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ORIGINAL ARTICLE

Age-related differences in efficiency of visual and vibrotactile biofeedback for balance improvement

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Abstract

OBJECTIVES: The purpose of this study was to determine the effectiveness of visual (VF) and vibrotactile (TF) biofeedback obtained from the lower trunk (L5) tilts signal and their combination (VF+TF) in reducing postural sway in young and elderly people.
METHODS: Twenty healthy elderly subjects (8 males, mean age 74 years) and 20 healthy young subjects (7 males, mean age 27 years) were tested in biofeedback conditions (VF, TF and VF+TF) and in control conditions (eyes open) during the stance on firm and foam surface.
RESULTS: Young adults significantly reduced their postural sway (RMS – root mean square of CoP and L5 tilts) in all biofeedback conditions. Elderly people reduced their postural sway in conditions when the visual biofeedback was presented (VF and VF+TF) mostly during stance on foam surface. During TF conditions, an increase of velocity in anterior-posterior direction occurred.
CONCLUSION: Similar effectiveness of visual and combined biofeedback points out stronger influence of visual biofeedback because vibrotactile biofeedback alone had minimal effect in reducing postural sway in elderly. Used method of vibrotactile biofeedback was probably not enough intuitive for the body position control of elderly. An increase of velocity in anterior-posterior direction during TF conditions indicates higher voluntary activation of balance control in order to minimize amplitudes of postural sway.

Introduction

Balance control requires an integrative process involving information from visual, somatosensory (proprioceptive and tactile) and vestibular systems. As the central nervous system ages, the sensory systems become less sensitive and balance becomes more difficult to maintain which is one of the reasons that falls may occur (Maki & McIlroy 1996). Providing additional information about trunk sway to older adults could help improve their balance. It was found out that reduced trunk sway is highly correlated with a reduction of falls in elderly (Wu 1997).

The real-time visual biofeedback (VF) of the centre of pressure (CoP) during a standing task has been widely investigated in evaluation and training of the postural control (Dault *et al* 2003; Pinsault & Vuillerme 2008; Halická *et al* 2011, 2012). The use of an accelerometer sensor makes biofeedback devices more comfortable. We found that VF based on lower trunk (L5 – fifth lumbar vertebra) position is as effective as VF based on CoP position in reducing lower trunk tilts and CoP displacements (Halická *et al* 2014).

Vibrotactile biofeedback (TF) has been applied with varying degrees of success. Several studies examined positive effect of TF on balance in healthy young (Janssen *et al* 2009; Huffman *et al* 2010) and elderly (Verhoeff *et al* 2009; Haggerty *et al* 2012) subjects and also in patients with vestibular loss (Dozza *et al* 2007b). Different tactor display configurations of TF were tested. Dozza *et al* (2007b) used a vest with four columns of tactors with three tactors per unit around the trunk of the subject with two columns of tactors on the left side and two columns on the right side. Janssen *et al* (2010) used the elastic belt with 12 equally distributed actuators around the waist. Sienko *et al* (2012) evaluated the effectiveness of 4, 8 and 16-column array of tactors worn around the waist.

A frequent explanation for the decrease of postural sway observed with vibrotactile devices is an augmentation of intact native sensory inputs, giving the user more information about body position with respect to gravity (Haggerty *et al* 2012). However, for the simplest forms of vibrotactile display some limitations have been described. Janssen *et al* (2010) explored the effect of TF on body sway in stance in patients with severe bilateral vestibular losses in a placebo-controlled study. They found that body sway improved in 4 out of 10 patients using biofeedback, but the improvement with true biofeedback was only observed in those subjects where an improvement was present in placebo mode as well. Asseman *et al* (2007) showed that TF had limited value in triggering a protective step for even a simple stereotyped situation.

Some studies comparing VF and TF have reported task-dependent differences in reaction time and performance (Burke *et al* 2006). Multiple resource theory suggests that redundancy provided by multimodal biofeedback should improve performance in comparison to single-mode biofeedback (Wickens 2008).

The goal of our study was to investigate the efficiency of VF and TF obtained from lower trunk by the accelerometer in two age groups: young and elderly. It was hypothesized that both types of biofeedback provided separately and simultaneously would reduce postural sway in both age groups. We focused on the extent of balance improvement.

Methods

Twenty healthy young subjects (7 men and 13 women) within the range of 21–33 years (mean age 27 years, mean BMI 21 kg.m^{-2}) and 20 healthy elderly subjects (8 men and 12 women) within the range of 68–82 years (mean age 74 years, mean BMI 26 kg.m^{-2}) participated in the study. Subjects did not report any neurological, orthopaedic or balance impairments. They gave their informed consent and the study was approved by the local Ethics Committee.

Balance control was measured in eight conditions: two control conditions – standing on a firm (EO) / foam (thickness 10 cm) surface (FEO) with eyes open; six biofeedback conditions – standing on a firm / foam surface with visual biofeedback (VF); standing on a firm / foam surface with vibrotactile biofeedback (TF) and standing on a firm / foam surface with both visual and vibrotactile biofeedback (VF+TF) activated. Participants stood on the platform barefoot with heels together and feet positioned at an angle of about 30°. Each trial lasted for 50 s.

