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Impaired body balance control in adults with strabismus

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ABSTRACT

Previous studies revealed that people with binocular vision disorders have poor postural stability. However, most of the research was performed only on children and under binocular viewing condition, that could negatively affect the results. The aim of the current study was to investigate the influence of extra-ocular proprioceptive signals on postural stability in young adults with binocular vision disorders. Moreover, additional mental task was introduced to detect any postural compensation which could possibly hide the real influence of afferent extra-ocular signals.

21 Subjects, aged 18–45 yrs, with horizontal strabismus, were qualified to binocular vision disorders (B_{VD}) group. 41 subjects, aged 19–45 yrs, with no strabismus formed the normal binocular vision (N_{BV}) group. Posturography data were collected in 2 separate parts: (1) quiet standing (Single-Task), and (2) performance of a mental task while standing (Dual-Task). Each part consisted of three 60-s viewing conditions, with: (1) dominant/fellow eye (DE), (2) non-dominant/strabismic eye (NDE), and with (3) both eyes closed (EC). Subjects were looking at X located at the distance of 150 cm.

Generally, BVD group showed elevated body balance during quiet stance compared to NBV group. Interestingly, better stabilization in BVD group occurred under NDE viewing. Surprisingly, additional mental task improved the postural stability in BVD group almost to the level of NBV group. These findings emphasize the role of the eye-muscle signals in postural control and suggest that suitable vision therapy can be the appropriate way to improve body balance/motor functions in people with binocular vision disorders.

1. Introduction

Maintenance of postural stability is a multi-sensoral process which needs constant transformation of signals from the vestibular, somatosensory and visual systems (Brandt, Paulus, & Straube, 1986; Kapoula & Bucci, 2007; Matheron et al., 2007; Michalak, Przekoracka-Krawczyk, Nawrot, Woźniak, & Vieregge; ., unpublished data). Of these systems, the Romberg quotient shows that the visual one is most crucial in postural control since in normal subjects the sway area is 2–3 times larger with eyes closed than with eyes open (Edwards, 1946; Henriksson et al., 1967; Travis, 1945).

Gentaz (1988) suggested that one eye is usually more efficient in postural control, the so-called "postural eye" (not necessarily the dominant eye) allows for even better stability than when viewed binocularly. In some studies (Brandt, Paulus, & Straube, 1986; Kapoula & Bucci, 2007; Lê & Kapoula, 2006; Paulus et al., 1989), postural stability has been found to be impaired when the distance between eyes and the target increases due to a decrement of the angular size of retinal slip that makes it harder to detect. Another visual phenomenon to affect body equilibrium is motion parallax, that is relative motion of a far vs. a near object caused by body sway. This motion parallax has a positive influence on postural stability in both monocular and binocular viewing (Guerraz et al., 2001, 2000). What is more, Lê and Kapoula (2006) concluded that together with retinal slip and motion parallax, efferent signals (motor commands, top-down signals) and afferent signals (proprioceptive extra-ocular motor, bottom-up signals) from extra-ocular muscles related to vergence of the eyes, are also involved in postural stability. Convergence seems to significantly reinforce posture stability, which was shown in the studies on dyslexia (Kapoula & Bucci, 2007), strabismus (Gaertner et al., 2013a, 2013b) and interestingly, this effect is observed even with bilateral loss of vestibular function (Kapoula et al., 2013). It is commonly known that extra-ocular muscles have several proprioceptive receptors that provide information about the position of the eye in its orbit (Buisseret, 1995; Steinbach, 1987). Various studies (Brandt, Paulus, & Straube, 1986; Glasauer et al., 2005; Kapoula & Lê, 2006; Strupp et al., 2003) have shown that these signals affect

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postural control. Roll and Roll (1988) and Roll, Vedel, and Roll (1989) observed that vibration of individual extra-ocular muscles induce body sway significantly in the direction by stimulated muscles. Fox (1990) also stressed the role of proprioceptive signals from eye-muscles in postural stability. He found that in the dark, the body-sway was lower with both eyes open than with both eyes closed in quiet stance. This was explained by the influence of extra-ocular muscle tonicity on body balance control.

Legrand et al. (2011) reported that strabismus surgery is able to modify the quality of proprioceptive signals from extra-ocular muscles resulting in enhanced body stabilization. This occured even when binocular vision is not complete. Besides, Bucci et al. (2009) revealed that even non-strabismic children with abnormal vergence showed weaker postural stability compared to normal. This was explained as being from poor vergence input and/or immature compensatory mechanisms controlling postural stability (vestibular, somatosensory inputs or/and cerebellar processes).

The role of visual signals in body balance has been thoroughly investigated in strabismic children (Bronstein, 1995; Gentaz, 1991; Odenrick, Sandsted, & Lennerstrand, 1984). These studies indicated that strabismus influenced postural impairment. However, most of the studies aimed at comparing postural signals in strabismic subjects and normals were performed with both eyes open (Gaertner et al., 2013a; Legrand et al., 2011; Matsuo et al., 2006, 2010). Recently, Gaertner et al. (2013b) showed that in strabismic children, the effect of distance on posture depends on the direction of strabismic angle: the fixation depth at which postural stability was best was proximal for convergent strabismus and distal for divergent strabismus. The effort to overcome diplopia or vergence effort necessary to keep clear single vision could influence the center of pressure (CoP) excursions. Besides, as some strabismic subjects could have gross peripheral binocular vision (Gaertner et al., 2013b), the posture stability would be better due to peripheral cues from the strabismic eye (Amblard & Carblanc, 1980; Berencsi, Ishihara, & Imanaka, 2005). Thus, the separation of specific retinal and muscular signals from non-specific visual information (as diplopia or confusion) could appear difficult.

The aim of the current study was to investigate the influence of specific monocular oculomotor information on postural stability in young adults with binocular vision disorders (B_{VD} group). If the information from extra-ocular muscles is an important factor in postural stability, the B_{VD} group should exhibit significantly weaker body balance under both monocular viewing condition and with eyes closed (closing one's eyes does not eliminate proprioceptive signals related to eye muscle tension) (Matsuo et al., 2006). A posturography platform was used to evaluate the CoP excursions. Posturography was performed under monocular and eyes-closed condition to avoid the influence of destabilizing factors like diplopia, blurred vision or eyestrain caused by increased effort to maintain single clear vision under binocular viewing condition. It is important to note that we use a term extra-ocular muscle signals in our study, without distinguishing it between afferent or efferent signals, since it is not possible to judge which of them mainly influenced posturography results.

Since binocular vision deficits most often develop in childhood and adolescence, adults may have developed compensatory mechanisms (Bucci et al., 2009). As Friedrich et al. (2008) revealed, when the visual information is insufficient, compensation mechanisms such as vestibular, somatosensory and cerebellar processes can be activated to reach correct body balance. Furthermore, Peterka (2002) suggested, that if one sensory input is deficient, the other subsystem may compensate for the impairment through greater involvement in postural stability. Such compensatory mechanisms could hide the real influence of inadequate oculomotor signals on body balance. Similar motor compensatory mechanisms have been observed in dyslexia (Nicolson & Fawcett, 1990, 1999). It is possible that compensatory mechanisms may develop in B_{VD} adults. Therefore in the second part of the experiment, additional mental task (auditory Letter-Task) was performed while measuring the posturographic signals.

