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Sway ratio – a new measure for quantifying postural stability

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In the search of a reliable postural stability index, two sway time series: the center-of-mass (COM) and the center-of-foot pressure (COP) were recorded simultaneously in elderly subjects standing quiet with eyes open and with eyes closed. From a battery of commonly use sway measures, only the anteroposterior COM and the COP path lengths proved their high sensitivity and discriminative power to the imposed vision conditions. Based upon these indices, a new measure – sway ratio (SR) – was computed, as the COP-to-COM path length ratio. The measure can easily distinguish vision vs. no vision in the elderly. The SR can be successfully accessed base upon the COP signal only. In contrast to traditional sway indices, the SR as a relative measure is insensitive to the length of sampled record and to the signal sampling frequency. Its magnitude can be interpreted as an average amount of balance controlling motor activity that coincides with a unit COM displacement. The SR is recommended as a reliable measure that allows for assessment of postural stability.

Key words: sway ratio, posture, postural stability, balance, elderly

INTRODUCTION

Force plate posturography, an easy and safe method that is commonly used in contemporary laboratories, can furnish insights into the physiological correlates of postural stability. The problem, however, of identifying postural instability in the elderly and in patients with neurodegenerative disease using force-plate posturography, is still unsolved. The results of this method simply show a scale of the problem we found in the laboratory assessment of postural stability. For instance, an increased postural sway during quiet stance is not usually conclusive evidence for postural instability. Other proof, related to the dynamics of postural control, such as a decline in postural stability borders are usually needed (Błaszczyk et al. 1994, 2007). Moreover, most of the commonly exploited sway indices are neither sensitive enough nor do they exhibit specific effects, for a given postural dysfunction. It is usually a very sophisticated task to find in the center of foot pressure (COP) characteristics, those changes specific for instability. This is especially true for those with potential physiological meanings. Many parameters that are derived from the COP time series seem to provide very similar information and due to the specificity of experimental techniques used in different laboratories, it is almost impossible to compare posturographic results (Raymakers et al. 2005).

Discussion on the nature of postural sway has taken place recently in the literature (Bottaro et al. 2005, Raymakers et al. 2005). The question of why people sway and what is the physiological outcome of that movement is crucial for this discussion. The control of human upright posture stability is commonly viewed as a continuous process of the stabilization of a multilink inverted pendulum (for review see Maurer and Peterka 2005). In this model, the main controlled parameter is the center of mass (COM) position within limits of the base of support. Postural stability control involves the generation of appropriate stabilizing responses. This is done either by triggering and scaling preprogrammed reactions or by continuous updating the COM position in a feedback mode. During quiet stance stabilizing torques generated at different levels of the body's

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kinematic chain are transmitted mainly down to the base of support. They are observed as a compound COP signal (Winter 1995). These stabilizing processes shape COP characteristics (McClenaghan et al. 1994, Winter 1995). Since COP is a measure of whole-body dynamics, it represents the summed up effect of a number of different neuromuscular components. These neuromuscular components are acting at different joints (Collins and De Luca 1993, Eng and Winter 1993) and their characteristics are strongly dependent on the main inputs that control postural stability. These inputs include visual, proprioceptive and vestibular systems. Impairments of a central processing of these signals e.g., due to ageing or resulting from a pathology, also affect the COP characteristics (Błaszczyk et al. 2007).

While trying to trace potential impairments of postural stability, the comparison of postural sway characteristics during standing quiet with eyes open and with eyes closed, is commonly applied (Sabatini 2000, Błaszczyk and Klonowski 2001, Ladislao and Fioretti 2007). Most spatio-temporal as well as frequency spectrum output measures of static sway, however, usually lack sensitivity for detecting postural problems. They also lack relevance to physiological mechanisms. The latter notion concerns nonlinear models as well (Błaszczyk and Klonowski 2001, Ladislao and Fioretti 2007). The present study was undertaken to gain better insight into the discriminating power of different basic COP and COM indices. This is done in order to isolate parameter(s) that may exhibit a sufficient discriminative power to visual input manipulations in the elderly. It is meant to be easily interpreted. I assumed that a complex measure which combines characteristics of both COM and COP signals, may provide a wealth of information regarding postural control. In order to verify this hypothesis, a sway ratio (SR) – defined as the COP/COM path length ratio, has been analyzed. Sway ratios have been assessed in the elderly subjects while standing quiet with eyes open and with eyes closed. It has been posited that the SR should provide decent discrimination between these two experimental conditions and at the same time, it should not exhibit disadvantages of classic sway measures. Another challenge of this work was to develop a signal processing procedure, that would enable us to compute – with decent accuracy – SR based upon only the COP signal.