Lower trunk tilts were measured by ADXL203 (Analog Devices, Inc., MA, USA) dual-axis accelerometer with signal conditioned voltage outputs. The sensor measured in particular the static acceleration (gravitational part) with a full-scale range of ±1.7 g. The output was low-pass filtered with cut-off frequency of 10 Hz and the output (trunk inclination) was calibrated in stationary conditions for ±10 degrees range of body tilt. The accelerometer was positioned at the spinal column at the level of the fifth lumbar vertebra (L5) using an adhesive tape and flexible belt.

CoP represents overall stability of standing human; therefore we decided to evaluate it along with the lower trunk tilts. CoP displacements in the anterior-posterior (AP) and medial-lateral (ML) directions were measured by the custom made force platform, equipped with automatic weight correction for direct output of CoP.

The CoP displacements and the angle of trunk tilts were sampled at 100 Hz and directly recorded on a PC. The obtained data were analyzed with MATLAB program (Bučková *et al* 2014). Two parameters from CoP and lower trunk tilts (L5) were evaluated: root mean square (RMS) and velocity in AP direction (Vap) as a function of the time derivative of CoP displacement and L5 tilt.

During control conditions, subjects were instructed to concentrate on the black point placed in a white scene in front of them at a distance of 1 m, to sway as little as possible and to breathe normally.

In conditions with VF, subjects were instructed to minimize the extent of the red point movements around the centre of the monitor (38 x 31 cm) placed at a distance of 1 m in front of the subject. The VF signal was based on continuous 2D signal from the accelerometer ADXL203 attached on lower trunk (L5) and displayed on the monitor screen during VF. The signal for VF was magnified twice and filtered at 10 Hz (Figure 1a).

In conditions with TF, subjects were instructed to minimize the occurrence of vibrations according to the instruction: "Move in the opposite direction of the vibration." The vibrotactile device consisted of the ADXL203 accelerometer (L5) and the belt with controller and four vibrators. The vibrators were DC pancake vibrating motors, as used in mobile phones. The con-

