ACTA NEUROBIOLOGIAE EXPERIMENTALIS

Research paper Acta Neurobiol Exp 2014, 74: 433–442

Assessment of postural stability in young healthy subjects based on directional features of posturographic data: Vision and gender effects

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Directional characteristics of postural sway and their impact on postural stability control (PSC) still need to be clarified. To assess the directional characteristics of PSC, center-of-pressure (COP) while standing quiet was recorded and analyzed in 46 young healthy subjects. The participants completed five 60-s trials with 'eyes open' and five with 'eyes closed'. The control asymmetry was characterized using three standardized COP measures: mean sway velocity (V), sway ratio (SR), and sway directional index (DI). The COP data were low-pass filtered at 10 Hz. In such conditions the V, SR and DI revealed consistent and unique differences in both the anteroposterior (AP) and the mediolateral (ML) controls. Each of the COP measures showed the involvement of different neuromuscular and biomechanical mechanisms in the stabilization of standing posture. The DI documented a very stable proportion between frontal and saggital controls, with roughly 60% of the swaying movements being performed in the AP direction. The AP DI was significantly higher in comparison with the ML value (0.71±0.04 vs. 0.55±0.06). This proportion remained at the same level in both experimental groups and it was only slightly affected by the visual conditions. Analysis of the SR confirmed that to maintain stable stance the neuromuscular system must allocate 50% more effort to control AP stability. The results also documented gender-related differences in postural stability. Generally the female subjects appeared to have lower postural stability as evidenced by higher COM and COP velocities. Consequently the higher SR values observed in the female group indicate a need for higher neuromuscular efforts to maintain stable posture. The introduced here set of COP measures proved to be a valuable standard for static posturography, creating the opportunity for improved and reliable assessment of postural stability.

Key words: posture, stability, sway ratio, sway directional index

INTRODUCTION

The main task of postural stability control (PSC) in humans when standing still is to maintain the body's center of mass (COM) within a relatively small base of support (BOS) (Massion 1992, Błaszczyk et al. 1994, Baracat and Ferreira 2013). More specifically the PSC is the process of maintaining the COM in the optimal and rather limited area of the BOS, i.e. as far as possible from the recognizable limits of stability (Błaszczyk et al. 1994). This optimal area would be at least theoretically localized in the middle of the BOS (Horak et al. 1989, Błaszczyk et al. 1994, Popovic et al. 2000, Henry et al. 2006). Such central and symmetrical positioning of the COM in young able-bodied subjects would provide an equal probability of maintaining the postural stability in every direction (Massion 1992, Błaszczyk et al. 1994, 2000, Duarte and Zatsiorsky 2002).

The PSC during quiet stance is commonly viewed as a continuous process in the stabilization of a multilink inverted pendulum. For the simplicity of the model it is commonly accepted that the pendulum of the human body is controlled in the anteroposterior (AP) direction mostly in the ankle joints which are stabilized by the triceps surae (for review see Winter et al. 1996, Maurer and Peterka 2005). Due to anatomical constraints the force of gravity and its torques

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Received 05 June 2014, accepted 16 October 2014

Table I

Group characteristics (mean ± SD) of female and male subjects

	Age [yrs]	Height [cm]	Body mass [kg]	BOS Length [cm]	BOS Width [cm]
Females	21.1±2.2	167.5±5.7	57.8±7.0	24.6±1.1	23.9±1.9
Males	22.0±2.5	178.5±6.8	76.8±10.7	26.9±1.1	26.1±1.4
P value ≤	NS	0.00001	0.00001	0.00001	0.00004

(BOS) base of support; (NS) nonsignificant

continuously challenge the AP postural stability (Horak et al. 1989, Massion 1992, Błaszczyk et al. 1994, Winter 1995, Winter et al. 1996, Karlsson and Persson 1997, Maurer and Peterka 2005, Deliagina et al. 2007). The mediolateral (ML) control of postural stability during quiet stance is qualitatively different and mainly relies on a hip (load/unload) mechanism (Winter et al. 1996). These classical gain margins are one way to quantify robustness of the PSC.