2. Material and methods

2.1. Participants

Seventy-three young adults were recruited from optometry students and strabismic patients of Laboratory of the Vision Science and Optometry at Adam Mickiewicz University and Optics and Optometry Center of Adam Mickiewicz Foundation in Poznań. Based on a medical interview, all were healthy without neurological, vestibular, musculoskeletal or orthopedic diseases. None were dyslexic or receiving medications known to affect balance. A vision examination, with special emphasis on binocular vision functions, was performed on each individual. This included an: extensive history interview, ocular dominance (fixating via hole task), refractive error, monocular and binocular visual acuity at far distance (Snellen's letter chart) with and without optical correction, amplitude of accommodation (push-up test), and monocular and binocular accommodative facility (accommodative flipper ±2D). Binocular vision was evaluated by the following tests: alternating cover test with prism bar (angle of strabismus/phoria), fusional vergence ranges (prism bar base-in and base-out); pola mirror, cheiroscope, tranaglyphs (Bernell©, series 500), Worth 4 dot, red lens (level of suppression and fusion), Titmus stereotest (Stereo Optical©) for stereopsis. The Red-lens test was performed in 9 positions of gaze to detect any extra-ocular muscle paralysis. We also evaluated near point of convergence, and ocular fixation by direct ophthalmoscopy (Heine©) and a retinal correspondence using both the Hering-Bielschowsky after-image and Bagolini striated glasses test. The detailed instructions of listed procedures are included in the literature (Borish, 1970; Caloroso & Rouse, 1993; Griffin & Grisham, 2002).

After the evaluation of visual functions, participants were divided into 2 groups. Subjects with any ocular pathology, refractive amblyopia, accommodative dysfunction, eccentric fixation, history of eye-muscle surgery, vertical or paralytic deviation were rejected from the study:

(1) Binocular vision disorders group (B_{VD}) – A total of 21 subjects (16 females, 5 males) with an age range of 18–45 years (mean 28.2, SD 9.1) with binocular vision disorders in either the eso- or exo-direction were placed in the B_{VD} group. Thirteen subjects demonstrated manifest strabismus (3 of them with esotropia, 10 of them were exotropic) and eight showed latent strabismus (decompansated exophoria[1] >10Δ at near and >4Δ at far). Six of them suffered from constant and fifteen from intermittent eye-deviation. Mean visual acuity of the non-dominant/strabismic eye was 20/22 (SD 20/65), while the mean visual acuity of the dominant/fellow eye was 20/17 (SD 20/170). Some individuals with manifest strabismus had peripheral stereoacuity, while the mean stereopsis of latent strabismus subjects was not less than 50 s of arc. Table 1 presents the visual parameters of each strabismic subject.

(2) Normal binocular vision group (N_{BV}) – Forty-one subjects (28 females, 13 males) with an age range of 19–45 years (mean 24.4, SD 7.1) and monocular visual acuities in normal range (20/20 or better), stereoacuity of minimum 50 s. of arc,

[1] Decompensated heterophoria – the kind of heterophoria which is accompanied by symptoms due to large angle of heterophoria or/and inadequate motor/sensory vergence fusional reserve (Griffin & Grisham, 2002; Millodot, 2000).

Table 1
Clinical characteristics of subjects with strabismus.

Subjects	Dominant eye	Angle of strabismus (prism D)	Visual acuity	Interocular suppression	Stereoacuity
1	RE	CET 18 far CET 25 near	DE 20/16 NDE 20/50	Constant	–
2	RE	CXT 16 far CXT 14 near	DE 20/16 NDE 20/33	Constant	200″
3	LE	IXT 4 far IXT 14 near	DE 20/20 NDE 20/20	–	40″
4	RE	IXT 12 far IXT 12 near	DE 20/16 NDE 20/16	–	40″
5	LE	IXT 22 far IXT 25 near	DE 20/22 NDE 20/60	Constant	–
6	RE	IXT 10 far IXT 18 near	DE 20/16 NDE 20/16	–	40″
7	LE	CET 20 far CET 25 near	DE 20/16 NDE 20/100	Constant	–
8	LE	IXT 12 far IXT 18 near	DE 20/16 NDE 20/16	–	40″
9	RE	IXT 4 far IXT 15 near	DE 20/16 NDE 20/20	–	50″
10	RE	IXT 6 far IXT 18 near	DE 20/16 NDE 20/16	–	50″
11	RE	CXT 30 far CXT 30 near	DE 20/16 NDE 20/20	Constant	–
12	RE	IXT 6 far IXT 20 near	DE 20/20 NDE 20/20	–	40″
13	RE	IXT 18 far IXT 25 near	DE 20/20 NDE 20/20	–	50″
14	RE	IXT 22 far IXT 26 near	DE 20/16 NDE 20/16	–	40″
15	RE	IXT 16 far IXT 20 near	DE 20/16 NDE 20/22	–	50″
16	RE	CET 8 far CET 8 near	DE 20/20 NDE 20/20	Constant	–
17	RE	IXT 18 far IXT 25 near	DE 20/16 NDE 20/20	Intermittent	50″
18	LE	IXT 20 far IXT 30 near	DE 20/16 NDE 20/20	Intermittent	40″
19	RE	CXT 20 far CXT 18 near	DE 20/16 NDE 20/20	Intermittent	400″
20	RE	IXT 14 far IXT 25 near	DE 20/16 NDE 20/20	–	50″
21	RE	IXT 4 far IXT 25 near	DE 20/16 NDE 20/20	–	40″

RE: right eye, LE: left eye, DE: dominant eye, NDE: non-dominant eye. Type of eye deviation: CXT: constant exotropia, IXT: intermittent exotropia, CET: constant esotropia. Interocular suppression was evaluated with the Bagolini striated glasses test.

with wide fusional vergence ranges and normal phoria values (<3 exo, <1 eso at far; <6 exo, <2 eso at near). None of them reported a strabismus history, interocular suppression, or eyestrain symptoms.

2.2. Equipment

Posturographic data in upright stance were collected by AMTI AccuSway Plus (Advanced Mechanical Technology, Inc., Watertown, MA) force platform consisting of a square metal plate (width 50×50 cm; height: 4.5 cm). The point of projection in the vertical reaction forces was registered and decomposed by the AMTI Balance Trainer software into CoP signal. CoP data were sampled at a frequency of 200 Hz and filtered by the 4th order low-pass Butterworth filter with a cut-off frequency of 10 Hz to eliminate measurement noise (Ruhe, Fejer, & Walker, 2010; Schubert et al., 2012). Four parameters of CoP signal were analyzed to quantify postural control: standard deviation of antero-posterior (AP) and mediolateral (ML) sway, mean velocity od CoP (MV) and sway area (SA- the area of the ellipse that encloses 95% of postural sway).

