 5. Plenum Press, New York, pp 527–565

Peterka RJ, Benolken MS (1992) Role of somatosensory and vestibular cues in attenuating visually-induced human postural sway. In: Woollacott M, Horak F (eds) Posture and gait: control mechanisms. University of Oregon Books, Eugene, pp 272–275

Rabin E, DiZio PA, Bortolami SB, Lackner JR (1997) Haptic stabilization of posture: influence of fingertip contact localization in relation to axis of instability. Soc Neurosci Abst 23:610.6

Senders V (1958) Measurement and statistics. Oxford University Press, New York

Wilson VJ, Melvill Jones G (1979) Mammalian vestibular physiology. Plenum Press, New York