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RESEARCH ARTICLES

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Postural stabilization from fingertip contact: I. Variations in sway attenuation, perceived stability and contact forces with aging

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Abstract In this study, we compared the ability of young (*n*=10, 19–32 years) and older subjects (*n*=35, 60–86 years) to use fingertip contact as a balance aid during quiet stance under various conditions to determine whether aging would influence contact strategies. Experimental trials (duration, 60 s) included two visual conditions (vision; no vision), three fingertip contact conditions (no touch; smooth touch; rough touch) and two support surface conditions (firm; foam). In trials with contact, participants were required to maintain a light contact with their right index fingertip on an instrumented touch-plate. Subjects were not constrained to exert minimal contact force, although they were aware that the touch-plate was not designed for physical support. From displacements of the centre of foot pressure (COP), mean sway amplitude (MSA) was computed in the anterior-posterior (COP_{AP}) and medio-lateral (COP_{ML}) directions. Subjective estimates of stability were also obtained by asking participants to rate perceived stability on a visual analog scale in each condition. Mean normal force (F_N) and mean resultant tangential force (F_{TAN}) were computed from contact force data applied on the touch plate. In both age groups, touch conditions had a substantial effect on MSA in the AP direction under both support surface conditions, with reductions averaging between 40–55% when touch was allowed. Reductions in the ML direction, though less important (8–12% on average), were nevertheless highly significant, especially in the older subjects when standing on the foam. In the two groups, vision and texture had only marginal impact on MSA computed on both support surfaces. Contrasting with sway measurements, stability ratings were highly influenced by visual conditions in both age groups. Only in conditions of deficient support (foam surface) and absent vision did the perceived effect of touch exceed that of vision. Age had a major impact, however, on contact forces deployed during trials with touch. While individuals in the young group typically produced forces of <1 N (mean F_N, 0.32±0.15 N) to achieve postural stabilization, older subjects tended to use higher, though not too excessive, contact forces (mean F_N, 1.21±0.75 N) under the same conditions. From these findings, we conclude that the ability to use contact cues from the fingertip as a source of sensory information to improve postural stability is largely preserved in healthy older adults. The increase in contact force deployed by older individuals to achieve postural stabilization is interpreted as a compensatory strategy to help overcome age-related loss in tactile sensation, an issue that will be further addressed in a companion paper.

Keywords Light touch · Balance · Contact force · Aging

Introduction

All the major sensory systems involved in balance and mobility functions (i.e., visual, vestibular and somatosensory) undergo various degrees of decline as people advance in age, making older persons less able to cope with environmental demands and more prone to falls (Woollacott et al. 1986). Compensation strategies can sometimes help to overcome declining sensory abilities in older people, for example in the case of visual impairments (e.g. use of corrective lens). In other situations, however, such as with deficits affecting limb sensations, compensations are hardly, if ever, possible. Yet, recent studies indicate that impaired limb sensations, linked to large-fiber peripheral nerve dysfunction, are quite common in otherwise healthy people aged 65+ years and become more frequent with advancing age (Resnick et al.

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2001). Age-related impairments in foot and ankle sensitivity, in particular, have been shown to contribute to poor balance abilities and reduced mobility functions in elderly persons (Bergin et al. 1995; Gilsing et al. 1995; Resnick et al. 2000). In comparison, the impacts of age-associated changes in the sensory function of the hands, which can be dramatic and substantial in older persons (Stevens and Choo 1996; Tremblay et al. 2000), have received little attention as far as balance is concerned. Yet, the hands and the upper extremity in general are known to be important for balance control and not only in producing grasping reactions in response to sudden perturbations (Maki and McIlroy 1997) but also in a far more subtle and important way. Indeed, over the last decade, conceptions about the role of the hand and fingertips in balance control have changed dramatically as a result of the seminal works of Jeka, Lackner and their collaborators (see Jeka 1997; Lackner and DiZio 2000 for reviews) on the contribution of light touch contact to postural stabilization.

In pioneering experiments, these investigators were among the first to demonstrate that sensory cues arising from contact of the fingertip with a stable surface provided sufficient information about body motion to allow reduction in sway when people stood in the very unstable tandem-Romberg stance position (Holden et al. 1994; Jeka and Lackner 1994). Subsequent experiments by the same group showed that the stabilizing effect of light touch was not influenced by the properties of the touched surface in terms of slipperiness or roughness (Jeka and Lackner 1995) and was most effective when contact was maintained in the plane of greater instability [i.e. lateral touch with medio-lateral instability and anterior touch for anterior-posterior instability (Rabin et al. 1999)]. Consistent with this later finding, light fingertip contact in the sagittal plane decreased anterior-posterior sway in subjects standing in the normal bipedal stance position (Clapp and Wing 1999). Light fingertip contact was also shown to be effective in improving postural stability in patients with vestibular loss (Lackner et al. 1999) and, more recently, in patients with lower extremity sensory deficits secondary to diabetic polyneuropathy (Dickstein et al. 2001).

One caveat of the above studies on the contribution of light touch to balance is that most observations have been derived from young populations. When present, elderly subjects were limited in numbers and often mixed with young subjects to serve as controls for subjects with pathological conditions. Accordingly, there is still limited information as to what extent older persons can benefit from light touch contact as a balance aid. The question becomes more than trivial when one considers the substantial decline in hand sensibility that occurs with normal aging (Stevens 1992; Desrosiers et al. 1996; Tremblay et al. 2000). So far, studies have not specifically addressed how impaired tactile sensations could affect the ability of older persons to use sensory information at the fingertip for balance control. Another caveat is that in most studies, the range of contact forces exerted by subjects was constrained by the experimenter through the use of force-limiting feedback devices or by using materials that inherently limited the production of forces (e.g., filaments: Lackner et al. 2001). While this approach was deemed necessary to determine the nature of the stabilizing effects of experimentally regulated forces (i.e. either sensory-driven or mechanical support), it may also have hampered important information about how individuals adapt their contact strategy in response to more challenging balance conditions or when their ability to process sensory information is compromised. The question as to whether fingertip forces should be constrained or not has become even more relevant in the light of the work by Riley et al. (1999). These authors challenged the common interpretation that fingertip touch improves postural stability through sensorimotor integration. They presented evidence that in conditions wherein forces at the point of contact must be kept in a low range, sway attenuation might actually reflect attempts to minimize contact forces at the fingertip. The suggestion was that postural stabilization thus subserves the control of touch.

In the present study, we have addressed some of these issues by comparing the ability of young and older subjects to use fingertip contact for postural stabilization during quiet stance under different sensory and support surface conditions. The primary goal was to determine whether aging would influence contact strategies for postural stabilization when no attempt is made to minimize contact forces exerted at the fingertip. A secondary goal was to determine to what extent age-related impairments in sensory acuity at the fingertip could contribute to contact strategies in the context of haptic stabilization of posture. In this report, we describe how postural sway, perceived stability and contact forces varied as a function of age. In a companion paper, we will describe the relationships established between sensory thresholds measured at the fingertip and contact forces generated for postural stabilization. Preliminary accounts of this work have been published elsewhere (Mireault et al. 2002).

Materials and methods

The Institutional Review Ethics Board approved the study procedure and informed consent was obtained before the experimental session. All assessments were performed in a controlled laboratory environment. Each participant received an honorarium for his or her participation.

