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Aging-Induced Shifts From a Reliance on Sensory Input to Muscle Cocontraction During Balanced Standing

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Background. Peripheral sensation is the most important sensory system in the maintenance of upright posture in all age groups. With aging, visual and somatosensory processing change their prospective contribution to the maintenance of quiet standing, at debated percentages. Aging is associated with a decrease in balance abilities that, in turn, increases the risk of falling. We used force plate data to show that, with aging, while vision plays a significant role in regulating postural stability (PS), the individual's perception of his/her stability becomes more significant than vision. Moreover, under experimental conditions, electromyography (EMG) of the ankle musculature of elderly people reveals the adoption of a different strategy, a cocontraction strategy, with or without visual input. The aim of this study was to look at two distinct age groups to determine whether or not a shift takes place in the sensory modality typically relied on while maintaining PS during a static, postural-related task.

Method. The participants comprised two groups: a ''young'' (Y) group of 20 people aged 20–35, and an ''old'' (O) group of 32 people aged 65–84. The role of vision was tested with regard to two differently sized bases of support. They were tested during quiet upright standing on a single force plate in wide base and then in narrow base conditions. Surface EMG was recorded from the tibialis anterior, soleus, rectus femoris, and semitendinous muscles.

Results. The older group differed from the younger group when performing the task under the narrow base condition. When participants stood naturally, our EMG data indicated that, unlike the Y group, the O group used cocontraction around the ankle in order to deal with changing conditions and sensory inputs. Significant increases were found in the area, length, and mean velocity of body sway in the older group as compared with the younger group.

Discussion. The visual contribution to postural stabilization is significantly greater in the younger population than in the elderly population. Across the older group, lack of vision seemed to interfere less with PS; however, the EMG data indicated that, unlike the Y group, the O participants used cocontraction around the ankle in order to deal with changing conditions and sensory inputs.

Conclusion. To cope with the deterioration in their sensory input and processing ability, elderly individuals seemed to have developed a strategy of stiffening and freezing their lower legs during upright standing.

BALANCE is a somewhat ambiguous term, used to describe the ability to maintain or move within a weight-bearing posture without falling. Balance, whether in its static or dynamic form, is a derivative of postural stability (PS). Peripheral and central changes as the body reaches an advanced age decrease the ability of the older participant to control his or her PS and may result in falls. These changes—and the individual's response to them—may, in fact, be the very reason that a whole segment of the elderly population becomes ''fallers''—those with a tendency to fall, typically after a first fall. Given the increasing percentage of over-65-year-olds in the population, and the subsequent large numbers of individuals vulnerable to unpredictable falling, the control of posture and falls in elderly individuals constitutes a major health issue. Falls are the leading cause of injury-related visits to emergency departments and the primary etiology of accidental deaths in persons over the age of 65 years. The mortality rate for falls increases dramatically with age, accounting for as many as 70% of accidental deaths in persons 75 years and older, regardless of gender (1). Instability and falls can be markers of poor health and declining function, and they are often associated with significant morbidity. More than 90% of hip fractures occur as a result of falls, with most of these fractures occurring in persons over 70 years of age. One third of community-dwelling elderly persons and 60% of nursing home residents fall each year. One fourth of elderly persons who sustain a hip fracture die within 6 months of the injury. Hip fracture survivors experience a 10% to 15% decrease in life expectancy and a meaningful decline in overall quality of life (2).

It is not clear from simple deprivation experiments whether decreased PS results from reduced sensitivity of the remaining peripheral systems or decreased redundancy of the information used for postural regulation (3,4). While vision plays a significant role in the regulation of postural stability, some investigators have proposed that, with aging, the size of the base of support (BOS) (i.e., the position of the feet) becomes more significant than vision (5–7). Other studies, in which participants were given conflicting sensory information unrelated to the postural task, also showed that the ability of older adults to maintain PS was affected much more than that of young adults (3,8). A study based on several laboratory measures found the center of pressure (COP) motion in the mediolateral direction during stance to be the measure most predictive of falls in elderly people (9).

The studies mentioned were unable to unify the dominant neuromuscular strategy by which elderly individuals compensate for the diminished sensory information. We hypothesized that the O group would sway more than the Y group, especially with their eyes closed and in a narrow BOS, while maintaining upright standing posture.