2.3. Procedure

Static upright stance posturography measurements were carried out in a white-wall room with green mat floor, medium illumination, and with no objects or furniture in the subject's field of vision that could facilitate the posture (Guerraz et al., 2000). During the test, individuals wore their appropriate spectacle or contact lens correction.

Subjects stood barefoot on the force platform with a static, anatomically referenced posture (arms hanging along the body). The feet were positioned symmetrically at a comfortable angle, with heels 6 cm apart. After proper adjusting, each subject's foot position was traced by black pen on a clear sheet of paper was placed on the platform surface. This form was used to place the feet in exactly the same place for each subsequent trial.

The participants were instructed while standing, to maintain the straight ahead gaze position and constantly view a black letter X located on a white wall at eye level, at the distance of 150 cm. The angular size of the letter X was adjusted to reach 1° and the angle of vergence was about 2.3°.

Postural control was quantified in 2 separate parts: (1) quiet standing (Single-Task), and (2) simultaneous performance of a mental task (described below) while standing (Dual-Task). Each part consisted of three 60 s viewing conditions, with: (1) dominant eye (DE), (2) non-dominant eye (NDE), and with (3) both eyes closed (EC). The order of the viewing conditions was counterbalanced between participants. Each condition began with a command "start" given by the investigator and posturographic signals started to be recorded 5 s after. A soft, black eye patch was used to occlude the eye and the subject was asked to keep both eyes open during all monocular viewing conditions. The occluder was fixed on subject's forehead for the rest of the experiment.

Both experimental parts were identical, except the dual task was included. The Single-Task part was performed before the Dual-Task. A 5-min rest period was given between tests. During this break, the subjects were required to walk.

The investigation adhered to the tenets of the Declaration of Helsinki. An informed consent was obtained from all subjects after the explanation of the aim and nature of the procedure.

2.3.1. Mental task

The Dual-Task was composed of quiet stance posturography together with a modified auditory vigilance task (Letter-Task) proposed by Lang and Bastian (2002). Individuals were asked to listen to the recordings of 14-letter sequences. Each sequence consisted of a random series of the same four letters (A, K, O, and L) where one of the letter was treated as a target-letter. The target-letter was changed for each 60 s trial. 5 sequences were performed for each 60 s trial. The sequence started with the command "start", followed by 14 letters (at 1.75 Hz, 8-s duration), and then finished with the word "stop". Before the individual trial began the participant was informed of the target letter. The subjects were then asked to identify and state the number of times when the target-letter was heard.

Because of small amount of errors (1–2) in the Letter-Task, the number of wrong responses were not included in the study. The subject sat on a chair for 30-s rest period, while the investigator was zeroing the platform.

2.4. Statistical analyses

Four posturographic parameters (AP, ML, SA, MV) obtained from the Single-Task condition were statistically evaluated using the analyses of variance (ANOVAs) for repeated measurements with two within-subject factors: (1) *group* (B_{VD} vs. N_{BV}), and (2) *viewing condition* (DE vs. NDE vs. EC). In the case of Dual-Task, in order to check the effect of mental task on posture, ANOVA for repeated measurements with two within-subject factors: (1) *task* (Single vs. Dual), and (2) *visual condition* (DE vs. NDE vs. EC), was performed.

If necessary, the number of degrees was corrected according to the Huynh-Feldt method. The differences were considered significant with *p*-value equal or less than 0.05.

3. Results

3.1. Single-Task

3.1.1. Medio-lateral sway

The results are presented in Fig. 1 (left side). The mean medio-lateral (ML) sway was larger for B_{VD} group than for N_{BV} group: 3.8 vs. 3.1 mm, which was confirmed by the significant main effect of *group* ($F(1,60) = 5.58$, $p = 0.021$, $\eta^2 = 0.09$). Also, the main effect of *viewing condition* was observed in ML sway ($F(2,118) = 5.21$, $p = 0.007$, $\eta^2 = 0.08$). Post-hoc analysis (Tukey test) showed that larger ML sway in closed eyes condition was observed ($ML_{EC} = 3.7$ mm) when compared to non-dominant eye ($ML_{NDE} = 3.2$ mm) ($p = 0.011$) but not when compared to dominant eye ($ML_{DE} = 3.4$ mm) ($p = 0.054$). What is interesting, B_{VD} group showed a tendency to decrease lateral sway when looking with non-dominant/strabismic eye compared to dominant eye also (Fig. 1b) but this effect did not reach significant level, what was indicated by the lack of *group* × *viewing condition* interaction ($F(2,118) = 2.52$, $p = 0.086$, $\eta^2 = 0.04$).

3.1.2. Antero-posterior sway

In contrast, no significant differences were observed in antero-posterior (AP) sway between the groups ($AP_{BVD} = 5.6$ vs. $AP_{NBV} = 4.8$ mm; Fig. 1c) ($F(1,60) = 3.42$, $p = 0.070$, $\eta^2 = 0.05$), as well as between viewing conditions ($AP_{DE} = 5.1$, $AP_{NDE} = 5.2$, $AP_{EC} = 5.4$ mm) ($F(2,120) = 0.74$, $p = 0.478$, $\eta^2 = 0.01$). Additionally, insignificant interaction was observed between the *group* and *viewing condition* ($F(2,120) = 0.65$, $p = 0.525$, $\eta^2 = 0.01$; Fig. 1d).

3.1.3. Sway area (area of 95% confidence ellipse)

As Fig. 2a shows, track of CoP covered much larger area in the B_{VD} group than in the N_{BV} group ($SA_{BVD} = 420$ vs. $SA_{NBV} = 280$ mm^2), which was confirmed by significant main effect of the group ($F(1,60) = 7.20$, $p = 0.009$, $\eta^2 = 0.11$). What is crucial, the difference between groups was dependant on visual condition, which suggests significant *group* × *viewing condition* interaction ($F(2,120) = 3.13$, $p = 0.047$, $\eta^2 = 0.05$). Post-hoc tests (Fig. 2b) showed that higher sway area value for B_{VD} compared to N_{BV} occurred when viewing with dominant eye ($p = 0.048$) and with eyes closed ($p = 0.040$) but not with non-dominant eye ($p = 0.992$).

