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Haptic cues for orientation and postural control in sighted and blind individuals

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Haptic cues from fingertip contact with a stable surface attenuate body sway in subjects even when the contact forces are too small to provide physical support of the body. We investigated how haptic cues derived from contact of a cane with a stationary surface at low force levels aids postural control in sighted and congenitally blind individuals. Five sighted (eyes closed) and five congenitally blind subjects maintained a tandem Romberg stance in five conditions: (1) no cane; (2, 3) touch contact (<2 N of applied force) while holding the cane in a vertical or slanted orientation; and (4, 5) force contact (as much force as desired) in the vertical and slanted orientations. Touch contact of a cane at force levels below those necessary to provide significant physical stabilization was as effective as force contact in reducing postural sway in all subjects, compared to the no-cane condition. A slanted cane was far more effective in reducing postural sway than was a perpendicular cane. Cane use also decreased head displacement of sighted subjects far more than that of blind subjects. These results suggest that head movement control is linked to postural control through gaze stabilization reflexes in sighted subjects; such reflexes are absent in congenitally blind individuals and may account for their higher levels of head displacement.

Human bipedal stance is inherently unstable and small amounts of sway are observed during quiet, unperturbed standing. Simple, everyday acts that require precise control while standing, such as placing a key in a door lock, involve not only voluntary movements of the hand and arm, but also activation of postural musculature to compensate for small oscillations in body position as we "fixate" on the object of interest. Such postural corrections are influenced by a combination of cutaneous and kinesthetic mechanoreceptors embedded in the skin surface, muscles, joints, and tendons of the hand and arm. In conjunction with motor signals about movement plans, cutaneous receptors provide information about surface properties such as friction (Johnson & Hsiao, 1992 ; Loomis & Lederman, 1986), while kinesthetic receptors provide information about arm movement and position (Clark & Horch, 1986; Matthews, 1988). The combination of these sensory inputs has come to be known as the *haptic* perceptual sense (Gibson, 1966), which is most often studied in the context of object recognition through exploration (see, e.g., Gordon, 1978; Klatzky, Lederman, & Reed, 1987) or in manual motor activities such as wielding (Solomon & Turvey, 1988) and grasping (Johansson, 1991).

A series of recent studies in our laboratory has investigated haptic perception in the context of human spatial orientation, specifically, human postural control. We have shown that when a standing subject touches a stationary surface with his or her index fingertip, postural sway is greatly reduced even when the applied forces are physically inadequate to stabilize the body (Holden, Ventura, & Lackner, 1994; Jeka & Lackner, 1994). Sway attenuation achieved by light touch contact (≈0.4 N of applied force) is equivalent to that achieved with force levels capable of physically reducing body sway (e.g., ≈10 N of applied force). Subsequently, we demonstrated that sway reduction with light touch is achieved through the activation of postural musculature triggered by haptic cues derived from fingertip contact with the stationary surface (Jeka & Lackner, 1995). Two pieces of evidence indicated that sway attenuation was achieved through a sensorimotor control strategy with light touch, whereas with larger contact forces, mechanical support from the fingertip was significant. First, postural muscle activity was higher with light touch forces than with mechanically supportive fingertip forces,

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suggesting that muscular forces remote from the fingertip and arm were required to attenuate sway with light touch. Second, the activation of postural muscles with light touch was achieved in a feedforward manner. Changes in applied fingertip contact force led the initiation of muscular activity by 150 msec, which preceded changes in body sway by an additional 150 msec. By contrast, with mechanically supportive levels of applied force, fingertip contact forces and body sway increased and decreased almost simultaneously, which one would expect if subjects were primarily leaning on the contact surface for support.

In the present study, we focused on the use of haptic cues for postural control in blind versus sighted individuals.[1] Prior studies have observed higher levels of sway in blind subjects than in *blindfolded* sighted subjects (Easton, 1992; Edwards, 1946). A possible explanation for this difference stems from investigations of the spatial abilities of blind individuals indicating that visual experience may be a necessary prerequisite for establishing a precise frame of reference for spatial tasks based on nonvisual information (Pick, 1974; Rieser, Guth, & Hill, 1982, 1986; Warren, 1970; Warren & Pick, 1970). Both sighted and adventitiously blinded individuals are considered to possess a mental frame of reference dominated by a visual memory or metric that is crucial for performance during spatial tasks. In fact, congenitally blind individuals often perform with less accuracy than do sighted or adventitiously blind individuals on spatial tasks using somatosensory or auditory information (Easton & Bentzen, 1987; Pick, 1974; Worchel, 1951). For example, Rieser, Guth, and Hill (1982) had blind (congenital and adventitious) and sighted subjects learn the location of objects within a large unfamiliar room by walking to each object and then returning to the starting position. After training, all subjects were able to point to any object location with similar accuracy and speed from the starting position. However, when subjects were positioned at one of the object locations and asked to point to another object, the performance of congenitally blind subjects was far slower and less accurate than that of sighted or adventitiously blind individuals. Rieser et al. (1982) attributed such differences to the lack of experience that congenitally blind individuals have in linking the flow of environmental information with locomotor patterns that produce that flow. Sighted persons and persons who have had vision may draw on visual perceptual experience with self- and environmental-motion even when visual information is denied.

The sensory cues acquired through locomotion to various object locations in the Rieser et al. (1982) study were orientation free with respect to the self. In contrast, congenitally blind individuals perform closer to sighted and adventitiously blind individuals in spatial tasks that require sensory cues that are oriented with respect to the self. For example, Easton (1992) found that acoustic cues transmitted from a small head-mounted sonar device (Trisensor) that also received the reflected waves from objects and surfaces in the environment stabilized posture substantially more than did acoustic waves transmitted from a stationary object. Even though both types of acoustic signals could be a meaningful spatial referent, the head-mounted sonar device provided signals and feedback that specified a subject's own orientation relative to the stationary external environment. Such observations imply that postural stability in congenitally blind individuals may be enhanced by sensory signals from the surrounding environment if their own position is known relative to such information. In this regard, a commonly used mobility aid that blind individuals use for obstacle avoidance, namely the long cane (Blasch & De l'Aune, 1992; Farmer, 1980; Hill & Ponder, 1976), may also play a role in spatial orientation. It is possible that haptic cues from a cane also provide a spatial referent that congenitally blind individuals use to stabilize their stance.

To evaluate this possibility, we studied whether light touch contact of a cane to the ground is a source of sensory information that sighted and congenitally blind subjects can use to stabilize quiet upright stance. We predicted that postural sway in both congenitally blind and sighted individuals would be reduced by use of a cane because the cane provides egocentric spatial cues that do not require a visual frame of reference. Moreover, we expected that nonphysically supportive and physically supportive cane forces would reduce postural sway equivalently, similar to the results observed using fingertip contact with a stationary surface (Jeka & Lackner, 1994, 1995). We also assessed different orientations of the cane and analyzed the geometry of the orientations and the resultant haptic information available in terms of the functional effectiveness of the cane for postural control.

The measures we used to characterize postural control were similar to those used in our previous studies of upright stance with light touch versus mechanically supportive fingertip contact forces (Jeka & Lackner, 1994, 1995). Because postural control in the blind has never been rigorously quantified, we used measures designed to provide an overall picture of postural control in blind and sighted subjects. These included the following: (1) Mean body sway amplitude was approximated using the root mean square of center of pressure displacement,[2] which is highly correlated to movements of the center of mass at low sway amplitude and frequency (Murray, Seireg, & Scholz, 1967; Spaepen, Fortuin, & Willems, 1979; Winter, Patla, & Frank, 1990). Head displacement was also measured, because the head can move independently of the trunk and may be influenced by the lack of gaze stabilization reflexes in the congenitally blind (Leigh & Zee, 1980). (2) Timing relationships between center of pressure and applied cane forces were used to determine whether postural control with light cane forces implements a feedforward sensorimotor relationship versus a mechanically supportive relationship with larger cane forces, similar to that observed with the fingertip. (3) Power spectral analysis of center of pressure and head displacement was used to determine whether sway frequencies differ in blind and sighted subjects and whether haptic cues from a cane influence the movement frequency of the head or body. Thus, we sought not only to compare the influence of haptic cues on blind versus sighted individuals, but also to provide a more comprehensive picture of postural control in blind individuals than is currently available.

METHOD

Subjects

Five sighted subjects, 4 males and 1 female between the ages of 20 and 40 years, were recruited from the staff and student population of Brandeis University. All subjects were free of neurological and musculoskeletal impairments that might have influenced their balance. Five congenitally blind subjects were recruited from a pool of potential subjects with visual impairment maintained by the Boston College Psychology Department. The etiology of each blind subject is listed in Table 1.

Apparatus and Measures

Figure 1 depicts our test situation. The subject stands in the tandem Romberg position (heel-to-toe) on a force platform while holding a cane with the right hand. The force platform (Kistler Model 9261A) measures the reaction forces generated by the feet.