The present study aimed at identifying the shift to reliance on sensory modalities, especially the visual and somatosensory modalities, that take place during aging as a means for maintaining static postural stability.

Methods

Participants

Participants were two groups of healthy volunteers, none of whom had neurological or psychiatric disorders or showed signs of serious cognitive dysfunction. Twenty (8 men and 12 women) 20–34-year-olds (mean age 26.6 ± 3.2 years) comprised the young group (Y). Thirty-two (13 men and 19 women) 65–84-year-olds (mean age 77.8 ± 2.1 years) comprised the old group (O). All participants gave informed consent but were unaware of the aim of the experiment.

Apparatus

A force platform (AMTI, Model OR6-5-2, Newton, MA) was used to produce the COP measurements. The force platform signals were sampled at 200 Hz (12-bit A/D conversion). The COP coordinates were passed through a digital low-pass 5 Hz filter. The smoothed fluctuations of the COP were further processed by first-order differentiation of the displacements. Surface electromyograph (EMG) signals were recorded from the leg musculature of the dominant leg: rectus femoris (Q), semitendinous hamstring (HAM), tibialis anterior (TA), soleus (SOL); the dominant leg was determined based on a laterality questionnaire. The surface EMG signals were recorded using silver/silver chloride monopolar surface electrodes (Medicotest N-00-S 30 × 22 mm, Olstykke, Denmark). The electrodes were positioned at a 3 cm center-to-center distance, as described by Basmajian and DeLuca (10). The ground electrode was placed on the medial condyle of the femur. The EMG was recorded continuously on a portable MEGA ME 3000 data logger (MEGA Electronics, Ltd., Kuopio, Finland). Raw EMG signals were first treated by preamplifiers on the electrode leads and then filtered (15 Hz–500 Hz, CMMR 110 dB and gain of 412) and digitized (12 bit with sampling rate of 1000 Hz).

Task and Procedures

Balance was registered for 20 seconds. Participants stood erect on the force platform with 17 cm between heel centers (wide base [WB]), with each foot toeing out at a 14° angle from the sagittal midline (11). Narrow base (NB) of support was defined as feet with minimum separation with the medial borders of both feet in full contact. Participants were instructed to stand still as symmetrically as possible, with their hands folded behind their back and asked to stare at a letter ''X,'' which was displayed at eye level on white board, 3 meters away (eyes open [EO]). In eyes closed (EC) condition, the participants were blindfolded with instructions to close their eyes. No pretrial instruction concerning visual attention was given.

Four different conditions were measured: 1) upright standing with eyes open, wide base (WB + EO); 2) upright standing with eyes closed, wide base (WB + EC); 3) upright standing with eyes open, narrow base (NB + EO); (4) upright standing with eyes closed, narrow base (NB + EC). The experimental conditions were presented in the same order for each participant.

Data Analysis

The postural behavior of the participants was described by the length of the COP path, the elliptical area that covers 95% of the sampled COPs, the sway in the anteroposterior and mediolateral directions, and the mean COP velocities. The range of COP displacements reflects the maximum deviation of the COP, without regard to the direction of the displacement. The COP velocity indicates the mean speed of displacements of the COP over the sampled period; COP velocity is determined by dividing the sum of the displacement vectors by the sampling time. The displacement vectors indicate the cumulative distance covered by the COP over the sampled period. These vectors constitute an index of the amount of activity required to maintain stability.

The averaged EMG (AEMG) was obtained after sampling the raw data at 10 Hz. The AEMG amplitude in the stability tests was normalized as a percentage of the amplitude displayed during maximum voluntary isometric ankle plantar and dorsiflexion contractions as obtained on the isokinetic dynamometer in a semisitting position, knee flexed at 60° flexion. SOL/TA normalized EMG ratios were calculated in order to determine the cocontraction levels in the ankle joint.

The data for each dependent variable were submitted to a three-way 3 × 2 × 2 (age × BOS × vision) analysis of variance (ANOVA), with repeated measures of the last two factors. The difference among the three groups was analyzed by ANOVA, taking a two-tailed probability of 5% as the level of significance.

