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A novel determination of energy expenditure efficiency during a balance task using accelerometers. A pilot study

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ABSTRACT
The objectives of this study are to determine the displacement of the center of pressure (CoP) and its association with the spectral energy density of the acceleration required for the maintenance of postural balance in different standing positions in healthy participants using design observational and setting laboratorial studies. Participants were 30 healthy university students aged between 18 and 32 years old (mean [M] ± standard deviation [*SD*] = 21,57 ± 3,31 years). Triaxial accelerometer and a pressure platform were used in order to obtain energy spectral density and CoP sway measurements during four balance tasks. Statistically significant differences were found for anteroposterior ($p = 0.002$) and mediolateral ($p = 0.009$) CoP displacement between the conditions eyes closed and stable surface and the conditions eyes closed and unstable surface. A statistically significant correlation was also observed between Z-axis (anterior-posterior) of the accelerometer and mediolateral axis of the CoP ($r = 0.465$; $p = 0.01$) and between Y-axis accelerometer (mediolateral) and displacement of the CoP in the anteroposterior axis ($r = 0.413$; $p = 0.023$). Spectral energy density appears to be associated with the displacement of CoP in healthy participants.

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Accelerometer; center of pressures; postural sway; rehabilitation; risk of falls

Introduction

Postural control is defined as the ability of maintaining, achieving, or restoring a state of balance during any posture or activity (Pollock, Durward, Rowe, & Paul, 2000) and depends on the complex integration of information from the visual, the vestibular, and the proprioceptive systems (Duarte & Freitas, 2010).

Postural control related factors are useful markers of the overall health status of the individual, being powerful predictors of muscular and neurological disorders from childhood to adulthood (Fialka-Moser, Uher, & Lack, 1994). It is common to characterize postural control and balance by measuring the oscillations of the center of pressure (CoP) with a force/pressure platform (Visser, Carpenter, Van Der Kooij, & Bloem, 2008) or by using scales and clinical tests such as the Berg Balance Scale, the Tinetti Scale, or the Timed Up and Go test (TUG). Nevertheless, these measurement instruments and procedures cannot be used in all groups of individuals (e.g, individuals of stroke) or are expensive (e.g, force plates). Therefore, other assessment tools with wider applicability, such as accelerometers, have been developed. Accelerometry data are highly correlated with CoP measures taken using force/pressure platforms and showed good to excellent test–retest reliability (Whitney et al., 2011). In addition, accelerometers are very often lighter, less expensive, more convenient to transport, easier to use, and more useful in the real-time evaluation of postural control than most platforms used for CoP measurements (Genthon, Vuillerme, Monnet, Petit, & Rougier, 2007); however, these characteristics will depend on the hardware.

The instrumented assessment of balance is helpful to understand the pathophysiology of balance disorders: to evaluate the natural progression of a disease or the response of patients to therapy in a variety of diseases affecting the central nervous system, such as Parkinson's disease or stroke (Fialka-Moser et al., 1994; Maetzler et al., 2012; Verheyden, Ashburn, Burnett, Littlewood, & Kunkel, 2012). Regardless of the underlying disease, failure to diagnose poor balance may be critical, as poor balance is associated with a high risk of injury and falling (Nardone & Schieppati, 2010). Furthermore, one should be aware that clinical tests may provide more discrimination given objectivity on the underlying causes of poor balance, which are of relevance to an effective intervention (Nardone & Schieppati, 2010).

Although accelerometers do not currently determine the pathognomonic balance deficits of a condition, accelerometers provide an individual quantitative measure of postural control (Genthon et al., 2007) and gait (Zijlstra & Hof, 2003), and have been shown to be able to discriminate the effect of muscle fatigue on postural control (Janssen, 2007). Besides, accelerometers are an indirect marker of the spectral energy density of the measured acceleration, which may constitute as a marker used during the optimization of postural control in daily life activities (Houdijk, Brown, & Van Dieen, 2015; Paillard, 2012) as well as to analyze the level of everyday

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physical activity (Van Den Berg-Emons, Bussmann, & Stam, 2010). Nevertheless, the association between metabolic energy (as a measure of physical activity) and postural control is not clear, and studies on signal processing are scarce (Zijlstra & Hof, 2003).