Center of foot pressure displacement. Medial–lateral (CP_X) and anterior–posterior (CP_y) coordinates of foot pressure were computed from the force components (F_X, F_y, and F_z) registered by piezo-electric crystals in the corners of the force platform and the distances of the crystals from the center of the platform.

Head displacement. Medial–lateral (H_X) and anterior–posterior (H_Y) head displacement were measured with an ISCAN video system. A rigid metal tube attached to an adjustable headset protruded 5 cm outward from the subject's forehead in the sagittal plane. A light-emitting diode (LED) was attached to the end of the tube and the ISCAN camera mounted in front of the subject's feet tracked the movement of the LED to measure the H_X and H_Y directions of head displacement (Figure 1). The ISCAN system measures 2-D movement in a field of view 512 pixels (H_X) × 256 pixels (H_Y). Because of differing subject heights, we normalized the field of view across subjects by measuring the distance between the camera and LED and computing a calibration factor for each subject. The average resolution across subjects was 0.48 mm (H_X) and 0.96 mm (H_Y).

Cane and cane forces. The cane that the subject held with his/her right hand was made of aluminum tubing (adjustable from 82 to 115 cm in length) with a curved handle (12-cm radius) fashioned to resemble an everyday cane. The cane weighed approximately 0.68 kg. The subject held the cane so that its tip rested in a circular well attached to the top of a rigid metal bar (46 cm long × 1 cm wide × 2 cm deep). The circular well prevented the cane tip from slipping off the bar as subjects applied force. The metal bar was instrumented with two, dual-element, temperature-compensated strain gauges (Kulite Semiconductor, Type M[12] DGP-350-500) that transduced the lateral (C_L) and vertical (C_V) forces applied with the cane. The strain gauge signals were amplified and calibrated in units of force (Newtons),[3] and a comparator could trigger an auditory tone when an adjustable threshold force was reached. The metal bar was bolted to a rigid wooden platform (155 cm × 70 cm) that overlay the force plate and extended beyond its lateral edges. This arrangement ensured that the force platform detected all forces applied through the cane as well as all forces generated by the subject's feet. The weight of the cane was zeroed out before the start of each trial so that the recorded cane forces reflected only those applied by the subject with the cane.

All signals were sampled at 60 Hz and collected in real time on a personal computer instrumented with a Data Translation A/D board.

Procedure

The subject stood with his/her right foot directly behind his/her left foot along the center of the anterior–posterior axis of the force platform. Adhesive tape was used to mark the position of the feet on the platform so that the same configuration could be repeated on

Table 1
Blind Subject Characteristics

Subject	Age	Sex	Travel Aid	Cause of Blindness	Additional Information
J.B.	24	F	Dog guide	Agricultural pesticide during first 3-month gestation.	Head oscillation during balancing tasks.
M.B.	24	M	Dog guide	Probable Usher's syndrome.*	Mild hearing loss. Active participant in outdoor recreational activities such as skiing and climbing.
V.D.	44	F	Dog guide	Retinopathy of prematurity, with secondary glaucoma and subsequent enucleation.†	Reports having chronic fluid in her ears (but not experiencing any symptoms at time of experiment). Arthritis in knees. Reports having difficulty with balance when walking without dog guide.
M.P.	19	M	Long cane	Leber's congenital amaurosis.‡	
B.M.	44	M	Dog guide	Retinopathy of prematurity.	

*Usher's syndrome is an inherited disorder, primarily affecting males, which is characterized by degeneration of the retinal pigment epithelium, cataracts, and hearing loss. This subject also reports that he has an underdeveloped optic nerve. †Retinopathy of prematurity is a vascular abnormality of the retina characterized by neovascularization and resultant sequelae, occurring almost exclusively in premature infants. This subject developed acute, uncontrollable, and very painful glaucoma (increased intraocular pressure) in her teen years, and elected to have her eyes enucleated. ‡Leber's congenital amaurosis is an inherited disorder characterized by retinal pigmentary degeneration.

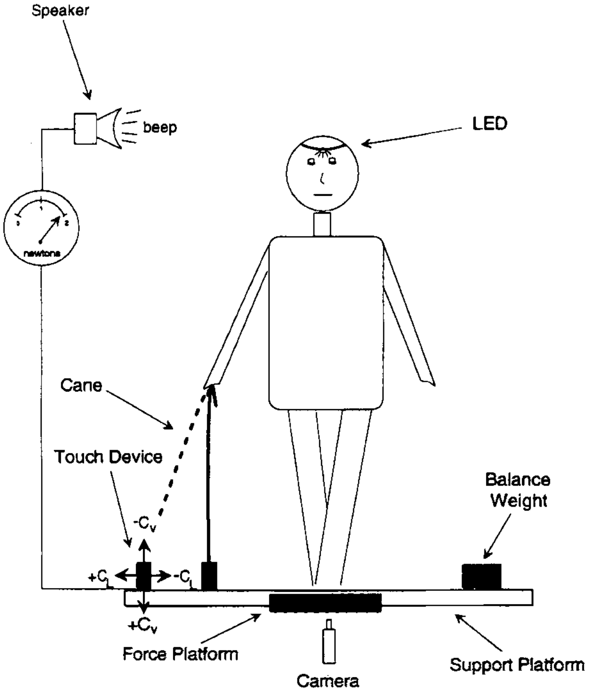

Figure 1. A subject depicted in tandem Romberg posture on the force platform holding a cane whose tip rests on the metal bar that measures applied forces. The solid and dotted canes show its orientation in the perpendicular and slanted conditions, respectively. For the sake of illustration, we show the subject exceeding a typical threshold of 1.5 N, which occured on <5% of all touch contact trials. In the force contact conditions, the alarm was turned off. In the control condition, the subject's arms hung passively by her side.

each trial. The cane was adjusted to a comfortable length for each subject.

There were five experimental conditions. Two levels of applied cane force were used: (1) light touch contact, where the subject was limited to a maximum of 2 N of applied lateral or vertical cane force without setting off the auditory alarm, and (2) force contact of the cane, during which the auditory alarm was turned off and subjects could apply as much force as desired with the cane. For each level of cane force, the cane was oriented at two angles relative to the metal bar: (1) perpendicular, the cane held vertically, and (2) slanted, the cane tilted toward the subject's right side at approximately a 70° angle relative to the metal bar. The metal bar on which the cane tip rested was bolted 35 and 55 cm to the right of the subject to insure the required perpendicular and slanted cane angles, respectively. Cane length was increased in the slanted conditions so that it was held at approximately the same elevation and elbow angle as in the perpendicular conditions. In the control condition, the subject stood with arms hanging passively by his/her side. The sighted subjects' eyes were closed in all conditions. The five conditions will be identified as follows: C = control (no cane); TP = touch contact, perpendicular cane; TS = touch contact, slanted cane; FP = force contact, perpendicular cane; and FS = force contact, slanted cane.

Practice trials (25 sec in duration) were given for each condition before the experiment began. Before a trial, subjects were told to look straight ahead and to take as much time as desired to assume a comfortable stance with or without the cane, depending on the condition. Once they felt ready, sighted subjects closed their eyes and said, "Go," and then the experimenter initiated data acquisition. If a subject was unsuccessful in a particular practice trial (e.g., lost balance or triggered the alarm more than once in the TP and TS trials), then that trial was repeated until it was performed correctly. The alarm threshold was initially set for 1.5 N. If a subject was able to complete a trial without setting the alarm off more than once, then the threshold was not changed. All subjects were successful at a threshold of 1.5 N except 2 blind subjects, whose TP and TS alarm threshold was therefore set at 2 N for the experimental trials.

Each condition was run five times (5 conditions × 5 trials = 25 total trials). Trial duration was 25 sec. The perpendicular (TP and FP) and slanted (TS and FS) cane conditions were divided into separate blocks of randomized trials. The five control trials were interspersed randomly between these blocks. The order of the perpendicular and slanted blocks was randomized across subjects. Seven subjects lost their balance before the end of one of their five trials in the control condition. These trials were repeated immediately and completed successfully on the second attempt. Only the repeated trials were included in the analysis. After each trial, the subject stepped off the platform and sat comfortably for about 1 min before the next trial. The experiment lasted approximately 1 h.

Analysis

To avoid anticipation effects associated with the beginning and end of a trial, the first and last 4 sec of data were excluded from analysis, leaving 17 sec of data for each trial. The experimental posture, tandem Romberg (heel-to-toe), was chosen to enhance medial–lateral sway. Previous experiments using heel-to-toe stance have shown that lateral and vertical fingertip contact forces are uncorrelated with anterior–posterior body sway (Jeka & Lackner, 1994). Consequently, we focused on measures related to medial–lateral body sway (i.e., CP_X and H_X). CP_X displacement within a trial was determined by subtracting the average position of CP_X from each data point. A first-order polynomial fit was subtracted from the time series of CP_X position to remove any drift of center of pressure that was not variation around its mean position. CP_X mean displacement was then calculated as the root mean square of the mean position of CP_X. The same technique was used to determine medial–lateral head displacement (H_X). Mean lateral and vertical forces applied through the cane were also calculated for the touch and force contact conditions.