Results

Wide BOS: Eyes Open

Force-plate data.—As shown in Table 1A, a significant difference took place in the COP path and mean velocity for the O group as compared with the Y group (80% and 77% of that of Y, respectively). Similarly, the elliptical area, anteroposterior sway and mediolateral sway of the O group showed significant increase from that of the Y group (Table 1, Eyes Open).

Muscle activity.—The EMG amplitude measured as participants stood on a wide BOS with eyes open showed that the activity of the TA and HAM muscles was significantly higher (fivefold and threefold, respectively) in the older participants than in the younger ones. No significant differences were found for normalized AEMG amplitude of the SOL and Q between older and younger participants (Figure 1A).

Eyes Closed

Force-plate data.—The COP path was 22.7% higher in the older group than the younger group (Table 1, Eyes Closed). No significant differences were found between the age groups in the elliptical area, anteroposterior sway, mediolateral sway, or mean velocity.

Muscle activity.—EMG amplitude during upright standing on a wide BOS with eyes closed was consistently higher in the older participants than in the younger ones. Figure 1B shows that motor unit recruitment of the TA, SOL, and HAM muscles was significantly higher (10-fold, 3-fold and 4-fold, respectively) in the older participants as compared with the younger ones. No significant difference was found in the EMG amplitude of Q between the older and younger participants (Figure 1B).

Eyes Open Versus Eyes Closed

Force-plate data.—As shown in Table 1, there were significant increases in the COP path in the EC condition as compared with the EO condition: a 19% increase for the O group and a 36.5% increase for the Y group. There were also significant increases in the mean velocity and anteroposterior sway: 18% and 26%, respectively, in the O group, and 95% and 71%, respectively, in the Y group. Significant differences in the elliptical area and mediolateral sway in the EC condition was found in the Y group only, as compared with the EO condition.

Muscle activity.—No significant differences were found in EMG activity in the lower limb musculature in the Y group during performance of the stability test with a wide BOS with EC as compared with EO. In contrast, the O group participants significantly increased the EMG activity in the TA muscle when their eyes were closed as opposed to open, while no significant changes occurred in the other muscles of the lower limb (Figure 1A and B).

Narrow BOS: Eyes Open

Force-plate data.—As shown in Table 1A, the COP path, elliptical area, anteroposterior sway, mediolateral sway, and mean velocity were significantly higher (93%, 102%, 34%, 69%, and 92%, respectively) for the O group participants as compared with the Y group participants.

Muscle activity.—A significant increase was found in the EMG amplitude of the TA, SOL, and HAM muscles (11-fold, 3.5-fold, and 4-fold, respectively) of the older participants as compared with the younger ones (Figure 1C). No significant difference was found in Q between the older and younger participants.

Table 1. Center of Pressure-Based Measures of Postural Steadiness Computed for the Young and Old Age Groups in Eyes Open and Eyes Closed Conditions During Standing With Wide Base of Support and With Narrow Base of Support (mean ± *SEM*)

	WB		NB	
	Young	Old	Young	Old
	Eyes Open			
COP path	12.9 ± 0.5	23.3 ± 2.4*	23.4 ± 1.1‡	45.2 ± 3.3*‡
Elliptical area	0.78 ± 0.5	1.3 ± 0.6*	3.0 ± 0.3‡	6.2 ± 0.7*‡
M-L sway	0.7 ± 0.06	0.9 ± 0.07*	2.0 ± 0.1‡	3.4 ± 0.2‡
A-P sway	1.5 ± 0.1	1.7 ± 0.1*	1.5 ± 0.1‡	2.5 ± 0.2‡
Mean velocity	0.7 ± 0.04	1.1 ± 0.1*	1.2 ± 0.04‡	2.3 ± 0.2‡
	Eyes Closed			
COP path	18.5 ± 0.9†	27.8 ± 2.8*†	38.7 ± 1.8†‡	66.2 ± 6.6*†‡
Elliptical area	1.3 ± 0.1†	1.8 ± 0.2	7.0 ± 0.5†‡	11.2 ± 1.2*†‡
M-L sway	0.8 ± 0.05†	1.0 ± 0.07	3.2 ± 0.2†‡	4.4 ± 0.3*†‡
A-P sway	2.0 ± 0.1†	2.3 ± 0.19§	2.8 ± 0.1†‡	3.5 ± 0.3*†‡
Mean velocity	1.2 ± 0.3†	1.39 ± 0.1†	1.9 ± 0.1†	3.3 ± 0.3*†‡

