Haptic Stabilization of Posture: Changes in Arm Proprioception and Cutaneous Feedback for Different Arm Orientations

ELY RABIN, SIMONE B. BORTOLAMI, PAUL DIZIO, AND JAMES R. LACKNER
Ashton Graybiel Spatial Orientation Laboratory and Volen Center for Complex Systems, Brandeis University, Waltham, Massachusetts 02454

Rabin, Ely, Simone B. Bortolami, Paul DiZio, and James R. Lackner. Haptic stabilization of posture: changes in arm proprioception and cutaneous feedback for different arm orientations. J. Neurophysiol. 82: 3541-3549, 1999. Postural sway during quiet stance is attenuated by actively maintained contact of the index finger with a stationary surface, even if the level of applied force (<1 N) cannot provide mechanical stabilization. In this situation, changes in force level at the fingertips lead changes in center of foot pressure by ~250 ms. These and related findings indicate that stimulation of the fingertip combined with proprioceptive information about the hand and arm can serve as an active sensor of body position relative to the point of contact. A geometric analysis of the relationship between hand and torso displacement during body sway led to the prediction that arm and hand proprioceptive and finger somatosensory information about body sway would be maximized with finger contact in the plane of body sway. Therefore, the most postural stabilization should be possible with such contact. To test this analysis, subjects touched a laterally versus anteriorly placed surface while in each of two stances: the heel-to-toe tandem Romberg stance that reduces medial-lateral stability and the heel-to-heel, toes-outward, knees-bent, “duck stance” that reduces fore-aft stability. Postural sway was always least with finger contact in the unstable plane: for the tandem stance, lateral fingertip contact was significantly more effective than frontal contact, and, for the duck stance, frontal contact was more effective than lateral fingertip contact. Force changes at the fingertip led changes in center of pressure of the feet by ~250 ms for both fingertip contact locations for both test stances. These results support the geometric analysis, which showed that 1) arm joint angles change by the largest amount when fingertip contact is maintained in the plane of greatest sway, and 2) the somatosensory cues at the fingertip provide both direction and amplitude information about sway when the finger is contacting a surface in the unstable plane.

INTRODUCTION

Maintenance of upright stance is highly dependent on visual and vestibular signals as well as motor, cutaneous, and proprioceptive feedback from the feet and ankles. Haptic cues from the finger and arm generated by lightly touching a stable surface are also highly effective in stabilizing stance, even when contact force levels are inadequate to provide mechanical stabilization (Holden et al. 1987, 1994).

The contribution of forces at the fingertip to attenuation of body sway can be estimated by a combination of experimental and modeling techniques. In an earlier study (Holden et al. 1994), we first measured subjects’ body sway when they stood with eyes closed either with arms by sides or with one finger touching a stable surface. The maximum touch force allowed was 1 N, ~102 g; but, in practice, subjects only applied ~0.4 N. We then computed, by using an inverted pendulum model of body sway (in which the entire mass of the body is assumed to be at the center of mass, and the body pivots about the ankles), the maximum attenuation of sway possible with 1 N applied at the fingertip. The forces at the fingertip would maximally attenuate body sway if they were 180° out of phase with sway. Using this assumption, we calculated the amount 1 N applied at the fingertip could attenuate the experimentally measured sway of the subjects standing without fingertip contact. This calculation predicted a maximum reduction of 2.4%. When the subjects actually had touched a surface, using much less than 1 N of applied force, their body sway had decreased by 68% relative to the no-touch control values. Light touch thus reduced sway 28 times more than could be expected from optimal mechanical considerations. Moreover, for noninverted pendulum, multilink body sway, 1 N of force at the fingertip would physically reduce center of mass sway much less than 2.4%.

Such finger contact allows labyrinthine-defective subjects to stand virtually indefinitely in the dark, which is otherwise impossible for them (Lackner et al. 1999a); is as effective as vision in stabilizing stance (Jeka and Lackner 1994); and can override proprioceptive misinformation from ankle muscles (Lackner, Rabin, and DiZio, unpublished observations).