Subjects

Two groups of subjects were recruited for this study. The young group consisted of 25 adults (12 females, 13 males, mean age 23 ±3 years) recruited among undergraduate and graduate students at the Health Sciences Campus, University of Ottawa. The old group consisted of 36 community-dwelling elderly persons between the ages of 60 and 86 years (26 females, 9 males, mean age 70±8 years). These were recruited mainly from seniors' social activity clubs in the Ottawa-Gatineau area. To be eligible for the study, subjects had to be free of conditions susceptible to affect their performance in the tests. Each potential participant was therefore screened prior to inclusion with a health questionnaire to rule out the presence of recent joint injuries (e.g., ankle or knee sprains, hip or knee joint replacement) or a diagnosis of chronic diseases (e.g., multiple sclerosis, stroke, Parkinson's disease, rheumatoid arthritis, type 2 diabetes). Older subjects were also specifically asked if they had experienced episodes of dizziness or if they had fallen in the last 6 months. Subjects who reported symptoms or falls were further scrutinized and dismissed if suspected to be fallers (i.e., one fall or loss of balance without any obvious cause in the last 6 months) or if they admitted having balance problems. Finally, subjects were also asked to report in the questionnaire the presence of any hand or feet sensory symptoms. Apart from one older subject (Female #28, 74 years), who was dismissed after her sensory examination revealed a profound reduction in tactile acuity and who was subsequently reported to have experienced recurrent episodes of carpal tunnel syndrome in recent years, all older subjects were considered to be in good health.

Measurements of center of foot pressure and contact forces at the fingertip

Ground reaction forces were recorded using dual AMTI force platforms (Advanced Medical Technology Instruments, OR6–5) and subsequently processed to obtain center of pressure (COP) coordinates in the medio-lateral (ML: COP_{ML}) and anterior-posterior (AP: COP_{AP}) directions (Fig. 1). To measure forces in trials with fingertip contact, a touch-plate apparatus was built. It consisted of an aluminum (6061T6) metal plate (12 cm^2) instrumented with three binocular spring elements. Each element consisted of four temperature-compensated strain gauges (Micro-Measurements Division, CEA-13–125UW-350) that transduced horizontal (mediolateral, F_x; antero-posterior, F_y) and vertical (F_z) components of the contact force. The strain gauge signal was amplified and calibrated in Newtons (N) using a differential amplifier (Burr Brown, INA101 M, sensitivity range 0.01–5 N). The plate was supported by sidewalls forming a square box, which was attached to a metal rod adjustable in height (1 m).

Since texture is an important aspect of tactile perception at the fingertips (Lederman 1982) and can influence contact forces deployed during object manipulations (Cadoret and Smith 1996), two contact conditions (rough and smooth touch) were incorporated into the design to test for the effect of surface texture. The two textured surfaces consisted of rectangular gratings (20×100×2 mm) with alternating ridges and grooves. The surfaces were made of flexible polymer and produced via a photo-etching process commonly used in letterpress printing (see Tremblay et al. 2002 for details). The two gratings were specified by their spatial period (ridge-to-ridge distance) since this factor has been shown to directly influence perceived roughness (Lederman 1974; Sathian et al. 1989). Thus, one surface (fine grating) was perceived as smooth with a spatial period of 0.70 mm (ridge width, 0.2 mm; groove width, 0.5 mm), whereas the other (coarse grating) was perceived as rough with a spatial period of 2.7 mm (ridge width, 0.2 mm; groove width, 2.5 mm). The two gratings were laid in parallel onto the touch-plate using double-side adhesive tape so that ridges were perpendicular to the long axis of the index finger. The experimental set-up is depicted in Fig. 1. The weight of the surfaces was subtracted from the touch-plate output prior to data acquisition.

Experimental protocol

Experimental trials included two visual (vision, V, no vision, NV), three touch (no touch: NT, smooth touch: ST, rough touch: RT) and two support surface (firm and foam) conditions. Trials were administered in two separate blocks: one for each support surface condition. In each block, two trials under each visual and touch condition (2×(2 V×3T)) was performed for a total of 12 trials per block. The order of trials within a block followed a predetermined random sequence and the order of testing in the two blocks alternated between subjects. Each trial lasted 1 min (60 s) since this duration has been shown to improve reliability of COP measurements (Carpenter et al. 2001).

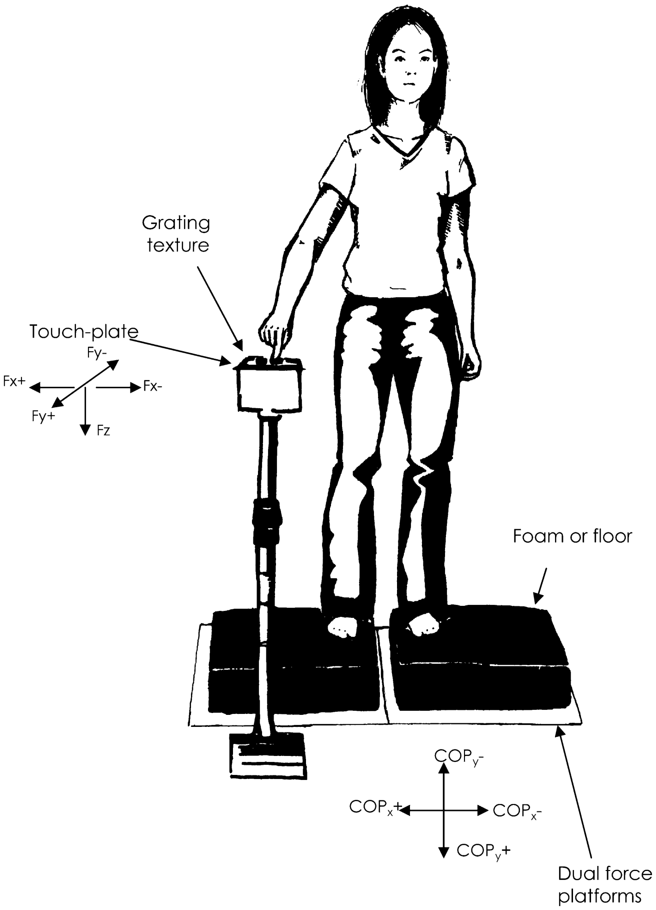

Fig. 1 Diagram of the experimental arrangement used to record postural sway and contact forces. For all trials, dual force platforms were used to record displacement of the center of foot pressure (*COP*) in the medio-lateral ($COP_{x/ml}$) and antero-posterior ($COP_{y/AP}$) directions. Although only the foam surface condition is shown here, trials were also performed while subjects stood directly on the force platforms (firm surface condition). For trials with touch, subjects were required to maintain contact with a touch-plate that measured horizontal (F_x and F_Y) and vertical (F_z) contact forces. Two grating surfaces (rough and smooth, 20×100×2 mm) were affixed on the touch-plate to test for the effect of texture

For trials on the firm surface, subjects stood barefoot directly on the force platforms assuming their normal standing position, head facing forward, feet comfortably apart and weight evenly distributed. The foot positions were recorded and maintained constant between surface conditions or between trials if a subject needed to get off the plate if they were tired and then got back on. For trials with vision, subjects were asked to look at a target placed on a wall at eye height approximately 2 m in front of the platforms. For trials with no-vision, they were asked to close their eyes for the whole duration of the trial. For trials without contact (NT conditions), subjects were asked to keep their arms relaxed and at their sides. For trials with fingertip contact (ST and RT conditions), subjects were instructed to bring the right arm at ~45° in front so that the tip of the index could maintain contact with either one of the designated texture surfaces (smooth or rough) on the touch-plate (see Fig. 1). The latter was placed slightly lateral and anterior to the participant's right side. The height was adjusted prior to testing for each individual so that contact could be maintained easily without leaning or bending the trunk, while keeping the arm relatively straight. Before testing, subjects were reminded that the index finger had to remain still and to not attempt to slide it over the surface during the trial. They were also told that the touch-plate was not designed to support heavy forces and therefore could not be used as a cane or other walking aid. Apart from these general guidelines, subjects received no further instructions as to the amount of force to be exerted and no attempt was made to regulate contact forces during the trials. For trials on the foam surface (Fig. 1), subjects stood on medium density temper foams (7.5 cm width) and testing proceeded in the different conditions as described above. The touch plate height was raised appropriately to maintain the touch surface at the same height relative to the body (arm extended the same amount). In all conditions, a second experimenter was always present behind the participant to ensure their security in case of sudden loss of balance. This measure was especially important to secure elderly subjects.

