The contribution of body weight distribution and center of pressure location in the control of mediolateral stance

Cédrick T. Bonnet a,⁎, Sarah Cherraf a, Sébastien Szafrarczyk a, Patrice R. Rougier b

a Laboratoire de Neurosciences Fonctionnelles et Pathologies, Université Lille 2, CNRS, Lille, France
b Laboratoire de Physiologie de l’Exercice, EA 4138, UPR CISM, Université de Savoie, Campus Scientifique de Savoie-Technolac,
F-73376 Le Bourget du Lac, France

A R T I C L E   I N F O

Article history:
Accepted 1 March 2014

Keywords:
Postural control
Body weight distribution
Center of pressure location
Methodology
Foot position

A B S T R A C T

The study investigated the mediolateral control of upright stance in 16 healthy, young adults. The model analyzed the body weight distribution and center of pressure location mechanisms under three stance width conditions (feet close, under standard condition, and apart). Our first objective was to discuss some methodological requirements to investigate the contribution of both mechanisms by means of two platforms. It is proposed that both the amplitude contribution (in variability analyses) and active contribution (in cross-correlation analyses) need to be studied distinctively. These analyses may be concerned with the strength and the degree of active contributions, respectively. Based on this theoretical proposition, we expected and found that the amplitude contribution of both mechanisms was higher and lower in wide and narrow stances compared with that in the standard stance, respectively. Indeed, the closer the two reaction forces, the lower their mechanical contribution. As expected, the active contribution of both mechanisms was significantly lower and higher in wide and narrow stances, respectively. Indeed, the further the feet apart, the less active both mechanisms needed to be to control mediolateral stance. Overall, only the center of pressure location mechanism really changed its significant contribution to control mediolateral stance under the three conditions. The result is important because this mechanism is known to be secondary, weaker than the body weight distribution mechanism to control mediolateral stance. In practical terms, these findings may explain why the mediolateral variability of center of pressure displacement was significantly higher in narrow stance but not lower in wide stance.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Research on postural control serves to better understand how stance is controlled (Winter, 1995) and why some individuals sway more or differently than others (Era et al., 2006). As shown by Winter’s studies (Winter et al., 1993, 1996), it is known that two mechanisms can explain the mediolateral (ML) center of pressure (COP) displacement, a body weight distribution mechanism and a COP location mechanism. The body weight distribution mechanism (denoted as COPv, “center of pressure vertical”; Fig. 2) is performed by loading more body weight on one leg and thus unloading the other leg (Fig. 1a). The COP location mechanism (denoted as COPc, “center of pressure changes”; Fig. 2) is performed by changing the COP location under the left and right feet (Fig. 1b). COPc and COPv were shown to be the primary and secondary mechanisms to explain the ML COP displacement when the feet are side-by-side (Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996). When the feet are close to each other, the contribution of both COPv and COPc gets higher (Gatev et al., 1999). Also, when the angle between the feet increases, the contribution of COPv gets lower (Rougier, 2008). Besides these results, the model of Winter et al. (1993, 1996) was rarely used under conditions changing the difficulty of ML stance.

In the literature, the authors who worked on ML postural control mechanisms (Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996) used analyses of the amplitude (root mean square or standard deviation (SD)) and/or cross-correlations of the time-series indistinctively to illustrate whether the strength of the mechanism changed from one condition to another. In their studies, when the amplitude of COPv or COPc increased under one condition, the cross-correlation between COPc or COPv and the COP displacement also increased (e.g., Lafond et al., 2004; Termoz et al., 2008). Hence, these results, going in the same direction, appeared redundant. However, if analyses of variability should be mainly concerned with the amplitude contribution of a mechanism, cross-correlation analyses...
in contrast may not deal with it. Indeed, two time-series of very different amplitudes can have a coefficient equal to 1 (Fig. 3).