We believe that the relevance of our study relies on the fact that we investigated a new variable (spectral energy density) using assistive technology (accelerometer). The potential relationship between the displacement of the CoP and spectral energy density could constitute another influential factor in postural control, which has not been studied until now.

Methods

Participants

A total of 40 university students volunteered to participate in this study. To enter the study, participants had to report no clinical condition (as diagnosed by a physician) susceptible of affecting balance and/or postural control deficits, such as scoliosis, dizziness, or vestibular disorders; no severe visual impairment; and no intake of medication with a potential effect on balance during the 90 days previous to data collection. In addition, participants had to be able to maintain balance on the top of a pressure platform with bipedal support for 30 seconds for all measurement conditions (Zijlstra & Hof, 2003). From the initial 40 participants that volunteered to participate, 30 met the inclusion criteria (13 males and 17 females; Figure 1).

Procedure

The research protocol was approved by the Institutional Review Board (Research Ethics Committee of the University of Extremadura, Spain); registration number 37//2013. The study procedures complied with the ethical guidelines of the Declaration of Helsinki. Written informed consent was obtained from all participants.

Participants' evaluations were performed as described by Roerdink, Hlavackova, and Vuillerme (2011): Measurements were taken by the same investigator in an environment without visual and auditory cues. Each participant was standing barefoot on the top of a pressure platform while having one triaxial accelerometer placed on the center of mass (L3–L4) and fastened to the back with straps as reported by Whitney and colleagues (2011; Figure 2). We decided to place the accelerometer at this location as it allows the recording of relative accelerations closely related to the movement of the center of mass from which