METHODS

The experiment has been approved by the Senate Ethics Committee of the University School of Physical Education in Katowice. Twelve healthy elderly subjects voluntarily participated in this study. They were 7 females and 5 males. Their mean age was 71.5 ± 3.6 years. The subjects reported having no neurological or movement disorders. All subjects signed an informed consent form.

During the experiment subjects stood barefoot on the force platform in a comfortable stance. Their postural sway was assessed from an independently recorded COP and COM time series. The COP motion was measured by means of the Accusway force platform (AMTI, USA). The COM sway was acquired with the 6 camera SMART video system (BTS Bioengineering, Italy) based upon 21 markers attached bilaterally to anatomical landmarks, that defined a 14 segment model (e.g., Lafond et al. 2004). Both the force-platform and the SMART data were sampled at the same frequency of 20 Hz. The postural sway in our subjects was recorded for two common experimental conditions: (1) while standing quiet for 60 seconds with eyes open (EO); and next, (2) with eyes closed (EC).

During the data processing, COM trajectories had also been reconstructed on the basis of the COP signal by means of digital filtering with the Chebyshev low-pass filter (Matlab v. 6.0, The MathWorks, Inc., USA). In order to obtain the best conformity between the SMART COM signal and its filtered-COP equivalent, the cut-off frequency of the filter was successively varied in the range between 0.3–0.5 Hz. The optimal cut-off frequency of the filtering was selected based upon the lowest path length estimation error. The COM obtained by video was used as the "gold standard" to which the filtered COP data were compared.

The collected signals were used to calculate the sway ratio. The SR had been defined initially as a ratio of COP-to-COM path lengths. Since the COM signals could be assessed either directly from the SMART time series or by means of low-pass filtering of the COP, the following sway ratios were calculated: (1) Actual: SR_a = COP/SMART COM path length; (2) Filtered: SR_f = COP/COP low-pass filtered path length.

All statistical analyses in this study were performed using Statistica version 5.0 software (StatSoft, Inc. USA). The Student's *t*-test for dependent samples was used to evaluated differences between COM and COP sway measures in both experimental conditions. Pearson's correlation test was also performed between COM and COP trajectory measures across experimental conditions. Additionaly, crosscorrelograms were computed for the signals (Matlab v. 6.0, The MathWorks, Inc, USA) to verify relationships between them.

RESULTS

The statistical analysis of the two independently recorded postural sway signals confirmed that the COM and the COP are highly correlated. The Pearson correlations were significant for both directions (r=0.98 ± 0.02 and r=0.91 ± 0.06 for the AP and ML path lengths, respectively recorded in EO conditions). The correlation remained at a similar level (r=0.94 ± 0.02) when the subjects were tested with eyes closed. The maximum values of the crosscorrelograms were for the time shift equal zero (Fig. 1). These results strengthened the hypothesis that the COM trajectory is an inherent part of the COP signal and it could be isolated from it using an adequate filtering procedure. Depending on applied low-pass filter parameters it was possible to match both actual and filtered COM with an accuracy depicted in Figs 2 and 3. An optimal cut-off filtering frequency for the anteroposterior COP component was 0.45 Hz. It was at the level of 0.4 Hz for the mediolateral COP trajectory. Statistical analysis (t-test for dependent variables)

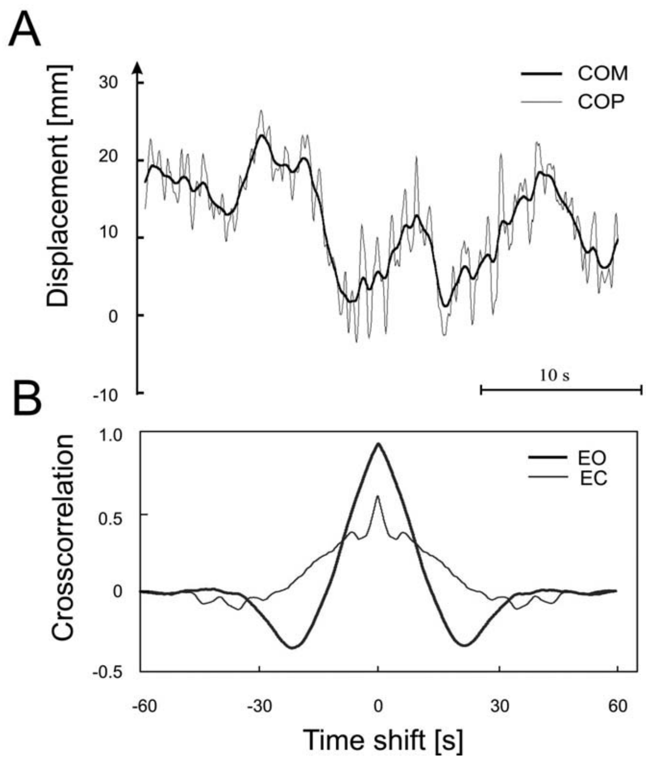

Fig. 1. (A) Center of mass (COM) and center of foot pressure (COP) signals recorded independently in an elderly subject standing quiet with eyes open. To improve quality of the graphic only half of the trial is shown. (B) crosscorrelograms of the COP and the COM time series for eyes open (EO) and for eyes closed (EC).