Subjective estimation of perceived stability

In addition to quantitative measurements of sway, we derived a subjective index of stability. Upon completion of a trial, subjects were asked to rate how stable they felt under the condition just tested using a visual analog scale (VAS). The VAS consisted of a 10 cm vertical line with two descriptors at each end (i.e., from “Very Stable-Firm” at the bottom to “Very Unstable-Precarious at the top). Prior to testing, subjects were informed how to use the VAS. It was emphasized that the ratings should reflect their own relative estimations of the stability conditions tested and not judgments about some absolute condition of stability. None of the participants expressed difficulties in using the VAS.

COP and contact force data reduction

The three dimensional forces measured under each foot and at the right index fingertip were recorded at a sampling rate of 20 Hz on a PC using the Ariel Performance Analysis System (APAS, Ariel Dynamics Inc.). To quantify COP displacements in both the AP and ML directions, we computed the mean sway amplitude (MSA), as used previously by Lackner and collaborators (Lackner et al. 2000, 2001). The MSA was derived in each direction as follows:

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

where N = number of samples, x = COP time series, $\bar{x}$ = mean COP displacement. Vertical contact forces (F_z) exerted on the touch-plate were averaged on each trial to derive a mean normal force (F_N). Horizontal forces were combined and averaged to derive a mean resultant tangential force $\left(F_{\tan} = \sqrt{Fy^2 + Fx^2}\right)$. Each COP and contact force measurement represented an average of the two trials performed under the same condition.

As in previous studies (Clapp and Wing 1999; Dickstein et al. 2001; Lackner et al. 2001), we also examined the temporal relationships between the displacement of the COP and the magnitude of contact forces recorded on the touch-plate. For this analysis, cross-correlations were performed for the COP$_{AP}$-F_N and COP$_{AP}$-F_Y couples using a time window of 2,000 ms with 50 ms between each step to derive maximal r values and corresponding time lags.

Statistical analysis

Trials performed on the firm and foam surfaces were analyzed as separate blocks. Repeated measures analyses of variance (ANOVA) were performed on each block of trials to determine the effect of visual (NV, V) and touch (NT, ST, RT) conditions (within-subject factors) on MSA measured in each direction (AP and ML). Gender (male, female) and age group (Y: Young; O: Old) were used as between-subject factors. Similar analyses were also performed on contact force measurements derived from the touch-plate to determine the effect of visual and texture conditions (2 × 2 ANOVA) and of gender and age group as well. Finally, VAS scores were also submitted to an ANOVA to determine the effect of the within- (vision, contact) and between-subject (gender, age group) factors on perceived stability. Since multiple comparisons increase the likelihood of Type 1 errors, only p values <0.01 (Bonferrroni’s correction) were considered significant. All statistical tests were performed using SPSS v. 11.0.1 for Windows.

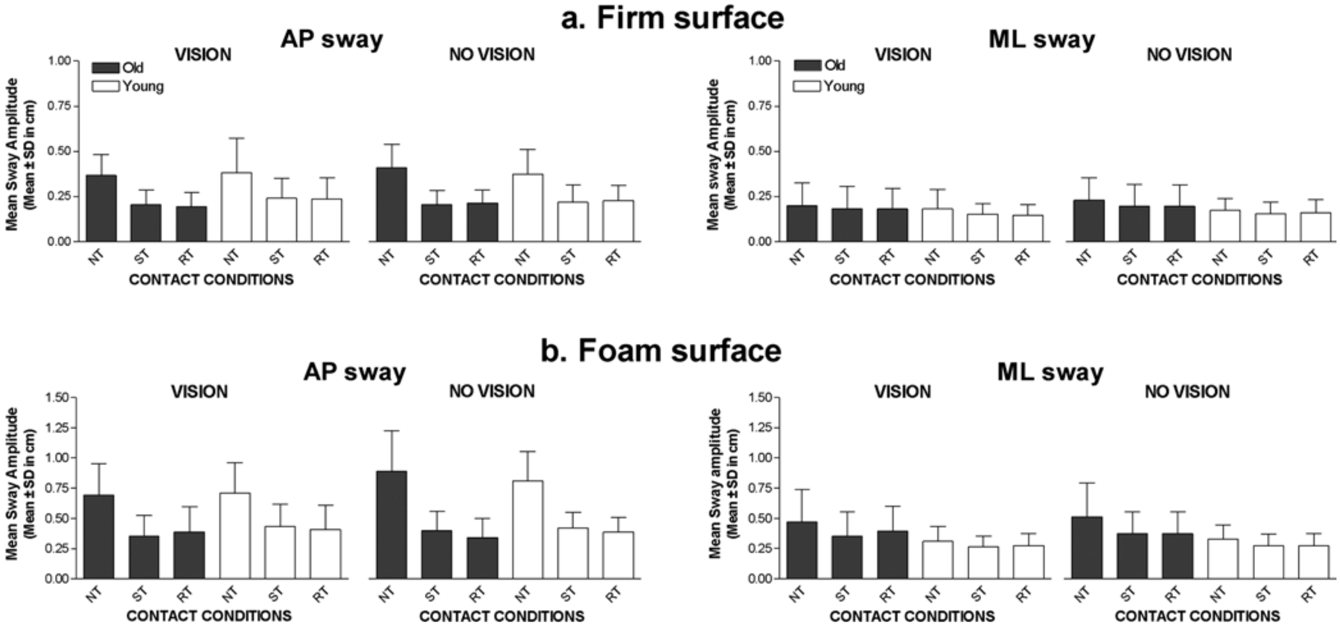

Fig. 2a, b Mean sway amplitude (MSA) computed in each direction in the two groups under each support surface condition. *Each column* is an average computed across all participants (old group, n=35, young group, n=25) in each condition. NT, ST and RT refer to no-touch, smooth touch and rough touch contact conditions, respectively. Note the large influence of touch conditions on MSA in the AP direction in the two groups

Results

MSA-COP displacements

All but three subjects (one man, two women) completed the testing without stepping or losing balance across the 24 trials. Two of these were in the old group (one man, one woman) and in all three instances the loss of balance occurred when standing on the foam with no vision and no touch. In these instances, the trial was aborted and repeated after a period of rest.

Figure 2 compares the MSA in each direction computed for the two groups under the different conditions while standing on the firm (a) or foam (b) support surface. In general, older and young subjects exhibited very similar responses with respect to the effect of touch and vision conditions. In both groups, vision had only marginal impact on MSA measured across all conditions on both support surfaces (see below). This contrasted with the marked reductions in MSA in the AP direction (~40–55%) seen when fingertip contact was allowed. The corresponding changes in the ML direction were comparatively smaller (~10–25%), but still evident, especially in the old group for trials on the foam. It is also evident from inspection of Fig. 2 that the texture of the touched surface had no influence on the magnitude of sway reduction.

For trials on the firm surface, the ANOVA confirmed the large effect of touch conditions on MSA reductions measured in the AP ($F_{(2,55)}$=84.9, p<0.001) and ML ($F_{(2,55)}$=5.4, p=0.007) directions, along with the absence of effect of vision (AP and ML directions, $F_{(1,56)}$<2, p>0.1). The factor “age group” was not significant in either direction ($F_{(1,56)}$<2, p>0.1) but gender came out as marginally significant in the AP direction ($F_{(1,56)}$=6.5, p=0.013). The latter gender effect was attributed to male subjects who, irrespective of age, tended to exhibit greater AP sway than females. Comparisons of MSA computed on the foam surface led to similar conclusions regarding the main effect of touch in the two directions (AP, $F_{(2,55)}$=131.1, p<0.001; ML, $F_{(2,55)}$=13.0, p<0.001) and the minimal impact of vision (AP, $F_{(1,56)}$=5.1, p=0.03; ML, $F_{(2,55)}$<1, p>0.1). A significant difference emerged between the two age groups for MSA computed in the ML direction ($F_{(1,56)}$=10.6, p=0.002), reflecting the increased sway amplitude exhibited by older subjects in this direction and the corresponding larger reductions seen in trials with touch as compared to the young group (mean reduction, 26% vs. 14%, respectively). The marginally significant gender effect attributed to male subjects for trials on the firm surface (AP direction) became significant for trials on the foam ($F_{(1,56)}$=10.5, p=0.002). Finally, tests for the contrasting effect of texture confirmed that touching the rough or the smooth grating had no influence on MSA computed in both directions on both support surface conditions ($F_{(1,56)}$<2.5, p>0.1).