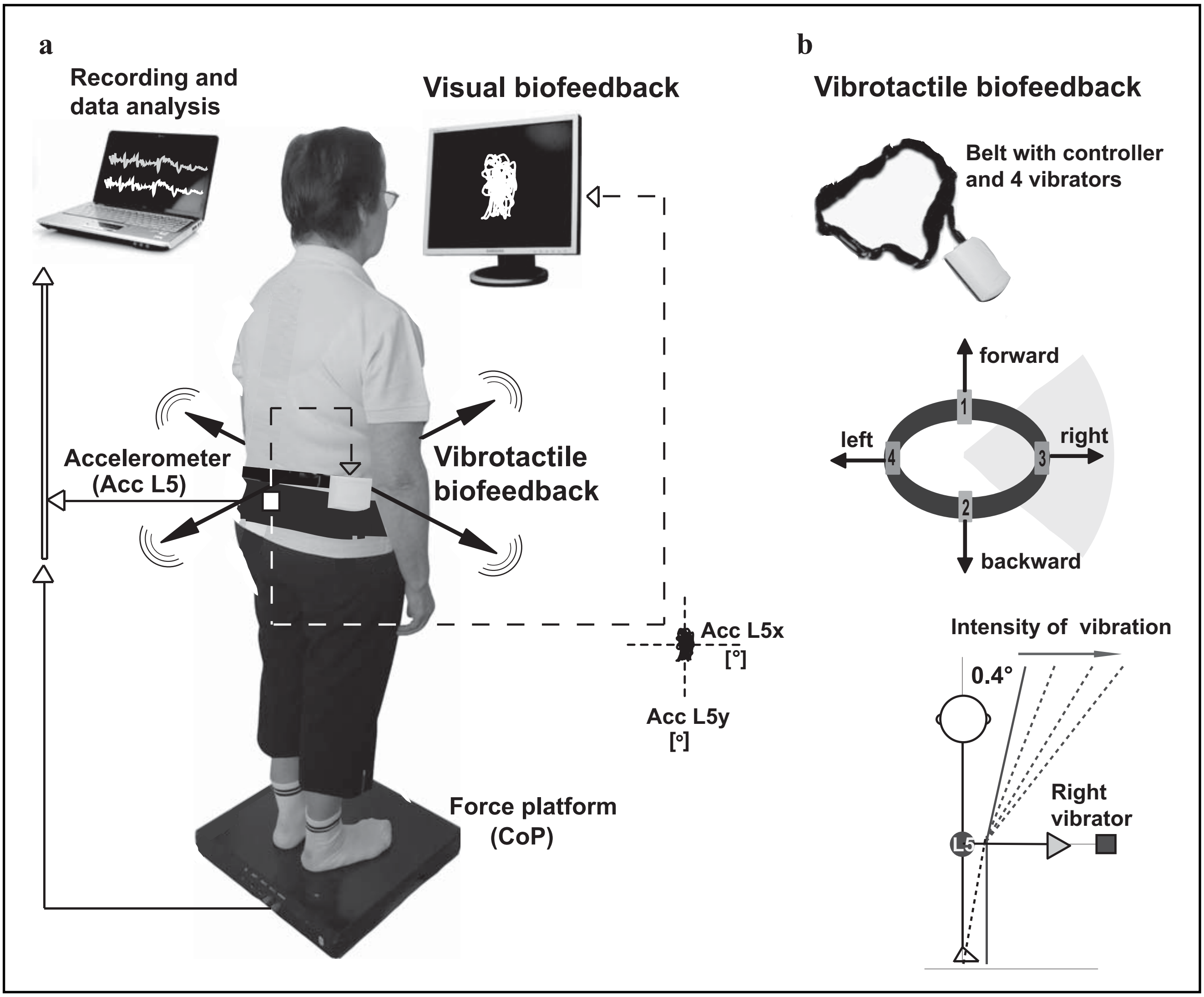

Fig. 1. a) Illustration of the visual (VF) and vibrotactile (TF) biofeedback systems. The VF signal obtained from the accelerometer ADXL203 attached on L5 is displayed as a moving red point on a monitor screen. The TF signal from the accelerometer is presented as vibrations around the waist. Simultaneously, all data from a force platform and accelerometer are recorded and analyzed on a PC. **b)** Vibrotactile biofeedback – belt with the controller and four vibrators. The vibration occurs at the angle of 0.4 ° in the tilting direction and its intensity increases with magnified tilt angle.

troller converted lower trunk acceleration to the signal relative to the vertical. This 2D signal was used as the vibrotactile feedback via vibrators which vibrated at the subject's waist in relation to the direction of trunk tilt as an alarm. The vertical position of device was adjusted for each subject before each condition. The vibration occurred at the tilt angle of 0.4° in the direction of trunk movement and its intensity increased with magnified tilt angle (Figure 1a, b). The simple design of the TF device was chosen in order to avoid overloading subjects with the stimulus. Therefore, vibratory stimulus was not active within the range of ±0.4 ° of lower trunk tilt. Subjects had enough time to practice with visual and vibrotactile devices before measurement.

Repeated measures ANOVA (main factors: surface, biofeedback; between-subjects factor: age) were performed for each parameter (RMS, Vap) and body segment (CoP, L5) separately. Greenhouse-Geisser adjustments were performed in the cases, where the assumption of sphericity was violated. *Post-hoc* pairwise comparisons with Bonferroni adjustments were performed on each level of surface for further exploration of differences between conditions. Student's *t-test* was performed for further exploration of differences between two age groups. The level of significance was set at $p<0.05$.

Results

The results showed a reduction of CoP displacement and lower trunk tilts indicated by a decrease of parameter RMS in conditions with visual, vibrotactile and combined biofeedback comparing to control conditions without biofeedback in young people. In elderly, a reduction of parameter RMS occurred in visual and combined biofeedback conditions mostly during the stance on foam support surface. Single vibrotactile biofeedback minimally reduced postural sway in elderly only during stance on foam support surface.

Examples of lower trunk tilt trajectories in the horizontal plane of representative young and elderly subjects recorded by the accelerometer attached on L5 are presented in Figure 2a. For illustration also time series of trunk tilts recorded by the accelerometer (L5) during stance on foam surface in AP direction are presented in Figure 2b.

Effect of age for parameter RMS

Repeated measures ANOVA performed on parameter RMS of lower trunk (L5), comparing control conditions with three types of biofeedback combined with two types of support surface in two age groups, gave a significant effect of between-subject factor age (F=180.88, df=1, $p<0.001$). Lower trunk tilt was used as a signal for visual and vibrotactile biofeedback. *Post hoc t*-tests revealed significant differences between young and elderly for parameter RMS of L5 during all tested conditions ($p<0.01$).

Repeated measures ANOVA performed on parameter RMS of CoP displacement, which represents overall stability of standing human, also showed significant effect of age (F=98.720, df=1, $p<0.001$). Differences between young and elderly groups in parameter RMS of CoP were also proven significant during each tested condition ($p<0.01$) by *t*-tests. These results showed that sway oscillations of CoP and lower trunk were significantly higher in elderly than in young adults in all tested conditions.

Effect of biofeedback and surface for parameter RMS

Repeated measures ANOVA gave a significant main effect of biofeedback (F=28.487, df=2.14, $p<0.001$) and surface (F=136.215, df=1, $p<0.001$) for parameter RMS measured on lower trunk (L5). *Post hoc* pairwise comparisons with Bonferroni adjustments were performed subsequently. Biofeedback conditions were compared to control conditions for both support surfaces (EO, FEO) separately. In young group, pairwise comparisons showed a significant reduction of parameter RMS in all biofeedback conditions comparing to control conditions during stance on both types of surfaces (Figure 3). In the group of elderly, RMS was significantly reduced in the conditions when the additional visual information was provided (VF and VF+TF conditions) while standing on foam surface. During the stance on firm surface, a reduction of RMS was observed only in VF condition. Reduction of RMS in TF condition comparing to EO during stance on foam surface was also observed in elderly, but this reduction was not significant (Figure 3).