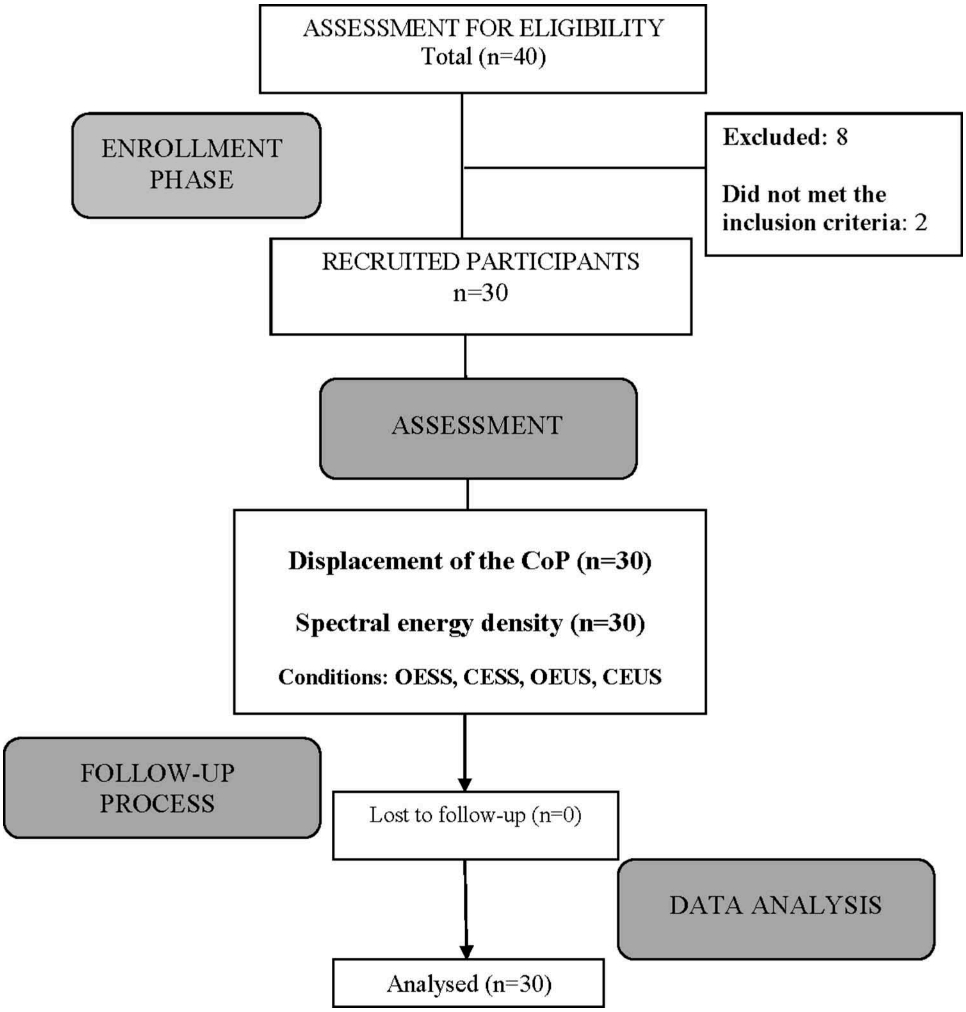

Figure 1. Flow-chart diagram of the study selection process.

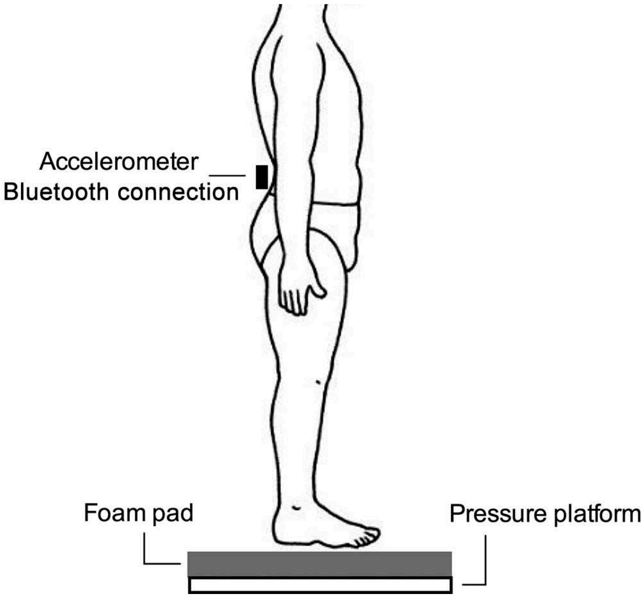

Figure 2. Evaluation with accelerometer located in the center of mass.

balance is characterized (Kamen, Patten, Du, & Sison, 1998; Whitney et al., 2011). Participants were asked to keep their arms along their body, their feet externally rotated in relation to the progression line (approximately 20 degrees), their heels 3-cm apart, to look at a fixed point at eye level to keep their head in the Frankfort plane, and to stay as still as possible for 30 seconds. Each participant completed four sessions of increasing difficulty in the following order: (a) standing on a stable surface and eyes open (OESS); (b) standing, eyes closed, and on a stable surface (CESS); (c) standing, eyes open, and on an unstable surface (OEUS); and (d) standing, eyes closed, and on an unstable surface (CEUS). A foam pad (TheraBand®) with a thickness of 10 cm was used on the top of the pressure platform to provide an unstable surface, similar to previous descriptions (Raymakers, Samson, & Verhaar, 2005). Measurements were taken three times for each condition and the best result (the best of three) was used for the statistical analysis (we considered that the best result was the result that showed a smaller displacement of the CoP).

Outcome measures

CoP

The CoP is the point that coincides with the perpendicular projection of the center of mass or gravity on the base of support (often with the assumption that less displacement indicates better control; Houdijk et al., 2015). A pressure platform PODOPRINT (NAMROL®) and one triaxial accelerometer (SHIMMER®) was used for the assessment of postural control, and spectral energy density. Both instruments have been used for the analysis of postural control, and are reliable and valid (Marchetti et al., 2013; Zuil Escobar & Martínez Cepa, 2011). Frequency of data collection was set at 100 Hz. The pressure platform used in this study has a total of 1,504 pressure sensors placed 1-cm apart. The range of measurable pressures is 1–120 N/cm^2, with an accuracy of ±5%.

