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

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ABSTRACT

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.

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 COP_v, “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 COP_c, “center of pressure changes”; Fig. 2) is performed by changing the COP location under the left and right feet (Fig. 1b). COP_v and COP_c 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 COP_v and COP_c gets higher (Gatev et al., 1999). Also, when the angle between the feet increases, the contribution of COP_c gets higher (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 COP_v or COP_c increased under one condition, the cross-correlation between COP_v or COP_c 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

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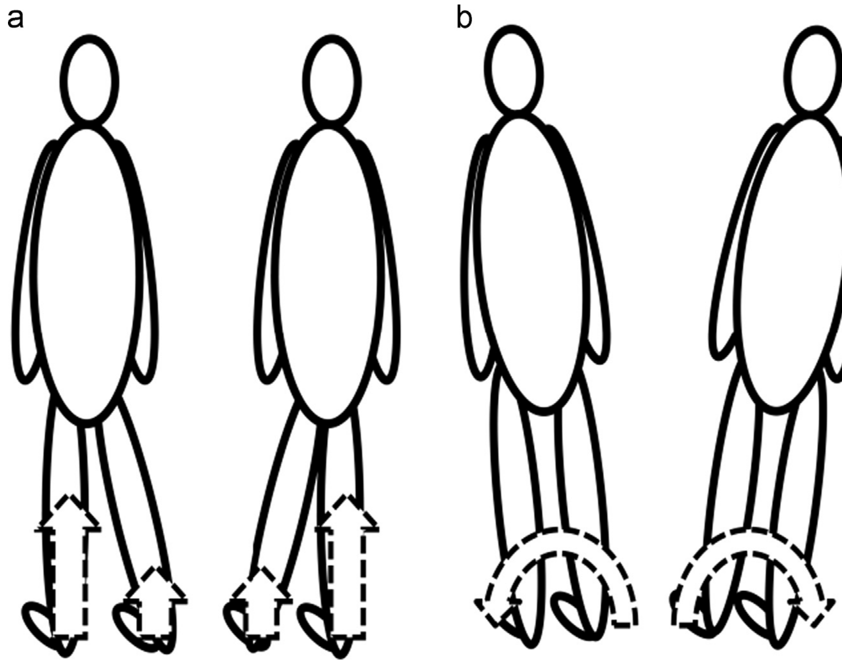

Fig. 1. Graphical representation (a) of the body weight mechanism. Vertical arrows represent the vertical reaction forces; the longer the vector, the greater the reaction forces and (b) of the center of pressure mechanism (also called inversion/eversion mechanism). Arrows represent movements of the body around the ankles in one direction or the other.

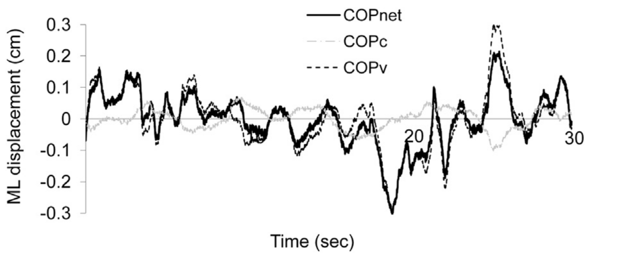

Fig. 2. Time-series for COP_{net}, COP_v and COP_c in one trial performed by the experimenter (units: cm) in the mediolateral (ML) axis for 30 s. COP_{net} (net center of pressure displacement) is the weighted average of $COP_l(t)$ and $COP_r(t)$. COP_v (COP vertical) is the part of COP_{net} that can be explained by the body weight mechanism. COP_c (COP change) is the part of COP_{net} that can be explained by the COP location mechanism.

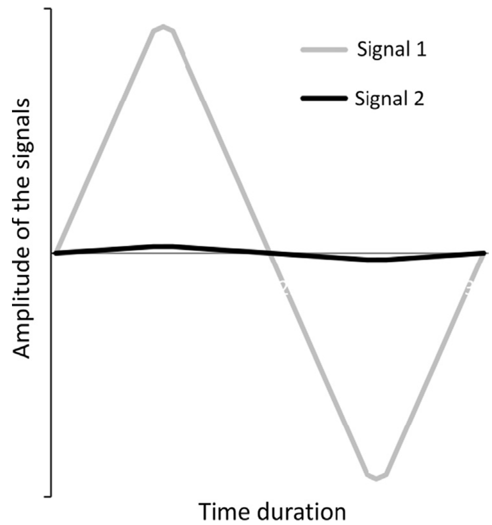

Fig. 3. Two time-series (or signals) exactly in phase ($r=1$) but with totally different magnitudes of amplitude (no scale because the magnitudes can be infinitely different).