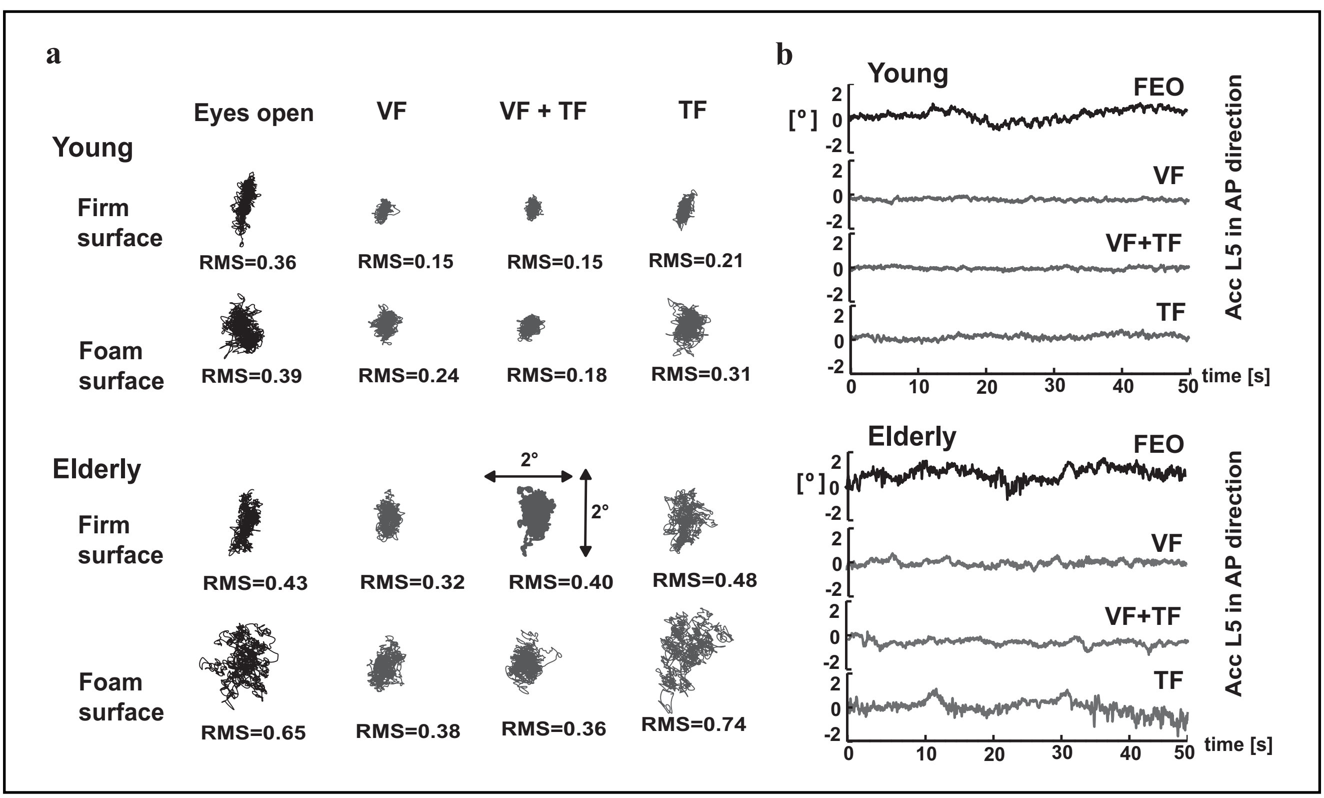

Fig. 2. a) Lower trunk tilt trajectories in the horizontal plane of representative young and elderly subjects recorded in all tested conditions with the accelerometer (L5). **b)** Time series of lower trunk tilts in young and elderly subjects recorded from L5 during stance on foam surface in anterior-posterior direction.