We should keep in mind that both the AP and ML controlling mechanisms are nonlinear in nature (Błaszczyk and Klonowski 2001). The long list of all possible nonlinearities in the PSC starts with sensory thresholds, delays related to a limited conduction velocity in the nervous system, discrete and electromechanically delayed muscle unit recruitment, inability of the muscles to maintain isometric force and narrowband frequency characteristics of all postural sensors (Błaszczyk and Klonowski 2001). Consequently the output of PSC (in the force-plate posturography this is the position of the center of pressure (COP) within stability limits) exhibits chaotic oscillations around the reference position (Błaszczyk and Klonowski 2001, Błaszczyk et al. 2003). The nature of the COP oscillations is well-known (Błaszczyk et al. 1993, Henry et al. 2006, Baracat and Ferreira 2013). Briefly, any deviation of the COP from its reference position results in gravity-induced destabilizing torques that are automatically countered by corrective actions generated in the feedback mode. So far, however, the question whether postural sway is detrimental or may improve PSC is still open (Błaszczyk et al. 1993). The present study is based on the assumption that the trajectory of the COP recorded during quiet stance should be determined by both the functional and structural properties of the PSC. Therefore the directional subcomponents (AP and ML) of the COP trajectory and their mutual relationships should furnish important inferences about the status of postural control.

From the perspective of an inverted pendulum control we hypothesized that the observed COP trajectories characterize performance and robustness of the PSC which simply provide how much the COP magnitude can change before the system becomes unstable (i.e. what are the gain margins of the system). Due to numerous anatomical and physiological constraints a substantial anisotropy in the PSC exists which in turn determines the asymmetry of COP trajectory (Błaszczyk et al. 1994, 2000, Duarte and Zatsiorsky 2002, Mizrahi et al. 2006). The experimentally observed COP asymmetry results initially from the two aforementioned control mechanisms (i.e. AP and ML) that are at least partially separated (Winter et al. 1996) Besides that the nervous system needs to constantly update the stability limits and the COP reference position to actual needs and these are strongly dependent on age-related decline in motor performance and equally to environmental conditions (Błaszczyk et al. 1994, 1997, 2007, Baratto et al. 2002, Błaszczyk and Orawiec 2011, Kirchner et al. 2013).

The present study was undertaken to search for COP indices that can differentiate subtle changes in postural stability control in a group of young able-bodied subjects. The objectives of this research were to: (1) determine which directional COP features are sensitive to differences in visual conditions (2) establish to what extent these directional characteristics are dependent on the subjects' gender and their antropometric features and (3) provide preliminary recommendations for COP data pretreatment. Completion of these objectives represents a preliminary step in establishing the feasibility of using static posturography for the assessment of human postural stability. With this aim the directional characteristics of PSC were assessed

using besides the classical COP velocity (V) two novel measures: the sway ratio (SR) and the sway directional index (DI). It is hypothesized that directional features of postural sway will provide better discrimination in the assessment of PSC performance and robustness.

METHODS

Participants

The research was accepted by the Senate Ethics Committee of the Jerzy Kukuczka Academy of Physical Education. The participants in the study consisted of two gender groups of able-bodied subjects: 23 female and 23 male students from the Academy. All subjects met the ethical requirements for the study. They reported having no known neurological or movement disorders and they engaged in regular physical activity. No further restrictions or participation criteria were used since the sample was aimed to represent as closely as possible a normal population. Each participant gave their informed consent. Basic anthropometric characteristics of the groups are shown in Table I.

Data collection and analysis

Subjects were instructed to stand barefoot on the force platform in a comfortable stance. There were 10 sixty-second trials performed to obtain the quiet stance data: five with eyes open (EO) and five with eyes closed (EC). Next individual means were computed for each visual condition and the means used in statistical analysis. Trials were separated with a rest-break to avoid fatigue or boredom.

The trajectories of the COP were determined by a force plate (Type 9281C Kistler Group, Switzerland). All data were collected with a 40 Hz sampling frequency. The COP time series were filtered digitally off-line with the 9th order Chebyshev low-pass filters (Cheby2 Matlab Mathworks© Natick, USA) to assess an optimal cut-off frequency. The cut-off frequency of the filter was changed systematically within the range of 5 to 11 Hz to assess an optimal COP filtering frequency. Then three standardized sway measures: COP velocity (V) COP directional indices (DI) and sway ratio (SR) were computed based on the optimal filter frequency of 10 Hz.