Additional post hoc tests performed between DE and EC conditions in both groups showed that none of them achieved significant

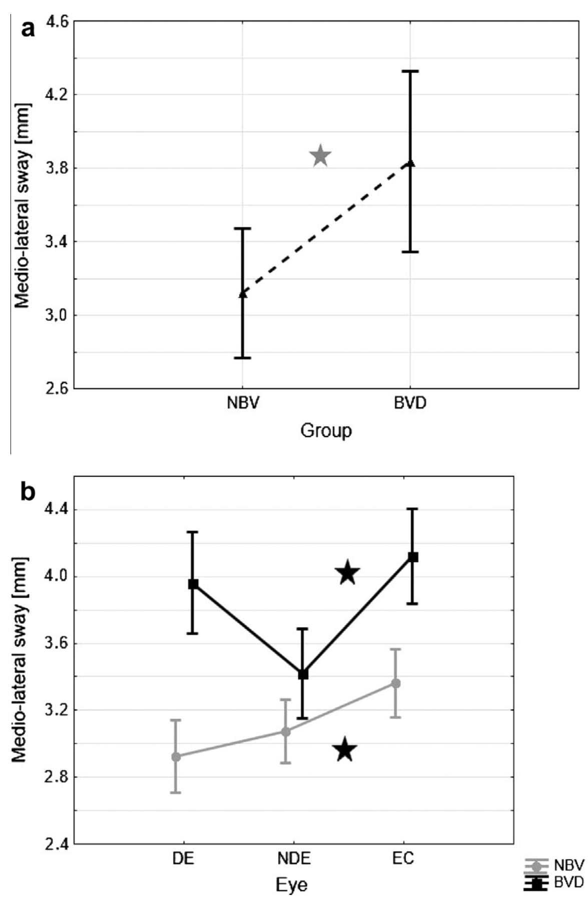

Fig. 1. Medio-lateral and antero-posterior sway during Single-Task. Circles indicate data for N_{BV} group, squares for B_{VD} group. Error bars indicate standard error. N_{BV} – normal binocular vision, B_{VD} – binocular vision disorders, DE – dominant/fellow eye, NDE – non-dominant/strabismic eye, EC – eyes closed. Gray star indicates $p < 0.05$ between groups; black star indicates $p < 0.05$ between visual conditions.

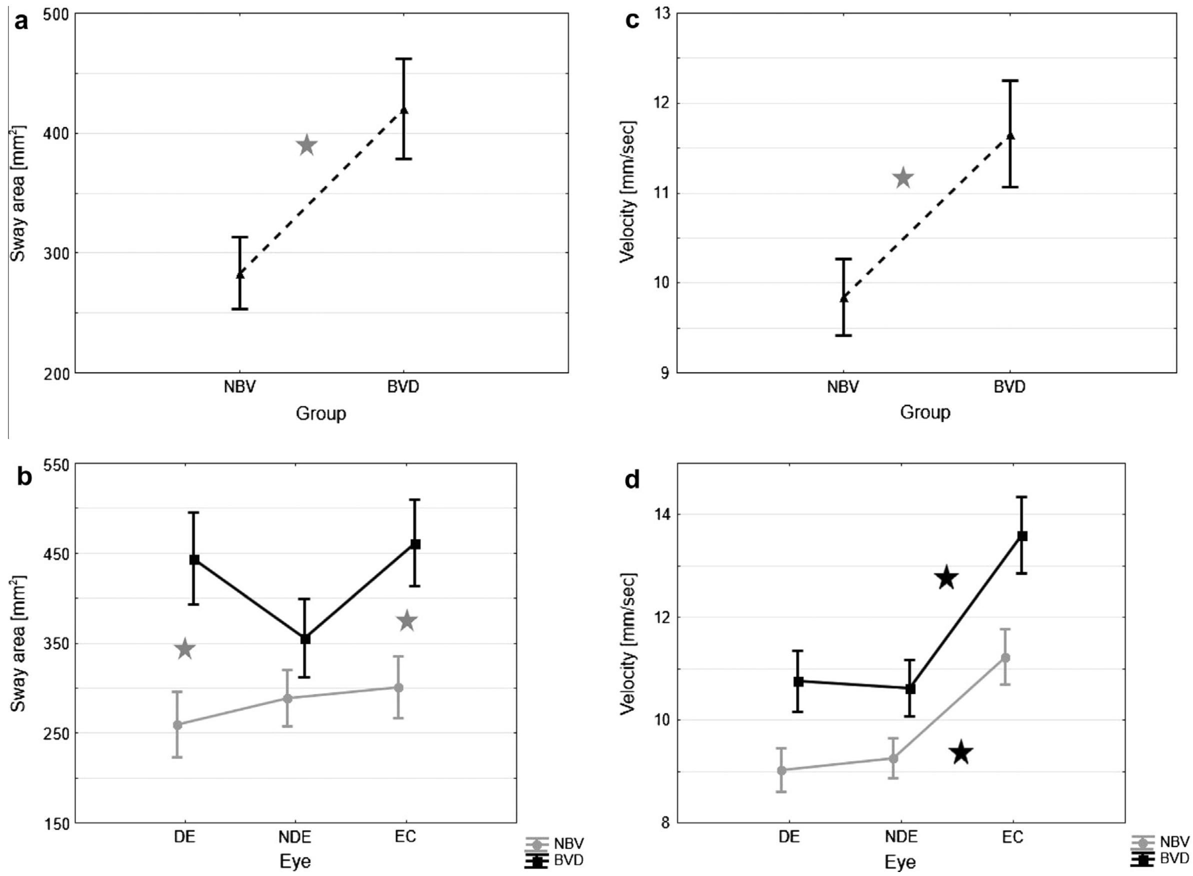

Fig. 2. Sway area and velocity of CoP during Single-Task. Circles indicate data for N_{BV} group, squares for B_{VD} group. Error bars indicate standard error. N_{BV} – normal binocular vision, B_{VD} – binocular vision disorders, DE – dominant/fellow eye, NDE – non-dominant/strabismic eye, EC – eyes closed. Gray star indicates $p < 0.05$ between groups; black star indicates $p < 0.05$ between visual conditions.

benefits from monocular vision, compared to the eyes closed condition. SA parameter for DE and EC conditions in B_{VD} group achieved similar level ($SA_{DE} = 444$ vs. $SA_{EC} = 461$ mm^2, $p = 0.998$). In N_{BV} group monocular viewing improved SA parameter when compared to eyes closed condition ($SA_{DE} = 259$ vs. $SA_{EC} = 301$ mm^2) but this difference was also statistically insignificant ($p = 0.701$).

3.1.4. Velocity

Velocity parameters (V) are presented in Fig. 2 (right side). Mean V value was greater in the B_{VD} than in the N_{BV} group ($V_{BVD} = 11.7$ vs. $V_{NBV} = 9.8$ mm/s). We also found velocity increment when both eyes were closed ($V_{EC} = 12.4$ mm/s) compared to monocular condition ($V_{DE/NDE} = 9.9$ mm/s). These differences were affirmed by significant main effect of the *group* ($F(1,60) = 6.19$, $p = 0.016$, $\eta^2 = 0.09$) and main effect of *viewing condition* ($F(2,104) = 71.56$, $p < 0.001$, $\eta^2 = 0.54$). As can be seen in Fig. 2d, increased CoP velocity was observed in both groups, shown by insignificant *group* × *visual condition* interaction ($F(2,104) = 2.19$, $p = 0.124$, $\eta^2 = 0.04$).

