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RESEARCH ARTICLE

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Passive tactile sensory input improves stability during standing

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Abstract The effects of passive tactile cues about body sway on stability during standing were evaluated in subjects with a wide range of sensorimotor and balance performance. Healthy young adults, diabetic subjects with varying degrees of peripheral sensory neuropathy and older subjects aged 70–80 years were studied. Body sway was measured when subjects stood on the floor and on a foam rubber mat, with or without an applied stimulus that rubbed on the skin at the leg or shoulder as the body swayed. The results show that this stimulus reduced body sway (mean reduction 24.8%±1.5) and thus had a stabilizing effect as big as vision or sensory information from the feet. The reduction in sway was not based on active touch. The stimulus was not restricted to a particular region of the body, but was more effective on the shoulder than the leg, and was more effective when standing with eyes shut or when standing on the foam mat. It was also most effective in those subjects who had the greatest sway during normal standing. Thus, the response appears to be graded with the amplitude of the stimulus. We concluded that, if passive sensory input about posture is available, the postural control process adapts to this input, modulating postural stabilizing reactions.

Keywords Posture control · Somatosensation · Human

Introduction

It is common for people with balance disorders to stabilize themselves by holding or touching a nearby stable object. In addition to gaining mechanical support, it seems likely that this provides sensory information related to body movements. Human standing is thought to depend on the interaction of multiple sensory systems involving visual, vestibular and somatic inputs. Recent investigations show that, during active light touch of a stationary reference, cues from a fingertip can reduce postural sway in blind individuals and those with vestibular loss (Jeka et al. 1996; Jeka 1997). Presumably, intact neural pathways transmit sensory input that is in some way equivalent to the absent input. These observations indicate that tactile information can, at least in part, substitute for absent visual or vestibular information. It is likely that this is one mechanism by which a walking stick improves stability in people with sensory deficits.

In younger adults without neurological disorders, lateral postural sway during tandem Rhomberg standing, or heel-to-toe with eyes shut, is reduced by active light touch with a fingertip on an external surface (Jeka and Lackner 1994). This stabilizing effect is evident even when the contact forces provided by the fingertip touch are too small to mechanically stabilize the body, and the effect on sway is as strong as either vision or a more forceful mechanical support (Jeka and Lackner 1995). Contact stimulation of the hands or feet can also induce illusions of body movement and altered orientation in blindfolded subjects (Lackner and Dizio 1992). The fact that even healthy young adults with fully intact sensorimotor pathways can further reduce postural sway with the addition of postural cues, and may erroneously perceive touch information to indicate self-motion, suggests that the nervous system integrates this tactile input in the same manner as other postural sensory inputs.

It is possible that the high density of sensory units in the finger and the large sensory cortical representation of the finger might enhance information about body sway. Such cutaneous input must be integrated with proprioceptive input about the orientation of the finger and arm, and perhaps with the motor command to touch the object. For example, information about the motor command for self-generated active touch, as signalled by efference copy, might be used with the known properties of the contact surface to stabilize sway. It remains unclear whether the stabilizing effect of light fingertip touch relies on the particular morphological and physio-

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logical characteristics of finger touch or the voluntary nature or motor command for active touch.

In healthy young adults, sensory input from the legs is sufficient for standing in the absence of visual and vestibular inputs (Fitzpatrick et al. 1994). With advancing age, vibration sense, joint position sense, and tactile sense are diminished in the legs (Kenshalo 1986). Reduced lower-limb sensation is associated with increased postural sway (Lord and Ward 1994; Simoneau et al. 1994) and falls (Lord et al. 1994) in elderly people and in younger subjects with peripheral neuropathy (Lord et al. 1993; Uccioli et al. 1997). Such naturally occurring changes in somatosensation and balance stability with age and pathology provide the opportunity to evaluate the potential integrative capacity of additional tactile sensory input when a pathway critical for standing stability has been compromised.

The present study investigates whether stability during standing is improved by passive tactile input related to body sway that does not involve active manual touch. To include subjects with a wide range of sensorimotor performances, this question was investigated in young healthy adults, diabetic subjects with peripheral sensory neuropathy and otherwise healthy elderly subjects.

Materials and methods

Subjects

Forty-seven subjects provided informed written consent and participated in these simple, non-invasive studies that were approved by the institute's human ethics committee. All subjects were naive to the study hypothesis.

To study a population with a wide range of sensorimotor function related to standing, subjects were drawn from four sources. A young group of eight subjects, four women and four men, aged 21–37 years (mean 26.9 years) was recruited from the staff and students at the institute. These subjects had no neurological or musculoskeletal problems. A diabetic group of 14 subjects with peripheral neuropathy was recruited from outpatients of the Prince of Wales Hospital Diabetes Center. This group comprised 3 women and 11 men, aged 49–68 years (mean 60.0 years), having a duration of diabetes of 8.1±2.1 years (mean ± SEM). Twenty-five subjects aged 70–79 years were recruited from the participants of an independent study concerned with determining risk factors for falling in community-dwelling elderly people. Those who could not stand and walk without the assistance of an aid were excluded to ensure that all participants could undertake the experimental tasks. Among this group, subjects who reported one or more falls in the previous 12 months were classified into an elderly faller group and those that reported no falls were classified into an elderly non-faller group. On this basis, 10 were fallers, 4 women and 6 men aged 74.2±2.9 years, and 15 were non-fallers, 9 women and 6 men aged 74.7±4.5 years.

Sensorimotor function

Five tests of sensorimotor function that relate to standing were administered over 1 h. The tests were: (1) visual acuity, (2) vibration sense, (3) touch sensation, (4) leg-muscle strength, and (5) voluntary reaction time.

Visual acuity was measured binocularly, with subjects sitting 4 m from a Snellen chart and wearing their normal glasses.

Vibration sensibility at the tibial tuberosity of each leg was measured using a 200-Hz vibrator that provided controlled, variable amplitude (0–100 μm) via a 10-mm hard rubber tip with a constant background force against the skin. In each trial, the amplitude was either slowly increased from an imperceptible level until the subject reported the vibration or slowly decreased from a clearly perceptible level until the subject reported that the vibration had ceased. Threshold for perception of vibration was calculated as the mean intensity of six alternate trials.