Cross-correlation coefficients were calculated between all combinations of CP_X displacement and lateral and vertical contact forces of the cane (C_L and C_V), to determine the strength of the coordinative relationships between these components. Because cross-correlations do not have a normal distribution, they were first transformed to the Fisher's Z_r statistic for statistical analysis (Senders, 1958). Cross-correlations were performed at each of 200 steps (16.07 msec/step) in both the forward and backward directions to determine if correlations were strongest at times other than $t = 0$. Mean correlations were calculated by collapsing maximum cross-correlation coefficients across trials and subjects. Time delays associated with maximum correlations were also collapsed into mean values. Positive time delays mean that changes in the second variable of the pair occur before changes in the first (vice versa for negative time delays). For instance, a positive time delay of 100 msec associated with a maximum $CP_X - C_L$ correlation would indicate that changes in C_L and changes in CP_X occurring 100 msec later were most highly correlated.

Power spectral density analyses were performed to determine the component frequencies of CP_X and H_X displacement, with a frequency resolution of 0.06 Hz. The first-order polynomial subtracted from the time series to calculate mean displacement also eliminated any low-frequency components due to drift in the mean position of the head or center of pressure. Such drift is not considered a component frequency of sway. Mean power spectra were calculated by collapsing across subjects and trial for each condition.

The statistical analysis consisted of two separate multivariate analyses of variance (MANOVAs). A 2 × 5 × 5 repeated measures MANOVA was performed to evaluate the influence of subject (sighted, blind), condition (control, TP, TS, FP, and FS), and trial

(1–5) factors for the measures: CP_X and H_X mean displacement. A separate 2 × 2 × 2 × 5 MANOVA was run to evaluate the influence of subject (sighted, blind), cane force (touch, force), cane angle (perpendicular, slanted), and trial (1–5) for measures involving cane forces: mean absolute C_L and C_V, CP_X-C_L, and CP_X-C_V mean cross-correlations and time lags.

RESULTS

The effect of trial order was not significant in either MANOVA [Wilks' lambda = 0.9072, $F(24,678) = .80$, $p > .7$; Wilks' lambda = .911, $F(24,455) = .516, p > .97$], and therefore the data were averaged across trials. The results of the MANOVA on CP_X and H_X displacement showed a significant subject × condition interaction [Wilks' lambda = 0.706, $F(24,678) = 2.96, p < .0001$]. The MANOVA for variables involving cane force showed a significant three-way subject × force × angle interaction [Wilks' lambda = .709, $F(6,162) = 11.04, p < .0001$]. Only the significant factors from the MANOVAs were considered in the follow-up univariate analyses for each dependent variable.The details of the univariate analyses of variance (ANOVAs) for each dependent measure are discussed below.

Cane Contact Forces

All subjects maintained the force levels below the required force maximum of 1.5–2 N in the TP and TS conditions. Figures 2a–2b show the mean cane forces applied in the lateral (C_L) and vertical (C_V) directions. Mean cane forces are collapsed across subjects because the same trends were observed with blind and sighted individuals. Negative forces are possible since the weight of the cane was zeroed out before each trial. Thus, if subjects applied slightly upward pressure on the cane handle, negative forces could result. Mean C_V force varied only as a function of force, increasing by as much as 60 times from the touch to the force conditions [$F(1,198) = 242.88, p < .0001$]. Changes in mean C_L force were observed as a function of force and angle [$F(1,198) = 103.32, p < .0001$]. With a slanted cane, mean C_L force changed from a negative value in the TS condition to a positive value in the FS condition. Very little change in mean C_L force was seen from the touch to the force condition with a perpendicular cane.

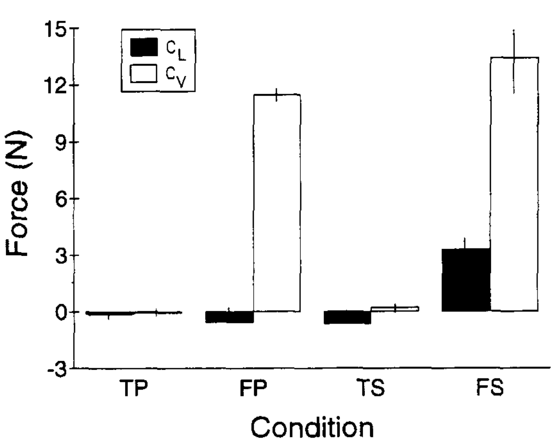

Figure 2. Mean applied cane forces in each condition collapsed across all subjects. All subjects were able to maintain cane force levels below the 1.5- to 2-N threshold. Applied forces were as much as 60 times greater with force contact than in the light touch contact conditions. TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, force contact, slanted cane.

Center of Pressure and Head Displacement

Medial–lateral center of pressure (CP_X). Figure 3 shows individual time series of CP_X displacement in each condition for a sighted and a blind subject. The time series illustrate that center of pressure displacement was highest in the C condition, in which subjects were standing without the aid of a cane. With a cane oriented perpendicularly (Conditions TP and FP), there was only a modest decrease in center of pressure displacement. Interestingly, postural sway attenuation was greatest with a slanted cane, no matter whether light touch (Condition TS) or physically supportive forces (Condition FS) were applied.

Figure 4a displays mean CP_X displacement in each condition for individual subjects (mean of five trials/subject) and the grand mean of CP_X displacment collapsed across subjects and trials in Figure 4b. Mean CP_X displacement was highest in the control condition, slightly lower with a perpendicular cane, and considerably lower with a slanted cane for both the sighted and blind subjects. Statistical analyses showed a significant subject × condition [$F(4,245) = 15.37, p < .0001$] interaction for CP_X displacement. Planned contrasts revealed that mean CP_X displacement was slightly lower for blind than for sighted subjects in the control condition and slightly higher for blind than sighted subjects in the FS condition. All other conditions showed no difference between subject groups for mean CP_X displacement. Furthermore, CP_X displacement was lower with light cane forces with a slanted cane (Condition TS) than with a perpendicular cane with physically supportive forces (Condition FP) for both sighted and blind subjects ($ps < .05$). This suggests that the direction of applied cane force in relation to the body may be more important than the absolute amount of force in stabilizing upright stance.

At the outset we hypothesized that nonphysically supportive surfaces and physically supportive cane surfaces would reduce postural sway equivalently. We also hypothesized that postural sway in both congenitally blind and sighted subjects would be reduced to the same degree by use of a cane, because the cane would provide egocentric spatial cues that do not require a visual frame of reference. To more directly assess these predictions, a 2 × 3 mixed ANOVA (sighted versus blind × control, touch vs. force) was performed by collapsing the data in Figure 4b across the cane orientation conditions. The results revealed a significant interaction between the two design factors [$F(2,16) = 8.27, p < .0004$]. A simple effects breakdown of the interaction revealed that blind subjects produced marginally less sway amplitude than did sighted subjects in the control condition [$F(1,8) = 3.75, p < 1$], whereas there were no differences between subject groups for either the nonphysically or physically supportive haptic cue

