



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



Espen A.F. Ihlen<sup>a,\*</sup>, Nina Skjæret<sup>b</sup>, Beatrix Vereijken<sup>b</sup>

<sup>a</sup> Department of Neuroscience, Norwegian University of Science and Technology, N-7489 Trondheim, Norway

<sup>b</sup> Department of Human Movement Science, Norwegian University of Science and Technology, Trondheim, Norway

## ARTICLE INFO

### Article history:

Accepted 21 October 2012

### Keywords:

Center of pressure  
Postural control  
Postural sway  
Fractal  
Scale invariance

## 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.

© 2012 Elsevier Ltd. All rights reserved.

## 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 Kolaczky,

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

\* Corresponding author. Tel.: +4747354674.

E-mail address: [espen.ihlen@ntnu.no](mailto:espen.ihlen@ntnu.no) (E.A.F. Ihlen).

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 inter-relation 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  $21.8 \pm 3.5$  yrs, height  $1.75 \pm 0.01$  m, and body mass  $80.5 \pm 11.8$  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  $\approx 1$  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):

$$\mu_{s,t_0} \propto s^{h_t} \quad (1)$$

where  $\mu_{s,t_0}$  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  $m$ :

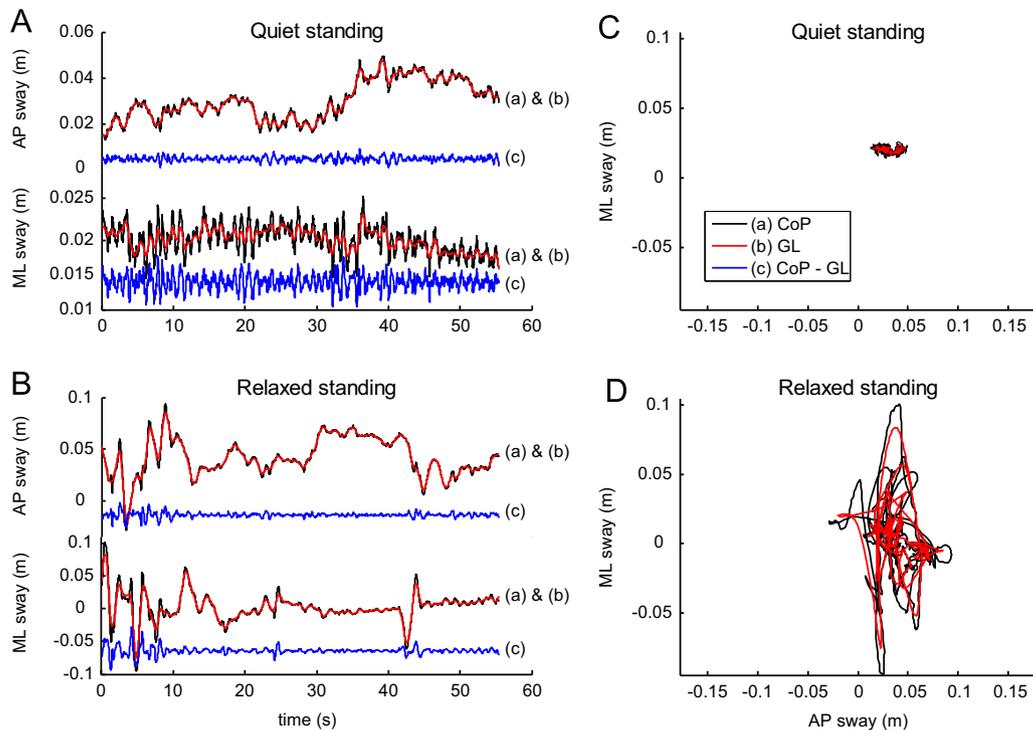
$$\mu_{s,t_0} = \sqrt{\frac{1}{s} \sum_{t=t_0-s/2}^{t_0+s/2} [X_t - P_{t,m}]^2} \quad (2)$$

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 (IAFFT) 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.