The average velocity $\overline{V}$ of the COP was calculated by taking the total distance traveled and dividing it by the time of the trial (T):

$$\overline{V} = \frac{\sum_{n=1}^{N} \sqrt{(X_{AP(n+1)} - X_{AP(n)})^2 + (X_{ML(n+1)} - X_{ML(n)})^2}}{T} = \frac{S_{TOT}}{T} \quad (1)$$

where N is the total number of data points for the given trial length and *XAP XML* – the position of the COP in the AP and ML direction, respectively.

In addition to the average velocity the collected data were also used to compute the sway directional indices (DI). The DIs have been defined as the ratio of the anteroposterior (S_{AP}) or the mediolateral (S_{ML}) path lengths divided by the total COP length (S_{TOT}):

$$DI_{AP} = \frac{S_{AP}}{S_{TOT}} \quad (2)$$

$$DI_{ML} = \frac{S_{ML}}{S_{TOT}} \quad (3)$$

The sway ratio (SR) has been computed as the COP-to-COP_{filter} path length ratio (Błaszczyk 2008). For this purpose the COP time series were filtered again with

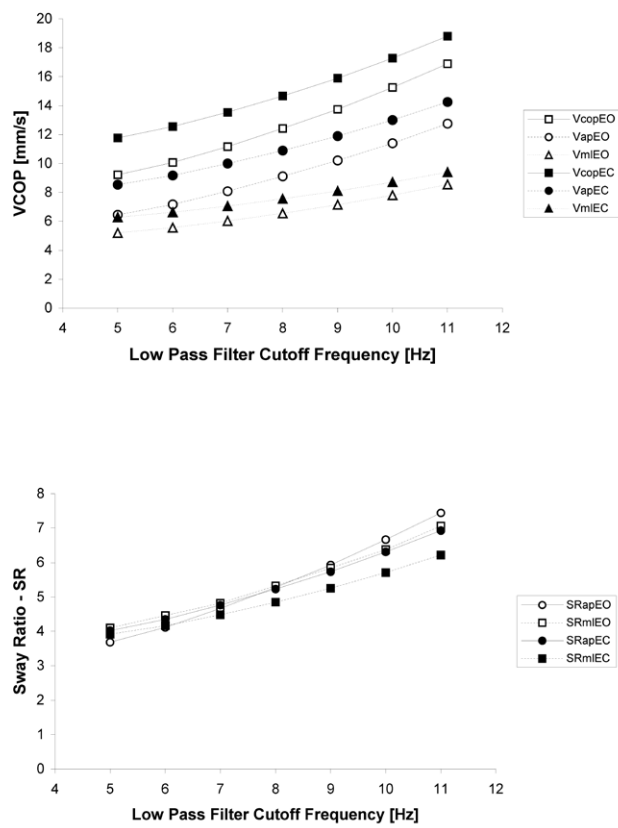

Fig. 1. Impact of low-pass filtering (the 9th order Cheby2 filter, Matlab) on the center-of-pressure (COP) velocity.

Table II

Postural sway (COP) characteristics in male (M) and female (F) group

Measure	Group	Eyes open	Eyes closed	Change %	*P* value
VCOP AP (mm/s)	M	11.9±2.2	14.0±2.5	18	0.00001
	F	14.0±2.5	15.1±2.4	8	0.00006
VCOP ML (mm/s)	M	8.0±1.3	9.3±1.6	16	0.0004
	F	9.4±1.6	10.2±1.6	9	0.0006
DI COP AP	M+F	0.71±0.04	0.73±0.04	3	0.004
DI COP ML	M+F	0.55±0.06	0.53±0.06	4	0.0007
SR AP	M	5.1±1.4	4.7±1.2	8	0.007
	F	6.5±1.6	6.0±1.5	8	0.0003
SR ML	M	4.5±1.2	4.0±1.2	11	0.02
	F	5.9±1.5	5.5±1.5	10	0.002

(V) velocity; (DI) directional index; (SR) sway ratio; (AP) anteroposterior; (ML) mediolateral

0.4 Hz (cut-off frequency) low-pass filters (the ninth order Chebyshev). Such filtering allows COM signal extraction from the COP data (Błaszczyk 2008). The anteroposterior and the mediolateral sway ratios (SR) in the AP and ML direction were calculated according to the following formulas:

$$SR_{AP} = \frac{S_{AP}}{S_{APfilter}} \tag{4}$$

$$SR_{ML} = \frac{S_{ML}}{S_{MLfilter}} \tag{5}$$

SAPfilter and *SMLfilter* represent pathlengths of AP and ML COP time series filtered at 0.4 Hz.