Touch sensibility at the fibula head and lateral malleolus of each ankle was measured with a set of 20 calibrated nylon monofilaments that applied forces between 4.5 mg and 447 g (Semmes et al. 1960). Thresholds were obtained by a forced-choice paradigm in which the subject nominated on which of two occasions the ankle was touched. After three trials, a smaller stimulus was applied if all three responses were correct, or a larger stimulus was applied if one was not correct. Using this stepwise threshold tracking procedure, the threshold was taken as the smallest of the last three stepwise reversals.

Strength of the ankle plantarflexion and dorsiflexion muscle groups was measured in both legs during maximal isometric contractions. Subjects sat in a chair with the hip, knee and ankle at right angles and the foot being tested on a force plate that measured torque about the axis of the ankle with a load cell. Dorsiflexion strength was measured by securing the foot with a wide strap over the metatarsals and having the subject forcefully raise the foot against the strap for 5 s while keeping the heel on the force plate. Strength was calculated as the mean of three maximal contractions, with a 1-min rest between tests. Plantarflexion strength was measured by stabilizing the leg and foot with a strap fastened over the knee and lower thigh to prevent the heel lifting. A composite measure of strength was obtained by summing all four results. Because a larger body load requires greater ankle torque to balance it, strength was normalized to the product of the subject's mass and the height of the centre of mass, measured as the height of the S2 vertebra.

Voluntary reaction time for foot movement in response to a visual stimulus was measured. While seated, subjects placed a foot on a foot switch and looked at a red light that was illuminated at random intervals. The switch was pressed as quickly as possible after the light came on, stopping a millisecond timer that began when the light came on. Reaction time was determined as the mean of ten trials.

Standing

Experimental conditions

Each subject participated in 14 different experimental trials in which body sway was measured. A different configuration of vision, tactile cues and the support surface were presented in each trial.

In some trials, tactile stimuli were provided by a 400-mm length of flat sprung steel attached to a rigid support at one end, with a 50×20 mm piece of fabric on the free end (Velcro soft surface, or "hairs"; see Fig. 1). For the leg stimulus, the fabric was positioned against the skin just below and lateral to the right knee and adjusted using the spring of the steel so that the horizontal force at the point of application was 0.25 N. For the shoulder stimulus, the fabric was applied with a 0.25-N vertical force to the skin overlying the lateral fold of the trapezius muscle. During standing, these stimuli produced a stabilizing shear force on the skin of less than 0.02 N.

Subjects were tested while they stood on a rigid floor with the eyes open and with the eyes shut. For both visual conditions, they were tested with no additional tactile cue (trials T1, 2), with the tactile sensory cue at the knee (T3, 4) and with the tactile sensory cue at the shoulder (T5, 6). When standing with the eyes shut, they were also tested with both the leg and shoulder tactile cues available (T7). Using the same seven configurations of vision and additional tactile cues, subjects were tested while they stood on a piece of 75-mm-thick foam rubber (trials T8–14; Fig. 1). For each sub-

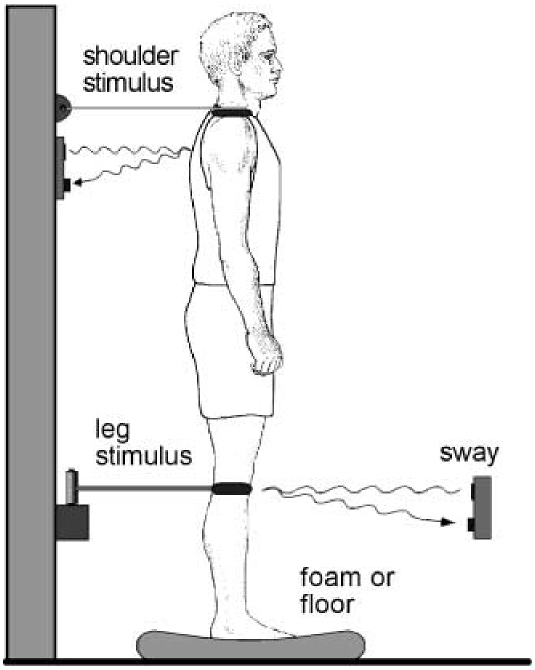


Fig. 1 Experimental setup. Subjects stood on the floor or on a foam mat with their eyes open and with their eyes shut, with or without a tactile stimulus at the knee, the shoulder or both sites simultaneously. Antero-posterior body sway was measured with optical displacement devices targeted at the tibial tuberosity and at the back

ject, the *floor* and *foam* trials were presented as separate sets, with a rest period between them, but the order of the two sets was rotated between subjects. Within each set, the seven trials were presented in random order to each subject. To identify any “placebo” effect of a similar stimulus, trials were undertaken with a 25-g weight (0.25 N) covered with the same fabric resting on the shoulder. The weight was placed on the shoulder in a manner that did not alert the subjects that this was different to the “stationary” stimulus. Because it was not attached to a rigid support, it did not move relative to the skin as the subject swayed, although through its inertia it could provide a very small tactile input related to sway.

Control experiments

In young subjects, two control experiments were undertaken using a tactile stimulus at the leg that provided no sway-related input. In the first, a servomotor driven by the subject’s sway signal moved the fabric to keep it aligned with the knee. Thus, as the subject swayed, the fabric moved so that there was no relative movement against the skin. Within the bandwidth of interest in these studies (below 1.5 Hz), the servomotor tracked the sway signal with errors of less than 2%. Thus, any movement relative to the skin was very small and not consistent in direction. In the second control experiment, the servomotor was used to produce a random movement of the fabric stimulus against the skin and not provide any signal of body sway. To achieve this, the signal driving the servomotor was a computer-generated stochastic signal with a similar power spectrum to the subject’s previously recorded sway that had the subject’s current sway signal subtracted from it. Thus, the relative movement against the skin was only the random stochastic signal.