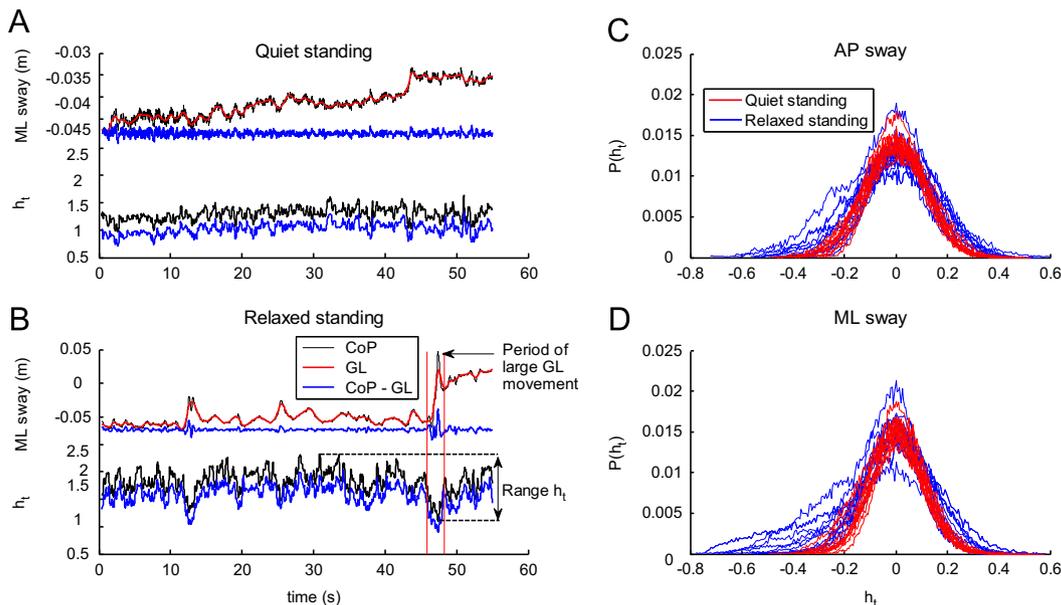
The range of variation in  $h_t$  and GL was defined and repeated-measures ANOVAs were used to test for differences between the quiet and relaxed standing conditions. Subsequent pair-wise comparisons were performed by paired samples  $t$ -tests with Bonferroni corrections of the  $p$ -values for multiple 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



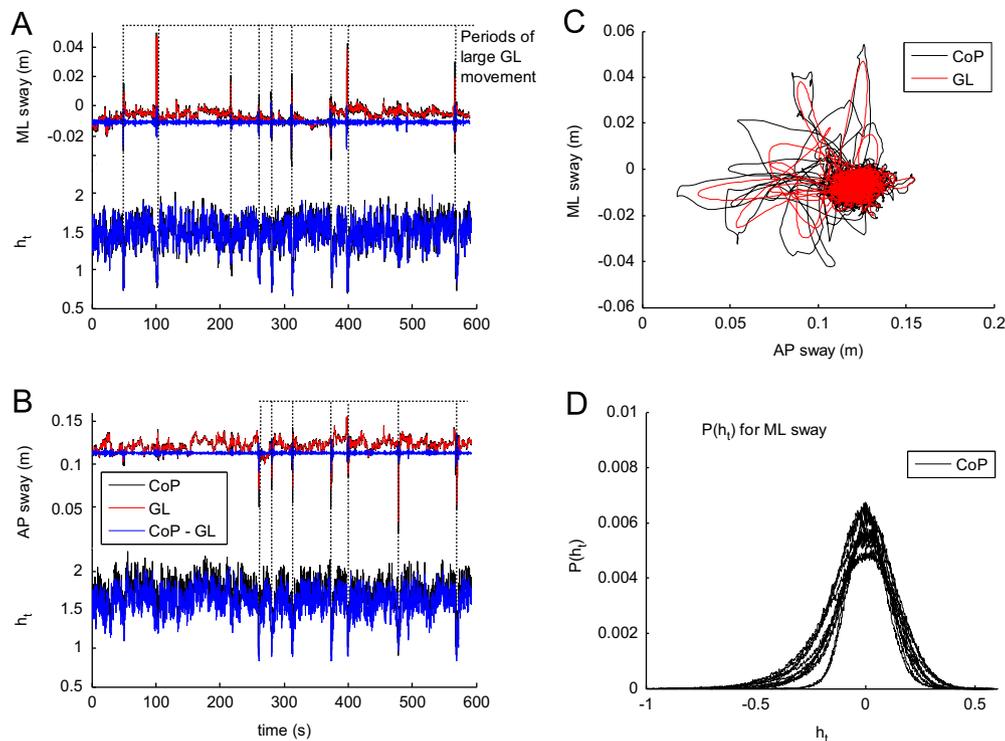
**Fig. 1.** A representative example of the temporal change of CoP (black traces), GL (red traces), and CoP-GL residuals (blue traces) for 60 s quiet (panel A) and relaxed (panel B) standing. The temporal changes in CoP, GL, and CoP-GL residuals are illustrated in each panel for the anteriorposterior (AP, upper part) and the mediolateral (ML, lower part) directions. The CoP and GL are also shown as a 2D stabilogram where the ML and AP direction are plotted together for both quiet (panel C) and relaxed (panel D) standing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 2.** A representative example of the variation in the structure  $h_t$  (lower part) of CoP and CoP-GL residuals (upper part) for 60 s quiet (panel A) and relaxed (panel B) standing. The relaxed standing condition has periods with less persistent structure (i.e., smaller  $h_t$ ) and large movements of GL. Panels C and D: the less persistent structure in periods with large GL movements leads to a distribution  $P(h_t)$  of  $h_t$  that is more negatively skewed in the relaxed standing condition (blue traces) compared with the quiet standing condition (red traces). Notice that the distribution  $P(h_t)$  for all participants are aligned at their modes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