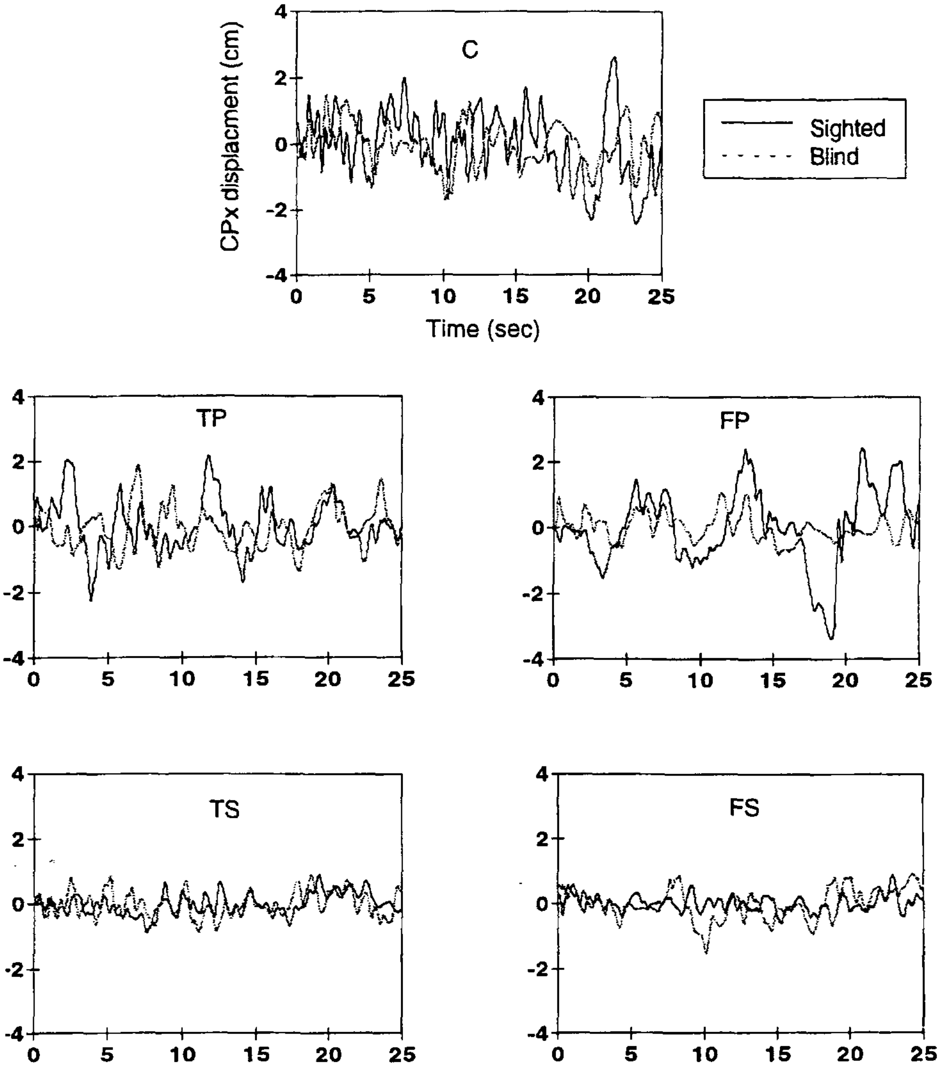

Figure 3. Individual representative time series of CP_X sway for a sighted and blind subject in each condition. C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

conditions (*F*s < 1). In addition, the presence of physically nonsupportive or supportive haptic cues significantly decreased sway amplitude for sighted subjects [$F(2,16) = 11.75$, $p < .01$], but only marginally decreased sway amplitude for blind subjects [$F(2,16) = 11.75$, $p < .01$]. The upshot of the analysis is that the larger effect of haptic force cues for sighted subjects was attributable to sighted subjects' marginally larger sway amplitude in the control condition. Both subject groups, in fact, achieved the same level of sway with each type of haptic cue.[4]

The results for mean CP_X displacement generally supported our main predictions: (1) Light touch of a cane was as effective as physically supportive forces in attenuating body sway, and (2) both sighted and blind individuals effectively used haptic cues from a cane to attenuate sway. The fact that blind subjects swayed less than sighted subjects in the control condition was unexpected and will be considered in the discussion.

Medial–lateral head displacement (H_X). Figure 5 shows individual time series of H_X displacement in each condition for a sighted and a blind subject. The time series illustrate that head displacement was highest in the control condition, with only a modest decrease in head displacement with a perpendicular cane (Conditions TP and FP), similar to the center of pressure displacement results (Figure 4). Head displacement attenuation was greatest with a slanted cane, with light touch or physically supportive forces (Conditions TS and FS). However, a slanted cane improved head control in sighted subjects far more than in blind subjects, whose head displacement was approximately twice that of sighted subjects in the slanted cane conditions.

Figure 6A displays mean H_X displacement in each condition for individual subjects (mean of five trials/subject), and Figure 6b shows the grand mean of H_X displacement collapsed across subjects and trials. A progressive decrease

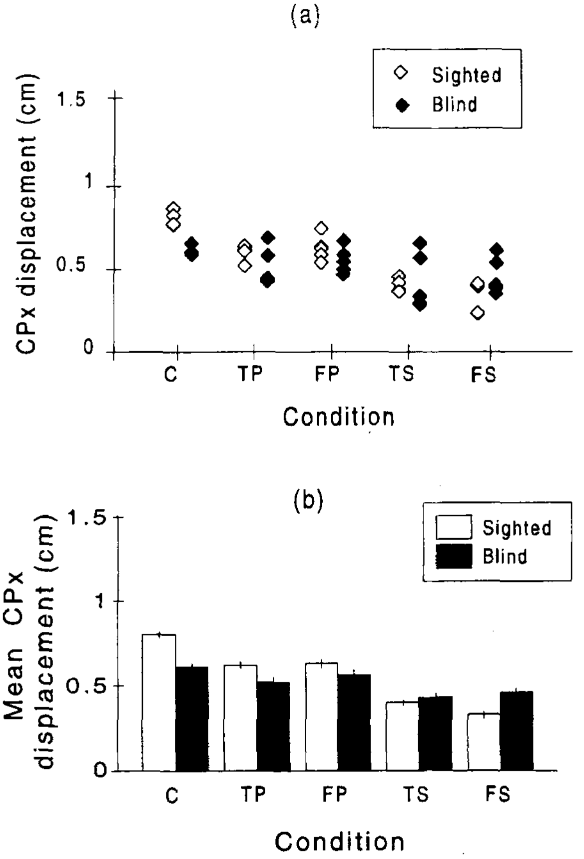

Figure 4. Mean center of pressure sway amplitude for sighted (eyes closed) and blind subjects in each condition. (a) Mean CP_X sway (five trials) for each of the 5 individual subjects. In some conditions (e.g., touch contact, perpendicular cane), fewer than five symbols appear due to overlapping mean values for different subjects. (b) Grand mean of CP_X sway (five trials × 5 subjects). C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

in mean H_X displacement was observed as a function of cane force and angle for sighted subjects. However, with blind subjects, the decrease in head displacement was observed only as a function of cane force rather than cane angle: Mean H_X displacement was actually *lower* with light cane forces (Conditions TP and TS) than with physically supportive cane forces (Conditions FP and FS). The differential effects of cane force on mean H_X displacement for sighted and blind subjects appear as a significant subject × condition interaction [$F(4,245) = 7.32, p < .0001$]. Planned contrasts revealed that head displacement was higher for blind than for sighted subjects in the FP, TS, and FS conditions. No differences were found between subject groups in the control and TP conditions. Moreover, a slanted cane with touch contact (Condition TS) attenuated mean H_X displacement more than did a perpendicular cane with physically supportive forces (Condition FP) in sighted and blind subjects ($ps < .05$). This emphasizes that cane orientation is far more important for head displacement attenuation than the amount of applied cane force.

In summary, the mean center of pressure displacement results are consistent with our hypothesis that postural control in both blind and sighted subjects would benefit equally from haptic cues though a cane. However, the larger head displacement observed in blind individuals indicates that control of the head and trunk may differ in blind subjects compared with sighted individuals with eyes closed. We address this finding more fully below (see Discussion).

Cross-Correlations

Center of pressure displacement and lateral cane force. The timing relationship between CP_X displacement and lateral cane force (C_L) changed dramatically from the perpendicular to the slanted cane conditions. Figure 7a shows how mean CP_X–C_L correlations were negative with a perpendicular cane and positive with a slanted cane. This means that with a cane oriented in a perpendicular fashion, subjects applied lateral forces to the left at the cane tip as they swayed to the right, and vice versa. However, with a slanted cane, the opposite relationship was observed; subjects applied forces in the same direction as their own sway. This difference in CP_X–C_L correlation resulted because rightward movement of the cane handle results in leftward lateral forces at the cane tip with a perpendicular cane. Rightward force applied to the handle of a slanted cane is translated through the tip in the same rightward (lateral) direction.

Mean CP_X–C_L correlations were stronger in the force contact conditions (FP and FS) than in the light touch conditions (TP and TS). These results were supported statistically by a significant force × angle interaction [$F(1,177) = 155.37, p < .0001$] for mean CP_X–C_L correlation. The mean time lags associated with the CP_X–C_L correlations, shown in Figure 7b, were generally close to zero, except in the TS condition, which had a mean time lag of ≈200 msec. This difference resulted in a significant force × angle interaction for mean time lag [$F(1,177) = 27.16, p < .0001$]. The time lag found in Condition TS indicates that changes in C_L force *led* CP_X displacement by approximately 200 msec. Previous studies have shown that this time lag may be indicative of a long-loop "reflex" triggered by contact forces to activate postural muscles and attenuate sway (Jeka & Lackner, 1994, 1995). The approximately zero time lag in Condition TP indicates that the contact forces are not triggering postural musculature to attenuate sway, although the negative CP_X–C_L correlation in Condition TP makes the time lag more difficult to interpret. The approximately zero time lags found in the force contact conditions (FP and FS) suggest that cane forces are being used to physically stabilize body sway, albeit not as effectively with a perpendicular cane as with a slanted cane (Figure 4). Importantly, and consistent with our hypothesis of no differences in the use of haptic cues for postural control in blind and sighted subjects, CP_X–C_L correlations and time lags were equivalent between sighted and blind subjects.

