FINGERTIP TOUCH AS AN ORIENTATION REFERENCE FOR HUMAN POSTURAL CONTROL

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INTRODUCTION

Somatosensory* information from cutaneous and proprioceptive receptors serves a dual role in the control of upright posture. Unlike the vestibular receptors which are located in the head and therefore must infer information about the head relative to the trunk and other body components, somatosensory receptors are distributed throughout the skin surface (e.g., mechanoreceptors) and musculature (e.g., spindles), providing crucial information about the relative position of different body components. At the same time, somatosensory information may also provide functional information about contact of a body part to an external object or surface, such as texture and compliance as well as the forces applied to the surface, allowing for accurate and flexible control of handled objects and tools.

The dual nature of somatosensory function is apparent when we perform everyday activities that require precise control of body posture such as making contact through fine adjustment of hands or fingers with a stationary object or surface. To grasp and smoothly pick up an object, one’s body position must be precisely controlled to maintain hand contact with the object while simultaneously exerting the adequate amount of force to grasp and lift the object without dropping it. Under such conditions, we rely heavily upon somatosensory information to simultaneously orient our own body position and manipulate the object. Until the “precision grip” studies of Johansson and colleagues (for a review see Johansson, 1991), such functional behavior had not been investigated.

Intuitively, we conceive of contact with a stable surface, such as leaning against a wall with the hand and arm, as providing postural stabilization through passive physical reaction forces that balance those imposed by movement of the body. A crucial concern,

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*Mergner and J. Hlavačka (1995) used the term “manual” and “proprioceptive” in the literature concerning object manipulation (Klaczky et al., 1987) as a combination of cutaneous and proprioceptive cues.

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however, is to separate physical support of the body provided by the forces applied though the hand from the sensory information about the external surface and one's own body position provided by cutaneous and proprioceptive receptors embedded in the fingertips, hand and arm. Recently, we have developed a paradigm to do just this; it allows us to separate purely physical support from the use of somatosensory cues to enhance postural control while touching an external object. Fig. 1 depicts our test situation. A subject is in the tandem Romberg stance (heel-to-toe) on a force platform touching a device used to measure the forces applied by the right index fingertip. The tandem stance is used to increase postural instability in the medial-lateral direction. The touch apparatus consists of a rigid horizontal metal bar attached to a rigid metal base. It is positioned laterally to the subject with the bar parallel to the sagittal plane of the subject. The subject places his/her right index finger on the middle of the bar while strain gauges mounted on the metal bar transduce the forces applied by the fingertip. A feedback circuit measures the magnitude of applied force (vertical and lateral directions) and triggers an auditory alarm if the applied force exceeds a predefined threshold. Subjects touch the bar with their right index finger and are required to keep the applied force below the threshold (i.e., keep the alarm from sounding). This allows control of the applied force below any desired level. Before the experimental trials begin, subjects are allowed to push on the bar to ascertain the force level that triggers the alarm. In over 95% of the experimental trials to date, subjects were able to complete the trial without exceeding threshold force levels. We have performed a series of investigations with this paradigm, the main results of which we summarize below.
1. CONTACT OF THE INDEX FINGERTIP WITH A STATIONARY BAR REDUCES HUMAN POSTURAL SWAY AT CONTACT FORCES FAR BELOW THOSE NECESSARY FOR PHYSICAL SUPPORT OF THE BODY

We have found that touch contact of a fingertip to a stable surface reduces postural sway in subjects standing unilaterally (Holden et al., 1994) and bilaterally (Jeka and Lackner, 1995). Subjects were tested under six conditions: two visual conditions, (V) vision, eyes open, and (D) dark; eyes closed; and three fingertip contact conditions: no contact, during which the subject's arms hung passively by their side; (T)ouch contact, in which the subject could apply up to 2 N (= 100 grams) of force on the touch apparatus before an auditory tone signaled the threshold of applied force; and (F)orce contact, during which subjects could apply as much force as desired. The six experimental conditions will be identified as follows: V = vision - no contact, VT = vision - touch contact, VF = vision - force contact, D = dark - no contact, DT = dark - touch contact and DF = dark - force contact.