Spectral energy density

A signal χ(t) can be defined as energy if its average energy is finite (i.e, 0< Ex< ∞), and its average power is zero; similarly, if the squared value of its integral exists and is finite (i.e., if it can be applied to signals of energy and measures the distribution of the energy of the signal in the frequency). The signal χ (t) is the frequency and Ex the integral of the squared χ(t).

An energy signal χ(t) has 0 < E< ∞ for average energy:

$$E = \int_{-\infty}^{\infty} |x(t)|^2 dt.$$

A power signal χ(t) has 0 < P< ∞ for average power

$$P = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} |x(t)|^2 dt.$$

Three-dimensional recordings of the triaxial accelerometer enabled us to register and calculate the power spectral density of the acceleration in different axes (Z axis; Y axis; X axis) as a measure of spectral energy density efficiency for each of the four measurement conditions previously described.

The calculation of spectral energy density was as follows: $S_{xx}(f) = |x(f)|^2$ expressed in [Joules/Hertz] were χ(f) is the Fourier Transform of χ(t) and the integral of this function in f axis is the value of the total energy of the signal χ(t):

$$E = \int_{-\infty}^{+\infty} S_{xx}(f) df.$$

The anteroposterior oscillations were reflected in the Z axis, the mediolateral oscillations in the Y axis, and finally the vertical oscillations in the X axis. Marchetti and colleagues (2013) tested the reliability of the triaxial accelerometer in a set of conditions similar to those used in the present study: (a) eyes open/stable surface [ICC: 0.86, 95%CI: 0.79–0.91], (b) eyes closed/stable surface [ICC: 0.85, 95%CI: 0.78–0.90], (c) eyes open/unstable surface [ICC: 0.74, 95%CI: 0.63–0.83], (d) eyes closed/unstable surface [ICC: 0.82, 95%CI: 0.72–0.88].

Reliability analysis

Test retest reliability of the pressure platform was assessed in two sessions 4 days apart using six participants (age: 20–26 years old) not included in the final sample, but who met the inclusion/exclusion criteria previously defined. Procedures were as described for the full study with the 30 participants.

Statistical analysis

Data from both the pressure platform and the accelerometer were obtained using 4.2 FreeMat software (Freemat is an interpreted, matrix-oriented development environment for engineering and scientific applications, *http://freemat.sourceforge.net/*). The Mann-Whitney U test was used to compare weight, height, and body mass index (BMI) between males and females. Association between gender *versus* displacement of CoP, BMI *versus* displacement of CoP, gender *versus* spectral energy density, and BMI *versus* spectral energy density was assessed using analysis of covariance (ANCOVA).

A student's paired t-test and a Wilcoxon signed-rank test or Friedman's two-way analysis were used to test for differences between the four conditions (OESS; CESS; OEUS; CEUS), both for data from the pressure platform and from the accelerometer. To explore the association between the displacement of the CoP and the spectral energy density in the four conditions (OESS; CESS; OEUS; CEUS), we used a Pearson correlation coefficient.

For the reliability analysis of the CoP displacement, an intraclass correlation coefficient (ICC) was calculated, and used to calculate the standard error of measurement (SEM), which was, then, used to compute the smallest real difference (SRD; Beckerman et al., 2001). The significance level was established at $p < 0.05$. Data analysis was performed with the statistic software SPSS, version 19.0 (SPSS Inc., Chicago, IL, USA) and Graphpad Prism 6.0 software.

Results

A total of 30 participants completed the study (M age ± *SD* = 21.57 ± 3.31 years old), of which 17 were females and 13 were males (Table 1).

Association gender/BMI versus displacement of CoP

At baseline, a statistically significant difference was found between males and females for anthropometric characteristics (Table 1). However, no statistically significant difference was found for the association between gender/BMI *versus* displacement of CoP or for gender/BMI *versus* spectral energy density nor for any of the axes of motion and conditions of measurement (OESS; CESS; OEUS; CEUS).

Reliability and CoP displacement in the anteroposterior and mediolateral axes

The ICC, SEM, and SRD for anteroposterior CoP displacement were 0.96 mm, 0.18 mm, and 0.51 mm, respectively. The ICC, SEM, and SRD for mediolateral CoP displacement were 0.66 mm, 0.38 mm, and 1.05 mm, respectively.