3.2. Single- vs. Dual-Task

3.2.1. Medio-lateral sway

When the results obtained in the Single- and Dual-Task for the B_{VD} group were compared, differences in main effect of the *task* were found. As can be seen in Fig. 3a reduced medio-lateral (ML) sway in the Dual-Task was observed ($ML_{DT} = 3.2$ mm) compared to the Single-Task ($ML_{ST} = 3.8$ mm) ($F(1,20) = 13.73$, $p = 0.01$, $\eta^2 = 0.41$). In this subject group, ML sway during non-dominant eye viewing was significantly smaller than with dominant eye viewing ($ML_{NDE} = 3.2$ vs. $ML_{DE} = 3.6$ mm) and closed eyes condition ($ML_{NDE} = 3.2$ vs. $ML_{DE} = 3.7$ mm). This observation was demonstrated by a significant main effect of *viewing condition* ($F(2,40) = 4.14$, $p = 0.023$, $\eta^2 = 0.17$). This tendency was present both in Single- and Dual-Task, indicated by insignificant interaction between *task* and *viewing condition* factors ($F(2,35) = 1.74$, $p = 0.193$, $\eta^2 = 0.08$; Fig. 3b).

Fig. 3a also shows that the mental task had no influence on the mean ML sway in the N_{BV} group ($ML_{ST} = 3.1$ vs. $ML_{DT} = 3.0$ mm; $F(1,40) = 0.40$, $p = 0.532$, $\eta^2 = 0.01$). In contrast to B_{VD} group, the smallest mean ML sway was observed under DE viewing, greater sway under NDE viewing and greatest under EC viewing condition ($ML_{DE} = 2.9$ vs. $ML_{NDE} = 3.1$ vs. $ML_{EC} = 3.3$ mm; $F(2,76) = 3.29$, $p = 0.045$, $\eta^2 = 0.08$). However, post hoc test showed that significant differences were observed only between DE and EC condition ($p = 0.033$). Fig. 3b showed that the mental task did not affect ML sway under any visual condition which was indicated by insignificant *task* x *visual condition* interaction ($F(2,75) = 0.31$, $p = 0.724$, $\eta^2 = 0.01$).

3.2.2. Antero-posterior sway

The additional mental task introduced for B_{VD} group impacted the CoP antero-posterior excursions. Mean AP sway decreased from 5.0 to 4.5 mm, in the Single- and Dual-Task, respectively (Fig. 3c; $F(1,20) = 12.59$, $p = 0.002$, $\eta^2 = 0.37$). The lack of *task* × *visual condition* interaction ($F(2,40) = 0.60$, $p = 0.554$, $\eta^2 = 0.03$), indicated that reduction of AP sway occurred in all three viewing condition (Fig. 3d).

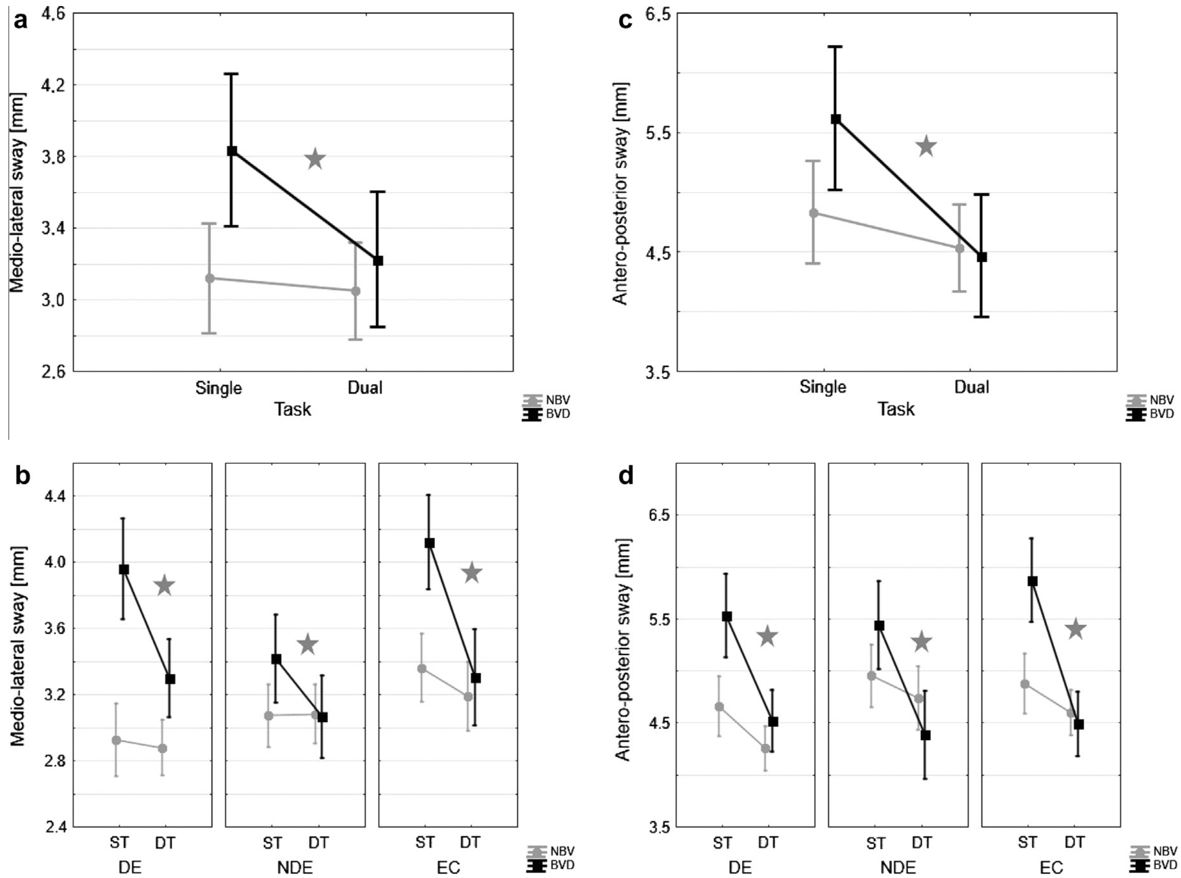

Fig. 3. Medio-lateral and antero-posterior sway during Single- and Dual-Task. Circles and gray lines indicate data for N_{BV} group, squares and black lines – for B_{VD} group. Error bars indicate standard error. N_{BV} – normal binocular vision group, B_{VD} – binocular vision disorders group, DE – dominant/fellow eye, NDE – non-dominant/strabismic eye, EC – eyes closed; ST – Single-Task, DT – Dual-Task; gray star indicates $p < 0.05$ between the tasks.

Compared to the B_{VD} group, the cognitive task for the N_{BV} group reduced the AP sway only slightly (Fig. 3c) and this change was statistically insignificant as evidenced by a lack of significant main effect of *task*, *viewing condition* and *task* × *viewing condition* interaction ($p > 0.05$).

3.2.3. Sway area (area of 95th percentile ellipse)

The impact of mental task on posture in the B_{VD} group was observed also in the sway area (SA) parameter. Compared to the Single-Task, mean value of SA decreased from 420 mm^2 in the Single-Task to 282 mm^2 in the Dual-Task (Fig. 4a; $F(1,20) = 25{,}33$, $p < 0.001$, $\eta^2 = 0.56$). As it is presented in Fig. 4b, this decrement did not depend on the viewing condition, hence the effect occurred under DE and NDE viewing as well as with EC ($F(2,39) = 1.38$, $p = 0.263$, $\eta^2 = 0.06$).

In contrast, there was no influence of cognitive task on the SA parameter in the N_{BV} group (Fig. 4a and d), where no statistically significant main effect or interactions between factors were obtained ($p > 0.05$).