Our purpose in the current study was to determine how to maximize the effectiveness of the hand and arm as a sensory-motor probe, or sensor, for stabilizing posture. Balancing while maintaining light touch of the fingertip is a dual task: a subject in addition to controlling his or her posture must actively control the fingertip. The subject’s body sway may be on the order of centimeters at the shoulder, whereas the fingertip moves a few millimeters at most (Lackner, Rabin, and DiZio, unpublished observations). To maintain finger contact at the same location, the subject must actively accommodate his or her arm to the displacement of the torso. In this circumstance, accurate registration of changes in joint angles may serve as a measure of torso motion relative to the fixed contact point. Such information coupled with somatosensory signals from the finger contact can be used to control muscle responses to sway.

The point of the present article is that the richness of the brachial proprioceptive and somatosensory information about body sway should be influenced by the location of the finger contact surface. This can be seen by a geometric analysis with...
the aid of Fig. 1, which illustrates a subject who is using two arm placements, anterior and lateral.

If the subject of Fig. 1A sways toward or away from the touch surface (along the axis of the arm) while maintaining the same position of fingertip contact, then a 1-cm displacement of the torso at the height of the shoulder results in a 1-cm displacement of the shoulder relative to the fingertip, requiring changes of elbow, shoulder, wrist, and finger joint angles where $l$ refers to the distance between shoulder and fingertip, and $b$ is the displacement of the body from its original position. However, 1 cm of sway orthogonal to the arm axis (shown in Fig. 1B) results in $< 1$ cm displacement of the shoulder relative to the fingertip and smaller changes in arm and hand joint angles (than with sway parallel to the shoulder-finger plane). In this case, the net change in shoulder-to-finger distance for small movements of the torso can be approximated as

$$\Delta L = l^{-1} \cdot \Delta b^2 \quad \ldots (2)$$

In conclusion, arm joint angle changes related to body sway are the most for sway directly toward and away from the fingertip, thus enhancing the likelihood that it is above the threshold of proprioceptive responsiveness.

The cutaneous receptors of the fingertip can provide sway-related feedback in three ways: by the changes in which receptors are active (spatial), by the degree to which those receptors are active (magnitude), and by when they are active (timing). When the body changes position, the finger can shear or roll across the touch surface, activating different groups of receptors. In this way, the differential activation of an array of cutaneous receptors codes body sway in a spatial fashion. The normal force on the fingerpad is systematically related to sway

Figure 1. The reaction forces ($f$) at the fingertip and the net change in shoulder-finger distance ($\Delta body$) for sway in two directions relative to a stable referent. When the body sways around the ankles toward and away from the stable referent (A), vertical forces at the fingertip would increase and decrease in magnitude, respectively, if the arm were held rigid. To maintain constant fingertip forces, changes in arm configuration ($\Delta L$) must accommodate the change in body position. When body sway is parallel to the referent (B) the magnitude of reaction force at the fingertip does not reflect the direction of body sway, and smaller changes in arm configuration are needed to maintain fingertip contact. $C$ and $D$: relationship between body sway in the unstable plane, arm position, and finger contact forces. When finger contact is in the unstable plane (C), the fingertip force reflects direction of sway, and changes in effective arm length are equal to changes in body position. When contact is in the stable plane (D), the normal force at the fingertip does not reflect the direction of body sway in the unstable plane, and only small changes in arm configuration are required to maintain finger contact.
around the ankles, assuming the remainder of the body and arm are rigid. However, the relationship differs for sway in the plane containing the contact point compared with the orthogonal plane of sway. The magnitude of normal force on the finger \( f \) codes magnitude and direction of body movement in the plane containing the touch bar (Fig. 1C)

\[
f \propto \Delta h
\]  

(3)

however, just the magnitude of sway is coded in the orthogonal plane, because the normal force changes similarly for both directions of body sway (Fig. 1D)

\[
f \propto |\Delta h|
\]  

(4)

Frequency of sway or timing of receptor activation is coded similarly for any finger placement location. In providing sensory information about body position, the cutaneous receptors of the fingertip are highly effective for coding movement in the directions toward and away from the fingertip.

Our analysis thus predicted that both brachial proprioceptive and finger somatosensory information about body sway are richest for finger placement in the plane of body sway. Accordingly, this finger placement should lead to maximum attenuation of sway in that plane. To evaluate this prediction, we measured the effects of contact location on the sway of subjects in two stances involving narrowed bases of support. The narrow dimension of the support base defines an unstable plane in which it is more difficult to balance because 1) there is a smaller possible range of body displacement before falling, 2) less foot leverage is available to generate torques to prevent center of mass excursions from going outside the base of support, and 3) compensatory torques must be initiated sooner, requiring short latencies for corrective maneuvers. Figure 1, C and D, shows the directional biases of sensitivity of cutaneous and proprioceptive feedback associated with body sway in the context of a narrowed base of support for touching in the stable plane (Fig. 1C) and the unstable plane (Fig. 1D).

