Significance of finger tactile information for postural stability in humans

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Abstract To maintain an erect posture, sensory information must be integrated from the vestibular, visual, and somatosensory systems. Additional somatosensory cues from the fingertips have been proposed to be able to improve postural stability during quiet standing. The present review paper focuses on the beneficial effect of light fingertip touch on postural control during quiet standing as follows: 1) First, the fundamental light touch procedure for the improvement of postural stability is introduced. 2) The effects of light touch on postural stability in instable persons, including elderly adults, infants, and patients with bilateral vestibular loss, congenital blindness, and somatosensory loss by diabetic neuropathy, are described, indicating that postural stability improves due to multisensory reweighting when a light touch stimulus is applied. 3) The relation between muscle activity and postural sway by light touch are described, demonstrating that the cross-correlation function between velocity information on the center of mass and the activity of the gastrocnemius muscle is stronger with somatosensory input by light touch than without it. 4) The effects of noise-like mechanical stimulation to the fingertips on postural stability are described based on the concept of stochastic resonance, which further enhances postural stability. The literature emphasizes that the effects of light touch on postural stability are purely caused by somatosensory information and not due to the mechanical support provided by the fingers. 5) In contrast to active touch, the efficacy of passive touch is summarized with respect to negligible friction between the skin and a touch device, leading to a decline in postural sway. 6) Finally, the effects of light touch in temporal relation to light touch, muscle activity, and postural sway, are interpreted, taking into consideration that light touch is effective for postural stability in many individuals, including patients with neuropathy, visual disorders, and diabetes.

Keywords: light touch, postural control, noise-like stimulation, sensory reweighting

Introduction

Human bipedal standing is inherently unstable because a large body mass with a highly elevated center must be kept in erect posture over a relatively small base of support. Therefore, we can easily lose balance with very little external force or disturbance in daily living. To achieve the proper position over the base of support, sensory information from the vestibular, visual, and somatosensory system is integrated in the CNS. In addition to this sensory information, tactile information from the fingertips and the voluntarily touch of a surface has been proposed to be able to improve postural stability during quiet standing. In this review, some unique perturbations, including the application of fingertip touch during quiet standing, are described with respect to the postural control system.

Procedure for light touch

In 1994, it was demonstrated that the light touch contact of a fingertip to a stable surface reduces postural sway in subjects standing for the first time. A series of studies by Jeka and Lackner has reported the efficacy of active light touch in postural stability in a heel-to-toe stance. Fig. 1A illustrates a subject in the bipedal stance on a force platform touching a device that is utilized to measure the forces applied by the tip of the right index finger. During the touching trial, the subjects stood in a similar way to the stance maintained in normal quiet standing while lightly resting the tip of their right index finger on a fixed device. The "touching device" was composed of a high-sensitivity tri-axial force transducer on a horizontal metal plate supported by a height-adjusting metal stand. For light touch contact, the subjects could apply up to 1 newton (N) of force, including horizontal anteroposterior (Fx), mediolateral (Fy) or vertical forces (Fz), during quiet standing with light touch (Fig. 1B). If the investigators decided that the subject was not in contact with the
touch device, or when the contraction finger force exerted by the fingertip exceeded 1 N, the subject began the trial again. The contact force between the fingertip and the ground-fixed device was adopted as less than 1 N, as a touching force below 1 N cannot mathematically support the body.

Effects of light touch on postural stability

The tactile information from a fingertip that lightly and voluntarily touches a fixed surface has been suggested to be able to enhance postural stability during quiet standing in the bipedal stance and the heel-to-toe stance. Jeka and Lackner confirmed the effects of light touch on postural sway by investigating the temporal correlation between postural sway and fingertip contact forces under two touching conditions of fingertip contact: light touch contact (less than 1 N) and force contact (equivalent to 5 N). With force contact, there was no time lag between the postural sway and fingertip contact force. In contrast, cross-correlation analysis revealed that postural sway delays fingertip contact force with light touch by approximately 300 ms. These results may indicate that fingertip contact might be preconceived in the body position with sensory information. Even if the contact force was limited to less than 1 N, it is possible that light touch can mechanically support the body. Thus, there is the possibility that light fingertip contact force contributes the mechanical support necessary for erect posture, as the horizontal ground reaction force during quiet standing has been reported to be light as well. Indeed, the fingertip contact force corresponds to more than 20% of the horizontal ground reaction force. This value is close to the value of the percentage reduction in postural sway due to light touch. Kouzaki and Masani examined whether light touch effects are purely neural processes that contribute to the stabilizing effects on posture. To this end, they applied tourniquet ischemia to the upper arm at 200 mmHg to block the fingers’ tactile feedback (Fig. 2A). As a result, even if the fingertips contacted a surface during quiet standing, the postural sway amplitude did not decrease with the light touch when tourniquet ischemia was applied (Fig. 2B). Concerning the results obtained from this previous study, it was demonstrated that the effects of light touch on postural stability are related to purely somatosensory information, and not due to the mechanical support provided by the fingertips. To examine the dynamics of postural sway, the center of pressure during quiet standing was calculated according to physical theory, in which the scaling coefficient can quantify whether postural sway denotes randomness. During stable standing, such as tip toe standing, the scaling coefficient calculated by stabilogram diffusion analysis (SDA) increases, indicating that postural sway in a particular direction facilitates efferent movement in the same direction. During quiet standing, the slope in the long-term region is lower with light touch than the slope without it (Fig. 3), possibly suggesting that light touch contributes to a feedback mechanism.