3.2.4. Velocity

B_{VD} group demonstrated also differences in the CoP velocity between the Single- and Dual-Task ($V_{ST} = 11.7$ vs. $V_{DT} = 10.7$ mm/s; $F(1,20) = 7.32$, $p = 0.014$, $\eta^2 = 0.27$), which was presented in Fig. 4c. However, the significant influence of the task was observed only with eyes closed, but not when eyes were open, which was confirmed by significant *task* × *viewing condition* interaction ($F(2,37) = 21.06$, $p < 0.001$, $\eta^2 = 0.52$). As it presented in Fig. 4d, significant decrement of CoP velocity after the mental task was introduced, appeared only with eyes closed (post hoc, $p = 0.010$), while velocity parameters in monocular viewing conditions remained comparable between the two tasks (post hoc, $p > 0.050$).

Fig. 4c shows that the mean *V* value occurred for the N_{BV} group in the Single-Task ($V_{ST} = 9.8$ mm/s) was comparable to the Dual-Task ($V_{DT} = 10.1$ mm/s), ($F(1,40) = 1.04$, $p = 0.314$, $\eta^2 = 0.03$). As can be seen also in Fig. 4d, reduction of COP velocity in Dual-Task was small and not significant for any visual condition, what was proved by insignificant *task* × *viewing condition* interaction ($F(2,71) = 1.55$, $p = 0.219$, $\eta^2 = 0.04$).

4. Discussion

The current study attempted to assess the influence of extra-ocular muscle signals on posture control in strabismic subjects.

Tests conducted under monocular viewing allowed to eliminate such nonspecific factors as diplopia or confusion that may hinder the postural stability. In this way, we were able to examine the influence of specific factors on posture control, that is, extra-ocular muscles signals and attention. The results obtained here, have shown that possibly inaccurate signals related to extra-ocular muscles have a strong impact on body balance and this effect can be observed even in adults. Moreover an additional mental task in the second part of the study allowed us to check if adult subjects with B_{VD} were able to develop postural compensatory mechanisms used for better body balance.

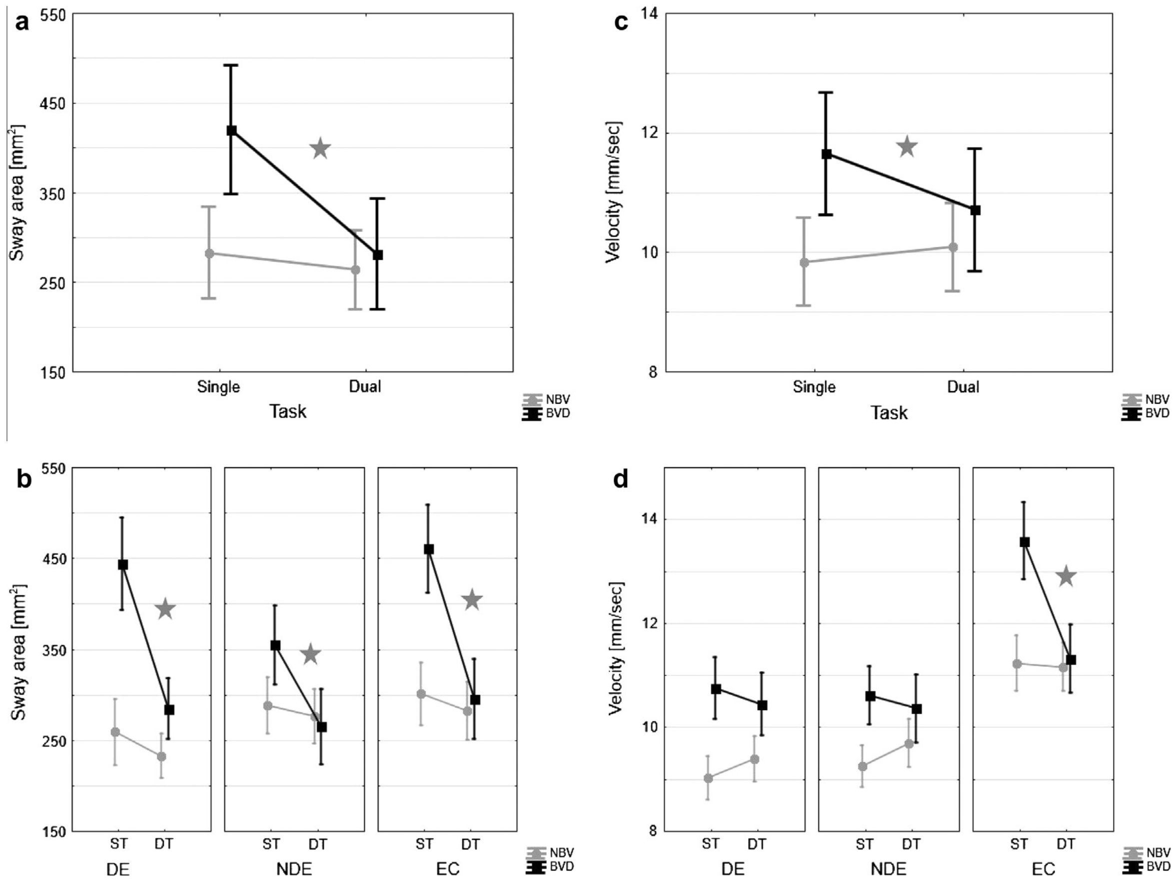

Fig. 4. Sway area and velocity of CoP during Single- and Dual-Task. Circles indicate data for N_{BV} group, squares for B_{VD} group. Error bars indicate standard error. N_{BV} – normal binocular vision, B_{VD} – binocular vision disorders, DE – dominant/fellow eye, NDE – non-dominant/strabismic eye, EC – eyes closed, ST – Single-Task, DT – Dual-Task; gray star indicates $p < 0.05$ between the tasks.

4.1. Postural control in Single-Task

In general, B_{VD} group showed significantly worse body balance control than N_{BV} subjects, in quiet stance condition. The difference between groups was observed mainly in side-by-side sway and sway area, but not in antero-posterior excursions. We showed also that adult strabismic subjects have poor postural stability even under monocular viewing condition when compared to a normal group. This effect should not be related to diplopia or confusion of the visual signals coming from the two eyes because examined monocularly.

Interestingly, normal group as well as strabismic group demonstrated similar CoP displacement when viewing with dominant eye and with eyes closed, which suggests weak impact of visual retinal information on controlling the posture when visual stimulus was placed at far distance. It is not surprising since previous studies have shown (Brandt, Paulus, & Straube, 1986; Kapoula & Lê, 2006; Lê & Kapoula, 2006; Paulus et al., 1989) that visual cues play important role in body balance mainly in the near visual space, where retinal slip and convergence tone are larger than in far visual space. The distance 150 cm used in our study is treated as extra-personal (far) space (Tzelepi, Lutz, & Kapoula, 2004) where convergence angle (2.3°) and angular size of retinal slip were small. The results of our study supports the view that at far distances, non-visual signals play crucial role in body balance control (Lê & Kapoula, 2006). Nonetheless, the effect of visual information cannot be neglected completely at this distance, as observed in the mean velocity parameter obtained in our study. We found that velocity significantly increased with eyes closed compared to monocular viewing conditions. It is believed that an increment of CoP velocity is related to the leg muscles activity, which reflects more energy necessary to stabilize posture (Amiridis, Hatzitaki, & Arabatzi, 2003; Jonsson, Seiger, & Hirschfeld, 2005). The result of a higher mean velocity value with eyes closed compared to monocular vision, suggests that subjects from both of our groups put more effort in maintaining body balance when retinal cues were absent.