larger for both the 60 s relaxed standing condition ( $t$ -tests:  $ps < 0.005$ , ML: mean=1.03, AP: mean=0.95) and 10 min relaxed standing condition ( $t$ -tests:  $ps < 0.0002$ , ML: mean=1.17, AP: mean=1.11) compared to the 60 s quiet standing condition (ML: mean=0.69, AP: mean=0.81). Furthermore, the range of  $h_t$  variation was strongly correlated with the range of GL movement in both the 60 s and 10 min relaxed standing conditions ( $rs > 0.76$ ,  $ps < 0.001$ ), but uncorrelated in the quiet standing condition

( $r < 0.02$ ). Even though the variation in  $h_t$  was dependent on the GL movements,  $h_t$  was not generated by the GL movements, as confirmed by the very high cross-correlations ( $rs > 0.95$ ,  $ps < 0.00001$ ) between  $h_t$  series from CoP and CoP-GL residual traces, irrespective of standing condition. In contrast, the median  $h_t$  significantly decreased ( $t$ -tests:  $ps < 0.001$ ) for CoP-GL residuals compared to the CoP trace for both the 60 s quiet standing condition (from mean=1.61 to mean=1.44) and the 60 s relaxed



**Fig. 3.** A representative example of the variation in the structure  $h_t$  (lower part) of CoP and CoP–GL residuals (upper part) for 10 min relaxed standing in the mediolateral (ML, panel A) and anteriorposterior (AP, panel B) directions. Panel C: CoP and GL movements in ML and AP directions combined in a 2D stabilogram. Multiple periods with large GL movements are reflected in the less persistent structure (i.e., smaller  $h_t$ ) of CoP and CoP–GL traces in both AP and ML directions. Panel D: the less persistent structure in the periods with large GL movements are reflected as a negative skew of the distribution  $P(h_t)$ , illustrated here for the ML direction. Notice that the distribution  $P(h_t)$  for all participants are aligned at their modes.

standing condition (from mean=1.85 to mean=1.65). Furthermore, the high correlation between the  $h_t$  of the CoP and CoP–GL traces indicates interactions between CoP and GL movements, as reflected by a significant phase coupling between temporal scales in the periods with large GL migration (see Fig. 4).

Summarized, the present results indicate that (1) variation in the scale-invariant structure  $h_t$  of CoP is present in both quiet and relaxed standing, (2) the variation in  $h_t$  is larger in both prolonged and short tests of relaxed standing compared to quiet standing, and (3) the variation in  $h_t$  is dependent on, but not generated by, the movements of the CoM.