Statistically significant differences were found for anteroposterior and mediolateral CoP displacement between the condition CESS and the condition CEUS (anteroposterior displacement: $p = 0.002$; mediolateral displacement: $p = 0.009$). No statistically significant difference was found for the CoP measurements during the sessions with OESS or OEUS (Table 2).

Table 1. Descriptive characteristics of the sample.

	M ± *SD*	
	Male (n = 13)	Female (n = 17)
Weight (Kg)*†	75.15 ± 8.45	58.82 ± 6.73
Height (cm)*†	177 ± 6.73	164.41 ± 3.97
BMI (Kg/m^2)*†	23.97 ± 2.39	21.73 ± 2.18
Left foot (Kg)	37.92 ± 4.51	37.23 ± 4.86
Right foot (Kg)	29.71 ± 3.68	29.06 ± 4.38

*p-Value ≤0.05; †Mann-Whitney U test.

Table 2. Comparison of CoP displacement in mediolateral and anteroposterior axes.

	Mediolateral	Anteroposterior		
Task	M ± *SD*	M ± *SD*	z	p-Value
OESS	3.65 ± 1.87	4.53 ± 2.22	−1.827	0.068$^{\dagger\ \dagger}$
CESS	4.06 ± 2.12	5.41 ± 3.32	−3.029	0.002$^{\dagger\ \dagger *}$
OEUS	4.31 ± 3.32	4.83 ± 3.33	−1.244	0.214†
CEUS	4.48 ± 2.21	6.38 ± 5.56	−2.617	0.009$^{\dagger\ \dagger 0 *}$

Note. z = statistical value of the normal frequency curve. Bold indicates.
$^{\dagger\ \dagger}$ = Test Wilcoxon signed-rank test.
† = Student's t-test.
*p < 0,05 = statistical significance.

Comparison between the vertical, mediolateral, and anteroposterior axes for spectral energy density

No significant difference was found for the comparison of the spectral energy density in the different axes of motion (i.e., vertical *versus* mediolateral *versus* anteroposterior). However, Figure 3 shows an increase in the spectral energy density with increasing difficulty of the measurement conditions (from the condition OESS to the condition CEUS), showing an increase in the Z axis (anteroposterior displacement).

Correlation between CoP displacement and spectral energy density

A statistically significant correlation was found between the displacement of the CoP and the spectral energy density efficiency. This correlation was observed between the energy of motion required to maintain postural control during an imbalance situation (power spectral density) in the Z axis (anteroposterior) of the accelerometer and the participant's response to disequilibrium in mediolateral axis of the CoP (r = 0.47; p = 0.01). A significant correlation was also observed between the Y axis (mediolateral) accelerometry and displacement of the CoP in the anteroposterior axis (r = 0.41; p = 0.023; Table 3).

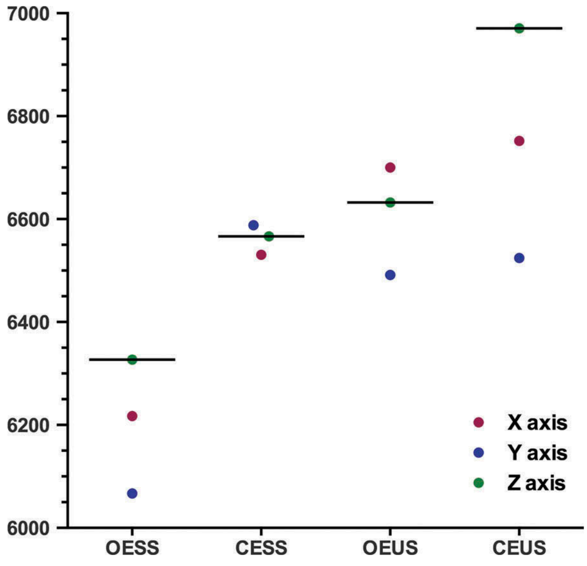

Figure 3. Energy spectrum of accelerations in the frequency band of 1.5–3 Hz in different conditions (OESS, CESS, OEUS, CEUS).