All statistical analyses were performed using Statistica v. 6.0 software (Statsoft, Tulsa, OK, USA). Two-way analysis of variance (ANOVA) with one dependent sample was used in order to examine statistically significant differences in the analyzed parameters between both genders and between the two experimental conditions (EO vs. EC). Linear correlation analyses (Pearson *r*) between the COP indices and the anthropometric measures were performed across conditions. A *P* value smaller than 0.05 was considered significant.

RESULTS

Analysis of variance showed highly significant differences between the male and female groups in body weight and height as well as in the size of their base of support (Table I). In the following analysis the effects of: gender (male vs. female) direction (AP vs. ML) and visual conditions (EO vs. EC) on postural sway indices were tested. Descriptive statistics of the analyzed sway parameters are summarized in Table II. Since in static posturography the pretreatment of the COP data (in particular COP time-series filtering) has a significant impact on the results of analyses (see Fig. 1), therefore, in order to unify postural sway analysis, and to allow comparison of results from different laboratories we have recommended here a preliminary 10 Hz low-pass filtering.

COP velocity

Two-way ANOVA revealed significant effects of gender ($F_{1,44}$=6.26, P≤0.02) direction of sway ($F_{1,44}$=577.1, P≤0.000001) and vision ($F_{1,44}$=71.6, P≤0.000001) on the COP velocity. The male subjects showed higher velocities of sway in both AP and ML directions. When the participants were tested while standing with their eyes closed the AP sway velocity increased by 18% in the male group and by 8% in the female group. The mean ML velocity was also affected by vision. In the EC condition we noticed a 16% increase of the mediolateral COP velocity in the male group and not more than 9% in the female group. *Post-hoc* analysis (Fisher's

Least Significant Difference – LSD test) confirmed a significant vision-effect within each of the tested groups. The mean values of COP velocity and details of statistical analysis are presented in Figure 2.

COM velocity

The COP signals filtered at 0.4 Hz were used to characterize center of mass (COM) sway in both gender groups. In the male group the mean COM AP velocity was equal to 2.4±0.5 mm/s when measured with eyes open and increased up to 3.1±0.7 mm/s in the EC condition. In the female group the mean COM AP velocity increased from 2.2±0.5 mm/s (EO) to 2.6±0.6 mm/s when measured with EC. Eye closure resulted in a 29% increase of the COM velocity in the AP direction in the male subjects and only an 18% increase in the female group. The ANOVA showed both a significant gender effect ($F_{1,44}$=4.94, P≤0.04) and vision effect ($F_{1,44}$=94.9, P≤0.000001) on the AP COM velocity. Group and vision interaction ($F_{1,44}$=4.7, P≤0.04) was also significant.

In the next analysis we examined the changes in the ML COM velocity. The ANOVA results followed by the *post-hoc* LSD test showed that the velocity in the ML direction were strongly affected by gender ($F_{1,44}$=7.3, P≤0.01) and visual condition ($F_{1,44}$=118.8, P≤0.000001). In both groups the observed increase was highly statistically significant. While standing with eyes open the mean value of the ML COM velocity was equal to 1.9±0.4 mm/s and 1.65±0.4 mm/s in male and female subjects, respectively. Exclusion of the visual input in the male group resulted in an increase in the ML COM velocity to 2.53±0.75 mm/s (P≤0.000001). The ML COM velocity while tested with EC also increased with statistical significance in the female group to 1.96±0.5 mm/s (P≤0.0004). Changes in mean ML COM velocity for both groups are shown in Figure 3.