Subjects were instructed to stand as still as possible during the 25-s trials. When the subject felt comfortable in the appropriate position he or she said “go,” and data collection was initiated by the experimenter. For trials requiring light fingertip contact, subjects were instructed to apply just enough force to keep the finger in one place on the touch bar. An auditory signal sounded if force applied to the touch bar exceeded 1 N (102 g). All signals were sampled by a computer at 60 Hz.

Procedure

The experimental conditions are illustrated in Fig. 3. Subjects assumed six stances: the tandem Romberg stance \( J \) with arms by side, \( 2 \) with lateral fingertip contact, and \( 3 \) with anterior fingertip contact, and the duck stance \( 4 \) with arms by side, \( 5 \) with anterior fingertip contact, and \( 6 \) with lateral fingertip contact. All manipulations of arm orientation and fingertip contact involved the right arm. The left arm remained by the subject’s side for all conditions. Trials were repeated 4 times for each condition. All touch condition trials were run twice to acquire data for fore-aft as well as lateral horizontal touch bar forces. Trial order was randomized for all subjects. The subjects’ eyes were closed throughout all trials.

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Analysis

The MSAs of head (H) and center of pressure (CP) were computed for each trial.
The CFB was also computed for \( CP_x \) and \( H_x \):

\[
CFB \triangleq \frac{1}{N} \sum_{j=1}^{N} \frac{CFB(x_j)}{x_j}
\]

for \( x = CP_x \) or \( H_x \).

The CFB was also computed for \( CP_x \) and \( H_x \):

\[
x_j \triangleq \frac{1}{N} \sum_{i=1}^{N} x_i
\]

where \( x = CP_x \) or \( H_x \).

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

where

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

for \( x = CP_x \) or \( H_x \).

Cross correlations were calculated between center of pressure and contact forces at the fingertip and center-of-pressure sway and head position at 16.07 ms/step over ±1,500 ms to identify where the maximum correlations occurred. In our nomenclature, positive time delays mean that the second variable of a pair is leading the first temporally.

Statistical analysis
To test our predictions about the influence of touch location (none, perpendicular to the unstable plane, or in the unstable plane) a repeated-measures ANOVA was performed for each experimental measure (MSA of center of pressure and of head, CFB of center of pressure and head, and mean shear force at the feet) for tandem and duck stances. Post hoc pairwise comparisons of individual conditions were made with Bonferroni corrections for multiple comparisons.

To evaluate fingertip contact force properties across contact location (perpendicular to unstable plane, in unstable plane) and stance (tandem and duck), we performed separate, \( 2 \times 2 \) repeated-measures ANOVAs on horizontal and vertical components of forces recorded at the touch bar, mean absolute force at the touch bar, CFB of touch bar shear forces, CFB of vertical touch bar forces, and correlations and time lags of touch bar force with center-of-pressure position.
RESULTS

Figure 4 presents representative trials from one subject for the six experimental conditions. The ANOVAs showed main effects of arm position for center-of-pressure MSA ($P < 0.0005$, both stances), CFB ($P < 0.004$ tandem, $P < 0.021$ duck), and head MSA ($P < 0.002$ tandem, $P < 0.0005$ duck). The results of post hoc comparisons are discussed in the following sections.

Tandem stance: center-of-pressure sway

Fingertip contact, both anterior and lateral, attenuated lateral center-of-pressure MSA relative to the no-fingertip contact condition ($P < 0.0005$; this and all subsequent levels of significance refer to post hoc comparisons). Fingertip contact in the unstable plane (lateral, for the tandem stance) led to greater stability than touching perpendicular to the unstable plane ($P < 0.0005$). With fingertip contact in the unstable plane, the MSA of lateral center-of-pressure sway was $\sim 0.35$ cm; with touch perpendicular to the unstable plane, $\sim 0.6$ cm; and with no touch, $\sim 0.9$ cm (Fig. 5).