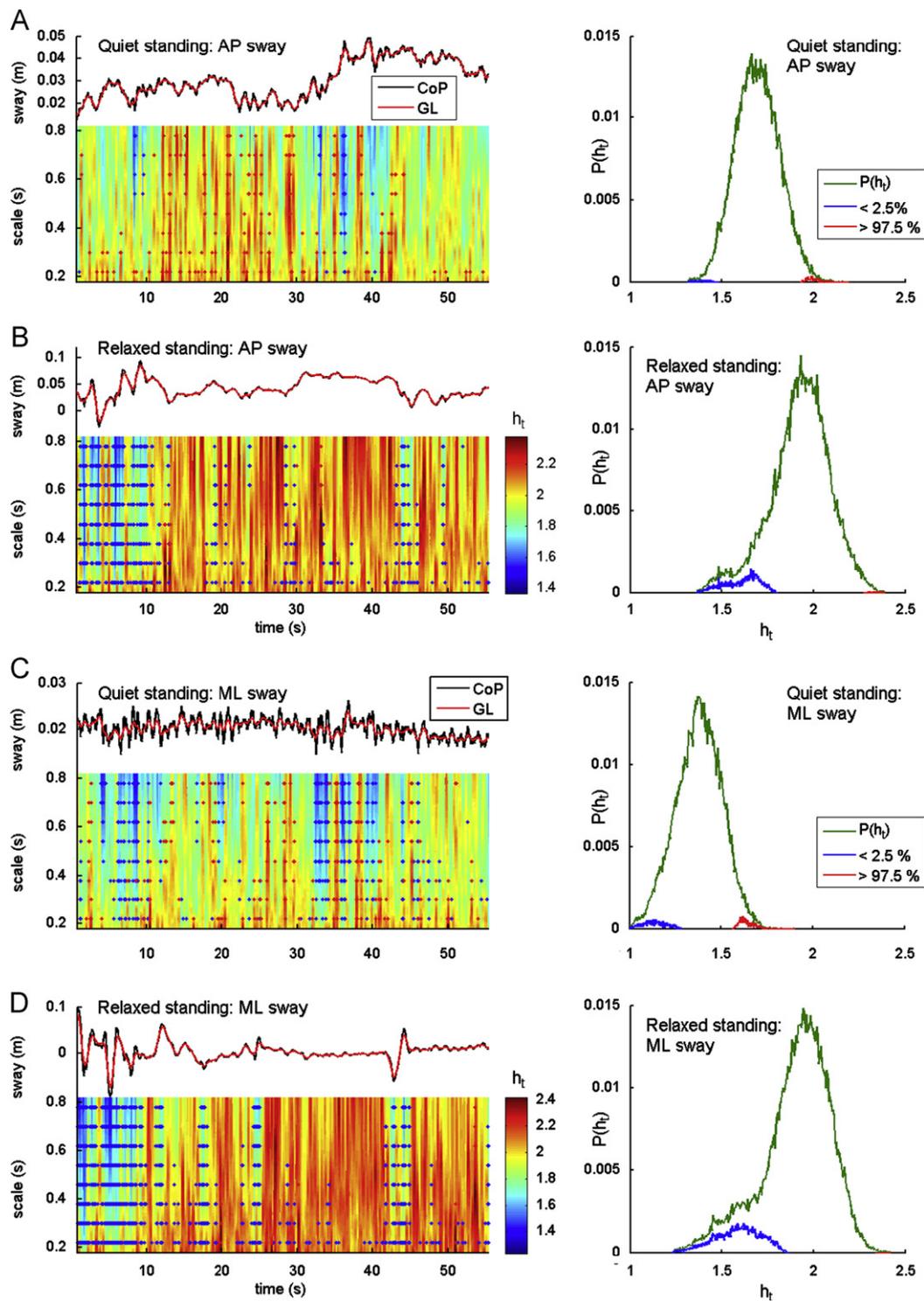
#### 4. Discussion

The current study identified the influence of movements of the GL on the variation in the scale-invariant structure of CoP in quiet and relaxed standing. The inverted pendulum control hypothesis has been invoked to explain the relationship between CoP and GL in human standing, whereas theories of stochastic processes can explain the scale-invariant structure of CoP. The presence of large variation in the CoP structure (i.e.,  $h_t$ ) in the intermittent periods of GL movement suggest that these theories can be combined as discussed in the paragraphs below.