Notes: *$p < .05$ significant differences old vs young.
$^†p < .05$ significant differences eyes closed vs eyes open in the same age group.
$^‡p < .05$ significant differences narrow base vs wide base.
$^§p < .05$ significant differences eyes closed vs eyes open for both age groups.
COP = center of pressure; WB = wide base; NB = narrow base; M-L = mediolateral; A-P = anteroposterior; *SEM* = standard error of mean.

Eyes Closed

Force-plate data.—The COP path, elliptical area, and mean velocity differed significantly for the O group (91%, 100%, and 96%, respectively) as compared with the Y group. Also, anteroposterior and mediolateral sway were significantly higher for the O group as compared with the Y group (Table 1, Eyes Closed).

Muscle activity.—The electrical activity of the TA, SOL, and Q muscles was significantly higher in the older participants as compared with that achieved by the younger ones (Figure 1D): 19-fold more for TA, 6-fold more for SOL, and 3.7-fold more for Q. No significant difference was found in the EMG amplitude of HAM between the old and young participants.

Eyes Open Versus Eyes Closed

Force-plate data.—Significant differences were found in all parameters of stability measured in both age groups. The COP path was significantly higher in the EC condition as compared with EO condition (46.5% for the O group and 65.4% for the Y group). There was also a significant increase in the elliptical area in the Y group (133%) over the O group (80.6%).

Muscle activity.—A significant increase was found in TA activity when the O group performed the stability test while

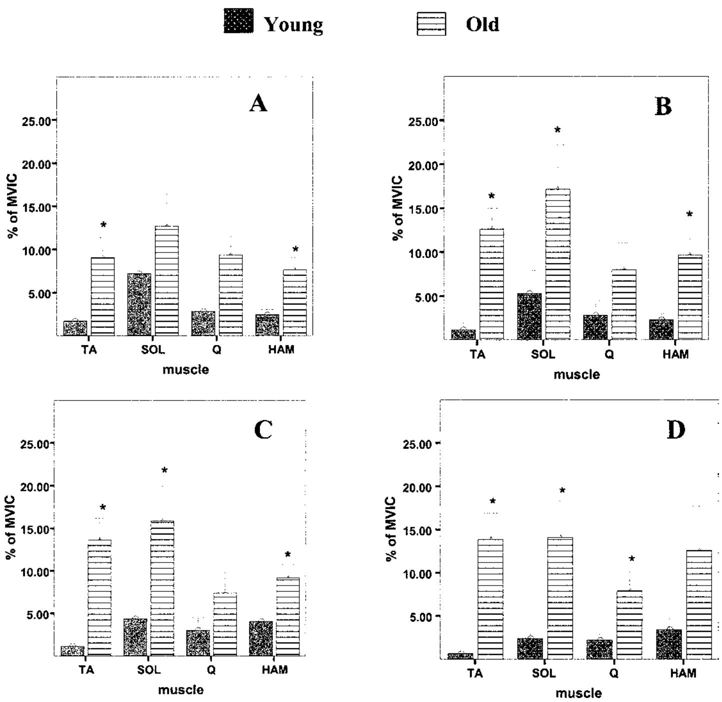

Figure 1. Normalized electromyographic amplitude in tibialis anterior (TA), soleus (SOL), rectus femoris (Q), and hamstring (HAM) muscles of young and old participants (mean ± *SEM* [standard error of mean]) as percentage (%) of maximum voluntary isometric ankle plantar and dorsiflexion contractions (MVIC). **A**, Standing on a wide base of support with eyes open; **B**, Standing on a wide base with eyes closed; **C**, Standing on a narrow base of support with eyes open; **D**, Standing on a narrow base with eyes closed. $*p < .05$ significant difference old vs young.

standing on a narrow BOS with EC as compared with EO (Figure 1C and D).

Narrow BOS Versus Wide BOS: Eyes Open

Force-plate data.—There were significant differences across all measures of EO with the narrow BOS as compared with the wide BOS, for both age groups (Table 1, Eyes Open). The COP length and elliptical area were significantly higher in the O group (93.4% and 376%, respectively) than in the Y group (81.4% and 284%, respectively).