Sway Ratio – SR (AP and ML)

ANOVA exhibited significant effects of gender ($F_{1,44}$=14.8, P≤0.0004) direction of sway ($F_{1,44}$=17.3, P≤0.0002) and vision ($F_{1,44}$=35.1, P≤0.000001) on the sway ratio. In female subjects the mean SRAP was significantly higher (6.5±1.6) compared with male subjects (5.1±1.4). In the EC conditions the mean SRAP decreased significantly in both groups and its value remained at the level of 6.0±1.5 and 4.7±1.2 for females and males, respectively.

The mediolateral sway ratios (SRML) when measured with EO and EC were characterized by lower values in both groups. Moreover the SRML was 12% lower in males (5.1 vs. 4.5, P≤0.0003). In the female group the mean SRML direction was 9% lower (6.5 vs. 5.9, P≤0.004) The differences along with the results of statistical analysis are summarized in Figure 4.

Directional Index for COP and COM sways

Directional indices were computed and analyzed for the COP and the COM time sway, separately. In case

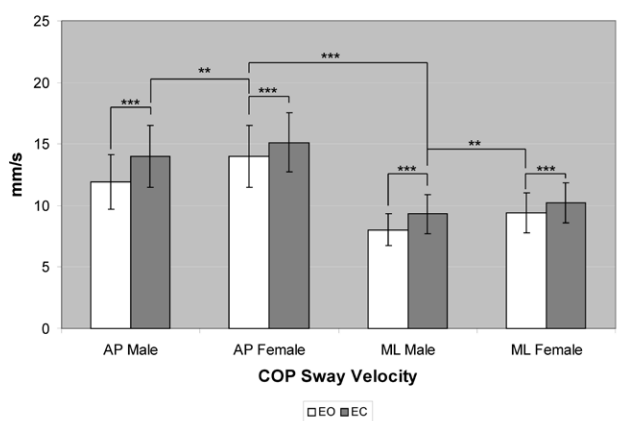

Fig. 2. Changes in anteroposterior (AP) and mediolateral (ML) COP velocity (mean ± SD) in male and female subjects while standing with eyes open (EO) and eyes closed (EC). Significant differences are denoted with asterisks: **P≤0.02; ***P≤0.01.

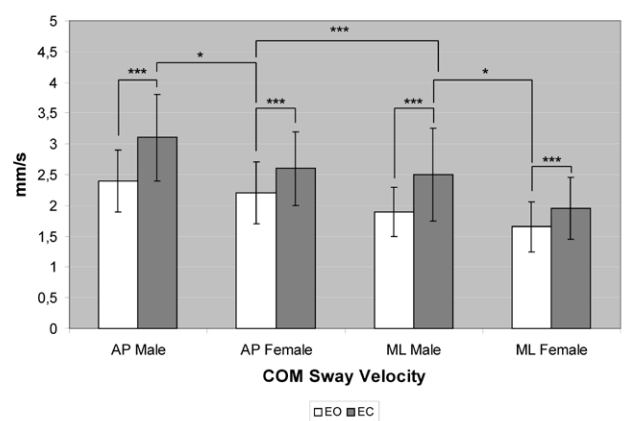

Fig. 3. Changes in anteroposterior (AP) and mediolateral (ML) COM sway velocity (mean ± SD) in male and female subjects while standing with eyes open (EO) and eyes closed (EC). Significant differences are denoted with asterisks: *P≤0.05; **P≤0.02; ***P≤0.01.

Table III

Correlations between the COP and COM parameters and selected anthropomorphic measures for all subjects (n=46, $P \leq 0.05$)

Variable	BOS	Weight	Height
VCOP AP/EO	−0.58	−0.59	−0.57
VCOP ML/EO	−0.52	−0.59	−0.41
VCOP AP/EC	−0.41	−0.35	NS
VCOP ML/EC	−0.35	−0.33	NS
SR AP/EO	−0.54	−0.54	−0.50
SR ML/EO	−0.62	−0.62	−0.53
SR AP/EC	−0.54	−0.54	−0.42
SR ML/EC	−0.66	−0.61	−0.58
VCOM AP/EO	NS	NS	NS
VCOM ML/EO	0.36	0.34	0.37
VCOM AP/EC	0.35	0.39	0.33
VCOM ML/EC	0.44	0.45	0.54