Protocol

Subjects stood with their hands lightly clasped in front of them. Before each trial, they were instructed to stand still. Each trial lasted 40 s. A wall with a moderate contrast pattern was approximately 2 m distant. The feet were aligned side by side in the normal standing position (Fig. 1). As the study considered only sway in the antero-posterior plane, subjects were allowed to adopt their preferred position for the distance between the feet within the range 5–15 cm. However, for each subject, a tracing of the outline of the feet was used to keep the position of the feet constant between trials so that the between-trial results were unaffected.

Subjects were not told anything about the tactile stimulus before or during the testing, although clearly they were aware of it being placed on the leg or shoulder before each trial. To avoid fatigue, a 1-min rest period between trials was allowed for subjects to relax and move their legs. Subjects sat and rested for 5 min between the two sets of seven trials.

Data measurement and analysis

The tactile stimulus being tested moved across the skin in the antero-posterior plane, but there was only a small (less than 0.04 N) change in the force applied in the lateral plane, because the flat spung steel was compliant in that direction. Therefore, body movement in the antero-posterior plane (*sway*) was used as the measure of postural stability. Body sway about the ankles in the antero-posterior plane was measured with an optical displacement device (MEL Mikroelektronik, Eching: M5L/200), which was targeted at the right tibial tuberosity. To estimate the amplitude of the tactile cue at the shoulder relative to the amplitude at the leg, and to determine whether there were specific effects on the movement of the upper body, a second device was targeted at the centre of the back at the level of the T2–4 vertebrae.

During each 40-s trial, data were sampled at 25 Hz through an analog-digital interface and stored for computer analysis. The data sequence was bandpass-filtered (0.1–10 Hz) and root-mean-square (rms) values were calculated after subtracting the mean. Power spectra were calculated using a fast Fourier transform.

Statistical analysis

The rms estimates of sway were analyzed by a 4-way analysis of variance (ANOVA; unbalanced model, type III sum of squares) using SPSS software (SPSS 1993). Stimulus was the primary factor (five levels: none, leg, shoulder, both, weight). Vision (open, shut), support (floor, foam) and the subject group (young, diabetic, non-faller, faller) were secondary factors. Where significant interactions ($P<0.05$) that involved the primary factor (stimulus) were present, separate ANOVAs were performed to identify the effects of the stimuli at each level of the secondary factors.

To compare the effects of the different tactile stimuli across this broad group of subjects, who had different baseline performances for normal standing under the different visual and support conditions, the rms sway measures were normalized for each subject by calculating the percentage sway reduction for each tactile cue condition compared to the no stimulus condition. These normalized changes in sway with the different tactile stimuli were compared by 3-way ANOVA (stimulus, vision, support), with the primary factor, stimulus, at 4 levels (leg, shoulder, both, weight). Student-Newman-Keuls (SNK) post hoc corrections were made for the multiple comparisons, with a significance level of 0.05. Pearson correlations were calculated to assess whether improvements in stability with the tactile stimulus were associated with subjects’ sensorimotor performance (i.e. visual acuity, peripheral sensation, ankle strength tests, voluntary reaction time and sway during standing).

Results

Sensorimotor function

There were significant differences in sensorimotor performance among the four subject groups (Fig. 2). The

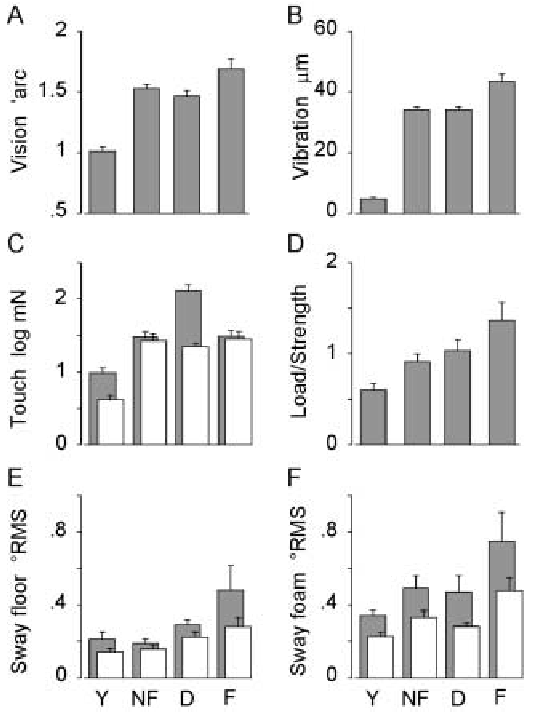


Fig. 2A–F Sensorimotor function. In each graph, data (mean ± SEM) are shown for the four subject groups (*Y* young, *NF* non-faller, *D* diabetic, *F* faller). In general, sensorimotor function worsened in that order. Visual acuity (**A**) is minimum angle resolvable, vibration (**B**) is the amplitude of indentation, and touch thresholds in log millinewtons (**C**) are shown for the ankle (*shaded*) and knee (*white*). The strength data (**D**) are dimensionless, calculated as the subject's body load (mass × g × height in newton-metres) divided by the total plantarflexion and dorsiflexion strengths (in newton-metres). Relative to body load, the young group was the strongest and the fallers group was the weakest. Body sway without a tactile stimulus on the floor (**E**) and foam (**F**) is shown for eyes open (*white*) and eyes shut (*shaded*)