By definition, cross-correlation analyses express the degree of similarities between two time-series both in terms of direction and proportionality of the time series. When a curve is used to explain the other, their proportional similarity may reveal the degree of active contribution of the mechanism, or how much this mechanism is active to explain the resultant COP displacement. In the literature, we were not able to find a similar assumption and we thought it to be interesting to discuss in the present manuscript.

If the variability and cross-correlation analyses could vary in opposite directions (one increasing and the other decreasing), this would validate our argument that both analyses should be interpreted differently. In fact, such reversed results are expected when manipulating the distance between the feet side by side. On the one hand, the amplitude contribution of COPv and COPc should be mechanically lower in narrow stance than in standard stance. Indeed, the closer the feet, the smaller the lever arm from the vertical projection of the center of mass to the ground reaction force under the foot, and thus the weaker a given force generated on the ground to counterbalance ML COP displacement. However, postural control is more difficult in narrow stance (e.g., Day et al., 1993), thus requiring a greater overall contribution – adding both amplitude and active contributions – of the postural control mechanisms. Hence, on the other hand, the degree of active contribution of COPv and COPc necessarily needs to be higher in narrow stance than in standard stance since ML postural control has to be maintained.

The objective of the present study was to improve our understanding of ML postural control mechanisms and to further understand the control of ML upright stance. We tested changes in the COP displacement, amplitude and active contributions under a control condition (standard stance) and two other stance width conditions (narrow and wide stances). We expected to replicate findings that the COP displacement is larger in narrow stance (e.g., Day et al., 1993) and smaller in wide stance (Winter et al., 1998) than in standard stance. The overall contribution of COPv and COPc – adding both amplitude and active contributions – was expected to be higher and lower in...
narrow and wide stances, respectively. Indeed, narrow and wide stances are mechanically less and more stable than standard stance. The contribution of COP was expected to change more than that of COPc, at least between standard stance and narrow stance. Indeed, COPc can still increase whereas the overall contribution of COP was already almost maximal in standard stance (COP = v=COP displacement = 1.00; Termoz et al., 2008). If valid, this finding would indicate that the weakest ML mechanism — COPc (cf. Winter et al., 1993, 1996) — has a real role in the control of ML stance.

2. Methods

2.1. Participants

Sixteen university students (10 females and 6 males) participated. Their mean age, body mass and height were 21.06 ± 1.81 years, 63.75 ± 12.65 kg and 1.69 ± 0.10 m, respectively. All the participants were healthy, that is with no known disease, injury, recent surgery or disability. They were excluded if they had any known specific issue or recent injury at the ankle and hip levels. All the participants gave their written informed consent to participation. The study was performed in accordance with the tenets of the Declaration of Helsinki.

2.2. Apparatus

A dual-top force platform (AMTI, Watertown, MA, USA) was used at 100 Hz. The platform was placed 1.50 m from a facing wall on which a paper with a black dot (1 of visual angle) was taped at the participant’s eye height.

2.3. Conditions

In narrow stance, participants placed their feet close to each other, with one foot on each platform. In standard stance, participants chose the most comfortable foot position. In wide stance, they chose their stance angle but had to place one part of the foot on the outer edge of the platform. Stance angle corresponded to the angle between the lines going through the middle of the big toe and the heel center for each foot (cf. McIlroy and Maki, 1997). Stance width corresponded to the distance between the heel centers (McIlroy and Maki, 1997). The purpose of letting the participants partially choose their foot positions was to avoid uncomfortable stance (Kaptein et al., 1981; McIlroy and Maki, 1997). Moreover Rougier (2008) showed that the stance angle does not affect COP and COPc, significantly between -30 and 60. We controlled the confounding influence of stance width, stance angle and other variables before analyses (see below).

2.4. Procedure

The participants were barefoot. Before starting the experiment, foot positions under the three stance conditions were marked on two large papers (24.7 cm × 40 cm). In all trials, participants were told to relax, hold their hands by the side of the body and look at the dot on the facing wall. The experiment was run with four blocks of three conditions in a random order. Each block was run with two successive trials per condition. Overall, there were 24 trials, each lasting for 35 s.