To keep stable body balance, non-visual signals were compared with information coming from both the retinas and eye muscles. It seems that one of the most important visual cues when viewing in extra-personal space are the extra-ocular proprioceptive signals (Ivanenko, Grasso, & Lacquaniti, 2000; Roll, Vedel, & Roll, 1989). It was suggested by others (Isotalo & Kapoula, 2004) that binocular vision and stereopsis play little role in postural control in quiet stance. At the same time however changes in proprioceptive signals and eye-muscle tonicity may affect body balance (Fox, 1990).

Our study, together with others (Fox, 1990; Isotalo & Kapoula, 2004), shows that subjects with manifest or latent strabismus may demonstrate poor postural stability that is not related to the lack of binocularity, stereopsis, or lower visual functions from amblyopic eye, but as an effect of weak oculomotor signals. The influence of extra-ocular muscle tonicity on posture control was also observed by Matsuo et al. (2010). They measured posturographic signals in children with strabismus before and after eye-muscle surgery. It was observed that 3 days after surgery, body balance significantly decreased and was interpreted as the effect of proprioceptive changes in muscle tone. In a contrary paper, Legrand et al. (2011) reported that eye-muscle surgery improved body balance by an increase in muscle tonicity. These studies together with results of our experiment prove that ocular muscle tonicity plays a more important role in the control of posture than does binocular vision per se.

The role of the oculomotor signals in postural stability, was also examined by Kapoula and Lê (2006). During depression or elevation of the eyes, healthy participants showed better postural stability than when looking straight-ahead. It was interpreted as the reinforcement of extra-ocular signals when inferior and superior (recti and oblique) muscles were more active while looking down or up. The additional input from eye muscles may have improved stability. Similar effects could possibly be observed when both medial extra-ocular muscles are contracted during convergence. Such a condition also improved balance (Kapoula & Lê, 2006).

Better stabilization in B_{VD} group when viewing with non-dominant/strabismic eye was the most important and surprising observation in our study. Improvement in body stabilization was observed in CoP parameters as side-by-side sway and sway area, but not in CoP velocity. As it was mentioned above, increased CoP velocity is related to the energy given by leg muscle activity in order to stabilize posture (Lê & Kapoula, 2006). The increase in CoP velocity together with decrease in CoP excursions would suggest that stabilization was not improved but participants used different stabilization strategy to avoid fall: stronger legs muscles activation to keep better body balance. This effect should be reflected in smaller CoP excursions but higher CoP velocity. However, in our study, both CoP excursions and CoP velocity decrease was found when viewing with the non-dominant eye, when compared to eyes closed condition. This observation proves a real beneficial influence of strabismic eye fixation on posture control.

Improvement in postural stabilization in the cases of exo-deviations when fixation was performed at far distance, was observed also by Gaertner et al. (2013a,b). It is important to note that the majority of our strabismic subjects also suffered from exo-deviation (divergent heterotropia: 18 of 21 total participants). Exo-deviation is related to weak extra-ocular muscle tonicity. Based on this phenomenon and results obtained in the present study, we can speculate that better body stabilization when viewing with strabismic eye reflects reinforcement in extra-ocular muscles tonicity, which is related mainly to the exo-deviations groups of strabismic subjects. Future studies should focus on exploring the influence of monocular viewing at far and near distances on posture control in relation to eso- and exo-deviation cases. It may answer the question whether viewing with worse/strabismic eye can stabilize the posture by the increase in extra-ocular muscles tonicity in general, or it is dependant on the type of eye-deviation.

Taken together, when viewing with dominant eye or with eyes closed, postural stability in B_{VD} group was worse than when viewing with non-dominant eye. This suggests that when the non-dominant eye/strabismic eye is turned to the tonic position (as it happens when viewing with fellow eye and strabismic eye is occluded), extra-ocular signals coming from the non-dominant eye became weak and may disturb posture. When fixation is controlled by this non-dominant weaker eye, eye muscle tonicity must increase to keep stable fixation. This muscle action may then increase extra-ocular signals and improve postural control.

4.2. Postural control in dual (mental) task

In the second part of the experiment additional mental task was performed while maintaining upright posture. As it was mentioned in the introduction, motor dysfunctions and postural control deficits can be compensated for by higher cortical activity and at the same time would eliminate the possibility of detecting motor dysfunctions. This effect was observed in dyslexic children (Nicolson & Fawcett, 1990) whose balance control was impaired while standing with the addition of a cognitive task compared to Single-Task without any mental effort. Similar effects were found in patients with vestibular dysfunctions whose reactions were weak during the cognitive task, (Kerr, Condon, & McDonald, 1985; Lajoie et al., 1993; Maylor & Wing, 1996). The interaction of cognitive task with motor behavior was also observed in cerebellar patients (Lang & Bastian, 2002). It suggests that both central executive resources and attention were required to perform both tasks (Lang & Bastian, 2002). To detect real motor deficits it has been suggested that an additional cognitive task be introduced that will engage higher cortical regions. Since postural control is not fully automatically regulated, some part of attention is always required in upright stance (Lajoie et al., 1993). The competitive mental task requires attentional resources that then cannot be used for body balance control. It was expected that in our adult B_{VD} group some compensatory mechanisms would be observed, that would improve posture only in quiet stance, but not when performance of more complex task was required.

To detect motor-compensatory effects, the additional cognitive task was introduced in the second part of our experiment. The mental task was based on an auditory vigilance task (Letter-Task) proposed by Lang and Bastian (2002). In this condition, attention would be divided between mental counting and posture control to assess if any motor compensation developed in the B_{VD} group. The obtained results were surprising. It is important to stress that the cognitive task neither disturbed the posture nor was neutral for body sway. The mental task used in quiet stance improved body sway in the B_{VD} group where postural control reached the normal level. This phenomenon could be explained in two ways.

First, it suggests that improper oculomotor signals, which are related to poor body stabilization, may be inhibited while concentrating on non-visual cognitive task. Human studies (Grafton, Hazeltine, & Ivry, 1995; Jenkins et al., 1994) revealed that sensory input to some modality could decrease the level of arousal in areas related to other modalities (Lang & Bastian, 2002). Considered in this way, the improvement of body balance observed in Dual-Task in our B_{VD} group would be the effect of improper visual and/or oculomotor signal suppression, when subject was focused on the mental task. Compared to our results, this explanation looks rather doubtful. Impaired oculomotor signals should influence body balance especially when non-dominant/strabismic eye was viewing, and should have been observed in the first part of the experiment, where Single-Task was performed. The opposite was observed in our study. Weak body balance was improved during a mental task, especially when subjects were viewing with the better/dominant eye and with eyes closed. This was not observed when viewing with non-dominant/strabismic eye. Interestingly, when viewing with weaker eye that has lower visual acuity and poor oculomotor signals, posturographic parameters improved. These effects eliminates the possible disturbing influence of weak retinal signals on posture and the inhibition of these signals during Dual-Task.