(BOS) base of support; (V) velocity; (SR) sway ratio; (NS) nonsignificant

of the COP oscillations, results of ANOVA confirmed a significant effect of two factors on the DI: direction of sway ($F_{1,44}$=173.3, $P \leq 0.000001$) and vision ($F_{1,44}$=16.5, $P \leq 0.0002$). The subject's gender had no effect on the COP DIs. In both groups the mean value of the AP directional index was significantly higher in comparison with the ML DI values (0.71±0.04 vs. 0.55±0.06, $P \leq 0.000001$). Eye closure resulted in a slight but statistically significant ($P \leq 0.004$) increase in the AP DI (up to 0.73±0.04) whereas in the same testing conditions the mediolateral directional index decreased slightly (about 4%) to 0.53±0.06 ($P \leq 0.0007$). Details of these analyses are shown in Figure 5.

Analysis of variance revealed no differences in COM directional indices. In both groups and for both visual conditions DI remained at the same level 0.64±0.08 (in AP direction) and 0.64±0.07 (in ML).

Correlation analysis

The results of the correlation analysis are summarized in Table III. The COP velocity while standing with eyes open and its AP and ML components correlated negatively with body weight and height as well as with the size of the individual's base of support. The Pearson r Test demonstrated a significant positive correlation between the ML COM velocity and all anthropometric measures under both EO and EC conditions. In contrast, the AP COM velocity showed only such correlation in the EC condition.

The AP and ML sway ratio also correlated negatively with the aforementioned anthropometric measures, both in the EO and EC conditions. Such correlations, however, were not observed in the directional indices.

DISCUSSION

The purpose of the research presented here was to quantify the characteristics of postural sway in order to establish a method for the assessment of postural stability based on COP signals recorded during quiet stance. For this purpose the COP signals were recorded in young able-bodied subjects while standing quietly with their eyes open and then with their eyes closed. Such tests show how robust is the PSC i.e., how much the postural sway can increase before the standing posture becomes unstable.

The use of postural sway in the assessment of postural stability is not new but no widespread consensus has emerged so far about the methods and interpretation of the COP data. From numerous traditional sway measures, the COP velocity has been commonly recommended to characterize postural stability (Barratto et al. 2002, Raymakers et al. 2005) The present study acknowledges, however, that there is an enormous and detrimental impact of sway data pretreatment on resultant COP velocity (Błaszczyk 2008, 2010, Beck et al. 2011). In this line of research, we documented that two basic factors: the analog-to-digital (AtoD) sampling frequency and the COP filtering, if selected incorrectly, may critically contaminate the posturographic results and make their interpretation incorrect. We have therefore considered here the application of sway directional indices for the assessment of PSC. The DI seems to be the most reliable COP measure so far. Results of the generalizability study (G-study) confirmed that both directional indices (DI AP and ML) attained a desirable reliability coefficient (higher than 0.80) with a single 60-s trial (Beck et al. 2011).

The next important point about the classical sway measures (e.g. COP velocity) is that they are descriptive and do not inherently provide any direct information about underlying control mechanisms. The PSC is a multidimensional dynamic process where efficiency depends on many physiological and anatomical factors (Horak et al. 1989, Massion 1992, Simoneau et al. 1995, Era et al. 1996, Deliagina et al. 2007, Saripalle et al. 2014). It appears that the decline of integrity in some physiological systems particularly in the sensory has a profound effect on the range of postural stability during upright stance (Horak et al. 1989, Błaszczyk et al. 1994, Henry et al. 2006). Postural sway in both anteroposterior and mediolateral directions represents the effectiveness of the postural control system to maintain stable posture (Winter et al. 1996). Consequently the major sway axis corresponds to the direction of least stability (Saripalle et al. 2014) and therefore our directional sway measures seem to be the most convenient for postural stability assessment.