The hypothesis of inverted pendulum control suggests that the structure of the CoP trace will be continuously driven towards the equilibrium GL trace in both quiet and relaxed standing by an elastic-like modulation of the ankle stiffness (Winter et al., 1998,2001). As a consequence, CoP will vary around the slowly evolving GL trace and the CoP velocity towards the GL trace will increase with the magnitude of the residual CoP–GL trace by increases in the ankle stiffness (Zatsiorsky and Duarte, 1999,2000). However, this hypothesis of inverted pendulum control suggests

continuous control of CoP in accordance with GL movements, whereas the significantly smaller  $h_t$  of CoP compared with the  $h_t$  of IAAFT surrogates (see Fig. 4) suggests intermittent phase couplings between GL and CoP–GL residuals in time periods with large GL movements. The variation in  $h_t$  found in the present study numerically defines changes in the structure of CoP in both quiet and relaxed standing that are dependent on the intermittent phase couplings with the GL movements. These findings are more consistent with a hypothesis of intermittent ballistic control of the inverted pendulum (Bottaro et al., 2005; Morasso and Schieppati, 1999,2002), in which the GL position is considered as an unstable equilibrium point and small perturbations cause intermittent shifts in the CoP traces. Intermittent ballistic control is further supported by a series of experimental studies (Loram and Lakie, 2002a,2002b; Loram et al., 2005) that indicate intermittent ankle torque generation rather than continuous modulation of ankle stiffness. However, the hypothesis of intermittent ballistic control of human standing has so far not introduced numerical methods that parameterize the particular features of intermittent postural control. The GL-dependent variation in  $h_t$  introduced in the present study is a promising numerical method to parameterize the intermittent structure of the CoP movements that might be important for clinical applications as well.

Two-component theories, such as open- and closed-loop control (Collins and De Luca, 1993) and conservative and operative control (Dijkstra, 1998; Gatev et al., 1999), have been developed to explain the short- and long-range components of the CoP structure. However, these two-component theories do not consider the influence of GL movements like the hypothesis of inverted pendulum control above does. The present results indicate that the short-range persistent and long-range anti-persistent structure of both CoP position and velocity profiles in quiet standing are influenced by the lack of GL movement.



**Fig. 4.** Representative example of phase coupling between temporal scales (i.e., contour plot) of the CoP movements (upper trace) in AP (panels A and B) and ML (panels C and D) directions for both quiet (panels A and C) and relaxed (panels B and D) standing. The variations in  $h_t$  are illustrated in a contour plot for multiple temporal scales where the periods with red colors reflect large  $h_t$  (i.e., more persistent structure of CoP) whereas blue colors illustrate small  $h_t$  (i.e., less persistent structure of CoP). The vertical alignment of blue and red dots illustrates the time instants where  $h_t$  are significantly larger or smaller ( $p < 0.05$ ) than the ensemble of surrogates and, consequently, the structure (i.e.,  $h_t$ ) is significantly influenced by phase couplings between the temporal scales.  $h_t$  is significantly influenced by phase couplings between the temporal scales in periods with large GL movements, particularly in the relaxed standing condition. The significantly smaller  $h_t$  contribute to the negatively skewed distributions  $P(h_t)$  for relaxed standing, illustrated by the larger blue sub-distributions in the right parts of panels B and D compared to the blue sub-distributions for quiet standing (right parts of panels A and C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The present results further suggest that the lack of differences found in the long-range anti-persistent structure of the CoP position and velocity between younger and older persons (Collins et al., 1995) and between older persons with high and

low risk of falling (Norris et al., 2005), may only reflect the constraints on the GL movements in quiet standing. Furthermore, the differences between these same groups in the short-range persistent structure are likely related to the larger magnitude of

variation in the CoP–GL residuals in older adults with high risk of falling, which may reflect alterations in the timing of the intermittent ankle torque generation (Loram et al., 2005). Without the imposed constraint to stand as still as possible, additional characteristics about postural control can be picked up, and these characteristics show up both in longer (10 min) and shorter (60 s) tests of relaxed standing. Therefore, relaxed standing should be introduced in future studies to investigate differences in GL movements and, consequently, differences in the long-range component of the structure of CoP position and velocity in different age and clinical groups.