Summarizing, in the two groups, fingertip contact was particularly effective in reducing sway in the AP direction on both support surfaces. Older subjects further benefited from light fingertip contact with reduction of sway in the ML direction, especially when standing on the unstable foam surface. In both age groups, the contact texture did not influence the level of stabilization in terms of sway reductions.

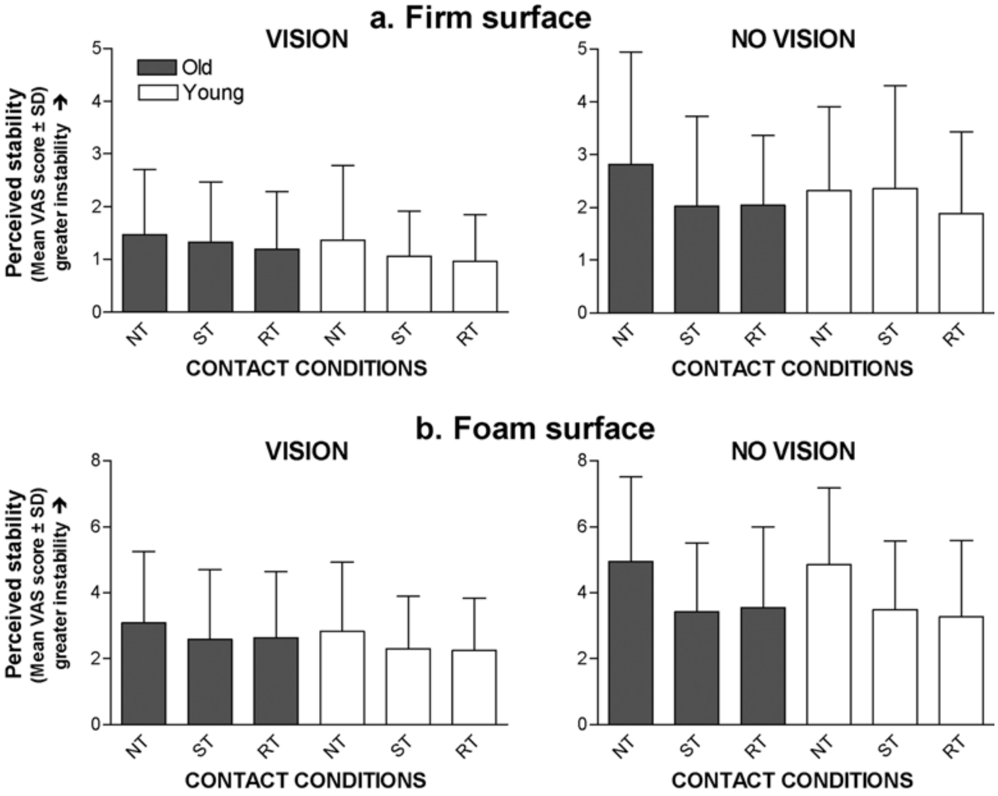

Fig. 3a, b Mean subjective stability ratings in the two groups derived from visual analog scale scores under each support surface condition. Figure legend and abbreviations are similar to those in Fig. 2. Note the large influence of vision conditions on stability ratings

Perceived stability

The mean stability ratings derived in the two groups on each support surface condition are illustrated in Fig. 3. In general, perceived stability ratings were comparable in the two groups and matched relatively well with the corresponding sway amplitudes measured in the AP direction illustrated in Fig. 2. However, unlike MSA measurements, vision exerted a major influence on stability ratings on both the firm ($F_{(1,56)}$=40.4, p<0.001) and foam surfaces ($F_{(1,56)}$=48.4, p<0.001). The main effect of touch, while significant for ratings obtained on the firm surface ($F_{(1,56)}$=7.5, p<0.001), exceeded that of vision only for ratings performed on the foam ($\mathrm{F}_{(1,56)}$=53.3, p<0.001). Not surprisingly, a highly significant vision*-touch interaction ($F_{(2,55)}$=22.5, p<0.001) was detected under these conditions, owing to the increased influence of touch when vision was absent for trials on the foam surface (Fig. 3b). As for MSA measurements, stability ratings were not influenced by the factor "texture" under both support surface conditions ($F_{(1,56)}$<1, p>0.1).

Modulation of contact forces at the fingertip with respect to vision, texture and support surface conditions

Although levels of sway attenuation from fingertip contact were generally comparable in the two groups, examination of force patterns generated on the touch-plate indicated that older subjects tended to use higher contact forces than their young counterparts. This difference is evident on inspecting the time series illustrated in Fig. 4. In the young subject (Fig. 4a), it can be seen that, when standing with eyes closed on the firm surface, COP fluctuations in the AP direction were greatly reduced with fingertip contact of the smooth grating (ST condition). This reduction in AP sway was accompanied by a sustained low modulation of the normal contact force (F_N) exerted on the touch-plate, which was maintained <0.5 N throughout the trial. In the older subject (Fig. 4b), fingertip contact also led to a substantial reduction in AP sway which approached the level of stabilization seen in the young subject. To achieve this level, however, the older subject typically produced much wider modulations in the contact force with large peaks and troughs, although the forces exerted rarely exceeded 1 N. To further illustrate this difference, the distribution of individual mean contact forces computed in the normal direction in each group has been plotted in Fig. 4c.

The mean contact forces, normal and tangential, obtained from all conditions are illustrated in Fig. 5a, b. Here, the two- to threefold greater magnitude of forces exerted by older, as compared to, young subjects can be appreciated. Accordingly, age group accounted for most of the variance in contact forces measured on both the firm (F_N, $F_{(1,56)}$=33.5; p<0.001; F_{TAN}, $F_{(1,56)}$=15.1, p<0.001) and foam (F_N, $F_{(1,56)}$=37.1, p<0.001; F_{TAN}, $F_{(1,56)}$=10.6, p<0.01) support surfaces. All other factors, including vision and texture, had no significant effects.

Relationships between contact forces and MSA

The observation that older subjects tended to deploy higher contact forces when touching pointed to a possible link between actual force magnitudes and the previously described reductions in MSA. To examine this question, individual percent reductions in MSA in the AP direction from trials performed on the firm (A) and foam (D) surfaces with smooth touch (ST condition) have been plotted in Fig. 6 against the corresponding contact forces measured on the touch-plate. As evident in the figure, reductions in sway were largely independent of the magnitude of the normal forces exerted on the touch-plate. In fact, the majority of older subjects achieved substantial reductions in AP sway while keeping normal forces at the fingertip <2.0 N (Fig. 6a, d).