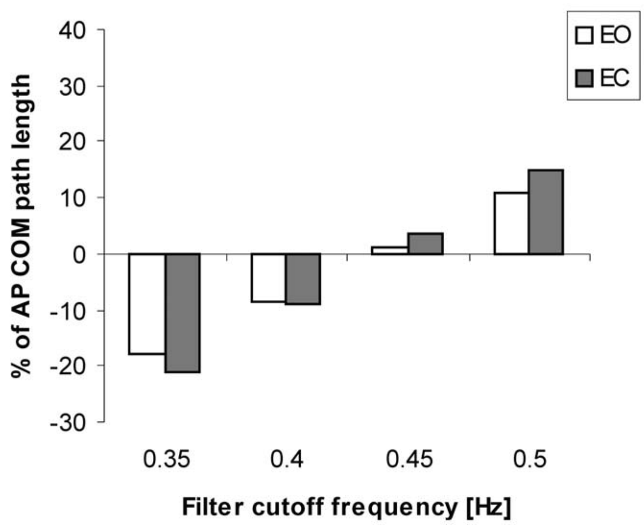

Fig. 2. Relative error of the AP COM path reconstruction from the low-pass filtered with different cut-off frequencies COP time series. The optimum filtering was at the frequency of 0.45 Hz.

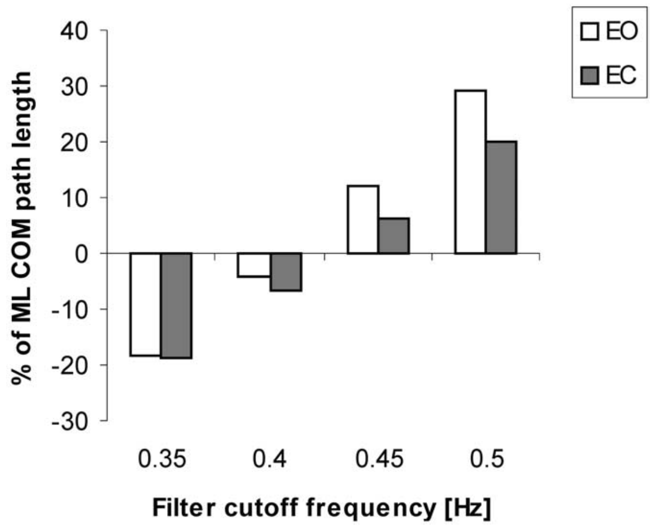

Fig. 3. Relative error of the ML COM path reconstruction from the low-pass filtered with different cut-off frequencies COP time series. The optimum filtering was at the frequency of 0.4 Hz.

Table I

Values of main spatio-temporal COP measures (mean ± SD) in the elderly subjects while standing for 60 s with eyes open (EO) and with eyes closed (EC)

COP Measure	Experimental conditions EO	Experimental conditions EC	P level
AP range [mm]	27.58 ± 8.54	28.48 ± 8.99	NS
ML range [mm]	12.25 ± 3.77	14.65 ± 6.45	NS
Total path length [mm]	552.4 ± 208.6	745.8 ± 351.4	0.005
AP path length [mm]	469.1 ± 198.0	662.4 ± 331.7	0.002
ML path length [mm]	207.2 ± 52.1	231.6 ± 85.6	NS
Sway area [mm^2]	179.5 ± 114.1	239.6 ± 173.4	NS
Mean sway velocity [mm/s]	8.89 ± 3.1	9.85 ± 4.02	NS

(NS) non significant

showed no significant difference between path lengths of the SMART COM and its optimally filtered COP equivalent, in both AP and ML directions.

The results confirmed that the controlled factor i.e., vision, significantly affects postural control in the elderly. Elimination of a visual feedback in our subjects during quiet stance, resulted in an increase of the spontaneous body sway. This was evidently seen in some COP and COM sway measures (Table I and II). Statistically significant changes due to visual conditions were noticed in a total COP path length and its anteroposterior subcomponent. Surprisingly, the effect of vision on the mean mediolateral path length remained insignificant.