Tandem stance: head sway

Head sway in the tandem stance followed a pattern identical to center-of-pressure sway (Fig. 6). Both fingertip contact positions reduced MSA of medial-lateral head sway relative to the no-touch condition ($P < 0.0005$). A greater reduction occurred with touching in the unstable plane relative to touching perpendicular to the unstable plane ($P < 0.01$). Correlations of lateral center of pressure and head sway were $\sim 0.75–0.85$ for all conditions.

Duck stance: center-of-pressure sway

In the duck stance, the MSA of center-of-pressure sway followed the same pattern as in the tandem stance (shown in Fig. 5). Touching in the unstable plane (anteriorly) significantly attenuated fore-aft sway relative to touching perpendicular to that plane, and both touch locations attenuated sway relative to no touch ($P < 0.0005$). The MSA of fore-aft center of pressure was less with anterior touch ($\sim 0.3$ cm) than with lateral touch ($\sim 0.8$ cm) and was highest in the no-touch condition ($\sim 1.1$ cm).

Duck stance: head sway

MSA of fore-aft head sway was reduced with fingertip contact in the unstable plane ($P < 0.001$) and contact perpendicular to the unstable plane ($P < 0.026$) relative to the no-fingertip-contact condition. The MSA of head sway was less with touching in the unstable plane than with touching perpendicular to the unstable plane ($P < 0.02$; Fig. 6). Correlations of head and center-of-pressure sway were $\sim 0.75–0.85$.

Forces at the fingertip and correlations of body sway and fingertip forces

Figure 7 shows mean magnitude and CFB of forces applied to the touch bar by the fingertip, collapsed across trials and subjects, for conditions involving fingertip contact. There was no significant effect of fingertip contact location on force level for a given stance. Horizontal touch bar forces, both lateral and fore-aft, averaged $\sim 0.2$ N across all conditions. Vertical touch bar forces averaged $\sim 0.5$ N in the tandem stance and $\sim 0.6$ N in the duck stance. CFBs of touch bar forces in all directions and conditions were $\sim 0.75$ Hz.

Correlations of fingertip contact forces with center-of-pressure sway and their associated time lags are shown in Fig. 8. The location of finger contact did not affect the correlations between the shear force of horizontal fingertip contact and body sway. In the tandem stance, lateral center-of-pressure sway was highly correlated with lateral horizontal touch bar shear forces for both fingertip contact positions ($r = -0.55$); in the duck stance, fore-aft center-of-pressure sway was highly correlated for both fingertip contact locations, with fore-aft horizontal touch bar shear force ($r = -0.6$). Maximum correlations between touch bar forces and center-of-pressure sway in the unstable plane were present when the change in fingertip contact location.
contact force was ~250–300 ms ahead of center-of-pressure sway.

Vertical forces were less highly correlated with center of pressure and more variable than horizontal touch bar forces. Only fore-aft center of pressure and vertical touch force in the anterior touch condition of the duck stance had a correlation >0.4.

**DISCUSSION**

We predicted from a geometric analysis that light fingertip contact with a stable surface located in the unstable plane of the body would most attenuate sway. Finger contact in the unstable plane leads to substantial changes in joint angles, and there is potentially a direct relationship between direction of body motion and fingertip forces. By contrast, for the same magnitude of sway, finger contact in the stable plane leads to smaller changes in arm configuration, and the changes in normal force at the fingertip do not code direction of sway (Fig. 1, A–D). This means that proprioceptive thresholds for detection of change in arm configuration are reached with smaller amplitudes of body sway with fingertip contact in the unstable plane and that the directionally coupled shear force at the fingertip should assist performance as well.

These predictions were fully borne out. The MSAs of head and center of pressure were significantly lower with touch in the unstable plane than in the stable plane. Moreover, the CFB was also consistently higher across all comparisons, as would be expected if sway were corrected at smaller excursion amplitudes. Although the effectiveness of finger contact was different for the different positions of the arm, the pattern of results shows that the same overall strategy was used with touch in the stable and unstable planes. The CFB of center of pressure was lowest in the no-touch conditions for each stance, as would be expected. The correlations between center-of-pressure sway and touch bar forces were comparable across all touch conditions, regardless of location of touch surface, and the time lags were similar with changes in touch bar shear forces leading changes in center of pressure by ~250 ms. This
overall pattern indicates that the fingertip is not used as a passive probe to gauge sway but is actively controlled.