Most stochastic models suggested for CoP movement, like the Ornstein–Uhlenbeck process (Frank et al., 2000; Newell et al., 1997), the stochastic time-delayed process (Boulet et al., 2010), and the pinned polymer model (Lauk et al., 1998), consist of additive processes that are only capable to replicate the central tendency of  $h_t$  but not the range of  $h_t$  as found in the current study. The central tendency of  $h_t$  and other conventional scaling exponents are not robust against changes in the superposition of additive sub-processes, like subtraction of trends, as reflected by the significant difference of the central tendency of  $h_t$  between CoP and the residual CoP–GL traces in both relaxed and quiet standing. In contrast, the variation of  $h_t$  as illustrated by the width of the distribution  $P(h_t)$  (see Figs. 2–4) is robust against the subtraction of the GL movements but nevertheless sensitive to multiplicative interactions between sub-processes as seen in the intermittent periods with GL movements. The width of distribution  $P(h_t)$  of  $h_t$  (see Figs. 2–4) is directly related to the width of the so-called multifractal spectrum (Ihlen and Vereijken, 2010). Multifractal variation is generated by multiplicative processes, not by conventional additive processes, indicated by the significant difference between the structure (i.e.,  $h_t$ ) of CoP and  $h_t$  of the additive IAAFT surrogates in the intermittent periods of GL movements (see Fig. 4). Multifractal spectra with non-zero widths have previously been reported for CoP traces during quiet standing (Morales and Kolaczky, 2002; Shimizu and Thurner, 2001), but the large change in  $h_t$  in the intermittent periods of GL movements suggest that the multifractal variation of CoP is dependent on GL movements. The smaller central tendency of  $h_t$  and narrower spectrum width (i.e., the narrower range of  $h_t$  in Fig. 2) found in the CoP dynamics of Parkinson's patients (Morales and Kolaczky, 2002) and persons with balance disorders (Shimizu and Thurner, 2001) indicate that these patients have less movement in GL and larger variation in CoP–GL residuals, resulting from a decoupling between the time scales of the CoP dynamics. Furthermore, older persons have less GL movements in relaxed standing compared to younger persons, illustrated in Duarte and Sternad (2008) as a decrease in the central tendency of  $h_t$  as computed by detrended fluctuation analysis. These results indicate a decoupling between temporal scales of the CoP dynamics of older persons, numerically defined as a decrease in the variation of  $h_t$ , which might be similar to Parkinson's patients and patients with balance disorders. Thus, the numerical definition of variation in  $h_t$  could be an important method to identify alterations in postural control in clinical groups.

The present study has a few shortcomings. Firstly, the indirect estimation of GL from the ground reaction force might inflate variations in CoP–GL traces for the relaxed standing condition with large voluntary CoM movements. Inflated variations in CoP–GL might originate from a poor estimation of GL in the periods of large CoM movements and might lead to artificial changes in  $h_t$ . However, King and Zatsiorsky (1997) found that indirect estimation of GL from ground reaction force performs well for large cyclical movement of the CoM during standing. Nevertheless, further studies should validate the present indirect estimation of CoM from the ground reaction force with the direct

estimation from kinematic and anthropometric data in the periods of large CoM movements. Secondly, this study did not introduce explicit models for the variation in  $h_t$  of the CoP and CoP–GL residuals. Future studies should employ the present methods for CoP dynamics obtained from multi-segmental models with intermittent ballistic control (Bottaro et al., 2005; Morasso and Schieppati, 1999,2002) and hybrid models that involve stochastic processes (e.g., Peterka, 2000,2002). Thirdly, this study did not measure the ankle, knee, or hip joint kinematics, nor the activation of flexors and extensors muscles of these joints. In subsequent studies, these measurements will be necessary to obtain further information about the intermittent generation of joint torques during quiet and relaxed standing and the contribution of flexor and extensor muscles to this intermittent torque generation. Fourthly, this study did not compare different age or clinical groups to investigate changes in the variation of  $h_t$  of the CoP trace and the CoP–GL residuals. Further studies of the relationship between variation of  $h_t$  and GL movements in for example older persons, patients with balance disorders, and persons with high risk-of-falling, are important to further our understanding of changes in postural control with age and neurodegenerative disease. Finally, further studies should also address the test-retest reliability of both  $h_t$  and  $P(h_t)$  measures in these clinical groups.

## 5. Conclusion

Variation in the scale-dependent structure  $h_t$  of CoP during human standing is dependent on changes in GL position. The range of  $h_t$  was significantly larger in relaxed standing compared to quiet standing because of a less persistent structure (i.e., smaller  $h_t$ ) in the CoP and CoP–GL in intermittent periods of larger movements of GL. These intermittent periods of GL movements were generated by intermittent phase couplings between the multiple time scales of both CoP and residual CoP–GL traces. The current method for identification of variation in the structure of CoP and CoP–GL traces might contribute to further developments of models of intermittent postural control and improved differentiation of postural adjustments in older persons and patients with neurodegenerative diseases.