Suomi and Koceja (1994) showed that in normal healthy subjects, the AP sway is larger than the sway in ML direction with a ratio of approximately 1.5 during both EO and EC conditions. Many inferences on the PSC may be derived therefore from an ellipse covering 85.35% of the sway area (Duarte and Zatsiorsky 2002). In fact, the elliptical shape of the COP sway area mirrors the shape of stability borders (Błaszczyk et al. 1994) and the eccentricity of the ellipse allows the assessment of the COP directional control. In our model the probability of postural stability following a gravity-induced perturbation depends on the velocity and direction with which the COM is perturbed. If a change in the magnitude of these parameters exceeds certain limits, the PSC may become unstable and the subject would be prone to falls. These depend on both the body sway magnitude and the functional stability limits (Błaszczyk et al. 1994). In young able-bodied subjects the AP and ML margins of stability during stance are quite symmetrical whereas in older adults the

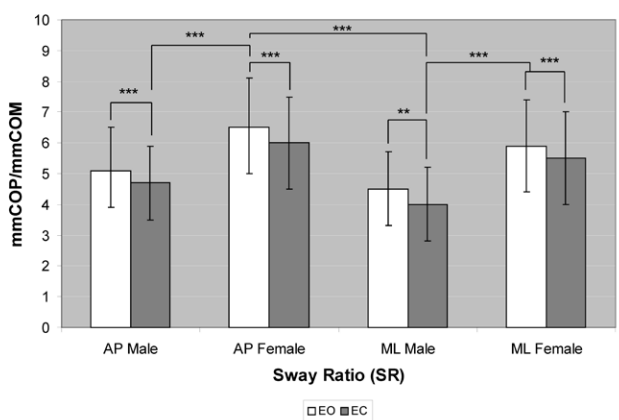

Fig. 4. Effects of vision and gender on anteroposterior (AP) and mediolateral (ML) on the sway ratio (SR) (mean ± SD) in male and female group tested with eyes open (EO) and eyes closed (EC). Significant differences are denoted with asterisks: **$P \leq 0.02$; ***$P \leq 0.01$.

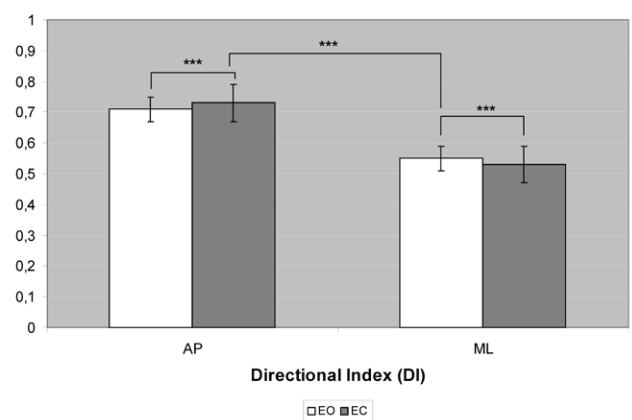

Fig. 5. Mean (±SD) anteroposterior (AP) and the mediolateral (ML) sway directional index (DI) for the center-of-mass (COM) sway in young subjects while standing with eyes open (EO) and eyes closed (EC). Significant differences are denoted with asterisks: ***$P \leq 0.01$.

stability area is characterized by significant asymmetry (Błaszczyk et al. 1994). There is also a growing body of evidence that mediolateral instability is an important posturographic marker of functional balance impairment. In particular an increased lateral sway is associated with an increased risk of falling in the elderly (for review see Błaszczyk et al. 2007) and in parkinsonians who are prone to falls (Mitchel et al. 1995, Błaszczyk and Orawiec 2011). In this context, compared with AP, a relatively greater increase of the ML COM sway while standing with eyes closed may suggest a decline in postural stability.

Our DI and SR results are consistent with previous findings and they confirmed that to maintain upright stance the neuromuscular system must allocate 50% more effort to control anteroposterior stability. The mean value of both DIs computed here, which document the relative contribution of the COP motion in frontal and sagittal planes showed that two-thirds of the swaying movements (roughly 60%) is in the AP direction. This proportion is maintained even though the visual input is altered. Standing with EC resulted in changes in DI that were only slight, though statistically significant and similar in both directions (AP and ML). These results show that despite an increased sway velocity, the contribution of the AP and ML control remains at the same level.