The vertical component of forces applied at the fingertip averaged 0.5 N, which is in the range of maximal dynamic sensitivity of cutaneous receptors, (Johannsson and Westling 1987; Westling and Johannsson 1987). This is more than twice the magnitude of the horizontal shear components of fingertip force, which averaged 0.2 N. The vertical forces are more likely to activate pacinian corpuscles in the fingertip. Thus, the magnitude coding of sway toward and away from the touch bar may be enhanced by these fast-adapting, deep cutaneous receptors acting in concert with more shallow receptors. This hypothesis is consistent with findings of Lackner, Rabin, and DiZio (unpublished observations) showing postural stabilization by fingertip contact with the end of a rigid metal rod of ~1-mm diameter. The rod tip indents the skin more than the flat surface of the touch bar, reaching deeper receptors in the fingertip while simultaneously restricting the total number of shallow receptors activated in the fingertip. Touching the rod attenuates sway as much as touching the flat surface of the touch bar.

The present observations enable us to understand more fully several earlier findings. We have tested blind and sighted subjects (tested blindfolded) in the tandem-stance posture while they used a cane to stabilize their balance (Jeka et al. 1996). The subjects held the cane laterally with its shaft oriented either vertically, with the tip touching the ground directly below the hand, or at a slant, with the tip touching laterally 55 cm from the feet. The force exerted with the cane was measured and could not exceed 2 N. The slanted orientation, with the cane being similar to an extension of the arm, attenuated sway more than holding the cane upright. We recognize now that the upright cane functioned with the same shortcomings as did the arm in the present experiment when touch was maintained perpendicular to the unstable plane. With the cane upright, the subject had to allow the cane to pivot around its tip as he or she swayed. When the cane pivoted, the configuration of the subject’s arm remained relatively unchanged, and the subject experienced a twisting of the handle in his or her grip, much like the rolling of the fingertip that occurred in the present experiment with touch contact perpendicular to the unstable plane. By contrast, the slanted cane was aligned with the arm and provided normal reaction forces at the handle in response to sway, just as subjects experienced a normal force.
from the touch bar in response to sway to and from the finger with touch in the unstable plane. The rigidity of the cane in the slanted orientation also forced the subjects to reconfigure their cane-holding arms, thereby affording proprioceptive cues about sway. These same considerations explain why the entrainment of postural sway when an oscillating surface is touched is influenced by the location of the surface relative to the subject (Jeka et al. 1997).

Our earlier work showed that light touch of the fingertip with a stable surface allows cutaneous signals from the fingertip to be interrelated with proprioceptive information about arm and hand configuration to gauge torso motion and allow appropriate innervation of leg muscles to enhance postural stability (Holden et al. 1987, 1994; Jeka and Lackner 1994, 1995). A physical analysis of the relationship between forces applied at the fingertip and body sway showed that forces below 1 N cannot mechanically attenuate sway; nevertheless, they stabilize the body (Holden et al. 1994). We have shown in the

FIG. 7. Horizontal and vertical forces at the fingertip: mean absolute force and CFB for tandem and duck stances for finger contact in and perpendicular to the unstable plane (12 subjects, 4 trials; error bars, SD).

FIG. 8. Correlations of CP sway in the unstable plane with coplanar forces exerted by the fingertip. Left: CP sway and touch bar shear force; right: CP sway and touch bar normal force (12 subjects, 4 trials; error bars, SD).
present study that finger contact is most effective when it is in
the unstable plane of the body where contact at high force
levels would also provide direct mechanical support. The direct
mechanical linkage also translates to sensory-motor advan-
tages. The somatosensory and proprioceptive systems are me-
chanically activated and by optimizing these sensory systems
to the sway of the body, postural control becomes so efficient
that precision touch of the fingertip can be more effective than
vision (Holden et al. 1987, 1994), ankle proprioception (Lack-
ner, Rabin, and DiZio, unpublished observations), or vestibular
function (Lackner et al. 1999a) in attenuating postural sway.

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Address for reprint requests: J. R. Lackner, Ashton Graybiel Spatial Orien-
tation Laboratory, Brandeis University, Waltham, MA 02454-9110.
E-mail: lackner@brandeis.edu
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