Both actual and filtered sway ratios were also significantly dependent on imposed experimental conditions (Table III). Elimination of visual input during quiet stance resulted in an increase of the total SR_a. The increase observed for the AP path length was even more pronounced. In the eyes open conditions the AP SR_a remained at the level of 3.27 ± 0.89. This increased to a mean value of 3.76 ± 0.91 (P<0.003), while the subjects were tested with eyes closed. Similarly, in the case of the sway ratio calculated from the filtered COP

Table II

Values of the COM measures (mean ± SD) in the elderly subjects standing quiet for 60 s with eyes open (EO) and with eyes closed (EC)

COM Measure	Experimental conditions EO	Experimental conditions EC	P level
AP range [mm]	22.31 ± 8.04	21.94 ± 7.58	NS
ML range [mm]	9.21 ± 3.2	10.9 ± 5.61	NS
Total path length [mm]	160.57 ± 33.08	194.4 ± 31.9	0.03
AP path length [mm]	136.25 ± 26.15	170.75 ± 23.7	0.02
ML path length [mm]	57.35 ± 15.51	65.23 ± 26.3	NS
Mean sway velocity [mm/s]	8.25 ± 3.14	8.7 ± 3.37	NS
Sway area [mm^2]	157.3 ± 101.7	197.3 ± 124.5	NS

(NS) non significant

data, only the AP SR_f exhibited significant changes due to experimental conditions (Table III).

DISCUSSION

Two basic assumptions have driven this study: (1) that the COM signal is inherently inscribed into the COP; and (2) that the COP and the COM while analyzed together may yield quality of postural control (Winter 1995). In the literature, there are several complementary studies that used different techniques to reveal a COP and COM interrelation (Benda et al. 1994, Caron et al. 1997, Zatsiorsky and King 1998, Kuczyński 1999, Lafond et al. 2004). Benda and coworkers (1994) were among the first researchers, who documented that COM may be extracted from the COP by a simple low-pass filtering. Since then, to get the best results, different research groups applied diverse filtering techniques. In particular, various cut-off frequencies of low pass filters ranging between 0.3 to 0.5 Hz (Benda et al. 1994) and 2 Hz (Kuczyński 1999) have been reported. The COP has been also successfully decomposed using a cubic spline smoothing (Zatsiorsky and King 1998) which is an equivalent of low-pass filtering. Continuing this line of experiments, Lafond and coworkers (2004) showed that satisfactory results could be obtained by the zero-point-to-zero-point double integration technique.

The present study showed that the quality of the COM signal extraction from the COP is very sensitive to parameters of applied filter. It depends especially on the filter's cut-off frequency. The best results were obtained for a nine order, Chebyshev type II low-pass filter with a cut-off frequency of 0.45 Hz and 0.4 Hz, for the AP and ML COP signals, respectively.

The next step in this study was to find a simple, easy to calculated COP parameter that might be relevant to postural stability. There is a long history in the field of posturography of attempting to extract meaningful information from the COP signal. Traditional measures such as sway path length, sway area, mean sway amplitude, etc. have been used extensively to characterize differences between experimental manipulations (for review see Winter 1995, Raymakers et al. 2005). These classical indices of sway, and even the results of spectral analysis, turned out not to be sensitive enough in most cases. An individual experimental design, which substantially varies from laboratory to laboratory, may strongly affect the spatiotemporal measures making the results incompatible. Despite these difficulties, a hypothesis that some qualitative and quantitative inferences on postural stability could be drawn from the spontaneous sway recorded during quiet stance, keeps gaining increasing support (Prieto et al. 1992, Newell et al. 1997, Sabatini 2000, Hisao-Wecksler et al. 2003, Bottaro et al. 2005, Maurer and Peterka 2005, Raymakers et al. 2005, Ladislao and Fioretti 2007).

In numerous studies COP characteristics have been analyzed with the aim of finding the most significant measure to distinguish between different experimental conditions (Prieto et al. 1992, Newell et al. 1997, Sabatini 2000, Błaszczyk and Klonowski 2001, Rocchi et al. 2004, Raymakers et al. 2005, Ladislao and Fioretti 2007). Most of these studies were methodologically rigorous and promising for investigation of the dynamics underlying postural stability. They have not

Table III

Sway Ratio (mean ± SD) in the elderly subjects standing quiet for 60 s with eyes open (EO) and with eyes closed (EC)