The COM sway trajectory depends on a complex interaction of several sensory inputs with the motor output (Massion 1992, Simoneau et al. 1995, Deliagina et al. 2007). Increase of the COM velocity is usually definite when stability declines (Henry et al. 2006). Limitations in any of the sensory controls may strongly affect the PSC. This impact is commonly examined in static posturography by testing subjects while standing still with their eyes closed. In these conditions, the PSC is working at less than optimal level since it must rely on depleted information. To compensate for such deficiency, the PSC has to be reorganized accordingly to cope with new conditions. In our study, the reorganization of the PSC affected the COM and COP characteristics differently. The increase in swaying velocity was observed in both genders albeit the magnitude of changes was differently pronounced. As documented here, the increase in the COM velocity while standing with EC was different in the AP and ML direction and correlated with the subject's anthropometry (i.e., body weight and mass, and the size of their base of support). In full control conditions (EO test), however, such correlations were not observed. In contrast with the COM, the increase in the COP velocity while standing without vision exhibited much stronger and negative correlations with the anthropometric factors.

We also found that in young subjects standing with their EC there was a greater (almost twofold) increase of COM velocity compared with the COP velocity. This result provides details on the PSC reorganization strategy while coping in sensory impoverished conditions. Such conditions lead to greater amplitude and faster COM oscillations within the reference area despite increased efforts of the postural system (documented by higher COP values). An interaction of these effects had a direct impact on the level of the SR. To our surprise both AP and ML SRs decreased when the visual input was unavailable. This contrasts with older adults and parkinsonians who demonstrated a significant increase of the sway ratio in EC conditions (Błaszczyk 2008, Błaszczyk and Orawiec 2011) The magnitude of SR is interpreted as an amount of a balance controlling muscular activity that coincides with a unit displacement of the COM (Błaszczyk 2008). There is increasing support for the hypothesis that the PSC performs optimally within a limited range of the stochastic muscular activity. Collins and De Luca (1995) proposed that the level of muscular stochastic activity across joints controls the stiffness of the postural system and is considered the main mechanism of the PSC. In accordance with this hypothesis, Mitchell and colleagues (1995) have documented an increase in stochastic activity in the ML direction in Parkinson's disease patients with very unstable posture. Thus, in our subjects, the observed decrease of SR magnitudes in EC may result from: (1) increased COM oscillations (which may suggest a decline in postural stability) that are not fully compensated by (2) an increase in the muscular stochastic activity. The lack of full compensation for COM sway increase may, however, indicate only that in young healthy subjects with a robust PSC, such compensation may not be necessary.

Our results also documented gender differences in postural sway characteristics. Generally the female subjects in the current study appeared to have lower postural stability, as evidenced by higher COM and COP velocities compared with the males. Consequently, the higher SR values observed in the female group indicate a need for higher muscular activity to maintain stable standing posture. Both groups, however, did not differ in DI values. We are convinced that body

anthropometry (mean body weight and height) can explain the aforementioned group differences in postural sway. Considering the inverted pendulum model (for details and references see Winter et al. 1996, Maurer and Peterka 2005), a taller subject (which corresponds to a longer lever arm in the model) would exhibit a greater sway amplitude (Era et al. 1996). In addition, other body properties such as body weight and an individual's location of their center of body mass, as well as foot length, are assumed to have an effect on sway characteristics (Era et al. 1996, Błaszczyk et al. 2009). Finally, the female subjects have a relatively lower mass of muscle tissue, which determines the overall muscle strength. The latter notion holds true for the triceps surae complex, the main muscle group that controls the inverted pendulum of human posture (Winter et al. 1996, Maurer and Peterka 2005). All these factors differed substantially in our experimental groups, and may account for the observed differences in gender-related postural stability.

CONCLUSION

The combined results of this study allow us to recommend two new measures of postural sway, i.e. the sway ratio and the sway directional index which can be more useful in postural stability assessment. This assessment encompasses biomechanical and physiological characteristics. Both measures are more reliable than standard sway measures since they are not sensitive to the COP signal sampling frequency and to the length of a trial.

ACKNOWLEDGMENTS

This research was supported by the Polish Ministry of Science and Education grant no. NN404 0473 39 and the statutory funds from the Jerzy Kukuczka Academy of Physical Education in Katowice. The authors are indebted to Diana Chwiejczak for her valuable comments and edits on the manuscript.

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