Center of pressure displacement and vertical cane force. Figure 7c shows that mean CP_X–C_V correlations

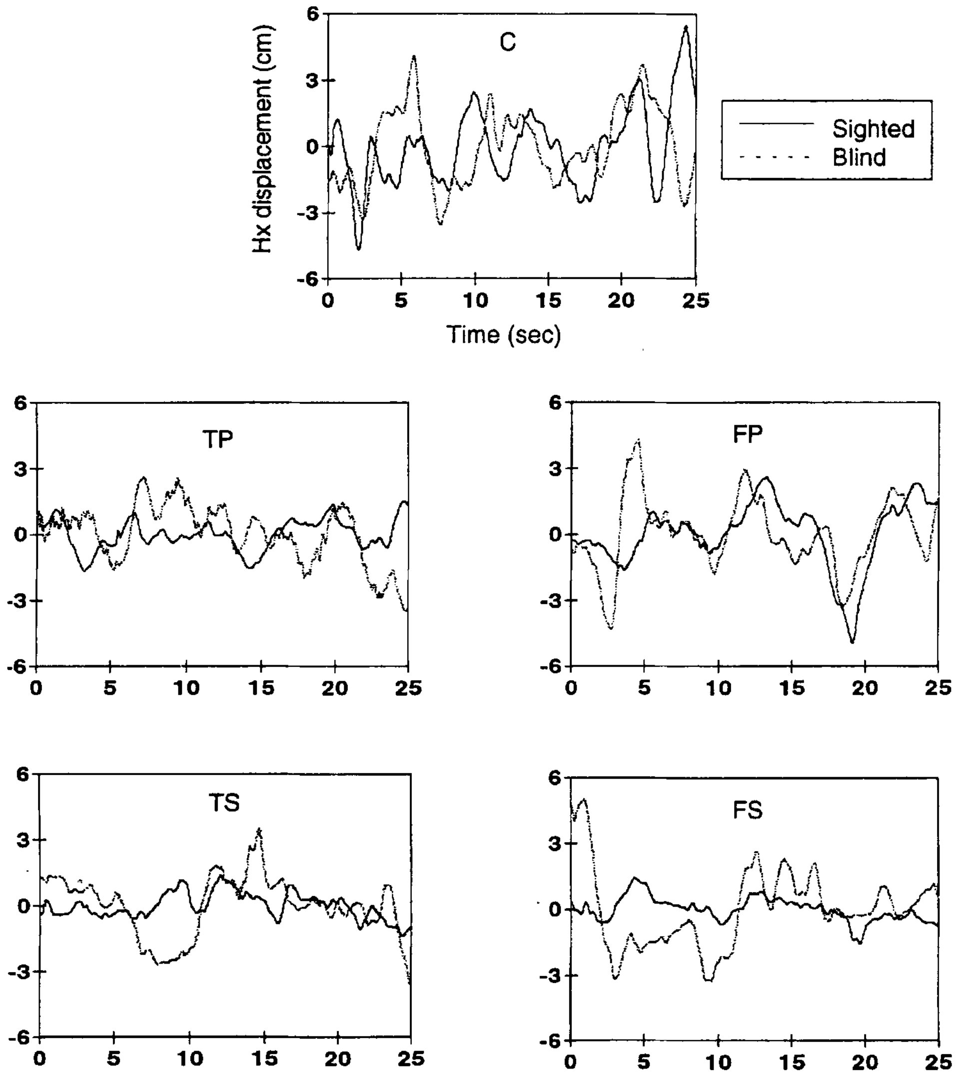

Figure 5. Individual representative time series of H_X sway for a sighted and blind subject in each condition. C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

were (1) always positive and (2) higher in the force contact conditions than the touch contact conditions, regardless of cane angle. Signficant subject × force [$F(1,177) = 4.15, p < .05$] and subject × angle [$F(1,177) = 4.06, p < .05$] interactions were found, but the most meaningful differences in CP_X–C_V correlations were primarily in terms of applied cane force. Figure 7d shows that CP_X–C_V time lags averaged slightly above zero in the TP, FP, and FS conditions, with an increase to ≈200 msec in the TS condition. This increase resulted in a significant force × angle interaction [$F(1,177) = 18.76, p < .001$] for CP_X–C_V mean time lag. No differences were found for CP_X–C_V correlations or time lags between sighted and blind subjects.

Head displacement versus cane forces and head displacement versus center of pressure displacement. Cross-correlations between head displacement (H_X) and cane forces in each condition were equivalent to those between CP_X displacement and cane forces, indicating that both blind and sighted subjects were swaying like an inverted pendulum. As an additional check of this conclusion, we ran cross-correlations between CP_X displacement and H_X displacement. The results showed that across all conditions, CP_X–H_X correlations averaged 0.70 (*SE* = .04) with a time lag of −118 msec (*SE* = 14.6 msec) for blind subjects, and sighted subjects averaged 0.72 (*SE* = .04) with a time lag of −69 msec (*SE* = 21.8 msec). The high CP_X–H_X correlations and negative time lags mean that the head movements were strongly related but temporally behind center of pressure movements. At the small amplitude and low frequency of sway observed in the present test situation, it is reasonable to assume that all body segments were essentially moving together as a single unit

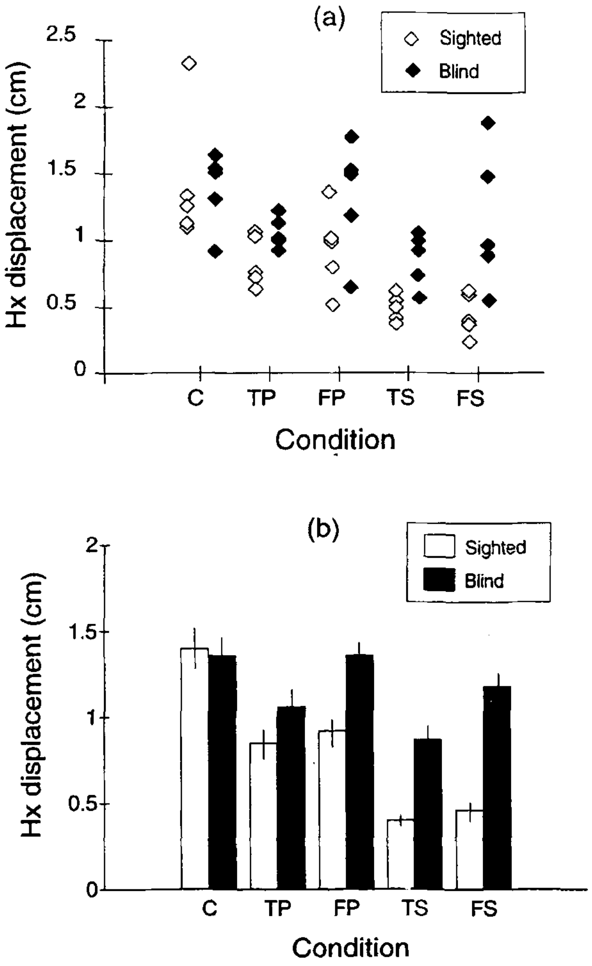

Figure 6. Mean head sway amplitude for sighted (eyes closed) and blind subjects in each condition: (a) Mean H_X sway (five trials) for each of the 5 individual subjects. (b) Grand mean of H_X sway (five trials × 5 subjects). C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

in both blind and sighted individuals, even though the head movements of the blind subjects were slightly larger in the force contact conditions.

Power Spectra

Figures 8 and 9 show the mean power spectra in each frequency bin for CP_X and H_X displacement, respectively, in each condition. CP_X displacement frequencies were generally more broadband than H_X displacement. CP_X displacement spectral power was concentrated (80%-90%) below 0.8 Hz. The majority of H_X displacement spectral power fell below 0.4 Hz, except in the control and FS conditions for blind subjects, for whom spectral power was more widely distributed (below 0.8 Hz). There were no discernible shifts in CP_X or H_X displacement frequency from the no-cane to the cane conditions in either the blind or sighted subjects.

The most notable differences between sighted and blind subjects appeared in the spectral power of H_X displacement. With light touch of a cane, a fourfold decrease in H_X spectral power from the control condition was observed for both sighted and blind subjects. However, use of a cane with force contact (FP and FS) did not decrease H_X spectral power from the control condition as effectively with blind subjects as it did with sighted subjects. Generally, the results are similar to the results for CP_X and H_X mean displacement (Figures 4 and 6); conditions with higher displacement also displayed higher spectral power, partly because changes in displacement frequency across conditions were relatively small.

Statistically, this pattern was confirmed by ANOVAs performed on each cane condition for CP_X and H_X displacement. A mixed design (subject groups, frequency components) was used, entering only the first 10 frequency bins, because the power plateaued at basement after about .6 Hz. For CP_X displacement, there were no main effects of subject groups or interactions between subject groups and frequency components for all four cane conditions. In contrast, for H_X displacement subject groups interacted with frequency components, especially in the two force conditions (FP and FS). As a breakdown of the interactions, simple effects tests of blind versus sighted subjects at frequency components revealed for the TP and TS conditions that 30% of the tests were significant (out of 20), whereas for the FP and FS conditions 75% were significant (out of 20).