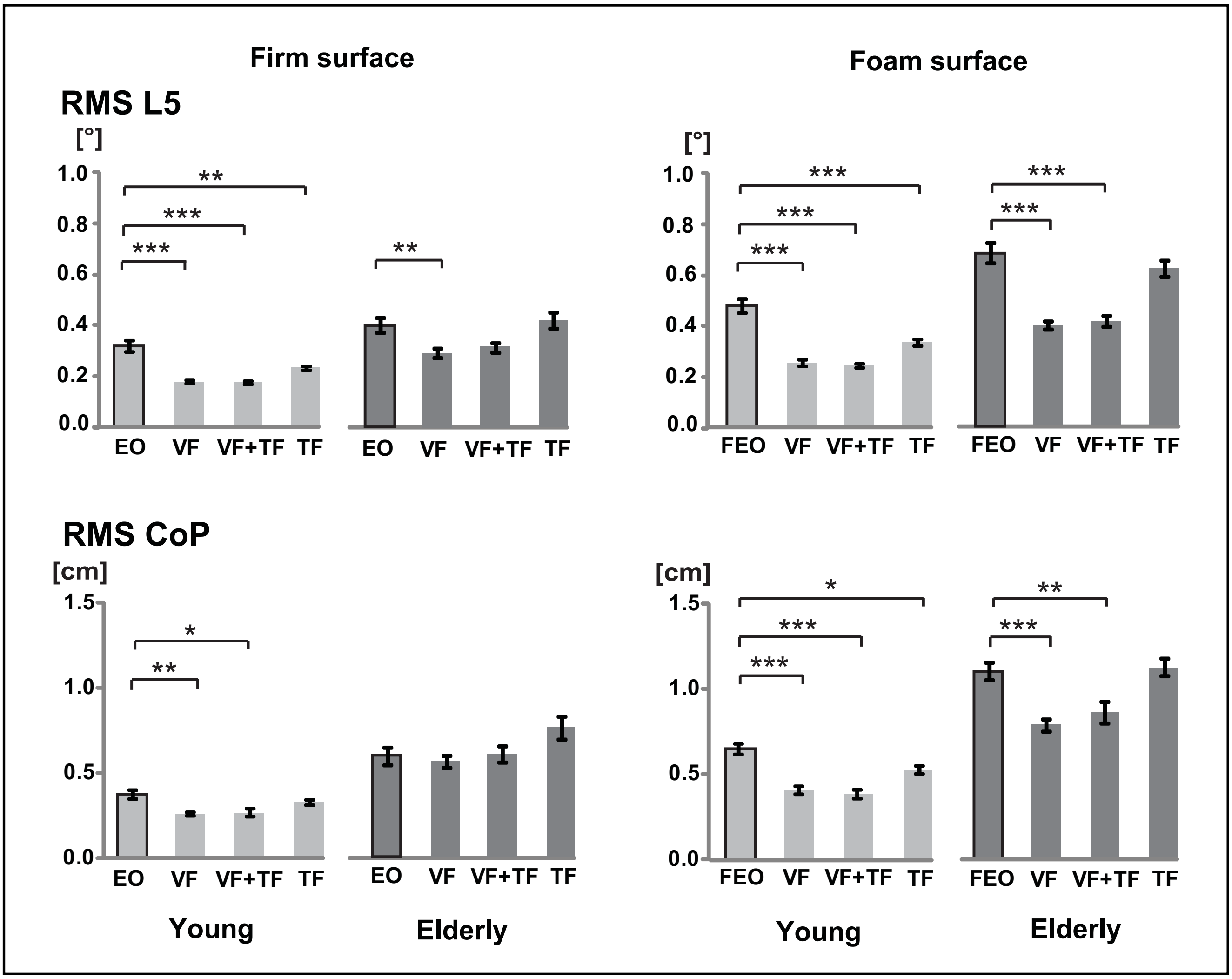

Fig. 3. Grouped averages of parameter RMS in young (light grey) and elderly (dark grey) groups recorded from CoP and L5 during the stance on firm and foam surface in all tested conditions. The averaged data are presented as mean values ± SEM. Post hoc differences between control conditions (EO,FEO) and biofeedback conditions (VF, VF+TF, TF) are marked *p<0.05, **p<0.01, ***p<0.001.

For parameter RMS of CoP displacement, ANOVA showed a significant main effect of biofeedback (F=32.299, df=2.43, p<0.001) and surface (F=307.889, df=1, p<0.001). In young group, pairwise comparisons realized for both support surfaces (EO, FEO) separately, showed a significant reduction of RMS in all biofeedback conditions comparing to control conditions during stance on both types of surface, except TF condition during stance on firm surface (Figure 3). In the group of elderly, there was a significant reduction of parameter RMS in VF and VF+TF conditions comparing to control condition (FEO) during stance on foam surface. Significant reduction of RMS in TF conditions was not found in elderly on CoP displacement (Figure 3).

For better presentation of the biofeedback influence in both age groups during stance on both support surfaces, RMS values were normalized to control conditions (EO, FEO) as 100%. Young adults reduced RMS values of CoP and L5 in all biofeedback conditions. Elderly effectively reduced lower trunk tilts, from which the biofeedback signal was obtained, almost in all biofeedback conditions except in TF condition during stance on firm surface. Overall oscillations of elderly group, represented by normalized RMS of CoP, were reduced in VF and TF+VF conditions, mostly during stance on foam surface (Figure 4).

<u>*Effect of main factors for parameter Vap*</u>

Repeated measures ANOVA performed on velocity parameter in AP direction (Vap) of lower trunk (L5) gave a significant effect of age (F=4.708, df=1, p=0.036). *Post hoc t*-tests revealed significant differences between young and elderly for parameter Vap of L5 during one control condition: EO (p=0.043). Young and elderly did not differ in velocity parameter in biofeedback conditions measured on lower trunk.