Figure 6 also illustrates the averaged r values (b and c) and the corresponding time lags (e and f) derived from the cross-correlation analyses between $\mathrm{COP_{AP}}$ displacements and contact forces (F_N and F_Y) for trials with contact of the smooth texture. As reflected in the low r values (b) and the large variability in time lags (e), temporal variations in the normal contact force (F_N) were only poorly related to $\mathrm{COP_{AP}}$ fluctuations. In fact, approximately one-quarter of the subjects in each group (young, n=7; old, n=8) failed to show peaks in the $\mathrm{COP_{AP}}$-F_N cross-correlograms in the 2,000 ms time window and, therefore, had to be excluded. In contrast, temporal relationships between variations in the tangential force in the AP direction (F_Y) and $\mathrm{COP_{AP}}$-displacements were far more consistent across individuals. As shown in Fig. 6c, the two groups exhibited similar positive correlations between $\mathrm{COP_{AP}}$displacement and variations in F_y, although r values tended to be slightly higher in the old group. The time lags at which these correlations occurred also followed a similar pattern in the two groups with slight shortening in the no-vision condition and a more marked lengthening for trials on the foam. In the young group, changes in F_y preceded $\mathrm{COP_{AP}}$ displacement by ~300 ms when standing on the firm surface. The corresponding time lags increased to ~450 ms for trials on the foam surface. In the old group, the transition between the two support surfaces was less abrupt and the overall mean time lag remained, on average, between 200 and 300 ms across all conditions. The observed difference between the two groups for time lags computed on the foam was highly significant ($F_{(1,45)}$=28.6, p<0.001).

Discussion

In the present study, we compared the ability of young and older subjects to use fingertip contact as a balance aid during quiet stance under various conditions to determine whether aging would influence contact strategies. The

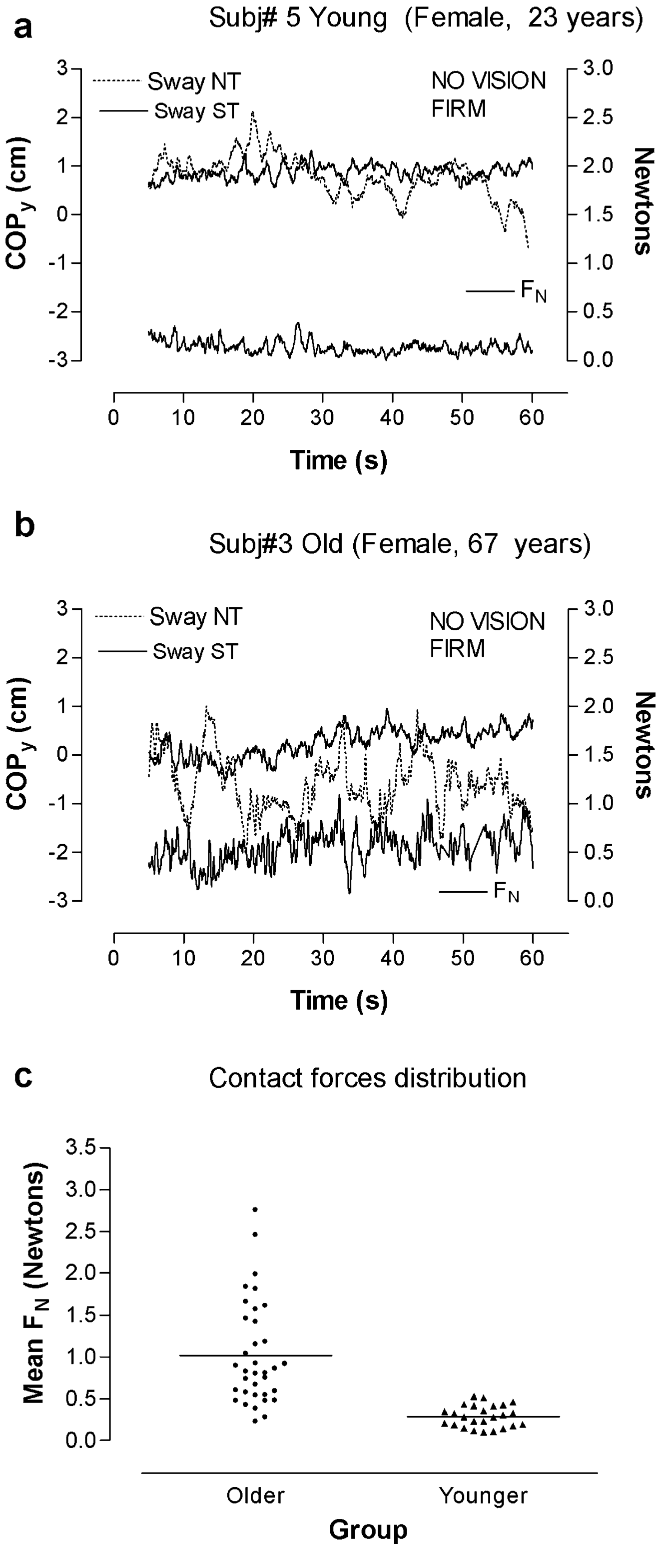

Fig. 4a–c Example of sway attenuation observed during trials on the firm surface with no-vision and smooth touch contact (NV, ST condition) in a representative subject of the young **(a)** and old **(b)** group. Note the reduction in COP$_{ap}$ displacement when touch, as opposed to no-touch, was allowed (ST Sway vs. NT sway) and the greater modulation of the contact force (F_N) required by the older subject to achieve stabilization. The difference in terms of contact strategies between the two groups is further illustrated in **c**, showing the distribution of individual normal force values (*horizontal bars, mean values*) for the condition illustrated above (NV, ST condition)

main result was that, while older subjects generally achieved a similar level of stabilization as their young counterparts, they did so by exerting higher, though not excessive, contact forces on the touch-plate. We will discuss the contribution of light touch to postural stabilization with respect to the differences seen in the two groups under the different testing conditions. We will then focus on the issues pertaining to differences in contact strategy between young and older subjects.

Influence of aging on postural stabilization from fingertip contact

Consistent with the notion that normal aging has only a minimal effect on spontaneous sway measured during quiet stance (Fernie et al. 1982; Maki et al. 1990; Wolfson et al. 1995), our group of elderly showed very similar postural adaptations to changes in sensory conditions as those seen in the young group for trials on the firm surface. Such an observation brings support to our contention that our selected group of elderly was indeed free of pathological conditions. When subjects were allowed contact with the touch-plate, MSA in the AP direction was reduced by ~40% in both groups. This reduction is in the same order of magnitude as the one reported by Clapp and Wing (1999) in a sample of young adults under similar conditions (i.e., firm surface, eyes closed, eyes open). Also consistent with Clapp and Wing's (1999) findings, sway reductions in the ML direction (~10%) were considerably smaller than those measured in the AP direction, although still highly significant in our groups of subjects. Such differential effects were expected given that the stabilizing effects of light touch were exerted mainly in the plane of greater instability (i.e., in the sagittal plane when standing in the normal bipedal stance (Rabin et al. 1999). During trials on the unstable foam surface without fingertip contact, older subjects showed evidence of greater lateral instability, as indexed in the increased sway amplitude in the ML direction. In recent years, a number of studies have pointed to lateral instability as a marker of impaired balance control in older persons (Maki and McIlroy 1996, 1997). In a recent study, Dickstein et al. (2001), using a similar paradigm as in the present experiment, also found evidence of increased lateral instability in older patients with severe diabetic neuropathy while standing on a foam or a firm surface in the normal stance posture. Thus, the increased ML sway exhibited by our older subjects when standing on the foam appears to be a typical manifestation of the aging postural system. Interestingly, the increased sway manifested by older subjects in the no-contact condition was largely cancelled out by allowing contact with the touch-plate. The contribution of fingertip contact in this regard was substantial, largely surpassing the effect of vision, and allowing older subjects to reach comparable levels of

