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The influence of center-of-mass movements on the variation in the structure of human postural sway

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ABSTRACT

The present article investigates the influence of center-of-mass movements on the variation of the structure in human postural sway. Twelve healthy younger persons performed 60 s quiet standing, 60 s relaxed standing, and 10 min relaxed standing on two force plates. Center-of-pressure (CoP) and gravitational line (GL) profiles were calculated from the ground reaction forces and moments. The temporal variation of CoP structure was calculated by the local scaling exponent h_t and a Monte Carlo surrogate test was used to identify phase couplings between temporal scales. The range of variation of h_t was significantly larger in relaxed standing compared to quiet standing ($p < 0.00001$) and highly correlated with the range of GL movements ($r > 0.76$, $p < 0.001$). However, the variation in h_t was not generated by the GL movements because the CoP–GL traces was close to identical variation in h_t ($r > 0.95$, $p < 0.00001$). The Monte Carlo surrogate test indicated the presence of intermittent phase couplings between the temporal scales of both CoP traces and the CoP–GL residuals in the periods with GL movements. The present results suggest that human posture is controlled by intermittent phase coupling of the CoP and GL movements. Furthermore, the investigation of the variation in CoP structure might extend existing theories of changes in postural control for example older persons and patients with a neurodegenerative disease.

1. Introduction

Postural control is a fundamental aspect of human locomotion and whole body movement, and is commonly investigated through the traces of the center of pressure (CoP). In most studies, magnitude-based parameters like range, standard deviation, root-mean-square, and coefficient of variation are used to quantify the mean magnitude of the CoP traces. However, these measures are insensitive to the structure of variation and might conceal fundamental principles of postural control (Newell et al., 1993; Norris et al., 2005). Several studies have introduced scaling exponents that numerically define the structure of the CoP traces instead of the mean magnitude of its variations (Collins and De Luca, 1993; Delignières et al., 2003; Duarte and Sternad, 2008; Duarte and Zatsiorsky, 2000). The migration of CoP has a persistent structure (i.e., large exponent) over a short time span and anti-persistent structure (i.e., small exponent) over a long time span and the exponents have been shown to be sensitive to age (Collins et al., 1995; Kim et al., 2008), risk-of-falling (Norris et al., 2005), and neurodegenerative disease (Morales and Kolaczyk, 2002). Furthermore, the scaling exponent of CoP has high inter-test reliability (Lin et al., 2008) and is shown to be a good predictor for risk of falling in the older population (Bigelow and Berme, 2011).

However, contemporary studies of the scale-invariant structure of CoP traces have a number of important shortcomings. Firstly, even though previous methods define the structure of the CoP by a short-term ($s < 1$ s) and long-term ($s > 1$ s) scaling exponent, they assume that the short- and long-term scaling exponents do not change over time. In other words, previous methods are based on the assumption of monofractality that could average out important local variations in the scaling exponents due to small movements of the center of mass (CoM). The monofractal exponent would then conceal fundamental multifractal characteristics (i.e., temporal variation in the scaling exponents) of postural control in a similar way as the mean magnitude of variation conceals the monofractal characteristics (cf. Newell et al., 1993). Secondly, most studies of postural control investigate the structure of CoP traces in quiet standing, that is in standing as still as possible (e.g., Collins and De Luca, 1993; Norris et al., 2005). The argumentation for this is to eliminate the influence of voluntary movements of the gravity line (GL, the 2D ground projection of the CoM along the direction of the gravitational force) during relaxed standing that might

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obscure control mechanisms revealed in involuntary adjustments of CoM. However, a recent study found that voluntary control of CoP through visual feedback changes the structure of the CoP more than its amplitude due to modulations in GL and residual CoP–GL (Danna-Dos-Santos et al., 2008). Furthermore, differences were also found between younger and older persons in the structure of CoP for relaxed standing that are not present in quiet standing (Duarte and Sternad, 2008; Duarte and Zatsiorsky, 1999). Thirdly, postural control is influenced more by the interrelation between GL and CoP than by the CoP alone (Corriveau et al., 2004). According to the inverted pendulum model of human standing, CoP must vary around GL to maintain an upright posture and prevent falls or stepping responses (Winter, 1995). An earlier study found that the somatosensory system and muscle strength explain the amplitude of the CoP variation around GL in both healthy older persons and patients with stroke and neuropathy (Corriveau et al., 2004). The voluntary modulation of the GL and CoP–GL structures were also found to be dependent on the standing task condition (Reynolds, 2010) and visual feedback (Danna-Dos-Santos et al., 2008). Thus, the long-term structure of GL movements necessarily influences the structure of CoP dynamics.