DISCUSSION

We investigated the influence of a cane on postural control in blind and sighted individuals. As in previous studies allowing fingertip contact with a stationary surface (e.g., Jeka & Lackner, 1995), applied forces in the light touch conditions with the cane were too small to stabilize the body physically, but nevertheless reduced postural sway as much as did physically supportive forces.[5] Moreover, the magnitude of decrease in CP_X displacement was dependent on the orientation of the cane relative to the body. When the cane was held perpendicular to the ground, CP_X displacement decreased roughly 20% relative to the control condition. With a slanted cane, CP_X displacement decreased 50% or more. In fact, light touch with a slanted cane attenuated postural sway more than did physically supportive forces with a perpendicular cane. This indicates that haptic sensory information can be as effective as physical support in stabilizing upright stance when the haptic cues are functionally meaningful for the task.

That this is a truly haptic process is strongly supported by the similarity in performance between sighted people who were blindfolded and congenitally blind people (including the temporal patterning underlying performance). This similarity rules out the possibility that haptic stabilization of posture can occur only within a visually based reference system, that is, "visualization" of self-orientation given haptic cues. It is also of note in this regard that reported advantages in spatial performance for sighted over blind people typically require processing of allocentric (nonviewer specific) information, whereas more comparable spatial performance between sighted and blind in-

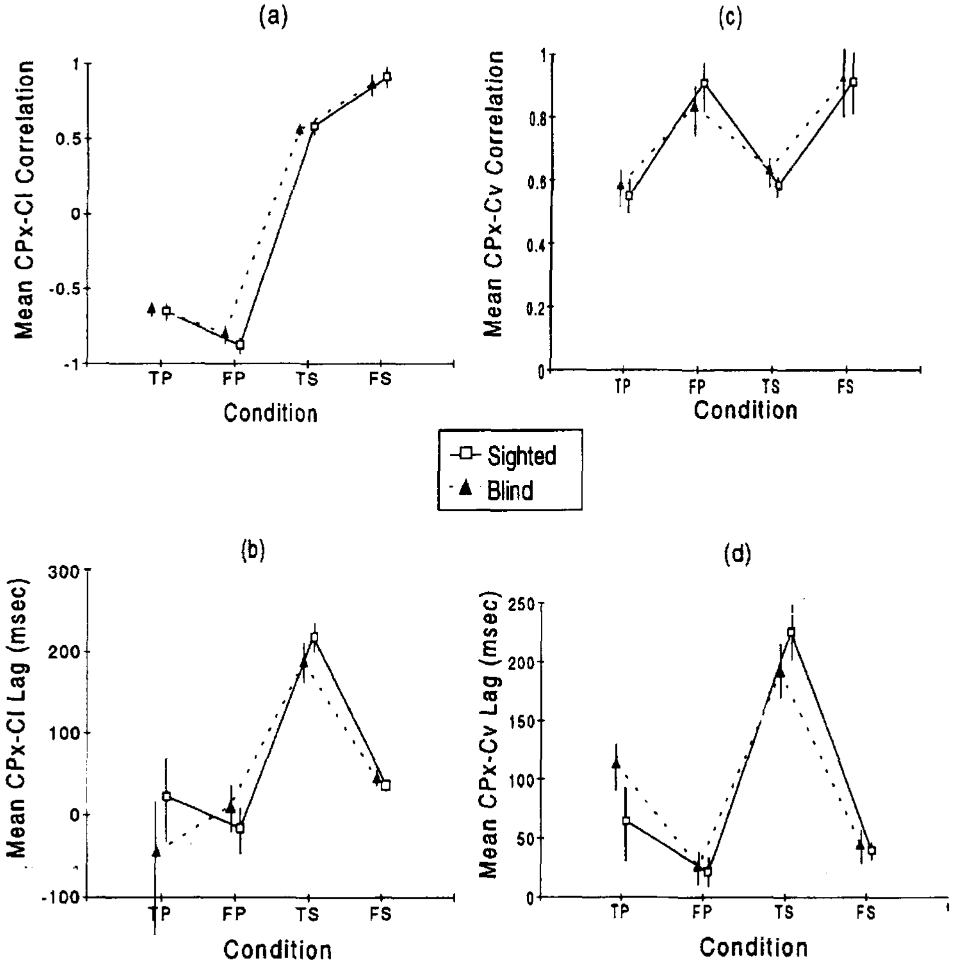

Figure 7. Mean cross-correlation coefficients and mean time lags between CP_X sway and cane forces (lateral = C_L & vertical = C_V). (a) Mean CP_X–C_L cross-correlation coefficients. (b) Mean CP_X–C_L time lags. (c) Mean CP_X–C_V cross-correlation coefficients. (d) Mean CP_X–C_V time lags. TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, force contact, slanted cane.

dividuals occurs for tasks involving egocentric (viewer-specific) information (Warren, 1984). A hand-held cane, like a head-mounted sonar device (Easton, 1992), provides sensory feedback that specifies a subject's orientation with sufficient precision to substantially improve postural stability. In fact, the cane improves performance to levels comparable to those achieved with visual information or mechanical support (see Jeka & Lackner, 1994, 1995).

Temporal Relationships

The cross-correlations between center of pressure displacement and cane forces emphasize the role of lateral cane forces in stabilizing stance. Correlations between center of pressure displacement and lateral cane force changed from negative to positive values with perpendicular versus slanted canes, respectively. The reversal in sign of CP_X–C_L correlations was associated with a large decrease in CP_X mean displacement in all subjects. No changes in correlations between center of pressure and vertical cane force were observed as a function of cane orientation, suggesting that vertical cane force was playing a lesser role in the control of postural sway. Lateral forces correspond to shear forces at the cane tip, which correlate with the direction of body sway. Moreover, our own observations of how subjects manipulated the cane and the geometry of the situation indicate that with a cane held vertically, slight body sway to the right and cane handle displacement to the right generate leftward shear forces at the tip of the cane (Figure 10). This accounts for the sign reversal between body sway and lateral cane forces for the perpendicular versus slanted cane conditions and why the lateral contact forces are directly linked with the direction and magnitude of sway when the cane is in a slanted orientation. Interestingly, in our earlier experiments using light fingertip contact forces with a stationary surface, subjects spontaneously chose an angle of the arm relative to the contact surface that was similar to that of the slanted cane. The present results emphasize that control is not merely a matter of the amount of force, but also the time course and direction of applied cane forces relative to body sway. Light touch with a slanted cane was far more effective in reducing sway than forces 60 times as large with a perpendicular cane.