2.5. Variables and analyses

Classical variables were used to analyze the variability of the COP displacement, that is the SD and range of displacement (e.g., Bonnet and Desprets, 2012; Era et al., 2006).

With one single force platform, it is not possible to measure the loading/unloading of body weight under each foot (Winter et al., 1993). Hence, for investigating ML COP and COPc, we used our dual-top force platform and an updated version (Rougier, 2007, 2008) of the validated model of ML postural control (Lafond et al., 2004; Termoz et al., 2008; Winter et al., 1993, 1996).

The COP displacement is calculated by eliminating the COP displacement explained by the COP displacement (constant mean of body weight under both feet, throughout the trial, Eq. (1)). The COP displacement explained by eliminating the COP displacement explained by the COP displacement, constant mean of COP location under both feet throughout the trial: see Eq. (3)).

Two complementary analyses were performed to analyze the contribution of each mechanism. The first analysis compared the amplitude. That of COPc and COPc, and the second analysis calculated the COP displacement explained by the COP displacement, constant mean of COP location under both feet throughout the trial: see Eq. (3)).

The second analysis calculated the cross-correlation coefficient between COP and COPc, on one hand and COPc, on the other hand (denoted as COP vs. COPc, and COPc vs. COPc, respectively; Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996). It compared the similarity of the COP vs. COPc and COPc vs. COPc time-series, both in terms of direction and proportionality of the time series, but not the amplitude of the signals (as usually supposed in the literature, Gaveau et al., 1999; Winter et al., 1993, 1996). Indeed, two signals of very different amplitudes can have a coefficient equal to 1 (Fig. 3). In the case of one curve explaining the other (as in our case), this analysis of the amplitude contribution looked for the mechanisms to control COP displacement.

The second analysis calculated the cross-correlation coefficient between COP and COPc, and to explain ML COP displacement, the contribution of a mechanism may be statistically significant if both its amplitude and active contributions are sufficiently high.

To eliminate transitory behavior at the start of the trials, the first 5 s of data were not analyzed (Rougier et al., 2006). All the analyses were performed exclusively in the ML axis. As we evaluated the influence of stance width on the contribution of COP and COPc, we normalized the data in terms of stance width. We used the deflection normalizing procedure recommended by O’Malley (1996) to remove the influence of stance width on the data (O’Malley, 1996). This procedure reduced the correlation coefficient – it removed the trends – between the stance width and the dependent variable to zero. Thus, the stance width spontaneously adopted by the participants could not be a confounding variable.

To define a summary of the experimental procedure (see O’Malley (1996) for more details), in a first step, a linear regression was performed with the COP dependent variable and the stance width of all the participants. The analysis provided the slope of the line (m) and the offset (c). In a second step, the initial recorded COP dependent variable (v=COP) of each participant was transformed by the equation: v=COP = m × v=COP + c. In this way, we normalized the COP displacement variable, v=COP-stance width and m = average of the COP dependent variable of the group of participants. This equation was applied to each participant to get the v=COP time series. This procedure was applied for each dependent variable.

Matlab 7.10 software (MathWorks Inc., MA, USA) was used to compute all the dependent variables. All these variables were normally distributed. One-way repeated measure ANOVAs and post-hoc Newman–Keuls analyses were performed on the dependent variables. A Statistica 8.0 software (Statsoft Inc., OK, USA) was used to perform statistical analyses. When the cross-correlation coefficients were close to 0, one-sample t-tests were used to compare these coefficients to 0. These analyses served to know whether the concerned mechanism (COP, COPc, COPc) was significantly active or not under the tested conditions. The thresholds for statistical significance were set to p < 0.05 and p < 0.01 (0.05/3: Bonferroni adjustment) for the ANOVAs and the additional analyses (i.e. post-hoc and one-sample t-tests), respectively. The partial eta squared (v2) was used to quantify the proportion of the total variance that is attributable to the effect (effect size). Fig. 4 shows representative data for the COP_net vs. COP, and COP_net vs. COPc cross-correlations under the wide and narrow stance conditions.