## Conflict of interest statement

The authors declare that no conflict of interest is associated with the present study.

## Acknowledgments

We thank engineer Dr. Xiangchun Tan for her contribution to the current study. The authors also thank the 12 younger volunteers that participated in the study. The Matlab code for Eqs. (1) and (2) can be found at the web site [www.ntnu.edu/inm/geri/software](http://www.ntnu.edu/inm/geri/software) and the instruction for these codes in Ihlen (2012).

## References

- Bigelow, K.E., Berme, N., 2011. Development of a protocol for improving the clinical utility of posturography as a fall-risk screening tool. *Journal of Gerontology A: Biological Sciences and Medical Sciences* 66 (2), 228–233.
- Black, F.O., Wall, C., Rockette, H.E., Kitch, R., 1982. Normal subject postural sway during the Romberg test. *American Journal of Otolaryngology* 3, 309–318.
- Bottaro, A., Casadio, M., Morasso, P.G., Sanguineti, V., 2005. Body sway during quiet standing: is it the residual chattering of an intermittent stabilization process? *Human Movement Science* 24, 588–615.

- Boulet, J., Balasubramanian, R., Daffertshofer, A., Longtin, A., 2010. Stochastic two delay differential model of delayed visual feedback effects on postural dynamics. *Philosophical Transaction of the Royal Society A: Mathematical, Physical, and Engineering Sciences* 368, 423–438.
- Collins, J.J., De Luca, C.J., 1993. Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research* 95, 308–318.
- Collins, J.J., De Luca, C.J., Burrows, A., Lipsitz, L.A., 1995. Age-related changes in open-loop and closed-loop postural control mechanisms. *Experimental Brain Research* 104, 480–492.
- Corriveau, H., Hébert, R., Raïche, M., Dubois, M.-F., Prince, F., 2004. Postural stability in the elderly: Empirical confirmation of a theoretical model. *Archives of Gerontology and Geriatrics* 39 (2), 163–177.
- Danna-Dos-Santos, A., Degani, A.M., Zatsiorsky, V.M., Latash, M.L., 2008. Is voluntary control of natural postural sway possible? *Journal of Motor Behavior* 40 (3), 179–185.
- Delignières, D., Deschamps, T., Legros, A., Caillou, N., 2003. A methodological note on non-linear time series analysis: is Collins and De Luca 1993s open- and closed-loop model a statistical artifact? *Journal of Motor Behavior* 35, 86–96.
- Delignières, D., Torre, K., Bernard, P.-L., 2011. Transition from persistent to anti-persistent correlations in postural sway indicates velocity-based control. *PLoS Computational Biology* 7 (2), <http://dx.doi.org/10.1371/journal.pcbi.1001089>.
- Dijkstra, T.M.H., 1998. Dynamics of frame of reference captures the two scaling regimes of human postural control. Abstract of the Society of Neuroscience. 28th Annual Meeting, 1768.
- Duarte, M., Sternad, D., 2008. Complexity of human postural control in young and older adults during prolonged standing. *Experimental Brain Research* 191 (3), 265–276.
- Duarte, M., Zatsiorsky, V.M., 1999. Patterns of center of pressure migration during prolonged unconstrained standing. *Motor Control* 3, 12–27.
- Duarte, M., Zatsiorsky, V.M., 2000. On the fractal properties of natural human standing. *Neuroscience Letters* 283, 173–176.
- Frank, T.D., Daffertshofer, A., Beek, P.J., 2000. Multivariate Ornstein-Uhlenbeck processes with mean-field dependent coefficients: application to postural sway. *Physical Review E* 63, 011905.
- Gatev, P., Thomas, S., Kepple, T., Hallett, M., 1999. Forward ankle strategy of balance during quiet standing in adults. *Journal of Physiology* 514, 915–928.
- Ihlen, E.A.F., 2012. Introduction to multifractal detrended fluctuation analysis in Matlab. *Frontiers in Physiology: Fractal Physiology* 3 (141), 1–18.
- Ihlen, E.A.F., Vereijken, B., 2010. Interaction dominant dynamics in human cognition: beyond  $1/f^2$  fluctuations. *Journal of Experimental Psychology: General* 139, 436–463.