Fig. 2a shows the CPX displacement of one subject in a dark-no contact (D) trial overlaid upon a dark-touch (DT) trial, illustrating the reduction in center of pressure displacement due to the addition of touch contact. Fig. 2e displays the mean CPX displacement in each condition collapsed across five subjects: medial-lateral (CPX) center of pressure mean displacement was highest in the dark-no touch (D) condition and significantly lower in all other conditions (p < .01). The important finding is that touch and force contact lowered mean CPX displacement equivalently, with or without vision present, despite mean force levels which were over 10 times greater with force contact (= 400 grams) than touch contact (= 40 grams). In a model designed to evaluate the reduction in body sway due to passive mechanical forces at the fingertip (Holden et al., 1994), contact forces of 40 grams would produce a maximum reduction of sway of < 5%. In fact, touch contact reduced sway by 50-60% for all subjects.

2. THE TEMPORAL RELATIONSHIP BETWEEN POSTURAL SWAY AND FINGERTIP CONTACT FORCE CHANGES WITH DIFFERENT LEVELS OF CONTACT FORCE

Fig. 3a-b shows in a typical force contact (Fig. 3a) and touch contact (Fig. 3b) trial, the time series and respective correlations between CPX displacement and lateral fingertip contact force (FL), along with the respective time lags at which maximum correlations occurred. Correlations between CPX and FL were highest with force contact (r = 0.9), with very small time lags between the two signals (< 50 ms). This means that fingertip contact forces in the force contact condition were in-phase with body sway: subjects were partially leaning on the contact surface with their finger for support. Correlations between center of pressure (CPX) and lateral contact force (FL) were lower with touch contact (r = 0.3) and changes in fingertip force led

* These first studies have estimated postural sway through center of foot pressure movements on a force platform, which tend to be larger and of higher frequency than center of mass movements (cf., Winter et al., 1990). Center of pressure is a linear measure while body sway is an angular measure and therefore not completely analogous. However, we 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 larger than 0.8 (Jeka and Lackner, 1995). Thus, at the low amplitude of body sway observed in these experiments, center of pressure displacement can be considered to be approximately equivalent to angular body sway.
changes in body sway by ~300 ms. This suggests that as subjects swayed towards the touch bar with only very light touch, contact forces initially increased, but as sway continued towards the bar, contact forces began to decrease so as not to trigger the alarm threshold. This means that subjects must use musculature remote from the fingertip to arrest sway towards the touch bar, because touch contact forces alone are inadequate to damp sway of the body. Therefore, the stabilization provided by touch contact is due to a sensory-motor relationship: forces generated by the musculature remote from the fingertip (legs, trunk, etc.) are guided by sensory information provided by cutaneous receptors in the fingertip (Johansson, 1991) and proprioceptive information about arm position (e.g., Matthews, 1988).

Evidence in support of this interpretation can be found in "precision grip" studies (cf. Johansson, 1991) in which maximal dynamic cutaneous afferent activity is found at approximately 35-50 grams of load force (Westling and Johansson, 1987). Interestingly, this is the same range of contact force subjects spontaneously adopted in our touch contact conditions, even though up to 100 grams of force was allowed. This means that subjects were adjusting touch force to levels where neurophysiological sensitivity was greatest to provide the highest resolution of contact force vectors. They were making use of "precision contact" of a single finger with a surface, analogous to the "precision grip" of Johansson and his colleagues, in which two fingers contact the external object.
3. LEG MUSCLE EMG ACTIVITY WAS LOWER WITH FORCE CONTACT THAN WITH TOUCH CONTACT

In a subsequent study (Jeka and Lackner, 1995), we measured EMG activity in the peroneal muscles, which are particularly important in stabilizing lateral body sway in the tandem Romberg stance, to determine whether leg muscle activity changed with different finger contact force levels. We predicted that muscle activation should be higher with touch contact than force contact, because touch contact was providing spatial cues about body orientation, rather than the physical support associated with force contact of the fingertip. We found that EMG amplitude was 50% higher with touch contact than with force contact, indicating that postural leg musculature played a larger role in reducing postural sway when subjects applied very small contact forces than when subjects were partially leaning on the bar for support.

Timing relationships between CPx displacement and EMG activity in each leg indicate that EMG activity led CPx displacement by ±150 ms in each condition. This means that with touch contact, the changes in lateral contact force at the fingertip began 150 ms...
ahead of correlated changes in EMG activity, enough time for a stabilizing long-loop reflex to be initiated (Diener and Dichgans, 1986) or for conscious anticipatory interventions to be employed. By contrast, in the force contact conditions, fingertip contact forces were approximately in-phase with CPx displacement and lagged behind leg muscle EMG activity, indicating that the contact forces were not precuing a particular muscle activity pattern but physically counteracting body sway. Fig. 4 illustrates schematically the change in timing relationships between CPx displacement, lateral contact force (FL) and left leg EMG activity from the touch contact to the force contact condition.