Sway Ratio		Experimental conditions EO	EC	*P* level
SR_a total [mm/mm]		3.43 ± 0.99	3.72 ± 0.81	$P \leq 0.01$
SR AP [mm/mm]	SR_a	3.27 ± 0.89	3.76 ± 0.91	$P \leq 0.003$
	SR_f	3.42 ± 1.30	3.85 ± 1.12	$P \leq 0.036$
SR ML [mm/mm]	SR_a	3.71 ± 0.80	3.58 ± 0.66	NS
	SR_f	4.78 ± 2.34	4.19 ± 1.52	NS

yet, however, entered clinical or lab practice. The important point about these measures is that they are descriptive and do not inherently provide any direct information about underlying control mechanisms. For instance Collins and De Luca (1993) applied the theory of stochastic processes to the analysis of postural control. They claim that there are two distinct processes in the postural control: open- and closed-loop. Although the existence of the two controls is somewhat controversial (Newell et al. 1997), their stabilogram diffusion technique made impact as a new way to characterize differences in postural control. Recently, Raymakers and colleagues (2005) analyzed COP characteristics obtained in 114 persons aged 21–87 years. This study proved that the many sway parameters, which had been derived from the COP trajectories seemed to provide very similar information. The exception was Collin's diffusion stabilogram. In the latter case, the critical time interval proved to be sensitive to visual and proprioceptive conditions, as well as it might be influenced by a cognitive task. It was not, however, significantly dependent on subject's age.

The present study was undertaken to gain better insight into the discriminating power of different COP and COM measures. This means those that appear to be the most sensitive to visual input manipulations in the elderly, and at the same time which could be easily interpreted. As the result, sway (COP-to-COM) ratio has been selected because of its salient features and its decent sensitivity to detect experimental conditions. Our analysis showed that SRs sensitivity for discriminating vision vs. non-vision conditions in the elderly remained at a similar level in both the AP, and the total path lengths. This is not surprising since our filtered signals were matched to the video assessed COM signal, which was treated as a reference and our "gold standard" was also collected with rather limited accuracy. This may result in a decrease of SR sensitivity compared with both the COP, and COM path length. However, in contrast to both the latter sway indices, the SR has several beneficial features. Firstly, it is independent on the length of the sampled record. Additionally, the SR as the relative measure may be interpreted as an amount of a balance controlling motor activity that coincides with a unit displacement of the COM.

The next question is, whether the sway ratio can be considered as a postural stability measure. Results of studies on relationships between muscular activity and postural balance advocate for this notion. Without a doubt the COP contains information on motor activity involved in maintaining stable upright posture and it has been well documented, that postural stability is optimal within a limited range of the motor activity. Both a very small and a very large amount of the activity result in postural instability (Newman et al. 1996, Laughton et al. 2003, Bosek et al. 2005). This hypothesis gained strong support from experimental studies on older individuals, who experienced recent unexplained falls. Greater amounts of postural sway associated with an increased lower-extremity muscle activity during quiet stance were observed in these subjects compared to those of healthy elderly (Laughton et al. 2003). Bosek and colleagues (2005) showed also a larger level of muscular stochastic activity that affected COP characteristics in elderly subjects standing quiet with eyes closed as compared to the young ones. Changes in sway characteristics, as indexed in our study by increased actual and filtered sway ratios complement the aforementioned results. Our data advocates that in the elderly subjects eye closure results in an increase of motor stochastic activity in the postural system, that in turn may substantially affect subjects' postural stability (Błaszczyk at al. 1993, 1994). In a number of tentative analyses (unpublished data from our laboratory) the SR proved their sensitivity not only to visual conditions but also specificity to postural dysfunctions e.g., in Parkinson's disease. At this point, it is hard to judge what is an optimal range of SR values for a stable posture. It seems that postural instability may result in either a very high (as in Parkinsonians) or in lower than normal (as in obese subjects) sway ratios.

CONCLUSIONS

Taken together, these results allow us to recommend sway ratio as an useful measure of postural control. Although the present data confirmed only that the SR is sensitive to visual conditions in the elderly, there is an increasing body of evidence that it has sufficient discriminative power for pathological changes as well. Thus, SR may provide supplementary assessment of the postural stability control. This assessment is both in terms of biomechanical and physiological characteristics. Such the output posturographic measure can be easily interpreted by clinicians, physical therapists and researchers. Additionally, SR as a relative measure, is insensitive to the length of the sampled record and to the signal sampling frequency, if properly selected.

The SR, which has been originally defined as COP-to-COM path length ratio, may be easily accessible from the COP signal only. Its computation seems rather uncomplicated. However, further intensive research is needed to establish physiological ranges of the $SR_{f0.4}$ in different age groups as well as in different pathological conditions.

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