3. Results

3.1. Differences between conditions

The one-way repeated measures ANOVAs were significant for the range of the COP displacement, the standard deviation of the COP displacement (F(2,30) = 122.82, p = 0.05; Fig. 5A and B) and for %SD COP/COP_pmp, %SD COP/COP_net, COPc vs. COP and COPc vs. COPc (F(2,30) = 19.17, p = 0.037; p < 0.005; Fig. 5C and D). Post-hoc analyses showed a significant difference between narrow stance and wide stance for all variables and between narrow stance and standard stance for all variables but %SD COP/COP_net (p < 0.001). The one-sample t-test showed that the contribution of COPc was active in...
narrow stance (no analysis needed) and in standard stance ($t(15) = 3.84, p < 0.017; \text{Fig. 5D}$) but not so in wide stance ($p = 0.83$).

### 3.2. Control analyses

The normalization procedure of O’Malley (1996) was used again. Instead of normalizing the original data in terms of stance width, they were normalized in terms of stance angle, height, weight and age, each individually. The normalized variables did not change the significant findings in SD amplitude, cross-correlation and COP displacement analyses. The normalized variables only slightly changed the strength of the findings: $n_s^2$ increased or decreased by less than 0.05 in all analyses. Therefore, stance angle, height, weight and age were not confounding variables in all our analyses. An additional one-way repeated measures ANOVA compared any potential body weight asymmetry under the three stance width conditions. The analysis did not show any significant effect in the ML COP mean position ($p = 0.96$). Therefore, the participants loaded their body weight on their legs in the same way under the three conditions.

### 4. Discussion

As expected, the findings for the amplitude and active contributions were reversed in sense from narrow stance to wide stance. They were lower and higher in narrow stance and higher and lower in wide stance compared with standard stance, respectively. These findings showed the distinct role of the amplitude and active contributions to explain changes in the overall contribution of the mechanism to control ML stance. It was also found that the overall contribution of the two mechanisms was higher in narrow stance and lower in wide stance than in standard stance. In the discussion, we explain why the ML COP displacement was higher in narrow stance than in standard stance and similar between wide stance and standard stance.

#### 4.1. Standing control under the standard stance condition

Like Winter et al. (1993) and Termoz et al. (2008), the body weight distribution mechanism had the main significant role in explaining the ML COP displacement (Fig. 5C and D). The active and amplitude contributions of COP$_v$ were higher than those of...
4.2. Standing control under the narrow stance condition

The narrow stance condition has been found to increase the difficulty of maintaining postural control (Day et al., 1993; Kirby et al., 1987; Mouzat et al., 2004). We confirmed that finding because the variability of the COP displacement was significantly higher in narrow stance than in standard stance (Fig. 5A and B). This was expected because the closer the feet, the less effective the force generated to control ML postural sway (Henry et al., 2001; Winter et al., 1996). Logically in our study, the amplitude contribution of COPc was found to be lower in narrow stance than in standard stance (cf. Fig. 5C). Consequently, under narrow stance conditions, ML postural control needed to be more actively controlled to avoid individuals from falling (cf. Fig. 5D).