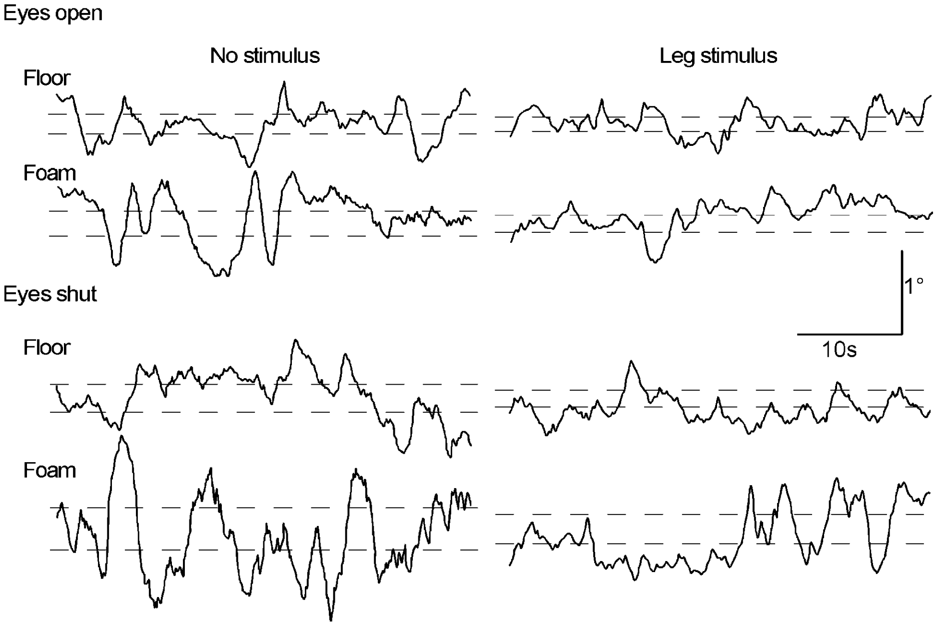
young subjects had the best visual acuity, the lowest vibration and touch thresholds, and the greatest leg-muscle strength relative to body load. The group of older subjects with a history of falling had the poorest visual acuity of the four groups, the lowest muscle strength and the highest vibration thresholds. Consistent with peripheral sensory neuropathy, the diabetic subjects had the highest touch threshold at the ankles but were similar to the elderly groups at the knee. The young subjects had shorter voluntary reaction times (247±5 ms, mean ± SEM) than the other groups (ANOVA, $P<0.01$), who had similar reaction times (diabetic, 332±18 ms; non-faller, 307±14 ms; faller, 285±9 ms). Baseline sway also provides a measure of sensorimotor performance. When no additional tactile cue was available, sway during standing paralleled the other sensorimotor differences between groups. In all situations, the young group swayed the least and the elderly faller group swayed the most.

Standing

All subjects completed all trials without falling, stepping or reaching for a stable support. However, some subjects in the diabetic and elderly faller groups experienced difficulty standing on the foam with the eyes shut and appeared to be close to the limit of balance. The distances between the feet were not significantly different between subject groups (mean ± SD: young, 9.3±2.5 cm; diabetic, 10.0±2.0; non-faller, 9.3±2.7; faller, 9.5±3.2; $F_{3,43}=0.186$, $P=0.91$).

Recordings of sway in the antero-posterior plane for a typical subject (diabetic) show excursions of sway of approximately 1° when standing on the floor with the eyes open (Fig. 3). Sway was greater with the eyes shut and

Fig. 3 Typical performance with different postural and sensory conditions. Recordings of sway (40 s) are shown when standing on the floor and foam with eyes open and with eyes shut. *Broken lines* indicate the magnitude of the rms sway about the mean position. For each situation on the *left*, the tracings on the *right* show reduced sway when a tactile stimulus was applied at the leg



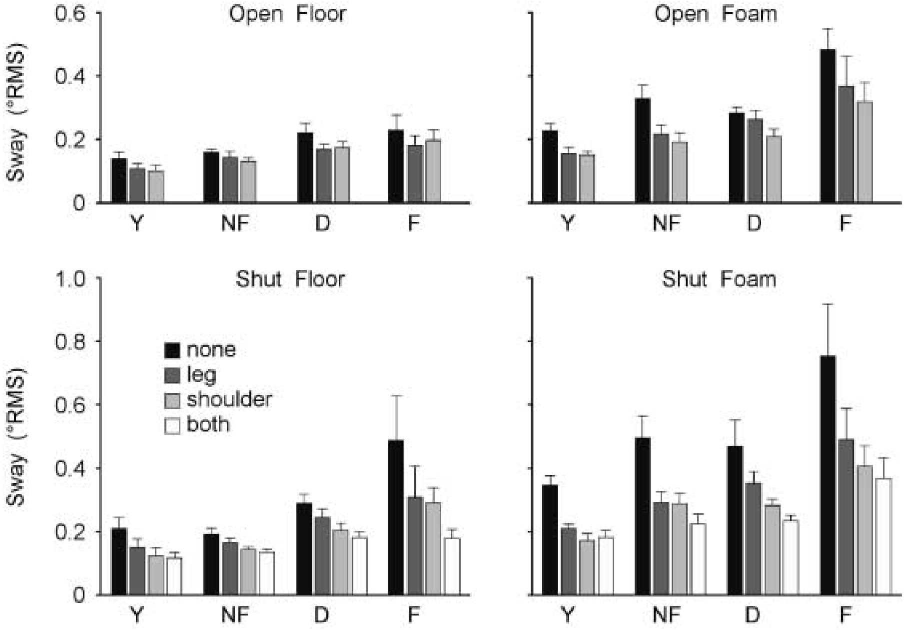


Fig. 4 Mean sway by subject group and experimental condition. The amplitude of sway (mean ± SEM) in degrees of rotation about the ankle is shown. The *top panels* show sway with the eyes open and the *bottom panels* show sway with the eyes shut. Subjects are standing on the floor in the *left panels* and on the foam in the *right*. Each graph shows data by subject group (*Y* young, *NF* non-faller, *D* diabetic, *F* faller), and each cluster shows data for the different stimulus conditions (none, leg, shoulder, both)

when standing on the foam: compare the rms amplitudes indicated by the broken lines in Fig. 3. Regardless of whether the eyes were open or shut, or whether standing on the floor or foam, sway was less when an additional tactile cue was available (compare right with left recordings). Figure 4 shows mean sway (rms ± SEM) for each of the four groups of subjects for the different visual and support conditions. For each condition of vision (open, shut), support surface (floor, foam) and stimulus (leg, shoulder, both), the application of the stimulus reduced sway. Averaged over all conditions, the addition of a tactile cue at the leg or shoulder reduced sway by 24.8±1.5%.