Significant effect of age was found by ANOVA for parameter Vap of CoP (F=54.144, df=1, p<0.001). *Post hoc t*-tests showed significant differences between

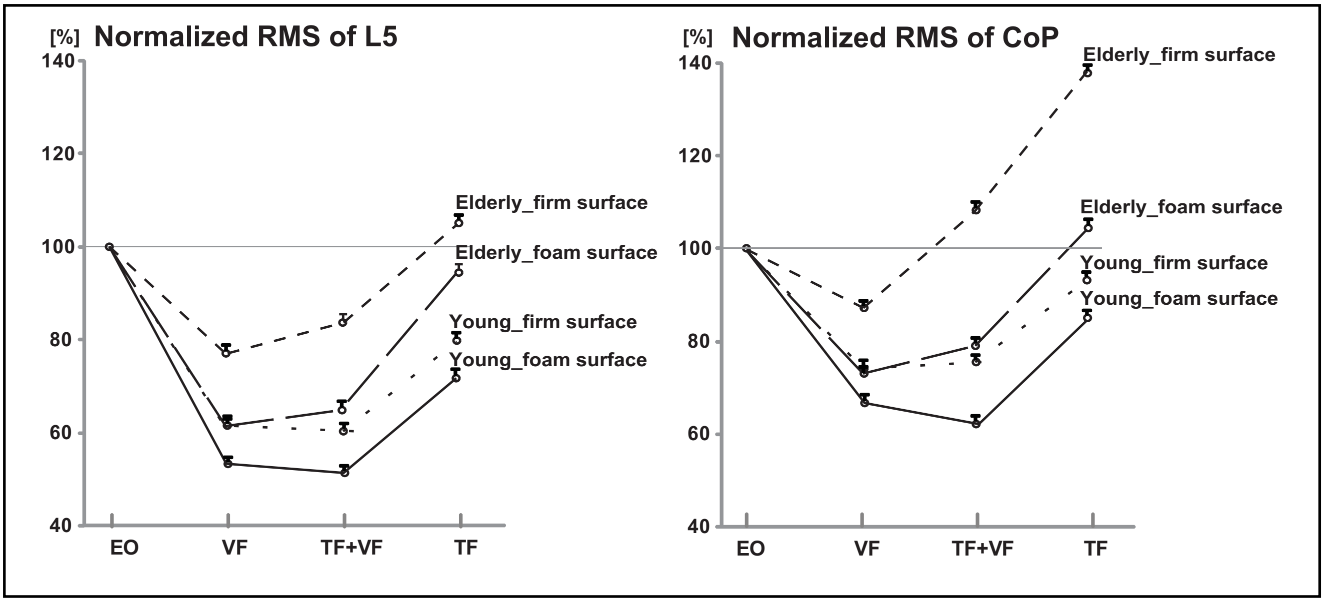

Fig. 4. Normalized averages of parameter RMS in young and elderly groups recorded from CoP and L5 during the stance on firm and foam surface in all tested conditions. Data are presented as mean values ± SEM.