4.3. Standing control under the wide stance condition

We did not report any significant difference for the range and standard deviation of the ML COP displacement between standard and wide stances (Fig. 5A and B). In the literature, young, healthy adults were sometimes found to sway significantly less in wide stance than in standard stance (Bonnet, 2012; Winter et al., 1998) or similarly under both conditions (Kirby et al., 1987; Stoffregen et al., 2009). Our analyses may explain why the ML COP displacement is not always reduced in wide stance. On the one hand, the force generated by postural control muscles is more effective in wide stance than in standard stance because the reaction forces acting under each foot are further apart (Winter et al., 1996). Consistently, the amplitude contribution of COPc and COPnet, or strength of the mechanisms, was significantly higher in wide stance (Fig. 5C). On the other hand, the mechanisms could be proportionally less active in controlling ML COP displacement to avoid losing energy unnecessarily. Henry et al. (2001) indeed found that all postural muscles activation (distal, intermediate, proximal) was lower in wide stance (distance between the heels center =32 cm) than under a smaller stance width condition (10 cm) in seven healthy subjects (age range: 21–41) in response to external ML platform motions. Their finding was more pronounced for proximal muscles at the trunk (Rectus Abominis, Erector Spinae) than distal muscles. Consistently in our study, the degree of active contribution of both mechanisms was significantly lower in wide stance than in standard stance (Fig. 5D). Overall, the reversed amplitude and active contributions neutralized each other and the ML COP displacement was similar in standard and wide stances.

4.4. Relationship between the contribution of the mechanisms and COP displacement

Under different conditions, we can discuss the individual contribution of each mechanism. For the body weight mechanism, the effect sizes in the analyses were almost equal in terms of the amplitude and active contributions ($r^2_a=0.38$ vs. $0.37$). Therefore, a change in stance width did not clearly modify the overall contribution of the body weight distribution mechanism. We need to recall that analyses of the amplitude and active contributions brought reversed results (when one increased the other decreased). However, a change in stance width modified the active contribution of COP, more than its amplitude contribution ($r^2_a=0.40$ vs. 0.29). Consequently, COP, definitely contributed more to ML standing control in narrow stance and less in wide stance. Complementarily, in another study, Rougier (2008) found that only the contribution of COPc significantly changed when the stance angle was modified (from −30° to 120°). Therefore, COPc has an important role to adjust ML postural control to passive conditions challenging ML stance.

4.5. Concluding remarks

Surprisingly, ML SD $\frac{\text{COP}}{\text{COP}_{\text{net}}}$ was found to be greater than 100% in wide stance ($109.10\pm 2.91$; Fig. 5C). In practice, it means that the COPc, time-series exhibited larger fluctuations than the COPnet, time-series in wide stance (Fig. 4). This finding is possible when COPc and COP displacements are in anti-phase. Indeed, the two mechanisms have complementary effects to explain COPnet and under the wide stance condition, the two mechanisms should have had opposite effects on COPc, to explain this result. Meanwhile, the SD values cannot illustrate these anti-phase contributions since, by definition, it can only be positive. This is a limitation of the model of Winter et al., (1993), (1996).

In brief, our study showed that ML postural control mechanisms are stronger (greater amplitude contribution) and therefore less active (lower active contribution) in wide stance and weaker and therefore more active in narrow stance. The significant overall contribution of COPc, under the three stance width conditions may be of special relevance. Indeed, former studies (Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996) emphasized the fundamental role of COPc to explain COPnet but did not discuss how much the secondary role of COPc could matter. This is critical because age-related deficiencies in postural control and coordination (Maki et al., 1994; Rogers and Mille, 2003) may be caused essentially by a deficiency in the secondary COPc inversion/eversion mechanism that controls changes in ML COP displacement at the ankle level. Indeed, it is known that about 30% of healthy older adults are affected by foot problems (Barr et al., 2005) such as lack of sensation in inversion/eversion (Gilsing et al., 1995) or physiological difficulties in inversion/eversion (Lentell et al., 1995). Future studies will be needed to better focus on age-related and disease-related physiological deficiencies in COPc. This is relevant because Bonnet et al. (2009) showed that patients with diabetic neuropathy oscillate clearly more than controls in the ML axis and Lafond et al. (2004) found a significant deficiency in ML COPc, but not in the primordial ML COPc, compared with controls.

Conflict of interest statement

There are no conflict of interests.

Acknowledgment

Nothing to declare.

References