The results of the ANOVA on the rms values of sway did not show any significant ($P<0.05$) 4-way or 3-way interactions between the tactile stimulus, vision, support surface and subject group. There were two significant 2-way interactions involving the primary factor, the tactile stimulus. There was an interaction between the stimulus and support surface ($F_{4,\ 688}=2.71$, $P=0.03$). This arose because sway on the foam was attenuated more when a tactile stimulus was available (compare left and right graphs of Fig. 4). There was a significant 2-way interaction between the stimulus and vision ($F_{2,\ 688}=3.01$, $P=0.05$). This was because sway with the eyes shut was attenuated more when a tactile stimulus was available (compare top and bottom graphs in Fig. 4). There was no interaction between subject group and stimulus ($F_{12,\ 688}=1.35$, $P=0.19$). Because of these interactions, separate 2-way ANOVAs for each level of vision and support were performed (i.e. stimulus × group for each graph in Fig. 4). They showed significant main effects for each factor ($P<0.001$ for group, $P<0.01$ for stimulus) and no interactions. Each ANOVA revealed that the presence of a stimulus reduced sway compared with the non-stimulus condition (Fig. 4). Among the secondary factors, there was a significant 2-way interaction between support surface and subject group ($F_{3,\ 688}=3.46$, $P=0.02$), because the elderly non-faller group had a larger (94%) increase in sway on the foam than the other groups (young, 54%; diabetic, 45%; faller, 66%). This is apparent in Fig. 4, where they resemble the young group on the floor but resemble the diabetic group on the foam.

There were highly significant main effects of subject group ($F_{3,\ 688}=35.1$, $P<0.0001$). The young subjects swayed the least, then the older non-fallers, the diabetic subjects and the older fallers whose mean sway was more than twice that of the young subjects ($P<0.05$ for each comparison, SNK correction). There were highly significant main effects of vision (Fig. 4, compare top with bottom graphs) and the support surface (Fig. 4, compare left with right graphs). Subjects swayed 38% more with the eyes shut than with the eyes open ($F_{1,\ 688}=35.9$, $P<0.0001$) and 63% more on the foam than on the floor ($F_{1,\ 688}=86.0$, $P<0.0001$).

Effects of different tactile stimuli

To determine the strength of the tactile stimuli on reducing sway during standing, for each subject, the percentage change in sway with the addition of a tactile stimulus was calculated. Figure 5 shows the mean (± SEM) percentage reduction in sway with the different tactile stimuli for the entire group of subjects. The results of the 3-way ANOVA on these data showed no significant 3-way or 2-way interactions. There was a significant main effect of stimulus ($F_{3,\ 552}=39.9$, $P<0.0001$). When the tactile stimulus was placed at the shoulder there was a greater reduction in sway (28.8±2.0%, Fig. 5) than when it was placed on the leg (21.6%±2.3, Fig. 5; SNK $P<0.05$). Simultaneous tactile stimuli at the leg and

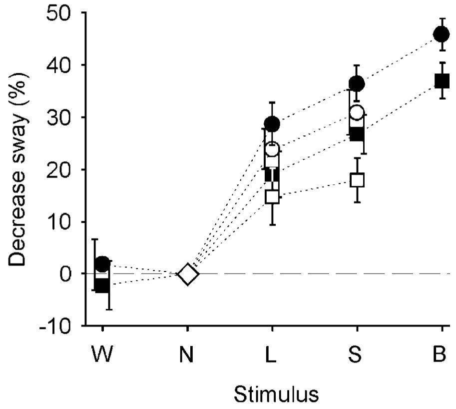


Fig. 5 Mean decrease in sway with different tactile stimuli. The percentage decrease in sway (mean ± SEM) across all subjects for the different experimental conditions. Some of the error bars are offset for clarity. *White symbols* are eyes open, *symbols* are eyes shut. *Squares* are standing on the floor, *circles*, on the foam. On the *abscissa* are the different tactile stimuli: *N* none, *L* leg stimulus, *S* shoulder stimulus, and *B* both leg and shoulder stimuli. On the *left* is the control (*W*) weight stimulus

shoulder were tested only for standing with the eyes shut. With both shoulder and leg stimuli, the reduction in sway was significantly greater (41.9%±2.9; Fig. 5) than when only the shoulder (and leg) stimulus was available (SNK $P<0.05$). In the trials in which the stimulus was a 25 g weight on the shoulder, there were no significant changes in sway (Fig. 5).

The tactile stimuli produced greater reductions in sway with the eyes shut than with the eyes open (Fig. 5; $F_{1,\ 552}=3.9$, $P<0.05$). There was a greater reduction in sway when standing on the foam than when standing on the floor (Fig. 5; $F_{1,\ 552}=11.8$, $P<0.001$).

Sway frequency

To determine whether the addition of tactile cues improved stability at particular frequencies, power spectra were calculated from the recordings of sway. Sway was minimal at frequencies greater than 1.5 Hz in any situation (Fig. 6). With the tactile cues available, sway was reduced approximately proportionally across the entire bandwidth of sway for both standing on the floor (shown in Fig. 6) and standing on the foam.

Control experiments

In the young subjects, two control stimuli that provided no sway-related input were tested. When the tactile stimulus was stationary relative to the subject's skin, there was no significant effect in reducing sway (3.9±9.1% increase). When the fabric moved against the skin in a stochastic, sway-like manner but unrelated to the subject's sway, there was no significant effect in either reducing or increasing sway (1.9±7.4% decrease).