The main aims of the present article are (1) to introduce a method that can assess the temporal variation in the structure of the CoP traces during standing, (2) to compare the variation in the structure of the CoP traces for quiet and relaxed standing, and (3) to investigate the influence of GL movements on the variation of the scale-invariant structure of CoP.

2. Methods

Twelve healthy young subjects (6 males and 6 females, age 21.8 ± 3.5 yrs, height 1.75 ± 0.01 m, and body mass 80.5 ± 11.8 kg) participated in the present study. The study was approved by the regional ethical committee, and all subjects signed a written consent before participation. The participants performed three trials, 60 s quiet standing, 60 s relaxed standing, and 10 min relaxed standing. The order of trials was fixed across participants, starting with quiet standing, followed by short and longer relaxed standing. Quiet standing was performed in the Romberg position (Black et al., 1982), looking straight ahead at the wall 7.5 m in front of the participants, with the instruction to stand as still as possible. In the two relaxed standing conditions, the participants were instructed to stand naturally and relaxed as when waiting for a bus. In all conditions, participants were instructed to stand with each foot on a separate force plate.

The 3D ground reaction forces and moments were sampled at 50 Hz by two Kistler force plates (Type 9286A, Kistler Group Switzerland) placed side by side ≈ 1 mm apart. The CoP was calculated after each component of the ground reaction force and moment data was filtered by a 10 Hz low pass 8th order recursive Butterworth filter. The maximum of the baseline noise for CoP in anteriorposterior (AP) and mediolateral (ML) direction was < 0.0005 m when measured from 80 kg stationary weights. A linear drift of 0.005 m was present in CoP in both ML and AP directions during a 10 min trial with 80 kg stationary weights. The linear drift was corrected for by linear detrending, and this correction did not influence the results of the scaling analyses below.

The gravitation line (GL) of the CoM was estimated by a two step procedure. First, GL was defined by double integration of the horizontal AP and ML components of the ground reaction force. A linear detrending of the obtained GL position was then performed to adjust for the unknown initial condition of the GL velocity (cf. GL-2 in King and Zatsiorsky, 1997). Nevertheless, this method is susceptible to small nonlinear trends in the horizontal components of the ground reaction force. The second step addressed this shortcoming of the King and Zatsiorsky algorithm. A low pass 8th order recursive Butterworth filter was used to numerically define nonlinear trends for both the obtained GL and CoP positions. The erroneous GL trend was then subtracted from the GL position and the CoP trend was added, since the CoP position must vary around the GL position in human standing (Winter, 1995). The cut-off frequency of the low pass filter was individually adapted to minimize the root-mean-square error between the horizontal components of the measured ground reaction force and the horizontal components estimated from the GL positions. The minima of the root-mean-square error was 0.07–0.40 N for the quiet standing condition and 0.10–1.05 N for the relaxed standing conditions and proportional ($\approx 23\%$) to the horizontal components of the ground reaction force for all participants under all conditions. The performance of this revised estimation of GL was superior to the algorithms suggested by King and Zatsiorsky (1997), as indicated by the reconstruction of the horizontal components of the ground reaction force from GL.