Table 3. Correlation values of CoP displacement and spectral energy density in the CEUS condition.

		CoP Displacement			
		CEUS ML-Axis		CEUS AP-Axis	
		R	*p*-Value	*R*	*p*-Value
Energy spectral density	CEUS X-axis	0,068†	0,720	0,247†	0,188
	CEUS Y-axis	0,268†	0,152	0,413†	0,023*
	CEUS Z-axis	0,465†	0,01*	0,291†	0,118

Notes. X-axis = vertical; Y-axis = mediolateral; Z-axis = anteroposterior; ML-axis = mediolateral; AP-axis = anteroposterior; *R* = correlation coefficient.

† = Pearson correlation test.

*$p \leq 0,05$ = level of significance.

Discussion

The study results suggest that both the pressure platform and the accelerometers were able to discriminate between study conditions, suggesting that they are able to detect changes in postural control of young people. In particular, CoP displacement and spectral energy density showed a greater ability to discriminate between stable and unstable conditions when the participant's eyes were closed. We think that the visual condition may explain the response to postural balance to a greater extent than the stability/instability of the base of support. Previous studies also pointed out that vision is a critical aspect of adaptive motor control and postural control, and visual deficits are key predictive factors of the risk of falls in older adults (Lamoureux et al., 2010; Reed-Jones, Dorgo, Hitchings, & Bader, 2012).

Gender, BMI, and postural control

Despite the fact that BMI is associated in young people with changes in balance and functionality for activities of daily living (Colné, Frelut, Pérès, & Thoumie, 2008), BMI and gender did not affect the present study results. This finding is in line with a previous study that reported a lack of a significant influence of these variables on the displacement of CoP and on the spectral energy density (Greve, Alonso, Bordini, & Camanho, 2007). Some authors claimed that higher BMI is associated with reduced postural control (Colné et al., 2008) and an increased risk of falling (Reed-Jones et al., 2012). Perhaps differences regarding the variability of BMI values and the age of participants may explain the different findings (McGraw, McClenaghan, Williams, Dickerson, & Ward, 2000). Regarding the variable gender, some authors argued that women tend to have a lower displacement of the CoP regardless of whether their eyes are open or closed compared to men (i.e., women have better postural control than men; Matheson, Darlington, & Smith, 1999). It is likely that the small sample size of the present study contributed to the lack of a significant result more than lack the ratio of men to women.

CoP displacement and spectral energy density under different conditions

Displacement of CoP was higher in the anteroposterior axis than in the mediolateral axis, but was not significant for all the measurement conditions analyzed. These results may suggest deficiencies in the standing position in the sagital plane due to the stabilizing action of the flexors and extensors of the trunk (Genthon et al., 2007). Raymakers and colleauges (2005) investigated the usefulness of different CoP displacement parameters in young and healthy individuals (age 21–45 years), in healthy older adults (61–78 years), and in older adults with Parkinson's disease (age 65–87 years). They found a greater displacement of the CoP in the mediolateral axis in both groups of older adults when compared to young adults (Raymakers et al., 2005). Woollacott and Shumway-Cook (2002), between other authors, explained these differences by varying attentional demands associated with postural control, depending on the complexity of the task for both young and older adults.

In this sense, as shown in the Raymakers and colleagues' study (2005), CoP displacement in the mediolateral axis in older adults has been found to be a more accurate predictor of fall risk than CoP displacement in the anteroposterior axis (Raymakers et al., 2005). Further studies comparing CoP displacement and spectral energy density between young adults and older adults are needed.

Regarding the degree of difficulty of the measurement conditions, the results of our study showed a statistically significant increase in the displacement of the CoP when participants had their eyes closed and were standing on top of an unstable surface. This finding contrasts with the results of Raymakers and colleagues (2005), who reported a larger displacement of the CoP when changing the stability of the support base while maintaining the eyes opened. The difference in findings between the two studies may suggest that proprioceptive information from the lower limbs when standing on top of stable/unstable surfaces is particularly important for older adults' postural control in the absence of visual information (Raymakers et al., 2005).