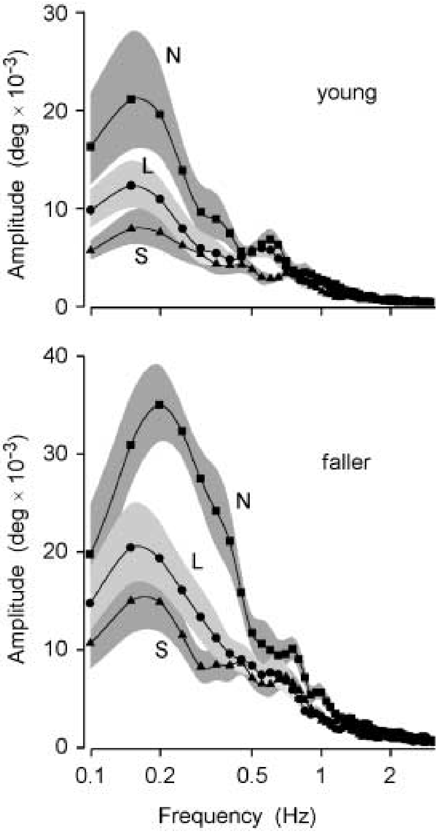


Fig. 6 Power spectra of sway. For the young group (most stable) and the faller group (least stable), sway power spectra (geometric means ± SEM) are shown for standing on the floor with no additional cues (*N*), a stimulus at the leg (*L*) and stimuli at the shoulder (*S*). With the additional tactile cues, sway decreased proportionately across the bandwidth without attenuation at a particular frequency

Sensorimotor function and tactile stimulus

There were no significant associations between the reduction in sway produced by the tactile stimuli and either the touch or vibration measure of subjects' peripheral sensation in any condition tested. Similarly, there were no significant associations between the reduction in sway produced by the tactile stimuli and either the measured muscle strength or voluntary reaction times.

There were significant associations between the effectiveness of the tactile stimuli and visual acuity when subjects were standing on the foam with the eyes open (Fig. 7A). Subjects with good visual acuity reduced their sway more with the tactile stimuli than subjects with poor visual acuity (80–90% improvement per minute of minimum angle resolvable). There was no difference among these associations between visual acuity and sway reduction for the leg stimulus ($\beta_1=-89.3\pm19.4$; $r=0.57$, $P<0.001$) and the shoulder stimulus ($\beta_1=-82.0\pm 18.0$; $r=0.56$, $P<0.001$). These significant correlations were not present when subjects shut the eyes and were not present when they stood on the floor. This effect rep-

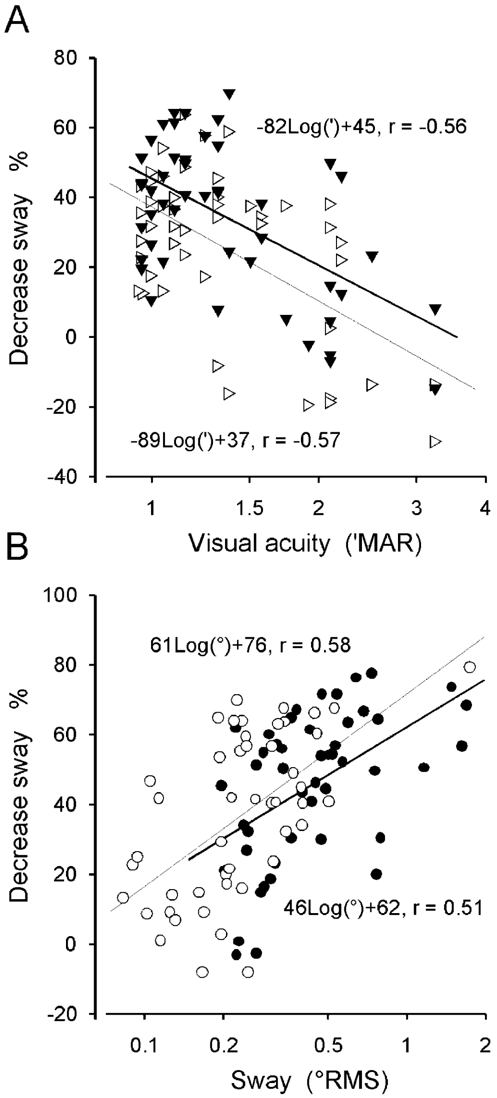


Fig. 7A, B Effects of visual acuity and sway on efficacy of the stimulus. **A** For all subjects, the percentage reduction in sway on the foam mat produced by the tactile stimulus at the leg (*open triangles*) and at the shoulder (*filled*) is plotted against visual acuity. The significant negative correlations indicate that the tactile stimulus is more effective in subjects with better visual acuity. **B** For all subjects, the percentage reduction in sway produced by the tactile stimulus at the leg is plotted against body sway when no tactile stimulus was applied. Data are shown for standing with eyes shut on the floor (*open circles*) and on the foam (*filled*). The significant positive correlations indicate that the stimulus had a greater effect in those with the greatest sway during normal standing

resents approximately 7% increase in the efficacy of the tactile stimuli for each line on a standard Snellen chart.

For each condition of vision, support surface and stimulus, there were significant correlations (r=0.14 to 0.58) between sway without a stimulus and the reduction in sway produced by the stimulus. Regressions of these data for standing on the floor and foam with the leg stimulus and the eyes shut are shown in Fig. 7B. Thus, subjects with the greatest sway while standing normally without any additional tactile stimulus had the greatest percentage reduction in sway when a tactile stimulus was applied.

Upper-body movement

For the data above, movement of the tibial tuberosity was measured, and from it sway was calculated as angular movement about the ankles. Movement of the back at the T2–4 vertebral level was also measured and expressed as angular movement about the ankles. In individual trials, these *back-sway* and *leg-sway* measures were highly correlated (mean ± SD: floor, r=0.89±0.07; foam, r=0.88±0.09), and overall the rms estimates of sway across all trials were highly correlated (r=0.92). Consistent with these correlations, analysis of the sway data recorded at the back produced the same pattern of between-trial differences as described above for the data recorded at the leg (Fig. 4).