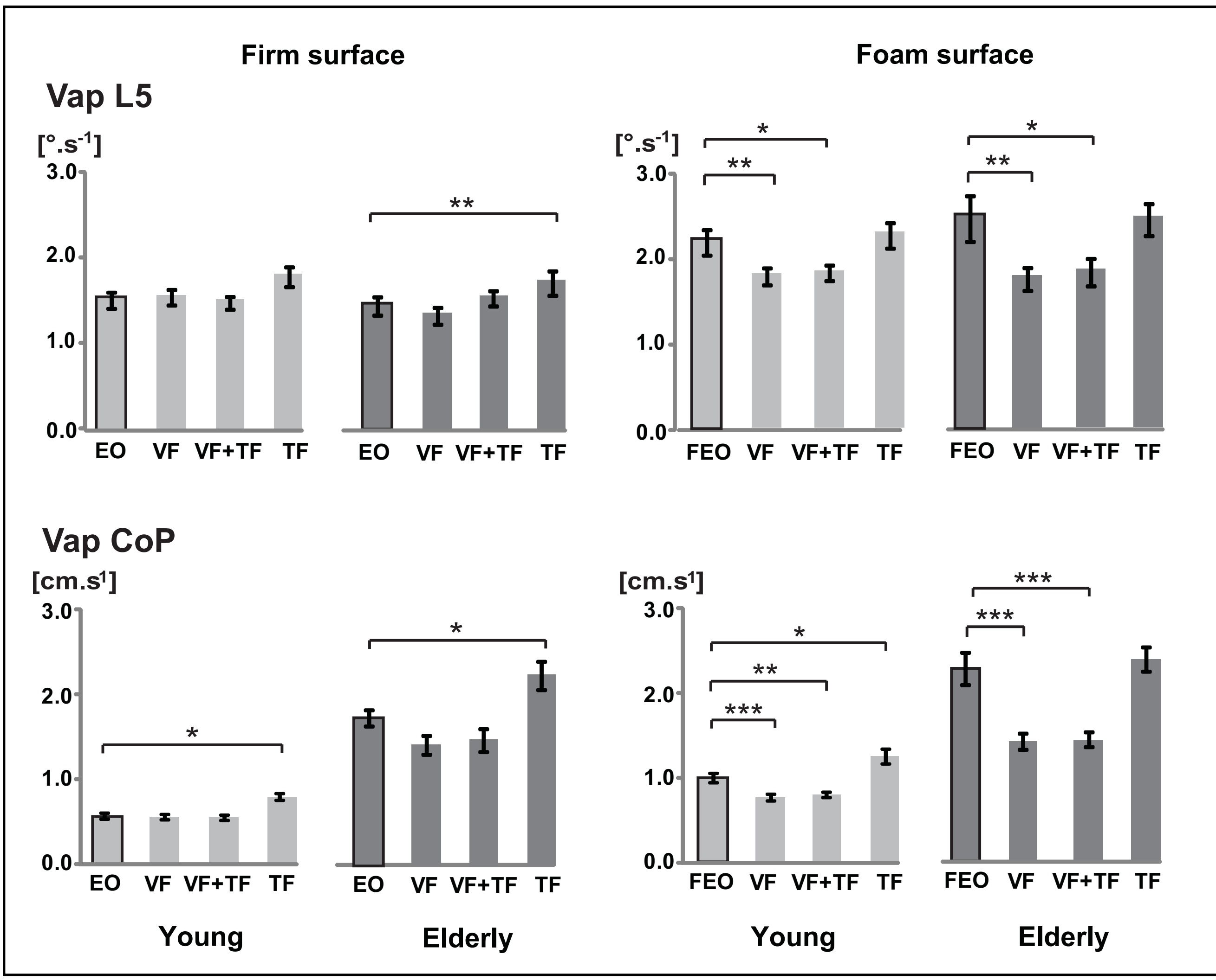

Fig. 5. Grouped averages of parameter Vap in young (light grey) and elderly (dark grey) groups recorded from CoP and L5 during the stance on foam surface in all tested conditions. The averaged data are presented as mean values ± SEM. Post hoc differences between control conditions (EO / FEO) and biofeedback conditions (VF, VF+TF, TF) are marked *p<0.05, **p<0.01, ***p<0.001.

young and elderly groups in each tested condition ($p<0.01$). Age-related differences in velocity parameter in AP direction were manifested more on CoP displacement, which represents overall stability.

For velocity parameter in AP direction (Vap) of lower trunk, ANOVA revealed a significant effect of biofeedback (F=22.909, df=2.41, $p<0.001$) and surface (F=73.459, df=1, $p<0.001$). *Post hoc* pairwise comparisons, realized separately for both support surfaces, revealed a reduction of Vap of L5 in VF and VF+TF conditions comparing to control condition (FEO) during stance on foam surface in both age groups (Figure 5). In contrast, an increase of Vap of L5 occurred in TF condition during the stance on firm surface in the group of elderly (Figure 5).

On CoP displacement, there was a significant effect of biofeedback (F=52.481, df=2.21, $p<0.001$) and surface (F=211.989, df=1, $p<0.001$) for parameter Vap. *Post hoc* pairwise comparisons revealed a reduction of parameter Vap of CoP in VF and VF+TF conditions during the stance on foam surface in both age groups. Similarly as on L5, an increase of Vap of CoP occurred in TF condition during the stance on both types of surface in young group and during the stance on foam in the group of elderly (Figure 5).

Discussion

The most substantial finding of this study is that all biofeedback modalities (visual, vibrotactile and their combination) based on the information from lower trunk tilts help to reduce postural sway and improve balance control. The final effectiveness of the particular biofeedback type depends on the support surface and age of the subject.

Young and elderly groups differ in RMS parameters during each tested condition measured on CoP and lower trunk. These results confirm previous findings about postural impairment related to age and somatosensory deficit (foam surface) (Abrahamova & Hlavacka 2008). The biofeedback signal was obtained from lower trunk tilts and it was there, where the sway oscillation was the most reduced in both age groups (Halická *et al* 2014). Young adults effectively reduced both L5 and CoP sway oscillations. Elderly effectively reduced lower trunk tilts, from which the biofeedback signal was obtained, almost in all biofeedback conditions. However their overall CoP oscillations were reduced only in visual and combined conditions, mostly during stance on foam surface. The most age-related differences appeared on CoP, which means that aging process affects overall human stability (Abrahamova & Hlavacka 2008). Elderly people were not able to use vibrotactile information obtained from lower trunk tilts for improving overall postural control (CoP) effectively enough. Possible explanation for this result could be limited information processing capacity in elderly. It is known that attention demands for postural control increase with aging (Shumway-Cook & Woollacott 2000). Concentration to additional vibrotactile information along with the natural visual and somatosensory feedback for balance control probably increased attention demands in elderly.

Young and elderly did not differ in velocity parameter in AP direction (Vap) measured during biofeedback conditions on lower trunk, from where the biofeedback signal was obtained. This result reflects that both age groups utilized additional sensory information using similar strategy of lower trunk velocity activation: decreasing velocity during visual and combined biofeedback conditions and increasing velocity during more challenging vibrotactile biofeedback conditions.