The second explanation could be the influence of attention (Maki & McLlroy, 1996; Maki & Whitelaw, 1993) and the activation of information processing necessary for body balance control (Bouisset & Duchéné, 1994; Maki & Whitelaw, 1993). It was shown that the implementation of a cognitive task during body balance measurement improves body balance via attention and working memory mechanisms (Dault et al., 2001). In healthy young individuals in a Dual-Task paradigm, CoP displacement was smaller than in the Single-Task, which was interpreted as more body stiffness by getting more general arousal (Dault et al., 2001; Hunter & Hoffman, 2001; Yardley et al., 2001). Holmes et al. (2010) in their study on Parkinson's disease (PD) proposed different interpretation of beneficial effect of Dual-Task on postural control. With the high complexity of the mental task, patients with PD showed better body balance than an age-matched healthy control group. It was explained by overstraining their body in order to focus their attention on mental task, without losing their balance (Holmes et al., 2010). With that kind of paradigm, attention resources must be divided between cognitive task and posture control. This shows an increased risk of one losing their balance. The results obtained in our study can be explained in a similar way. In order to avoid falling down, the B_{VD} participants' body could have gotten more rigid thus lowering the possibility of the fall.

Indirect evidence of attention influencing tonicity comes from a study on cats when the level of attention affected extra-ocular muscle tonus (Eliasson, Hyde, & Bach-y-Rita, 1957). Eyes position and eye movements are controlled by subcortical and cortical areas (Pierrot-Deseilligny, Milea, & Muri, 2004; Suzuki, 2007). The frontal cortical region is involved in voluntary eye movements (Connolly et al., 2005) as well as in convergence and accommodation (Gamlin, 2002; Gamlin & Yoon, 2000). Additionally, cortical activity is considered to exert inhibition on the tonus of extra-ocular muscles (Adler, 1965; Cogan, 1956). Studies on strabismic subjects showed that hyper-excitability induced eso-tonus, increasing the eso-deviation of the eyes (more convergent eyes position) or a decrease in the exo-deviation (less divergent eyes position) (Jampolsky, 1970). The influence of emotion or an over-altered state could increase extra-ocular muscle tonicity, This is often observed during ophthalmic/optometric examination when higher eso-tonus may mask real exo-deviation of the eyes (Jampolsky, 1970). These observations together with the results from the current study suggest that mental effort might influence not only skeletal muscles tonus but also extra-ocular muscles activity. Future studies using EMG measurements and Eyetracker would explore the effect of Dual-Task on muscle activity and eyes position in strabismic patients.

Moreover, mental task used in our study most likely engaged complex neural pathways connecting many brain structures that may be linked to those controlling gait and posture (Al-Yahya et al., 2011). It is possible that binocular misalignment is related to neural dysfunction of some structures in this network. An additional mental task may activate this structure and reinforce signals needed for maintaining posture. This interpretation seems apt but the results of the current study are far from indicating which brain structure would be responsible for the effects obtained here. In our B_{VD} group, the cerebellum may be the structure associated with poor body balance and eye misalignment. It is commonly known that cerebellum is responsible for the integration of signal to the limb position coming from basal ganglia, with signals from vestibular nucleus and motor cortex (Martin, 1996). This multimodal information must be integrated in the cerebellum to maintain stable posture. The cerebellum plays an important role in eye movement coordination and eye alignment. Various studies revealed that cerebellar dysfunctions may evoke strabismus (Lee et al., 2009; Pokharel & Siatkowski, 2004) and improper eye muscle coordination (Burde et al., 1975; Gamlin, 2002). While the cerebellum is considered to be responsible for motor control, recent studies showed that some part of this structure is also related to cognitive functions (Allen et al., 1997; Levisohn, Cronin-Golomb, & Schnahmann, 2000; Riva & Giorgi, 2000) and orientation of attention (Allen et al., 1997; Townsend et al., 1999). It was possible that attentional effort required for the mental task in our study provoked a more aroused state and stronger activation in the area of cerebellum and in network linked to posture control. Clearly, further research is needed to explore this topic.

4.3. The role of the vision therapy on extra-ocular tonus

When one considers adult subjects with strabismus and amblyopia, any vision therapy (VT) and/or eye-muscle surgery is usually treated as cosmetic cure only. Central vision acuity improvement, fusion and stereopsis is believed not possible to achieve (Griffin & Grisham, 2002). Since oculomotor signals are important cues for body balance control, it seems reasonable to consider vision therapy also in adult subjects. Additionally, increase in extra-ocular muscle tonicity and reinforcement of peripheral vision through active vision therapy, may influence not only vision but also motor control and posturographic signals in adults. Thus, vision therapy of strabismus should be focused not only on the improvement in visual acuity and binocular vision (fusion, stereopsis) but also on the increase in afferent/efferent eye-muscles signals. An increase in eye-muscle tonicity seems to play a very important role in visuo-motor coordination and body balance even in individuals who are not able to achieve full binocular vision and stereopsis.

Benefits of additional mental task on posturographic parameters in B_{VD} group also suggests that active vision therapy (optometric vision training, orthoptic) is able to improve visual and/or posturographic parameters by using compensatory mechanism enhancement. It is possible that better eyes position and/or vergence parameters after active vision therapy are the effect of activation in higher level cortical regions as the frontal and parietal areas (Alvarez et al., 2010). The improvement in visual functions on optometric/orthoptic tests after brief vision training may not be caused by the direct enhancement of vergence system or muscle stiffness but rather by compensatory mechanisms. If so, visual asthenopic symptoms might be still perceptible by the subject when she/he performs a more complex cognitive task. Thus, in planning vision therapy, it seems reasonable not only to obtain proper vision parameters on simple visual tasks but also to automatize the acquired skills through the regular and long-term vision training (Nawrot, Michalak, & Przekoracka-Krawczyk, 2013). This kind of long-term active therapy is used in behavioral optometry methods (Barrett, 2009).

Moreover, when using posturography as a method for effectiveness of any therapy, it is important to introduce additional cognitive task, in order to detect any compensatory effects occurred or developed during the therapy.

5. Conclusions

In conclusion, this study obtained that, when compared to normals, adults with binocular vision disorders have elevated body sway which is not directly caused by the lack of binocularity or improper binocular visual signal but may be related rather to poor oculomotor signals. No postural compensatory mechanisms are developed in these subjects since additional mental task do not disturb the posture, but, surprisingly, improve the body balance, compared to quiet stance condition.

It seems reasonable that active vision therapy or eye-muscle surgery, focused on reinforcement of the extra-ocular muscle signals are able to improve postural control in adults, although the binocularity is not fully achieved.

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