The variation in the scale-invariant structure was defined for the position and velocity of CoP and CoP–GL. The temporal change in the scale-invariant structure is defined by a local scaling exponent by the following equations (Mandelbrot, 1974; Riedi, 2002):

$$\mu_{s,t_0} \propto s^{h_t} \tag{1}$$

where μ_{s,t_0} is the local root mean square variation of the signal X_t in the time interval $[t_0 - s/2,\ t_0 + s/2]$ around a polynomial trend $P_{t,m}$ of order m:

$$\mu_{s,t_0} = \sqrt{\frac{1}{s}\sum_{t=t_0-s/2}^{t_0+s/2}[X_t - P_{t,m}]^2} \tag{2}$$

Eqs. (1) and (2) are multifractal extensions of the detrended fluctuation analysis (cf. Ihlen, 2012). The polynomial trend order in Eq. (2) is reported for $m=1$ in the present study, but additional analyses showed that the results were not dependent on m. Furthermore, Eq. (2) was computed with the scaling range $s=0.1$–0.8 s. Eq. (2) was employed directly to CoP and the CoP–GL residual trace X_t, to define the variation of h_t of CoP and CoP–GL velocity, and indirectly to the integrated profile of the same traces to define the variation of h_t of CoP and CoP–GL positions. Both the CoP trace and its integrated profile have been used to investigate the scale-invariant structure of CoP velocity and position, respectively (Delignières et al., 2011). However, our analyses indicate that h_t for CoP and CoP–GL velocity are approximately $h_t - 1$ for the h_t of CoP and CoP–GL position and, thus, only h_t for CoP and CoP–GL positions will be presented here. The local scale-invariant and random-walk like structure of CoP and CoP–GL positions are referred to as persistent when $h_t > 1.5$ and anti-persistent when $h_t < 1.5$. The scale-invariant structure is similar to a time-independent random walk in the special case $h_t = 1.5$. The advantage of Eqs. (1) and (2) compared to conventional methods like detrended fluctuation analysis, rescaled range analysis, and spectral analysis is that the scaling exponent h_t can be defined locally in both time t_0 and scale s. The magnitude of variation of h_t was defined by the range of h_t for $s=0.8$ s in Eq. (2). The variation in the local scale-invariant structure h_t can be generated by phase coupling between the temporal scales that are independent of the central tendency of h_t or the distribution of the CoP dynamics and CoP–GL residuals. A Monte Carlo simulation was performed to test for the presence of phase couplings between the temporal scales. In the Monte Carlo simulation, 1000 iterated amplitude-adjusted Fourier-transformed (IAAFT) surrogate time series were generated for each CoP and CoP–GL trace that replicated their spectral density (i.e., central tendency of h_t) and distribution, but eliminated the phase couplings between the temporal scales (Schreiber and Schmitz, 1996). Phase couplings between the temporal scales are present when 97.5% (i.e., two-tailed test; $p=0.05$) of the surrogates series have higher or lower h_t compared to the original CoP or CoP–GL dynamics.

The range of variation in h_t and GL was defined and repeated-measures ANOVAs were used to test for differences between the quiet and relaxed standing conditions. Subsequent pair-wise comparisons were performed by paired samples t-tests with Bonferroni corrections of the p-values for multiple comparisons. The similarities between the range of movements in GL and the range of the h_t scale were tested by Pearson cross-correlations. Furthermore, the similarity between the variation of h_t in CoP traces and CoP–GL residuals were tested by Pearson cross-correlations for each pair of h_t series.

3. Results

Fig. 1 shows representative examples of CoP and GL traces during 60 s quiet and 60 s relaxed standing. As expected, the range of GL movements was dependent on standing condition in both ML ($F(2,11)=21.35$, $p < 0.00001$) and AP directions ($F(2,11)=7.26$, $p=0.004$). Post-hoc comparisons with Bonferroni corrections indicated that both relaxed standing conditions were significantly different from the quiet standing condition (all $ps < 0.02$). The range of h_t for the CoP trace was dependent on the temporal changes in GL position, particularly during 60 s and 10 min relaxed standing (see Figs. 2 and 3). In time periods with large changes in GL position, the local scale-invariant structure of the CoP trace became less persistent (i.e., exponent $h_t < 1.5$) compared to the periods with little movement of the GL, as reflected by the negative skew of distributions $P(h_t)$ in Figs. 2 and 3. This variation in h_t was present for both CoP position and velocity. The range of h_t was dependent on standing condition in both ML ($F(2,11)=29.00$, $p < 0.00001$) and AP directions ($F(2,11)=19.25$, $p < 0.00001$). The range of h_t was significantly