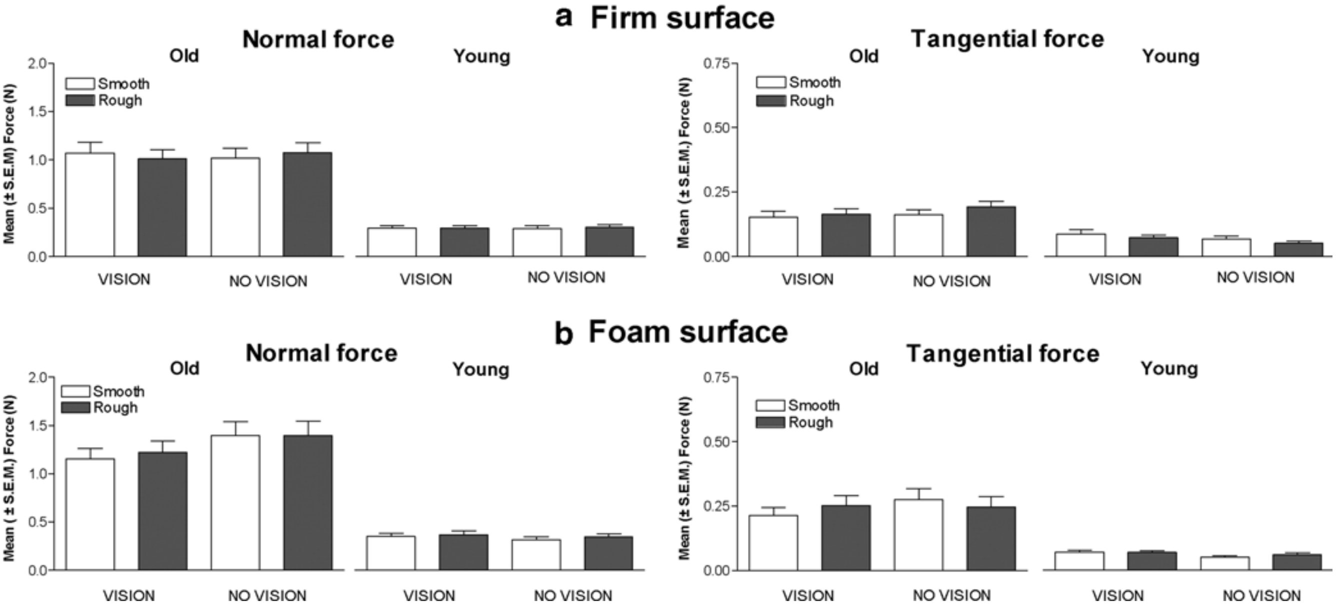

Fig. 5a, b Mean contact forces computed in the two groups while touching the smooth (*open columns*) or rough (*dark columns*) grating textures in each support surface condition. Mean normal force values were derived by averaging the vertical component (F_z) of the force exerted by the fingertip, while values for the tangential force represent a mean of the resultant horizontal force components $\left(F_{\tan} = \sqrt{Fy^2 + Fx^2}\right)$. Note the large difference in the magnitude of contact forces between the two groups, irrespective of vision and texture conditions

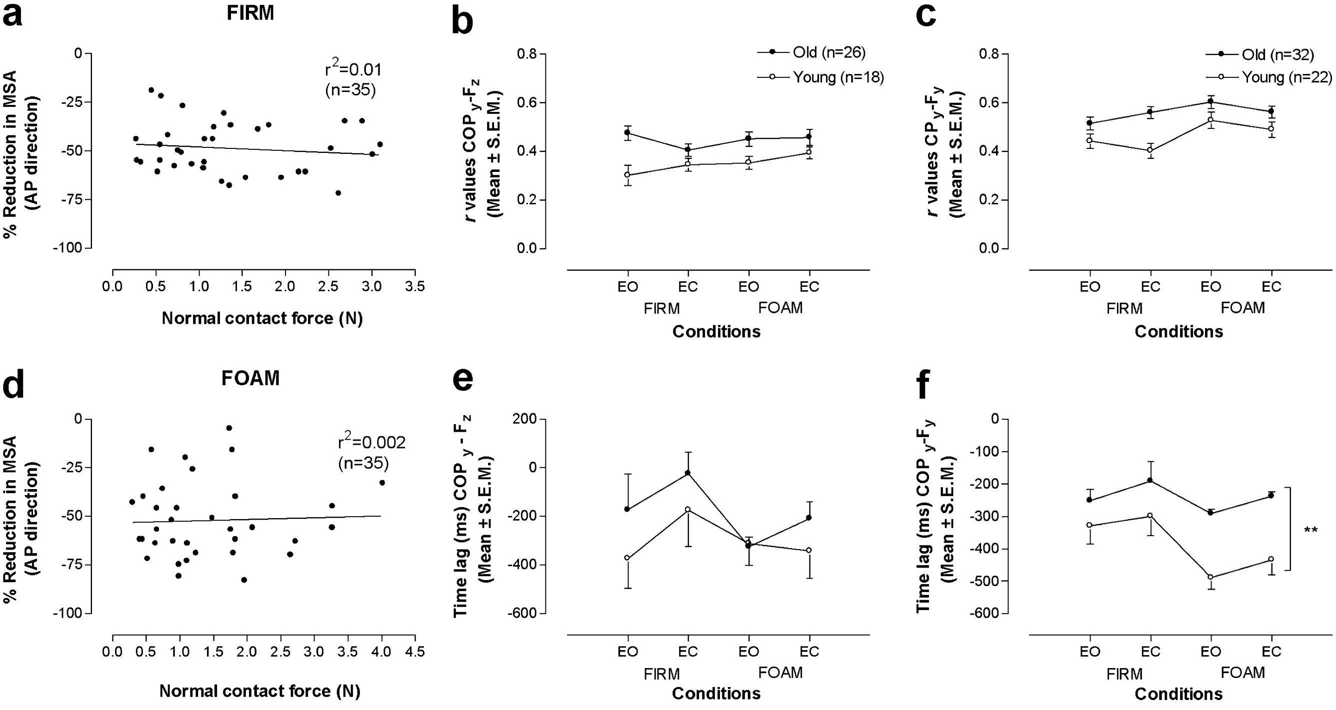

Fig. 6 **a, d** Relationship between normal contact forces deployed by older individuals when standing on the firm **(a)** or foam **(d)** surfaces in the no-vision, smooth touch condition and associated percent reductions in MSA (AP direction) computed relative to trials in the no-vision, no touch condition. **b** and **e, c** and **f**. Mean maximal *r* values and corresponding mean time lags derived from the temporal relationship between displacement of the COP_{AP} (ST condition, *EO* eyes open, *EC* eyes closed) and the magnitude of contact forces applied by the fingertip in the normal direction (**b** and **e** COP_{AP}-F_N couple) and in the antero-posterior direction (**c** and **f** COP_{AP}-F_y couple). Note that *error bars* in **e** and **f** are shown in only one direction to improve clarity (**significant difference between groups, $p<0.01$)

stabilization as those seen in young subjects. The latter observation is reminiscent of the results of Lackner et al. (1999) in patients with vestibular loss in whom light contact of the fingertip restored stability to control levels when standing in the unstable tandem-Romberg position in the dark. Dickstein et al. (2001), in their recent study on patients with diabetic neuropathy, also observed that light or heavy contact of the index fingertip improved postural stability to control levels when patients were standing in conditions of deficient surface or visual information. Thus, our observations bring further confirmation in the healthy older population of the powerful effect of fingertip contact in stabilizing postural sway during normal bipedal stance.