4. CHANGING THE FRICTIONAL PROPERTIES OF THE CONTACT SURFACE INFLUENCES POSTURAL CONTROL WITH FORCE CONTACT BUT NOT TOUCH CONTACT

To probe the differences between touch contact and force contact further, we evaluated the influence of different frictional properties of the finger contact surface on postural equilibrium by applying a lubricant to the contact surface (Jeka and Lackner, 1995). A slippery contact surface renders shear forces on the finger mechanically less effective to counteract body sway. This means that with physically supportive levels of fingertip force
on a slippery surface, subjects might: 1) sway more than with contact of a rough surface; or 2) switch to use a coordinative strategy more indicative of “touch contact”, in which fingertip contact force changes lead body sway by about 200-300 ms. We did not expect contact surface characteristics to influence postural stability with light touch contact of the finger, because sensory information about the fingertip is available through cutaneous and proprioceptive inputs. Consequently, with light touch contact of the fingertip, we predicted that the sway reduction and the timing relationships between fingertip forces and body sway should not be affected by contact surface properties.

The results showed that changing the touch bar surface from rough to slippery had no effect on postural sway amplitude with either touch contact or force contact. However, Fig. 5 shows that as we predicted: time delays between center of pressure (CPX) and lateral contact force (FL) with force contact of the fingertip changed from 76 ms on a rough surface to ≈266 ms on a slippery surface. Thus, the time delays for CPX displacement relative to fingertip force for force contact on a slippery surface were equivalent to those of the touch contact conditions, suggesting that subjects perceived the lack of horizontal physical support from the slippery surface and switched to a “light touch strategy” to enhance postural stability.

SUMMARY

Contact with the environment through touch of the hand can profoundly influence our body movements and sense of body orientation (cf. Lasker, 1981; 1992). Such observations suggested to us that touch contact could provide spatial information about body orientation that subjects might use to enhance their postural stability. We have found, in fact, that touch of the fingertip to a stationary surface at force levels far below those adequate to provide physical support can enhance the perception of body orientation and stabilize postural control. The crucial pieces of evidence which distinguish postural control with light touch contact from physically supportive contact forces are:
Time delays between body sway and fingertip contact forces are much longer with touch contact (<100 ms) than with force contact (>300 ms), suggesting that light touch forces are precuing postural musculature to stabilize body sway.

Postural muscle activity is much higher with touch contact than force contact, indicating that fingertip contact forces in the light touch conditions were inadequate to counteract center of mass movements, accordingly, leg muscle activity was necessary to attenuate lateral sway.

Changing the surface properties of the contact surface from a rough to a slippery texture influenced postural control with force contact but not touch contact, indicating that postural stabilization with touch contact is guided by sensory information provided by receptors in the fingertip and arm and proprioceptive information about arm configuration, rather than by physical support of the body.

These results suggest potential rehabilitation methods for patients with various sensory-motor deficits and disorders. For example, we have found that once contact with an external surface is available, postural control in patients with bilateral loss of vestibular function is equivalent to that of healthy individuals, indicating that touch cues can substitute for vestibular cues in the control of body orientation (Jeka et al., 1995a). Touch contact may also provide spatial cues for the orienting abilities of blind individuals. We have evidence that contact cues derived through common ambulatory aids such as the long cane provide stabilizing orientation cues for upright posture as well as information about obstacles and surfaces in the surrounding environment (Jeka et al., 1997b). Our findings also may have direct relevance to patients with gait disorders and imbalance attributable to neurological deficits (e.g., patients with hemiparesis, Parkinson's disease and some elderly individuals). Such populations are often capable of generating the appropriate level muscular forces to maintain stable balance and ambulation, but are unable to do so appropriately when unsupported. It is important to note that using contact of the hand with only small applied forces while standing requires innervation of leg musculature to stabilize posture. From this perspective, light touch contact is not a balance support, but a true balance aid that could potentially lead to improved long-term recovery of function by allowing appropriate recruitment of postural musculature involved in the maintenance of voluntary upright stance.

AUTHOR NOTES

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