To determine the extent to which the body swayed at the ankles as an inverted pendulum and whether the stimuli had specific effects on the upper body, the ratio of back-sway to leg-sway was compared for the different trials. On the floor, back-sway was 92±3% of leg-sway; that is, the angular excursion at the back was slightly less than at the leg. This effect was greater (83±3%; t_{23}=4.6, P<0.001) when standing on the foam. This indicates that the body does not move as a completely rigid pendulum and that upper-body movement tends to oppose some of the movement at the ankle. The height of the shoulder stimulus above the ankles was approximately 4 times that of the leg stimulus, therefore it is estimated from these data that the amplitude of the tactile stimulus at the shoulder was approximately 3–4 times that of the leg stimulus.

Discussion

When standing on the floor or on a compliant surface, either with the eyes open or shut, the application of the tactile stimulus providing sway-related cues significantly reduced body sway. This occurred across a large group of subjects, who had a wide range of sensorimotor function, and occurred without prior instruction or training. In standing humans, the correction of postural sway is often considered to depend on coordinated reflex responses from visual, vestibular and proprioceptive systems. The present study demonstrates that if passive tactile cues from other areas of the body are available they can be used to reduce sway. In fact, the improvement in stability produced by additional tactile input is of a similar magnitude to the improvement produced by vision or sensory input from the feet (Magnussen et al. 1990; Fitzpatrick et al. 1994).

The mechanisms responsible for this postural response to the tactile input are uncertain. The stimulus provided negligible direct stabilizing torque, less than 0.005 Nm or 0.02% of that required to balance the standing body, and therefore cannot account for this improved stability. To have an effect, the tactile stimulus must be related to body sway. For the control trials in young subjects, the stimulus produced no movement of the fabric relative to the skin or a random movement unrelated to body sway. In these situations there were no significant changes in the amount of body sway. It is interesting that the random movement stimulus did not increase sway. This indicates that, for it to be used, the stimulus must be correlated with sensory information about body sway from other sources.

There was a gradation of response to the size of the stimulus. There was no effect with the small stimulus weight on the shoulder that produced only very small sheer forces. As the body approximates an inverted pendulum during standing, the movement of the stimulus on the skin is greater at the shoulder than at the leg. In these experiments, the amplitude of the stimulus at the shoulder was approximately 3–4 times that at the leg. Accordingly, the stimulus at the shoulder produced a greater reduction in sway than the stimulus at the leg. The tactile stimuli were more effective when the eyes were shut and when standing on the foam, both conditions of increased sway, and therefore increased movement of the stimuli on the skin. Similarly, the tactile stimuli were most effective in those subjects with more sway during normal standing (Fig. 7B). Finally, the application of two stimuli at the knee and shoulder produced a greater reduction in sway than either stimulus alone.

The tactile stimulus used here was a homogenous piece of fabric so that if the subject moved to a different position the tactile input would be identical and at the same point on the skin. Thus, the stimulus does not improve stability by providing a fixed spatial reference that is used for orientation of the body. The stimulus acts by applying a small frictional force to the skin and therefore the direction and size of the force is related to the movement. This suggests that the additional tactile input is used to stabilize the movement of the body on its support in a manner similar to proprioceptive input from the legs rather than by providing a fixed spatial reference frame.

For normal standing, Clapp and Wing (1999) demonstrated a reduction in antero-posterior sway of approximately 50% when subjects actively touched a stable reference using very small contact forces. Jeka and Lackner (1994) considered two aspects of fingertip touch to be particularly important in providing for the postural response: the exceptionally sensitive glabrous skin of the fingertip and the process of active touch. The fingertip and sole of the foot have denser innervation and smaller receptive fields than the hairy skin of the leg and shoulder. However, it is likely that temporal resolution and not spatial resolution is crucial here, because the postural response to tactile cues is coupled to the velocity rather than the position of the stimulus (Jeka et al. 1997, 1998).

Rapidly adapting (RA) cutaneous receptors at the leg and shoulder include Pacinian and hair follicle receptors. They are very sensitive to light touch, vibration, and movement between the skin and a contact surface (Johnson and Hsiao 1992). Individually, these receptors are very sensitive and the discharge of a single Pacinian receptor results in a perception of touch (Macefield et al. 1990). The bandwidth of body sway during standing is remarkably small (less than 1.5 Hz; Fig. 6) and is much lower than the typical discharge rates of (10–300 Hz) for RA receptors (Johnson and Hsiao 1992). However, the stimulus used in the present study produced a movement of the textured fabric across the skin, and this is likely to modulate the high discharge rate of these receptors with the profile of body sway. Light fingertip touch produces either a shear force against the skin if the finger did not slip or a movement of the finger against a smooth surface if the finger slipped (Jeka and Lackner 1995). Each situation would have produced a different profile of cutaneous afferent activity. A different profile again would have been produced by the stimulus used in the present experiments. Thus, there is probably no single class of sensory receptors responsible for these postural responses.

The active nature of light fingertip touch, in which the subject controls the pressure and movement of the finger as it touches the stable surface, is also considered important to provide the postural response. Presumably, additional cues are available because the nervous system has access to its own output as the subject controls finger position and movement. In the present experiments, sway was reduced without such cues being available, and subjects were probably assisted by peripheral sensory input alone. This is in agreement with the notion that the central nervous system preferably uses sensory input from the periphery rather than the central command when making judgements about limb movement and position (McCloskey 1981). Tactile patterns can be discriminated with equal accuracy regardless of whether they are applied passively to the finger or whether the subject actively touches the pattern (Vega-Bermudez et al. 1991). This result implies that, at least for this task, the process of active control is not critical for the nervous system to interpret tactile information. However, active fingertip touch may provide additional cues.

The absence of significant associations between the reduction in sway produced by the tactile stimuli and the touch, vibration or strength measures of sensorimotor performance may not reflect the underlying physiology. Clearly, in an extreme case, a subject with a neuropathy so severe that the stimulus provided no neural input could not benefit from the tactile stimulus. It appears likely that these measures of touch and vibration sense, as applied here, are too crude and the level of the tactile stimulus is well below the sensitivity of the tests.