On both support surface conditions, the influence of surface texture proved to be insignificant in influencing postural sway during trials with fingertip contact. Thus, the relative roughness or smoothness of the grating contacted did not translate into changes in postural sway. The ability to appreciate changes in contact force as the body moved back and forth was evidently more important in the context of this experiment than the properties of the touched surface. In this regard, the input from type I and type II slowly adapting cutaneous afferents supplying the fingertip (SAI and SAII, respectively) might have been particularly important. Indeed, both types of afferents respond to sustained skin indentation and exhibit sensitivity (albeit at different degrees) to strain components and skin deformation (e.g. skin stretch), making them suitable to signal changes in contact force when touching external objects (SAI) and also in signaling the actual conformation of the hand with respect to joint position (SAII, review in Johnson 2001). Recently, both SAI and SAII were shown to be sensitive to directional changes in the tangential forces in the plateau phase of force stimuli applied to the fingerpad, SAI being more sensitive to forces in the distal direction, SAII being more sensitive to forces in the proximal directions (Birznieks et al. 2001). On the other hand, a contribution of fast adapting type I afferents (FAI) cannot be ruled out since these afferents are known to be highly sensitive to sudden changes in tangential load forces (i.e., slip detectors, review in Johnson 2001). However, in the context of this experiment, sensory inputs from FAI might not be have been as critical as those of SAI or SAII, since their ability to provide directional information about fingertip forces is limited to dynamic phases of force stimuli (i.e., no response in the plateau phase) and, as reported recently by Birznieks et al. (2001), their preferred direction may vary markedly from one phase to another (i.e., protraction vs. retraction). Thus, contact cues encoded in the discharge of SAI and SAII might have been the most critical source in providing information about the magnitude and direction of forces at the fingertip, allowing subjects to derive relevant information about hand/arm/body configuration, irrespective of the properties of the contacted surface.

In a sense, the lack of influence of texture in this experiment reiterates the previous conclusion of Jeka and Lackner (1995) that the frictional characteristics of contact surfaces have little impact on postural sway in conditions involving light touch. These authors, however, did report major effects related to frictional properties when large contact forces (8–10 N) were used, heavy contact with a rough surface leading to more efficient physical stabilization. While some of our older subjects exerted high contact forces, the range used might have been too low (3–4.5 N) when compared to Jeka's experiment to influence contact strategy. Conversely, the frictional properties of the two grating surfaces might have been too similar, although this is unlikely considering that, for any given level of contact force, friction increases as the spacing between raised elements increases (Smith et al. 2002a). It remains that our observations on contact surface texture fit with the general framework arising from recent works on the contribution of light touch to balance. Specifically, beyond locus of touch, modes of touch or properties of objects being touched, a fixed and stable reference point in the plane of greater instability remains the most important factor when contacts with body parts are used for balance control (Lackner et al. 2001; Krishnamoorthy et al. 2002).

Influence of sensory conditions on perceived stability

While experiments on light touch and balance have often alluded to subjects' reports of improved steadiness and stability (e.g., Lackner et al. 2001), very few studies have actually examined how changes in postural sway and in balance conditions are interpreted at the subjective level. In one of the few studies examining this issue, Schieppati et al. (1999) looked at the relationship between dynamometric indices of body sway and subjective reports of steadiness, as reflected on a numeric scale (0–10). The extremes on this scale referred to some pre-defined criterion conditions (0, standing unsupported on one leg with no vision; 10, standing on both legs while firmly grasping a bar). Using this scale, they found a close correspondence between subjective scores of perceived steadiness and mean sway area in both older and young healthy adults. The correspondence was particularly strong when vision was absent. In the present study, although we used a slightly different approach to assess perceived stability (see "Materials and methods"), we also found that vision had a major impact on stability ratings. Also consistent with Schieppati et al. (1999), no difference emerged between age groups and across gender, thereby providing further evidence of the preserved capacity of healthy elderly men and women to assess their own stability. The observation that vision had such predominance on perceived stability is not surprising given the major impact of visual input in maintaining upright stance (Nashner et al. 1989) and for spatial navigation (Borel et al. 1994; Takei et al. 1996). While touch did influence stability ratings, its impact over vision only emerged when conditions were more challenging with deficient vision and unstable support surface. Thus, it seems that under relatively stable support conditions, subjects may choose to disregard stabilizing information arising from fingertip contact, perhaps because it is too redundant with input coming from the foot and ankle, and only become aware of its importance when stability is highly compromised, such as when standing on the foam, eyes closed. The increased reliance of fingertip contact for perceived stability and for establishing postural orientation and navigational boundaries when vision is absent can also be appreciated in the light of daily experiences when contact with objects (e.g., walls) is almost instinctively sought upon entering into a dark room.

Modulation of fingertip forces and contact strategies with age

As discussed above, the overall effect of fingertip contact in terms of postural stabilization and perceived stability was quite similar in older and young subjects. In the context of these experiments, the only major difference that emerged between the two groups was in the amount of force deployed on the touch-plate. In this regard, contact forces produced by older subjects were, on average, two to three times larger than those produced by young subjects under the same conditions. In the young group, the range of normal (0.07–0.82 N) and tangential forces (0.01–0.4 N) closely corresponded to that reported in previous experiments on haptic stabilization in which force-limiting paradigms were used (Jeka and Lackner 1994, 1995; Clapp and Wing 1999; Lackner et al. 2001). In addition, such a range of forces corresponds closely to those deployed by young adults during tactile exploration of surface features (Smith et al. 2002b), hence its compatibility with a "sensory exploration" strategy. Consistent with such a strategy, changes of fingertip force (F_Y) at the touch-plate preceded those of the $\mathrm{COP}_{\mathrm{AP}}$ by 300–500 ms, indicating a proactive use of fingertip signals to attenuate COP displacements. The observations that young subjects adopted light contact forces spontaneously, even if they were not required to, provide further evidence that "sensory exploration" is the preferred strategy when fingertip contact with an external object is used for balance control. In this respect, our findings reinforce the interpretation that light touch does make an important contribution to postural stabilization and not vice versa, as suggested by Riley et al. (1999).

As for the old group, one would have predicted that, given the expected decline in sensory functions, the recourse to heavy contact forces (i.e., >4 N) to physically support the body would have been quite systematic across conditions. Our results showed that this was not the case. On the contrary, only a minority of older subjects (six to eight depending upon the conditions) actually used contact forces that could provide some physical support (>3 N) to reduce postural sway (Holden et al. 1994). In fact, in most cases, normal force values recorded on the touch plate never exceeded 2 N and for two-thirds of the subjects were <1.5 N. Contact forces of 1–2 N are hardly compatible with a physical support strategy. For example, during one-legged stance, forces of between 5 and 8 N are required to achieve significant reduction in sway of approximately 20% while a 1 N touch force provides approximately 2–3% sway reduction through mechanical stabilization (Holden et al. 1994). Further, if physical support was indeed a common strategy, then reductions in sway should have been proportional to the magnitude of contact forces exerted on the touch plate, but such a relationship was not found (see Fig. 6a, b). Thus, it seems that postural stabilization was achieved, for a majority of older subjects, by keeping fingertip forces in a light to moderate range, insufficient to provide significant mechanical stabilization, yet still appropriate to detect body sway through contact cues from a stable reference point. Further support for a predominant sensory exploration strategy in the old group comes from the analysis of a temporal relationship between variations in fingertip force signals and COP displacements in the AP direction. When standing on the foam, time lags computed in the old group were comparable (200–300 ms) to those measured in the young group. The shorter time lags found when older subjects were standing on the foam, although more compatible with a physical support strategy (Jeka and Lackner 1995), can be explained by the few subjects who relied on heavy touch to achieve some physical support under this condition.

One likely reason for the slight upward shift in the range of contact forces used by the majority of elderly appears to reside in the age-related decline in tactile sensory function of the hands. As emphasized earlier, advancing age is characterized by an elevation of perceptual thresholds measured in the palm and digits affecting the ability of older persons to detect and discriminate tactile stimuli and object features (Verrillo 1979; Kenshalo 1986; Stevens and Patterson 1995; Tremblay et al. 2000). Aging also impairs the ability to modulate fingertip forces during lifting and grasping tasks (Kinoshita and Francis 1996; Cole et al. 1999). For instance, Cole and Rotella (2001) reported a twofold increase in the tangential force required to evoke automatic grip responses to prevent slips in older adults. In this regard, the increased contact forces deployed by our older subjects in the context of haptic stabilization may be interpreted as a means to compensate for the decreased tactile sensitivity at the fingertip to allow detection of body sway. In a companion paper, we present evidence that reduced tactile sensations at the fingertips were indeed an important factor in determining contact forces, and hence contact strategies, to achieve postural stabilization from fingertip contact.