- Kim, S., Nussbaum, M.A., Madigan, M.L., 2008. Direct parameterization of postural stability during quiet upright stance: effects of age and altered sensory conditions. *Journal of Biomechanics* 41 (2), 406–411.
- King, D.L., Zatsiorsky, V.M., 1997. Extracting gravity line displacement from stabilographic recordings. *Gait and Posture* 6, 27–38.
- Lauk, M., Chow, C.C., Pavlik, A.E., Collins, J.J., 1998. Human balance out of equilibrium: nonequilibrium statistical mechanics in posture control. *Physical Review Letters* 80, 413–416.
- Lin, D., Seol, H., Nussbaum, M.A., Madigan, M.L., 2008. Reliability of COP-based postural sway measures and age-related differences. *Gait and Posture* 28, 337–342.
- Loram, I.D., Lakie, M., 2002a. Human balancing of an inverted pendulum: position control by small, ballistic-like, throw and catch movements. *Journal of Physiology* 540, 1111–1124.
- Loram, I.D., Lakie, M., 2002b. Direct measurement of human ankle stiffness during quiet standing: the intrinsic mechanical stiffness is insufficient for stability. *Journal of Physiology* 545, 1041–1053.
- Loram, I.D., Maganaris, C.N., Lakie, M., 2005. Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. *Journal of Physiology* 564 (1), 295–311.
- Mandelbrot, B.B., 1974. Intermittent turbulence in self-similar cascades: divergence of high moments and dimension of the carrier. *Journal of Fluid Mechanics* 62, 331–358.
- Morales, C., Kolaczyk, E., 2002. Wavelet-based multifractal analysis of human balance. *Annual Reviews in Biomedical Engineering* 30, 588–597.
- Morasso, P.G., Schieppati, M., 1999. Can muscle stiffness alone stabilize upright standing? *Journal of Neurophysiology* 83, 1622–1626.
- Morasso, P.G., Schieppati, M., 2002. Ankle muscle stiffness alone cannot stabilize balance during upright standing. *Journal of Neurophysiology* 88, 2157–2162.
- Newell, K.M., Slobounov, S.M., Slobounova, E.S., Molenaar, P.C.M., 1997. Stochastic processes in postural center-of-pressure profiles. *Experimental Brain Research* 113, 158–164.
- Newell, K.M., van Emmerik, R.E.A., Lee, D., Sprague, R.L., 1993. On postural stability and variability. *Gait and Posture* 4, 225–230.
- Norris, J.A., Marsh, A.P., Smith, I.J., Kohut, R.L., Miller, M.E., 2005. Ability of static and statistical mechanics posturographic measures to distinguish between age and fall risk. *Journal of Biomechanics* 38, 1263–1272.
- Peterka, R.J., 2000. Postural control model interpretation of stabilogram diffusion analysis. *Biological Cybernetics* 83, 335–343.
- Peterka, R.J., 2002. Sensorimotor integration in human postural control. *Journal of Neurophysiology* 88, 1097–1118.
- Reynolds, R.F., 2010. The ability to voluntarily control sway reflects the difficulty of the standing task. *Gait and Posture* 31 (1), 78–81.
- Riedi, R.H., 2002. Multifractal processes. In: Doukhan, P., Oppenheim, G., Taqqu, M.S. (Eds.), *Theory and Applications of Long-Range Dependence*. Birkhäuser Boston, Boston, MA, pp. 625–716.
- Schreiber, T., Schmitz, A., 1996. Improved surrogate data for nonlinearity tests. *Physical Review Letters* 77, 635–638.
- Shimizu, Y., Thurner, S., 2001. Multifractal spectra as a measure of complexity in human posture. *Fractals* 10, 103–116.
- Winter, D.A., 1995. Human balance and posture control during standing and walking. *Gait and Posture* 3, 193–214.
- Winter, D.A., Patla, A.E., Prince, F., Ishac, M.G., 1998. Stiffness control of balance in quiet standing. *Journal of Neurophysiology* 80, 1211–1221.
- Winter, D.A., Patla, A.E., Prince, F., Ishac, M.G., 2001. Ankle muscle stiffness in the control of balance during quiet standing. *Journal of Neurophysiology* 85, 2630–2633.
- Zatsiorsky, V.M., Duarte, M., 1999. Instant equilibrium point and its migration in standing task: rambling and trembling components of the stabilogram. *Motor Control* 3, 28–38.
- Zatsiorsky, V.M., Duarte, M., 2000. Rambling and trembling in quiet standing. *Motor Control* 4, 185–200.