Effects of light touch on instable posture

Sensory information from the vestibular, visual, and somatosensory systems is integrated to maintain an erect posture. The lack of some feedback information deteriorates postural stability; for example, the postural sway amplitude increases after short-term bed rest, which...
causes a decrease in vestibular function but not in visual and somatosensory functions for postural control. However, light touch during quiet standing is believed to be effective for postural stability even with the decrease in vestibular function. Subjects with bilateral vestibular loss were more stable in the dark with light touching than normal subjects in the dark without light touch, although subjects with vestibular loss could not stand for more than a few seconds in the dark without falling. In addition to postural sway amplitude, there is no difference in the temporal relation between postural sway and touch contact forces between vestibular loss and normal subjects. Similar to the effects in subjects with vestibular loss, inferior postural stability in individuals with congenital blindness improves due to light touch. It has been reported that large body sway during quiet standing is associated with a visual stimulus that consists of a pattern of random dots that is rear-projected on a translucent screen. When a light touch stimulus is applied during quiet standing with visual stimulus, postural stability is controlled by multisensory reweighting. These results indicate that enhanced somatosensory input from the fingertips makes it possible to compensate for lower postural stability due to a lack of vestibular and/or visual feedback.

Large postural sway in patients with somatosensory loss due to diabetic neuropathy is well established. When light touch is also applied in such patients, there is no difference in the postural sway amplitude between diabetic patients and healthy adults. This result may suggest that the enhanced somatosensory substitution from the fingertips can be used to improve postural equilibrium in diabetic patients. When mechanical vibration is applied to the soles of the feet, the position of the center of pressure dramatically changes in various directions due to an illusion of a proprioceptive sensation in the foot sole. In addition, mechanical vibration applied to the Achilles tendons of a standing subject induces body sway in a backward direction, and a loss of postural balance. Therefore, misrepresentations of somatosensory cues exert a negative influence on postural balance. However, the amplitude of postural sway during quiet heel-toe standing with vibration to the peroneus longus and brevis tendons decreases with light touch, indicating that haptic contact of the fingertips with a stable surface can suppress abnormal somatosensory information in leg muscles during quiet standing. Furthermore, vibration of the dorsal and lateral neck muscles, including lower limb muscles or tendons, also generates large body sway in the direction opposite to the vibration site. When subjects lightly touched a fixed surface with the fingertips during both neck vibrations, postural sway with light touch was similar to that of the control condition (without neck vibrations). In addition to the tactile information from the fingertips, the contribution of the motor control of the forearm and/or upper arm to postural stability has been suggested; therefore, Rabin et al. investigated the effects of light touch on the postural stability with differ-

Fig. 2 A. Schematic illustration of light touch standing with tourniquet ischemia of 200 mmHg around the upper arm. B. Mean velocity of the center of pressure (path length divided by the calculated time) during different somatosensory inputs (CON: control, TIS: applying tourniquet ischemia) with (closed bars) and without (open bars) light touch and with eyes open (left panel) and eyes closed (right panel).

Fig. 3 A resultant planar stabilogram-diffusion plot generated from the center of pressure during quiet standing with (solid line) and without (broken line) light touch. The scaling exponent is calculated from the slopes of the short-term and long-term regions.
Light touch effects on age-related postural instability