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References

Bergin PS, Bronstein AM, Murray NM, Sancovic S, Zeppenfeld DK (1995) Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. J Neurol Neurosurg Psychiatry 58:335–340

Birznieks I, Jenmalm P, Goodwin AW, Johansson RS (2001) Encoding of direction of fingertip forces by human tactile afferents. J Neurosci 21:8222–8237

Borel L, Le Goff B, Charade O, Berthoz A (1994) Gaze strategies during linear motion in head-free humans. J Neurophysiol 72:2451–2466

Cadoret G, Smith AM (1996) Friction, not texture, dictates grip forces used during object manipulation. J Neurophysiol 75:1963–1969

Carpenter MG, Frank JS, Winter DA, Peysar GW (2001) Sampling duration effects on centre of pressure summary measures. Gait Posture 13:35–40

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

Cole KJ, Rotella DL (2001) Old age affects fingertip forces when restraining an unpredictably loaded object. Exp Brain Res 136:535–542

Cole KJ, Rotella DL, Harper JG (1999) Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults. J Neurosci 19:3238–3247

Desrosiers J, Hebert R, Bravo G, Dutil E (1996) Hand sensibility of healthy older people. J Am Geriatr Soc 44:974–978

Dickstein R, Shupert CL, Horak FB (2001) Fingertip touch improves postural stability in patients with peripheral neuropathy. Gait Posture 14:238–247

Fernie GR, Gryfe CI, Holliday PJ, Llewellyn A (1982) The relationship of postural sway in standing to the incidence of falls in geriatric subjects. Age Ageing 11:11–16

Gilsing MG, Van den Bosch CG, Lee SG, Ashton-Miller JA, Alexander NB, Schultz AB, Ericson WA (1995) Association of age with the threshold for detecting ankle inversion and eversion in upright stance. Age Ageing 24:58–66

Holden M, Ventura J, Lackner JR (1994) Stabilization of posture by precision contact of the index finger. J Vestib Res 4:285–301

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

Johnson KO (2001) The roles and functions of cutaneous mechanoreceptors. Curr Opin Neurobiol 11:455–461

Kenshalo DR Sr (1986) Somesthetic sensitivity in young and elderly humans. J Gerontol 41:732–742

Kinoshita H, Francis PR (1996) A comparison of prehension force control in young and elderly individuals. Eur J Appl Physiol Occup Physiol 74:450–460

Krishnamoorthy V, Slijper H, Latash ML (2002) Effects of different types of light touch on postural sway. Exp Brain Res 147:71–79

Lackner JR, DiZio PA (2000) Aspects of body self-calibration. Trends Cogn Sci 4:279–288

Lackner JR, DiZio P, Jeka J, Horak F, Krebs D, Rabin E (1999) Precision contact of the fingertip reduces postural sway of individuals with bilateral vestibular loss. Exp Brain Res 126:459–466

Lackner JR, Rabin E, DiZio P (2000) Fingertip contact suppresses the destabilizing influence of leg muscle vibration. J Neurophysiol 84:2217–2224

Lackner JR, Rabin E, DiZio P (2001) Stabilization of posture by precision touch of the index finger with rigid and flexible filaments. Exp Brain Res 139:454–464

Lederman SJ (1974) Tactile roughness of grooved surfaces: the touching process and effects of macro- and microsurface structure. Percept Psychophys 16:385–395

Lederman SJ (1982) The perception of texture by touch. In: Schiff W (ed) Tactual perception: A source book. Cambridge University Press, Cambridge, pp 130–167

Maki BE, McIlroy WE (1996) Postural control in the older adult. Clin Geriatr Med 12:635–658

Maki BE, McIlroy WE (1997) The role of limb movements in maintaining upright stance: the “change-in-support” strategy. Phys Ther 77:488–507

Maki BE, Holliday PJ, Fernie GR (1990) Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc 38:1–9

Mireault AC, Dessureault L, Tremblay F, Sveistrup H (2002) Influences of light fingertip contact on balance during bipedal stance in younger and older adults. In: Kollmitzer J, Bijak M (eds) XIVth Congress of the International Society of Electrophysiology and Kinesiology, Department of Biomechanical Engineering and Physics, University of Vienna, Vienna, Austria, pp 379–380

Nashner LM, Shupert CL, Horak FB, Black FO (1989) Organization of posture controls: an analysis of sensory and mechanical constraints. Prog Brain Res 80:411–418; discussion 395–417

Rabin E, Bortolami SB, DiZio P, Lackner JR (1999) Haptic stabilization of posture: changes in arm proprioception and cutaneous feedback for different arm orientations. J Neurophysiol 82:3541–3549

Resnick HE, Vinik AI, Schwartz AV, Leveille SG, Brancati FL, Balfour J, Guralnik JM (2000) Independent effects of peripheral nerve dysfunction on lower-extremity physical function in old age: the Women’s Health and Aging Study. Diabet Care 23:1642–1647

Resnick HE, Vinik AI, Heimovitz HK, Brancati FL, Guralnik JM (2001) Age 85+ years accelerates large-fiber peripheral nerve dysfunction and diabetes contributes even in the oldest-old: the Women’s Health and Aging Study. J Gerontol A Biol Sci Med Sci 56:M25–31

Riley MA, Stoffregen TA, Grocki MJ, Turvey MT (1999) Postural stabilization for the control of touching. Hum Mov Sci 18:795–817

Sathian K, Goodwin AW, John KT, Darian-Smith I (1989) Perceived roughness of a grating: correlation with responses of mechanoreceptive afferents innervating the monkey’s fingerpad. J Neurosci 9:1273–1279

Schieppati M, Tacchini E, Nardone A, Tarantola J, Corna S (1999) Subjective perception of body sway. J Neurol Neurosurg Psychiatry 66:313–322

Smith AM, Chapman CE, Deslandes M, Langlais JS, Thibodeau MP (2002a) Role of friction and tangential force variation in the subjective scaling of tactile roughness. Exp Brain Res 144:211–223

Smith AM, Gosselin G, Houde B (2002b) Deployment of fingertip forces in tactile exploration. Exp Brain Res 147:209–218

Stevens JC (1992) Aging and spatial acuity of touch. J Gerontol 47:35–40

Stevens JC, Choo KK (1996) Spatial acuity of the body surface over the life span. Somatosens Mot Res 13:153–166

Stevens JC, Patterson MQ (1995) Dimensions of spatial acuity in the touch sense: changes over the life span. Somatosens Mot Res 12:29–47

Takei Y, Grasso R, Berthoz A (1996) Quantitative analysis of human walking trajectory on a circular path in darkness. Brain Res Bull 40:491–495

Tremblay F, Cuenco A, Backman A, Vant K, Wassef M-A (2000) Assessment of spatial acuity at the fingertip with grating (JVP) domes: Validity for use in an elderly population. Somatosens Mot Res 17:61–66

Tremblay F, Mireault AC, Letourneau J, Pierrat A, Bourrassa S (2002) Tactile perception and manual dexterity in computer users. Somatosens Mot Res 19:101–108

Verrillo RT (1979) Change in vibrotactile thresholds as a function of age. Sens Processes 3:49–59

Wolfson L, Judge J, Whipple R, King M (1995) Strength is a major factor in balance, gait, and the occurrence of falls. J Gerontol A Biol Sci Med Sci 50 Spec No: 64–67

Woollacott MH, Shumway-Cook A, Nashner LM (1986) Aging and posture control: changes in sensory organization and muscular coordination. Int J Aging Hum Dev 23:97–114