Muscle activity.—There were no significant differences in the activity of the lower limb musculature in the Y group during the performance of the stability test with EO on a narrow BOS as compared with a wide BOS. There were, however, significant increases in the TA activity (2.5-fold) of the O group participants under these conditions (Figure 1A and C).

Eyes Closed

Force-plate data.—Significant differences appeared across all measures of EC with the narrow BOS as compared with the wide BOS, for both age groups (Table 1B). The COP length increased significantly in the narrow base condition: 138.1% for the O group participants and 109% for the Y group participants. The elliptical area also increased significantly in both groups (5-fold for the O Group, 4-fold for the Y Group).

Muscle activity.—There were no significant differences in muscle activity in the Y group. There were, however, significant increases in the TA activity of O group participants during the performance of the stability test with EC on a narrow BOS as compared with a wide BOS (Figure 1B and D).

Effect of Vision and BOS on Cocontraction in Ankle

SOL/TA normalized EMG ratio, which represents the level of cocontraction of the muscles around the ankle, was significantly higher for the Y group than the O group in both EO and EC conditions (Figure 2A) and the two BOS conditions (Figure 2B).

Discussion

In this study, we found that the experimental reduction of visual input had a greater effect on postural sway in younger than in older participants. This finding was contrary to our hypothesis that stated, relying on the findings of others (12–15), that when the visual and somatosensory inputs are modified, the O group would have greater sway than the Y group. Simoneau and colleagues (12) found that postural sway increased in both young and old participants when the eyes were closed. Matheson and colleagues (13) also found a significant increase in postural instability with increasing age and eyes closed. Hytonen and colleagues (14) claimed that the visual system was most important for balance control in elderly persons. Woollacott and colleagues (15) reported that aging adults showed more loss of balance than the younger group when peripheral vision was removed or when the eyes were closed.

In contrast, the present study found that visual input was more important for balance control in the younger group (with a 36.5% increase in the COP path in the EC condition, as compared with the EO condition) than the older group (only a 19% increase). Do these findings suggest that the absence of vision forced the younger participants to shift to a reliance on proprioceptive and cutaneous input? Very possibly. We found that the younger participants increased their body sway in an eyes-closed condition, perhaps in an effort to rely more on the proprioceptive input from the lower limb musculature and cutaneous input from skin of the soles. Koceja and colleagues (16) found that, during static conditions, young participants produced significantly less postural sway than elderly participants, both with vision (with a sway amplitude of 3.80 mm and 4.89 mm, respectively) and without vision (with a sway amplitude of 5.44 mm and 5.95 mm, respectively). That is, in Koceja's study, the young participants in the without-vision condition increased their postural sway by 43% over those in the with-vision condition, whereas the elderly participants increased their sway by only 21.7%, very similar to our findings. Lord and Ward (17) found that up to the age of 65, reliance on vision for balance control increases while, beyond this age, the contribution made by vision declines. Turano and colleagues (18) showed that the visual contribution to postural stabilization is significantly greater in nonfallers than in fallers. They claimed, and we concur, that peripheral somatosensory sensation is the most important sensory system in the maintenance of static PS in all age groups. Teasdale and colleagues (19) found that the exclusion or disruption of one of the sensory inputs alone did not differentiate consistently between elderly adults and young adults, because of compensation by the remaining sensory sources. Nakagawa (20) found that, when vibration was applied to the triceps-surea tendon, the sway increased significantly in young participants, but not in old participants. This phenomenon might suggest that proprioceptive afferent information plays a less important role in the elderly participants than in young participants. Horak and Nashner (21) suggested that PS in elderly people is dependent on vestibular and cervical receptor input to general sensory feedback regarding the body's movement. In the present study, our findings are in agreement with Nakagawa (20). The increase in sway of the O group during EC trials, in comparison with those of the Y group, was smaller, suggesting that O participants do not rely or cannot rely on their untapped somatosensory inputs. An alternative explanation might be that the O group is better equipped or attuned to use smaller magnitude proprioceptive "sway" input, but this is less likely in view of the deteriorating proprioception (22,23) and/or cutaneous input (24) as a system that can fully compensate the visual system in elderly individuals. Conversely, the Y do not need to cocontract, since they generate greater magnitude "sway" input that is richer proprioceptive input, and thus they can manage the oscillations of the COP path better than the O participants. It is possible that, unlike the O participants, the Y participants do not fear to reach their stability limits.