Postural instability during quiet standing with aging is well documented (e.g., Kouzaki and Shinohara\(^{23}\)). Age-related deterioration in postural control is suggested to be caused by both qualitative and quantitative features of the main working muscles, including force steadiness, muscle volume, and physiological tremor of the plantar flexor muscles\(^{24}\). For example, the physiological tremor component of the soleus muscle is positively correlated with postural sway amplitude, while the muscle volume of plantar flexors, as the main working muscles for erect posture, is negatively correlated (Fig. 4). It has been reported that the path length of the center of pressure during quiet standing in elderly adults is approximately 1.5 times larger than that in young adults\(^{23,24}\). However, the path length of the center of pressure (COP) and the standard deviation of acceleration of the subject’s center of mass (as an assessment of amplitude of postural sway) in both young and elderly adults is significantly decreased after applying light touch; and this effect is significantly larger in elderly (~30%) than in young (~15%) adults\(^{25}\). As a result, the amplitude and time series of postural sway parameters are similar in both age groups due to the application of light touch. Careful observation in a time series of light touch force (Fig. 5) indicates that the trajectory of contact force in elderly adults shows more complex and higher fluctuations than in young adults. This observation implies that fingertip contact during light touch in elderly adults is regulated little by little to stabilize posture. Marked postural instability in elderly adults may improve due to enhanced somatosensory information from the fingertips to prevent falling.

Similar to elderly persons, there is less postural stability in infants that can walk on their own\(^{26}\). Chen et al.\(^{27}\) succeeded in assessing the effects of light touch on postural stability in infants and detected a decrease in the postural sway amplitude by light touch in infants, who have a larger high-frequency component of body sway than adults. The result that the large high-frequency component of sway decreased after light touch suggests that postural stability improves due to enhanced somatosensory information from the fingertips, even in infants.

Muscle activity as related to postural sway during light touch

In human quiet standing, plantar flexors act as important agonists for erect posture, as ankle torque controls the center of mass behavior\(^{28}\); therefore, the activity of the plantar flexors is correlated with non-stationary body sway\(^{29}\). The previous result\(^{29}\), that a series of muscle activity is reported to be correlated with center of mass velocity without time delay, suggests that the actual postural control system during quiet standing relies on velocity information about the center of mass interpreted in an anticipatory manner without using a feed-forward mechanism. Indeed, a simulation study has also demonstrated that center of mass velocity information is more
accurate than position or acceleration information for postural stability\(^{30}\). Thus, the degree of correlation between the center of mass velocity and the muscle activity of plantar flexors is believed to be significant for the postural control system during quiet standing. It seems likely that the rectified electromyogram (EMG) of the medial gastrocnemius (MG) muscle is similar to the center of mass velocity during quiet standing with light touch; and there is an analogy between contact force and both postural sway and electromyogram activity (Fig. 6A). Cross-correlation analysis revealed that the correlation strength from electromyogram activity of the plantar flexors to the center of mass velocity increases due to light touch with somatosensory input (Fig. 6B). From these results, it can be suggested that tactile inputs from the fingertips are of assistance in the advance detection of velocity information on body orientation in quiet standing.

With respect to periodic fluctuations, mechanomyographic studies revealed that physiological tremors with 8-12 Hz fluctuations of muscle activity generate high-frequency postural sway during quiet standing\(^{31}\). During static plantar flexion contractions with low intensity, the amplitude of the physiological tremor is dependent on the synchronization of motor units within the muscle, because a decrease in motor unit synchronization due to subthreshold electrical stimulation reduces force variability\(^{32}\). In addition, it has been noted that the fluctuations in the center of pressure during quiet standing result from a relatively higher recruitment threshold of motor unit discharge (Kouzaki et al. unpublished observation). During quiet standing, several motor units can be observed by using fine-wire electrodes (Fig. 7), and individual motor units are discriminated based on waveform amplitude, duration, and shape (Fig. 7, black dots). When a subject’s fingertips contact a fixed surface, the motor unit that exhibits a large amplitude disappears. Furthermore, individual motor units do not synchronize due to the application of a light touch. These results suggest that light touch modulates the motor unit recruitment strategy, and that it affects declined postural fluctuations during quiet standing.

Fig. 6 Relation between postural sway velocity and muscle activity. A. Typical time series of the center of mass velocity in an anterior-posterior direction, light touch force, and an electromyogram of the medial gastrocnemius during quiet standing. These data are low-pass filtered (cutoff frequency is 4 Hz). B. Cross-correlation function between the center of mass velocity and muscle activity of the medial gastrocnemius with (thin line) and without (thick line) tourniquet ischemia.