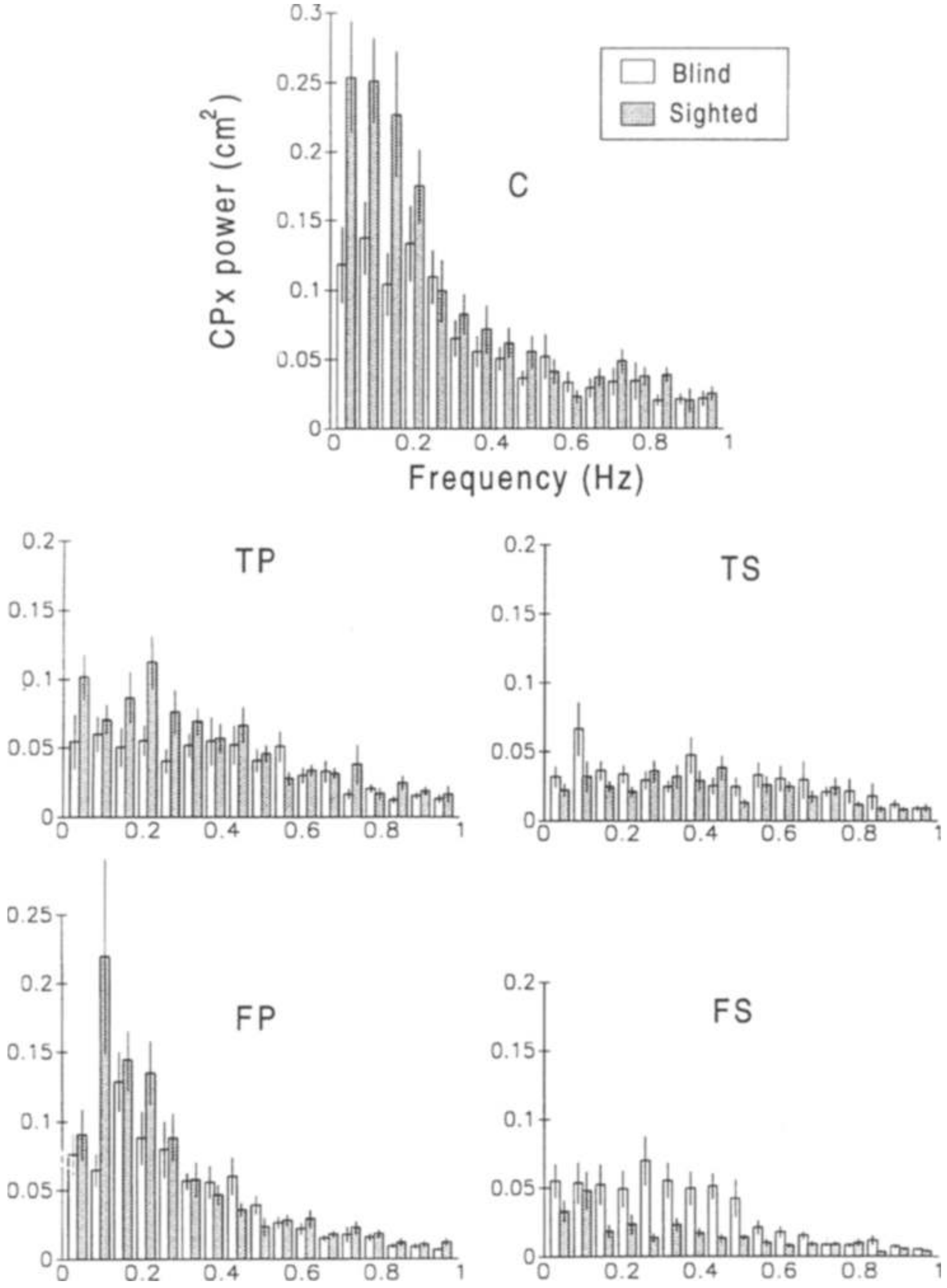

Figure 8. The distribution of mean power spectra, collapsed across subjects and trials, for CP_X sway. C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

Our previous work demonstrated that the time lags associated with maximum correlations between CP_X displacement and fingertip contact force depend on the level of applied force (Jeka & Lackner, 1994, 1995). Contact forces that were sufficiently high to provide physical stabilization of the body were always in-phase with body sway, meaning that as subjects swayed toward the touch surface, contact forces increased, and vice versa. By contrast, when subjects were limited to small contact forces (< 1 N) at the fingertip, changes in fingertip contact force led body sway by ≈300 msec. We have shown that the 300-msec time lag associated with light touch of the finger allows time for long-loop reflexive or voluntary activation of postural muscles guided by haptic cues (Jeka & Lackner, 1995). In the present study, similar 200–300-msec time lags were observed only with light touch of a slanted cane, indicating that postural muscles were activated most effectively with haptic cues from a cane in a preferential direction relative to the body.

The more effective attenuation of sway when CP_X–C_L correlations were positive rather than negative suggests that haptic cues were then more easily interpretable in terms

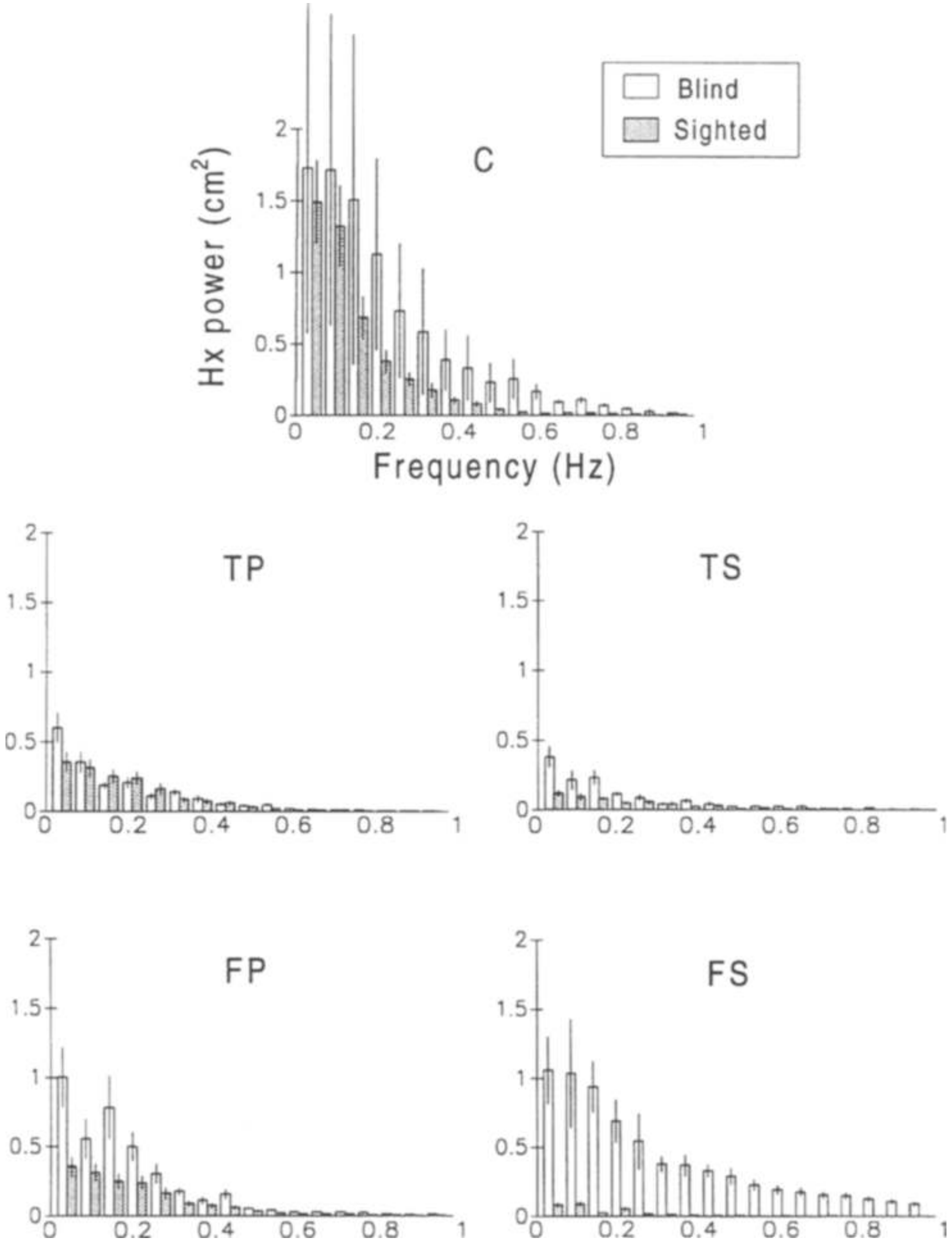

Figure 9. The distribution of mean power spectra, collapsed across subjects and trials, for medial–lateral head (H_X) sway. C, control; TP, touch contact; FP, force contact; TS, touch contact, slanted cane; FS, forced contact, slanted cane.

of body sway. This may seem curious because a negative timing relationship is as systematically related to body sway as a positive relationship. However, recent theoretical developments in human motor control (for reviews, see Jeka & Kelso, 1989; Schöner & Kelso, 1988) have demonstrated that patterns of coordinated behavior differ in terms of their relative stability. Analysis of spontaneous transitions between coordinative patterns produced by, for example, two oscillating human limbs (Kelso, 1984), has established that transitions can be characterized in terms of the differential stability of the patterns. As system parameters such as movement frequency were changed systematically, growing instability of the coordination dynamics led to transitions from a 180° antiphase pattern to a 0° in-phase pattern, the latter being more stable across a wider range of parameter values (Kelso, Scholz, & Schöner, 1986; Kelso & Jeka, 1992). Stability was characterized primarily through the variability of the temporal relationship between two components, with large variability interpreted as low stability. Spontaneous transitions between "perception–action" patterns of coordinated behavior have also been traced to instabilities of their coordination dynamics (Dijkstra, Schöner, & Gielen, 1994; Kelso, DelColle, & Schöner, 1990; Schmidt, Carello, & Turvey, 1990; Wimmers, Beek, & van Wieringen, 1992).

Such stability considerations may also explain why in the present experiment a negative CP_X-C_L timing relationship was less effective in attenuating postural sway. Even though negative and positive CP_X-C_L correlations were equivalent with perpendicular and slanted canes, mean CP_X-C_L time lags were more variable when the cane was held vertically than slanted (Figure 7b). This suggests a more stable temporal relationship between body sway and cane forces with a slanted than a vertical cane, which may translate into a more salient percept of body sway from the forces generated through the cane tip. This, in turn, suggests that subjects would be better able to activate the appropriate musculature to attenuate sway.