It is perhaps surprising that there was an association between the effect of the tactile input and vision, with a greater reduction in sway for subjects having better visual acuity (Fig. 7A). The result argues for facilitation between the visual and tactile inputs, whereas it is generally believed that there is redundancy, or occlusion, between postural sensory inputs. There were no significant differences between the visual acuities of the diabetic, non-faller and faller groups (Fig. 2; ANOVA with SNK post hoc test), but, within each of these groups, subjects with better acuity tended to reduce sway more when the tactile stimulus was available. Figure 2 indicates that subjects tend to be worse in multiple measures of sensorimotor performance, and regression showed that subjects with poor acuity tended to poor sensation, reaction time and strength. In subjects with diminished sensory acuity in the legs standing on foam so that proprioceptive input from the legs does not accurately reflect body sway, the reliable and correlated inputs are vision and the tactile cue. In this situation, these inputs may be facilitatory, and subjects with good visual acuity could show a greater response to the tactile cue. Alternatively, this interaction between the visual and tactile inputs could arise if the tactile stimulus reduced the sway of the body and head and this improved gaze stabilization, thereby augmenting the effect of vision on postural stability in those with good visual acuity.

Subjects who sway the most during normal standing improve the most when an additional tactile input is available (Fig. 7B). An explanation for this phenomenon is that subjects who sway more receive an enhanced tactile signal because of the greater velocity of the friction stimulus on the skin. There is general agreement that, for a process like standing in which there is ongoing adaptive control, a certain amount of sway is necessary, and it would probably be thought that the sway of young healthy subjects would represent near-optimal performance. It is therefore interesting that the tactile stimuli also reduced sway in the young subjects in this study with an effect about as strong as visual stabilization of posture. This suggests that the minimal amount of sway necessary by the controlling processes is itself a function of the availability of acuity of sensory input. A second possible explanation for the greater reduction in sway by subjects that sway the most is that these subjects have a sensorimotor deficit so that the additional tactile stimuli are not as redundant. Although the individual sensorimotor tests of touch, vibration or muscle strength do not correlate with the reduction in sway produced by the tactile stimuli, there could be an association with the overall sensorimotor function. Sway when standing without the tactile stimulus could be a surrogate for this overall measure, thus producing a significant correlation.

Increased postural sway associated with balance disturbances is a common clinical finding in people with specific neurological impairments and for elderly people who often have a more generalized decline in several physiological systems. Sway during standing is a strong, independent predictor of a subject's risk of falling (Brocklehurst et al. 1982; Lord et al. 1994). Thus, subjects at risk of falling are likely to benefit from any system that can provide additional tactile input that is related to body movement. In addition to quasi-static standing situations, there might also be a potential for tactile cues to modify postural reactions in other equilibrium activities such as the step response and walking.

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References

Brocklehurst JC, Robertson D, James-Groom P (1982) Clinical correlates of sway in old age – sensory modalities. Age Aging 11:1–10

Clapp S, Wing AM (1999) Light touch contribution to balance in normal bipedal stance. Exp Brain Res 125:521–524

Fitzpatrick RC, Rogers DK, McCloskey DI (1994) Stable human standing with lower-limb muscle afferents providing the only sensory input. J Physiol (Lond) 480:395–403

Jeka JJ (1997) Light touch contact as a balance aid. Phys Ther 77:476–487

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

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

Jeka JJ, Easton RD, Bentzen BL, Lackner JR (1996) Haptic cues for orientation and postural control in sighted and blind individuals. Percept Psychophys 58:409–423

Jeka JJ, Schoner G, Dijkstra T, Ribeiro P, Lackner JR (1997) Coupling of fingertip somatosensory information to head and body sway. Exp Brain Res 113:475–483

Jeka J, Oie K, Schoner G, Dijkstra T, Henson E (1998) Position and velocity coupling of postural sway to somatosensory drive. J Neurophysiol 79:1661–1674

Johnson KO, Hsiao SS (1992) Neural mechanisms of tactile form and texture perception. Annu Rev Neurosci 15:227–250

Kenshalo DR (1986) Somesthetic sensitivity in young and elderly humans. J Gerontol 41:632–642

Lackner JR, Dizio PA (1992) Sensory-motor calibration processes constraining the perception of force and motion during locomotion. Gait Posture 1:93–104

Lord SR, Ward JA (1994) Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing 23:452–460

Lord SR, Caplan GA, Colagiuri R, Colagiuri S, Ward JA (1993) Sensori-motor function in older persons with diabetes. Diabetic Med 10:614–618

Lord SR, Ward JA, Williams P, Anstey KJ (1994) Physiological factors associated with falls in older community-dwelling women. J Am Geriatr Soc 42:1110–1117

Macefield G, Gandevia SC, Burke D (1990) Perceptual responses to microstimulation of single afferents innervating joints, muscles and skin of the human hand. J Physiol (Lond) 429:113–129

Magnusson M, Enbom H, Johansson R, Pyykko I (1990) Significance of pressor input from the human feet in anterior-posterior postural control. The effect of hypothermia on vibration-induced body-sway. Acta Otolaryngol 110:182–188

McCloskey DI (1981) Corollary discharges: motor commands and perception. In: Brooks VB (ed) Motor control. (Handbook of physiology, sect 1, The nervous system, vol II, part II) Am Physiol Soc, Bethesda, MD, pp 1415–1448

Semmes J, Weinstein S, Ghent L, Teuber H (1960) Somatosensory changes after penetrating brain wounds in man. Harvard University Press, Cambridge, MA

Simoneau GG, Ulbrecht JS, Derr JA, Becker MB, Cavanagh PR (1994) Postural instability in patients with diabetic sensory neuropathy. Diabetes Care 17:1411–1421

SPSS (1993) Base system user's guide. SPSS, Chicago

Uccioli L, Giacomini PG, Pasqualetti P, Di Girolamo S, Ferrigno P, Monticone G (1997) Contribution of central neuropathy to postural instability in IDDM patients with peripheral neuropathy. Diabetes Care 20:929–934

Vega-Bermudez F, Johnson KO, Hsiao SS (1991) Human tactile pattern recognition: active versus passive touch, velocity effects, and patterns of confusion. J Neurophysiol 65:531–546