Fig. 7 Motor unit action potentials of the soleus muscle during quiet standing with (right panel) and without (left panel) light touch. Motor unit action potentials were measured by a bipolar fine-wire electrode, which consisted of stainless-steel wires (\(\phi = 50 \mu m\)). The bottom rows of both panels show an enlarged view with an extended time scale (100 ms) of the motor unit action potentials in the top row for visual purposes. Closed dots indicate a discriminated single motor unit by the identification of action potentials based on the waveform amplitude, duration, and shape. In contrast to quiet standing without light touch (7 motor unit recruitment), only 4 motor units are recruited when quiet standing with the application of light touch.
Enhanced effects of light touch by stochastic resonance

Light touch effects result from afferent information from the pressoreceptors of the fingertips. Based on the concept of stochastic resonance, a noise-like stimulation of a nonlinear system can increase the receptor’s response to a subthreshold input signal\(^\text{[31]}\). Kimura et al.\(^\text{[19]}\) examined whether a noise-like unperceivable vibration, with random frequency on the fingertips, enhances tactile sensation and facilitates the effects of light touch during quiet standing (Fig. 8A) with respect to this concept. As a result, the enhanced effects of light touch on postural stability are not due to vibration at intensities above the vibrotactile threshold, but to vibration at an intensity below the vibrotactile threshold (Fig. 8B). In particular, the effects of light touch were facilitated in the high-frequency component of postural sway when a subthreshold noise-like vibration was applied. This result may indicate that the effects of light touch on postural stability are purely due to somatosensory information from the fingertips without mechanical support, because noise-like stimulation does not give rise to afferent input but, rather, assists afferent activity\(^\text{[32]}\).

Passive touch

Light touch is a style of “active touch” in which a subject’s fingertips gain afferent information. In contrast to active touch, “passive touch” is based on the hypothesis that such a stimulus is not restricted to a particular part of the body, but is more effective on postural stability when quiet standing. In the case of passive touch, the contact force depends only on the friction between the skin and the touched surface (e.g., fabric), and this friction force may be negligible. Rogers et al.\(^\text{[35]}\) provided evidence that passive stimulus rubbing on the skin of the leg or shoulder reduces postural sway. Menz et al.\(^\text{[36]}\) expanded on the study by Rogers et al.\(^\text{[35]}\) to investigate the effects of a passive tactile cue at different sites of the leg (ankle, calf, and knee) on the improvement of postural balance in healthy young controls, elderly subjects, and patients with diabetic peripheral neuropathy. As a result, each stimulus could reduce the amplitude of postural sway in people with and without peripheral sensory loss; but the efficacy increased in proportion to the height of the stimulus above the ankle joint (knee > calf > ankle). This finding implies that stimulus to the cutaneous receptor around the knee effectively improves postural stability. Kimura and Kouzaki\(^\text{[37]}\) focused on the receptors around the knee joint, and demonstrated that postural sway during quiet standing decreases due to an unperceivable electrical noise stimulation applied to the knee joint (Fig. 9A), especially in the low-frequency component of the sway (Fig. 9B). These results may suggest that passively enhanced somatosensory feedback from various receptors can improve postural stability without positive touching on a given fixed surface.

Final remarks on the effects of light touch on postural stability

Since the effects of light touch during quiet standing were introduced by Holden et al.\(^\text{[3]}\) in 1994, many researchers have examined the effects of light touch on postural stability. Although the process of light touch, the analytical procedure for postural control, and the examined populations are different among researchers, it was universally concluded that enhanced somatosensory input

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Fig. 8  A. Schematic illustration of a light touch with fingertip vibration. A subject quietly stands with the index fingertip of the right hand lightly touching a fixed wooden surface, which is connected to a mechanical oscillator. The mechanical oscillator can create white noise using a pass-band width between 200 and 400 Hz. B. The normalized path length of the center of pressure and the high- and low-frequency components of the center of pressure sway at the three light touch conditions, including light touch without vibration (open bars), light touch at 0.5 times the vibrotactile threshold (grey bars), and light touch at 1.0 times the vibrotactile threshold (closed bars).
by light touch contributes to postural stability during quiet standing. The effects of light touch, as well as the temporal relationship among light touch, muscle activity, and postural sway (Fig. 10) are interpreted as follows: 1) afferent outflow from the fingertips due to light touch projects to the sensory cortex (Fig. 10, thick line); 2) on the basis of sensory information, relevant efferent activities redirect the sensory input toward the plantar flexors as the main working muscles for erect posture (Fig. 10, thin line); and 3) the regulation of ankle torque by the complex activity of plantar flexors produces postural sway (Fig. 10, broken line). Thus, the delay from the onset of light touch to that of postural sway is long (approximately 300 ms) due to such a process. This delay from light touch to postural sway implies that the light touch contact force vectors facilitate specific body orientations in the central nervous system. Thus, the tactile information from light touch recognizes the body axis in advance. To maintain the set point of anterior-posterior fluctuations in the center of mass position, the regulation of ankle torque produced by plantar flexors is essential. Therefore, these neurophysiological processes for postural control by light touch produce a long delay (~300 ms) from light touch to postural sway. Because a more rapid response is necessary for the prevention of falls in elderly people, infants, and patients with neuropathy, visual disorders, and diabetes, a more effective light touch procedure with quick responses should be investigated in the future.

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