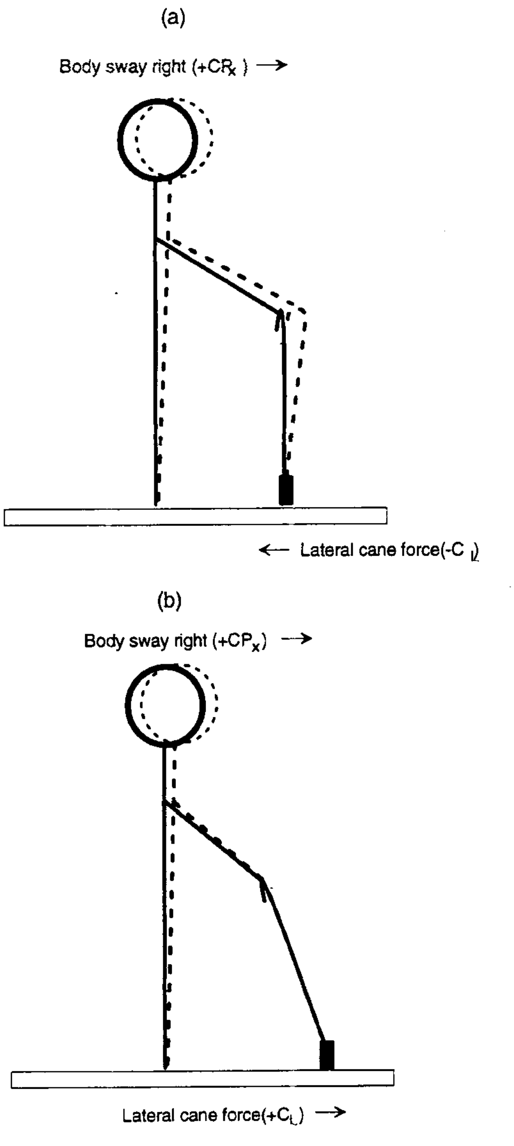

Figure 10. Schematic depictions of a subject holding a cane viewed from behind, showing the relationship between body sway and lateral cane forces with (a) a perpendicular cane and (b) a slanted cane. With a perpendicular cane, body sway to the right (positive CP_X sway) resulted in negative (leftward) lateral cane forces as the cane tip pivoted on the metal bar. With a slanted cane, lateral forces increased (rightward) with body sway to the right, implying that the cane remained stationary during body sway.

Physiological Mechanisms

Haptic cues derived from a cane originate from a variety of physiological mechanisms. Cutaneous receptors provide information regarding the texture, shape, and rigidity of the cane handle (Johnson & Hsiao, 1992), while muscle proprioceptors provide information concerning hand and arm configuration as the cane is held (Matthews, 1988). All of our subjects generally held the cane in the same fashion, with palms resting on top of the cane and fingers wrapped around the handle in a thumb-opposing grip. With this grip, haptic stimulation could originate in two ways. The simplest pattern would arise from body sway alone. With the cane firmly held, a wave of stimulation across the palm could then be interpreted in terms of body sway and appropriate muscular responses could be initiated to inhibit further sway. Haptic cues could be more difficult to interpret if the hand moved in relation to the cane—that is, if the pattern of stimulation across the palm could be due to movement of the cane, movement of the body, or a combination of both. In short, the pattern of haptic stimulation would be ambiguous relative to sway of the body. As shown in Figure 10a, the negative relationship between body sway and lateral cane forces implies that a perpendicular cane pivoted rightward with body sway to the right. Conversely, the positive CP_X-C_L correlations found with a slanted cane are feasible without movement of the cane. Consequently, haptic cues with a slanted cane are more easily interpretable in terms of body sway and resulted in more effective attenuation of body sway.

Studies of postural responses associated with voluntary arm movements have shown that postural compensations begin prior to the initiation of the arm movements (Belen'kii, Gurfinkel, & Pal'tsev, 1967; Cordo & Nashner, 1982; Marsden, Merton, & Morton, 1981). These anticipatory innervations have the effect of minimizing the perturbation of postural equilibrium associated with the arm movements. Similarly, if the hand is perturbed while grasping a handle, postural compensations can be initiated prior to the elicitation of electromyographic segmental activity in the arm muscles (Cordo & Nashner, 1982), even with load changes as small as .074 N (Marsden et al., 1981). The present results suggest that subjects were able to dissociate the haptic cues at the cane handle as a result of voluntary grasping of the cane from haptic cues arising at the handle that were caused by sway of the body, and to use the latter cues to attenuate their body sway. Thus, body sway may be detected through haptic cues at the cane handle and postural adjustments can be made for impending sway, much as adjustments are made in the external perturbation paradigms of Cordo and Nashner (1982) and Marsden et al. (1981).

Head Control

Our sighted and blind subjects exhibited systematic differences in measures related to head displacement. Sighted subjects with eyes closed had comparable decreases in center of pressure displacement, head displacement, and spectral power from the no-cane to the cane conditions. By contrast, for the blind subjects, head MSA and spectral power decreased considerably less from the no-cane to the cane conditions, particularly with force contact of the cane. The persistence of head movements in blind subjects, despite haptic cues for orientation, may be an example of what is often called a "stereotypic behavior" in the blindness literature. Such behaviors can include whole body movements such as rocking or swaying. These movements are often considered "attempts" to increase the general level of sensory stimulation via other sensory modalities, such as vestibular and somatosensory modalities (Siegel, 1966; Warren, 1984), possibly to gain significant information about body orientation.

An alternative view, however, is that head movement control in sighted humans and animals may be driven primarily by voluntary movements and reflexes directed toward orienting and stabilizing the eyes in space (Goldberg & Peterson, 1986; Outerbridge & Melvill Jones, 1971), which may not develop normally in those deprived of visual inputs from birth. For example, Leigh and Zee (1980) have observed that congenitally blind individuals are unable to voluntarily initiate saccades and show absent or markedly reduced vestibulo–ocular responses (VOR) to rotation, despite reporting normal sensations of self-rotation. Adventitiously or partially blind subjects, by contrast, show a clear preservation of the VOR and voluntary saccades. Cats reared in the dark show a significant reduction in VOR (Berthoz, Pavard, & Young, 1975; Harris & Cynader, 1979), suggesting that visual inputs are necessary early in life for oculomotor subsystems to develop normally. Thus, the larger levels of head displacement observed in blind subjects may not be subserving spatial orientation and postural control, but may result from the inability to coordinate head movements in terms of eye–head synergies and gaze control. This view is further supported by our recent findings that head movements of sighted subjects without a functioning vestibular system are attenuated during quiet stance when they are provided with haptic cues about their orientation (Jeka, DiZio, Horak, Krebs, & Lackner, 1994). Head stabilization is important in such subjects because neck proprioception becomes more important in gaze stabilization and gaze shifts through an enhancement of the cervicocollic reflex (Dichgans, Bizzi, Morasso, & Tagliasco, 1973). For these subjects, trunk stabilization achieved through arm–finger contact to a stationary surface would thus allow enhanced control of head orientation.

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NOTES

1. Unless otherwise stated, the word *blind* refers to persons who are congenitally blind, that is, persons who have no light perception from birth. In all comparisons between blind and sighted individuals reviewed here, vision in sighted individuals was eliminated with a blindfold or closed eyes.

2. Postural sway is often estimated through center of foot pressure movements on a force platform, which tend to be larger and of higher frequency than center of mass movements (Winter, Patla, & Frank, 1990). Center of pressure is a linear measure, while body sway is an angular measure and therefore not completely analogous. However, we have measured the relationship between center of pressure and center of mass movements in our experimental paradigm and found their magnitude to be equivalent in each condition and their average correlation to be >0.8 (Jeka & Lackner, 1994, 1995). Moreover, center of pressure and head displacement were highly correlated in the present experiment (≈0.7). Thus, our subjects were essentially swaying like an "inverted pendulum," and center of pressure displacement can be considered to be approximately equivalent to angular body sway.

3. For units of force, Newton (N) is the SI equivalent of the U.S. Customary Unit of pound (lb.); 1 lb. = 4.448 N.

4. The claim of comparable levels of sway amplitude for sighted and blind subjects in the nonphysically and physically supportive haptic cane cue conditions amounts to accepting the null hypothesis. A power analysis (Keppel, 1991) revealed that, given the very small sighted versus blind differences associated with nonphysically supportive (.51 cm vs. .47 cm CP_X displacement, respectively) and physically supportive (.48-cm vs. .51-cm CP_X displacement, respectively) haptic cue conditions, with $p = .05$, $MS_e = .024$, and power = .80, over 300 subjects would be required at this level of power to achieve statistical significance for these haptic cue conditions. Thus we are confident that the conclusion of no difference between subjects groups for these two conditions is correct.

5. Holden, Ventura, and Lackner (1994) have provided a systematic analysis of the amounts of passive and dynamic stabilization of posture that can be achieved with different levels of fingertip (or cane) contact force levels. In our touch conditions, the maximum applied force could have attenuated sway no more than 2.3% with respect to the control condition, a small fraction of the stabilization actually achieved.

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