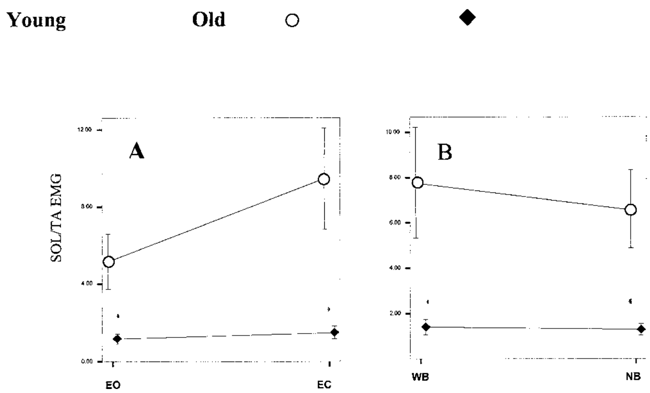

Figure 2. Soleus/tibialis anterior (SOL/TA) normalized electromyographic (EMG) ratios (% of MVIC [maximum voluntary isometric ankle plantar and dorsiflexion contractions]) between the age groups (mean ± *SEM* [standard error of mean]) in different task conditions: **A**, Eyes open (EO) and eyes closed (EC); **B**, wide base (WB) and narrow base (NB). $*p < .05$ significant difference old vs young.

In the present study we also found clear differences in the mode of EMG activity of the postural muscles in the two different age groups. We postulate that visual input played a significant role with the Y group, which increased its reliance on SOL activity, but a less influential role with the O group, which held a SOL/TA cocontraction pattern in order to control body sway. The observed lower limb activation pattern suggests that the older group employed a strategy of increased muscle activity, regardless of the size of BOS, especially in the TA muscle and to some degree in the SOL. This preference for stiffening the ankle joint has also been observed among the older participants performing a cognitive (8) or stepping (25) task. It should be noted that the Q and HAM activity ratios remained unchanged in both groups. HAM was used by the O group significantly more than the Y group, probably due to needed hip stabilization.

From our findings, we deduce that this decrease in reliance on visual input is accompanied by a greater dependence on the increased contraction of muscles, as manifested in the cocontraction around distal joints. The increase in sway of the O group during EC trials in comparison with those of the Y group was smaller. It is not clear if this lesser sway in the O group reflects that other sensory inputs are compensating for the lack of richer sensory information that typically arises during sway. Young participants in the present study showed more reliance on cutaneous and proprioceptive sensory input in no vision (EC) than the elderly participants, as evident from their higher sway values in EC condition in comparison with EO condition. In contrast, the O group increased their sense of stability not by using the richer sensory information (cutaneous and proprioceptive) that arises during increased sway to replace other sensory inputs (vision), but rather by maintaining/increasing the cocontraction as evident from low SOL/TA EMG ratio. By adopting this strategy, the O participants reduced their body sway as the solution to dealing with threatening conditions such as EC and narrow BOS. This suggests that the O group became less reliant on proprioceptive and/or cutaneous information, unlike the Y group who manifested greater reliance on proprioceptive input, perhaps due to improved quality of sensory information.

Conclusion

When maintaining upright standing, the Y group showed resourcefulness, and were able to shift from one sensory source (vision) to an alternative source (cutaneous and proprioception) when they were challenged. In contrast, the O group did not rely on the variety of sensory sources available when challenged, but rather responded uniformly to the full range of task conditions by stiffening the ankle joint and thus requiring less sway. We have shown that, in comparison with the Y group, sway in the elderly group is not a natural/logical adaptation of the central nervous system but, rather, is an unnatural, interfering occurrence that poses a threat to the individual's ability to stay stable. The different strategies for upright standing that elderly persons adopt during the advanced aging process are, in fact, tailored to compensate for the different deficiencies and decrease the ''interference'' of sway with static standing posture.

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