The frequency of most human movements lies between 0.3 Hz and 3.5 Hz, increasing in magnitude from head to ankles (Teixeira, Jesus, Mello, & Nadal, 2012). The movements that occur below 1.5 Hz are automatic or involuntary, those between 1.5 Hz and 3 Hz are voluntary and are associated with the search for balance in unstable situations, as shown in Figure 3. Nevertheless, there is conflicting evidence on whether greater accelerations occur in the mediolateral or in the anteroposterior axis. Mathie, Coster, Lovell, and Celler (2003) indicated that accelerations measured in the vertical axis (X axis) are more important than those occurring in the other two axes. Kamen and colleagues (1998) reported higher accelerations in the anteroposterior axis (Z axis) on unstable surfaces with eyes closed. Although spectral energy density of the acceleration is required to maintain postural balance, previous study findings are difficult to compare with the present study findings. Further studies are needed that provide standardized values for these parameters in different conditions (e.g., sitting, standing) and for different populations (e.g., in healthy older adults [age >60 years], and in older adults with Parkinson's disease [age >65 years]; Raymakers et al., 2005).

Correlation between CoP displacement and spectral energy density

The authors of the present study were unable to find previous studies investigating the role of spectral energy density on postural control. In the present study, a significant correlation was found between the degree of anteroposterior/mediolateral CoP displacement and the increase in spectral energy density in the mediolateral/anteroposterior axis, respectively. This finding may be related with voluntary movements preceded by anticipatory postural adjustments (APAs), which produce a shift in the body's center of mass to counteract the perturbations resulting from movement (Shiratori & Aruin, 2004). These APAs can themselves be a source of additional perturbations under unstable conditions. The decrease or modification of the APAs' patterns by the central nervous system as a strategy to control asymmetries on different support surfaces (Shiratori & Aruin, 2004) may explain the adjustments on the Z-axis (anterior–posterior) and Y-axis accelerometer (mediolateral) as spectral energy density used.

These observations are consistent with the association between increased CoP displacement and variability in measurement conditions where the eyes were closed, as reported by Whitney and colleagues (2011). Furthermore, they are also consistent with the hypothesis of a functional relationship and coherence, which is supported by modern neurophysiology. The architecture of the muscular and connective tissue plays a significant role in the coding of the proprioceptive information provided to the postural control system (Van Der Wal, 2009). Recent studies suggested that certain points in the deep (aponeurotic) fascia (called centers of coordination) coordinate the muscular forces involved in the movement of specific body segments in one specific direction (i.e., one coordination center coordinates the forces of the biceps femoris and gluteus muscle during standing; Stecco et al., 2010). These coordination centers, also named diaphragms, distribute the musculoskeletal forces produced, allowing for the balance of the postural adjustments during unstable conditions.

Clinical implications

Balance and postural control are often impaired in persons with certain health conditions and in older adults (Woollacott & Shumway-Cook, 2002) and closely related with fall risk (Inouye, Studenski, Tinetti, & Kchel, 2007). From a clinical point of view, an instrumented evaluation can inform the clinical decision regarding balance rehabilitation (Cadore, Rodríguez-Mañas, Sinclair, & Izquierdo, 2013). The results of this study suggest that it is possible to use accelerometers in the clinical setting. Nevertheless, caution should be taken when interpreting these study results because postural control optimization does not depend only on the magnitude of CoP oscillation, but also on the integrated response during a specific task (Houdijk et al., 2015) and on other parameters such as age (Nardone & Schieppati, 2010), recent physical exercise (Lamoureux et al., 2010), or muscle fatigue (Paillard, 2012). In addition, this study may not apply to other age groups and it is not known whether the measurement instruments used are able to identify changes in the individuals' postural control. Therefore, further studies are needed to investigate the validity of the proposed models in older adults or individuals with visual impairments. Future research should include larger cohorts, using additional instruments that assess myoelectric activity.

Conclusion

In conclusion, spectral energy density appears to be associated with the displacement of CoP in healthy participants. The results showed that assistive technology used could be an appropriate tool for monitoring human movement in clinical settings.

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