Young adults were able to use visual and combined biofeedback information to reduce their postural sway (indicated by a decrease of parameters RMS and Vap of CoP and L5) compared to control conditions in both types of support surface. Using vibrotactile biofeedback increased velocity of postural sway in AP direction occurred, which indicates activation of another type of strategy and subject's higher voluntary effort in order to achieve balance with minimal amplitudes (Krizková *et al* 1993). This type of biofeedback represents more challenging task than visual biofeedback, where the velocity significantly decreased comparing to control conditions. However, young adults were still able to use vibrotactile information effectively enough to minimize sway amplitudes and improve standing balance.

Elderly people reduced their postural sway effectively using visual and combined biofeedback mostly during the stance on unstable foam surface. It is known that stance on foam alters proprioceptive inputs from feet and causes higher reliance on visual information (Dozza *et al* 2005). Unstable environment helped elderly people to utilize the effect of additional sensory information to maximum in comparison with stable firm surface. The additional information was the most useful in the situations when it was needed the most.

Similarly as in young group, an increased velocity in AP direction occurred during TF conditions, but this strategy of velocity activation did not result in the reduction of amplitude in elderly group. This type of biofeedback was probably not enough intuitive for the body position control of elderly.

The impact of vibrotactile biofeedback might vary among people because of differences in the ability to learn how to use the vibrotactile biofeedback of body sway and how to interpret all sensory information to keep body sway within stability limits (Janssen *et al* 2010). Also both proprioception and tactile sensitivity decrease with age (Shumway-Cook & Woollacott 2000) demonstrating a reduction in vibratory and touch stimuli thresholds (Wall & Kentala 2005; Kadkade *et al* 2003).These sensory changes may impair orientation in space and appropriate balance strategies in elderly (Wall *et al* 2009). It seems that vibrotactile biofeedback is probably less intuitive than visual biofeedback. Dozza *et al* (2007a) hypothesized that practicing with vibrotactile biofeedback allowed integration to become more automated and to resembling the body's natural incorporation of sensory inputs.

Traditionally, and also in our study, repulsive cueing strategies (to move away from the activated tactor) have been used for balance-related application. Postural adjustment is considered to be a volitional response to a warning signal rather than non-volitional postural response (Lee *et al* 2012). However, according to Lee *et al* (2012, 2013) vibration-induced activity of cutaneous receptors is interpreted as a skin stretch corresponding to proprioceptive information. Cutaneous receptors provide exteroceptive and proprioceptive information similar to muscle spindles. They both encode movement kinematics and show directional sensitivity (Collins *et al* 2005). Likely attractive instructional cues ("Move in the direction of the tactile stimulus") should facilitate postural responses during vibrotactile biofeedback balance application by reducing the reaction time (response delay) for tactile cues.

Another disadvantage of our vibrotactile biofeedback device may be the only one setup of sensitivity for every subject without taking into account inter-individual variability. Our results indicate that the device setup of sensitivity should be changed for young, elderly and patients with various disabilities. Simplified vibrotactile device with only four vibrators related to anterior-posterior and medial-lateral directions used in our study may not provide useful continuous information about trunk tilting to the user. The increasing intensity of the vibration was probably not sufficient information for the elderly subjects. The multiple tactor display configuration when the tactor activation progresses from inferior to superior tactor row corresponding to a tilt (Dozza *et al* 2007b; Sienko *et al* 2012) or activation of the matrix zone of electrodes similar to tongue-placed tactile biofeedback (Vuillerme *et al* 2007) may provide more useful continuous information to minimize postural sway.

Observed differences in effectiveness of visual and vibrotactile biofeedback might be caused also by differences in ratio of feedback and feed-forward control (Dozza *et al* 2005). In visual biofeedback the feed-forward control expands over feedback control. Whereas vision provides continuous information about the external environment, it allows predictions of forthcoming events in the scene, the vibrotactile stimulus do not appear until the postural stability is disturbed. It seems that opportunity to predict postural changes is an important component of the effective biofeedback system. Therefore, using continuous vibrotactile information would be more intuitive and would allow subjects to predict postural changes similarly as with continuous visual information.

Despite of differences in effectiveness of single visual and single vibrotactile biofeedback, the multimodal biofeedback has been shown to significantly improve balance in healthy young and also in older adults (Verhoeff *et al* 2009; Davis *et al* 2010; Allum *et al* 2011).The values of parameters RMS and velocity in combined biofeedback conditions were very similar to single visual biofeedback conditions in both age groups. This finding points out stronger influence of visual biofeedback in reducing postural sway. Subjects evidently focused more on the stimulus which provided more useful information.

Conclusions

All biofeedback modalities (visual, vibrotactile and their combination) based on the information from lower trunk tilts helped to improve balance control, but with different efficiency. Visual biofeedback alone or in combination with vibrotactile biofeedback effectively improved standing balance in both young and elderly adults. Vibrotactile biofeedback had significant effect in reducing postural sway only in the young group. Elderly people may need more time for practicing with vibrotactile device. Moreover, it is desirable to optimize and customize biofeedback devices for each user (Kadkade *et al* 2003; Loughlin *et al* 2011), especially for elderly people and patients who could utilize the additional information for postural improvement in daily living.

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