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 COP_v and COP_c 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 COP_v and COP_c 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 COP_v and COP_c – 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_c was expected to change more than that of COP_v at least between standard stance and narrow stance. Indeed, COP_c can still increase whereas the overall contribution of COP_v is already almost maximal in standard stance (COP_v vs. COP displacement ≈ 1.00; Termoz et al., 2008). If valid, this finding would indicate that the weakest ML mechanism – COP_c (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 (Kapteyn et al., 1983; McIlroy and Maki, 1997). Moreover Rougier (2008) showed that the stance angle does not affect COP_c and COP_v 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 ($24.7\ \text{cm} \times 40\ \text{cm}$). 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 Despretz, 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_c and COP_v, 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):

$$COP_{net}(t) = COP_l(t)\frac{R_{vl}(t)}{R_{vl}(t)+R_{vr}(t)} + COP_r(t)\frac{R_{vr}(t)}{R_{vl}(t)+R_{vr}(t)} \quad (1)$$

$$COP_c(t) = COP_l(t) \times \text{mean}R_{vl} + COP_r(t) \times \text{mean}R_{vr} \quad (2)$$

$$COP_v(t) = \text{mean}COP_l\frac{R_{vl}(t)}{R_{vl}(t)+R_{vr}(t)} + \text{mean}COP_r\frac{R_{vr}(t)}{R_{vl}(t)+R_{vr}(t)} \quad (3)$$

In these equations, $COP_l(t)$ and $COP_r(t)$ correspond to the COP displacement under the left and right feet, respectively. COP_{net} is the resultant COP displacement. $R_{vl}(t)$ and $R_{vr}(t)$ correspond to the vertical reaction forces under the left and right feet, respectively. meanCOP_l, meanCOP_r, meanR_{vl} and meanR_{vr} correspond to the mean of each of these time-series.

The COP_c displacement is calculated by eliminating the COP_{net} displacement explained by the COP_v displacement (constant mean of body weight under both feet throughout the trial, Eq. (2)). The COP_v displacement is calculated by eliminating the COP_{net} displacement explained by the COP_c 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 of COP_{net} and COP_c and of COP_{net} and COP_v time-series (cf., Fig. 2). To this end, we calculated the SD of COP_c and COP_v relative to the SD of COP_{net} (Rougier, 2007, 2008). In the case of one curve explaining the other (as in our case), this analysis of the amplitude contribution looked at the strength of the mechanisms to control COP_{net}.

The second analysis calculated the cross-correlation coefficient between COP_c and COP_v on one hand and COP_{net} on the other hand (denoted as COP_{net} vs. COP_c and COP_{net} vs. COP_v, respectively; Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996). It compared the similarity of the COP_c vs. COP_{net} and COP_v vs. COP_{net} 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, Gatev 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), we assumed that the degree of similarity between COP_c (or COP_v) and COP_{net} may show the degree of active contribution of that mechanism to control COP_{net}. Indeed, we did not know what else (other than the amplitude and active contributions) could cross-correlation coefficients show otherwise. Cross-correlation analyses were performed with 0 lag as in former published studies (Lafond et al., 2004; Rougier, 2007, 2008; Termoz et al., 2008; Winter et al., 1993, 1996).

For the analyses, the amplitude contribution and active contribution of a mechanism were assumed to be both important to discuss the contribution of COP_c and COP_v and to explain ML COP displacement. We assumed that 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 (Kinsella-Shaw 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_c and COP_v, we normalized the data in terms of stance width. We used the detrending normalization 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.

Here is a summary of the normalization 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 (rdv) of each participant i was transformed by the equation: $tdv_i = rdv_i - c - m \times sw_i + \overline{dv}$ in which tdv=transformed COP dependent variable, sw=stance width and $\overline{dv}$=average of the COP dependent variable of the group of participants. This equation was applied to each participant to get the tdv_i 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 10 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_c or COP_v) was significantly active or not under the tested conditions. The thresholds for statistical significance were set to $p<0.05$ and $p<0.017$ (0.05/3; Bonferoni adjustment) for the ANOVAs and the additional analyses (i.e. post-hoc and one-sample t-tests), respectively. The partial eta squared $\left(n_p^2 = \frac{SS_{effect}}{SS_{effect}+SS_{error}}\right)$ 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_v and COP_{net} vs. COP_c 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 ($F(2,30) > 122.82, n_p^2 > 0.47$, $p<0.05$; Fig. 5A and B) and for %SD COP_v/COP_{net}, %SD COP_c/COP_{net}, COP_v vs. COP_{net} and COP_c vs. COP_{net} ($F(2,30) > 19.17, n_p^2 > 0.37$, $p<0.05$; 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_c/COP_{net} ($p<0.017$). The one-sample t-test showed that the contribution of COP_c was active in narrow stance (no analysis needed) and in standard stance ($t(15)=3.84$, $p<0.017$; 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_p^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.

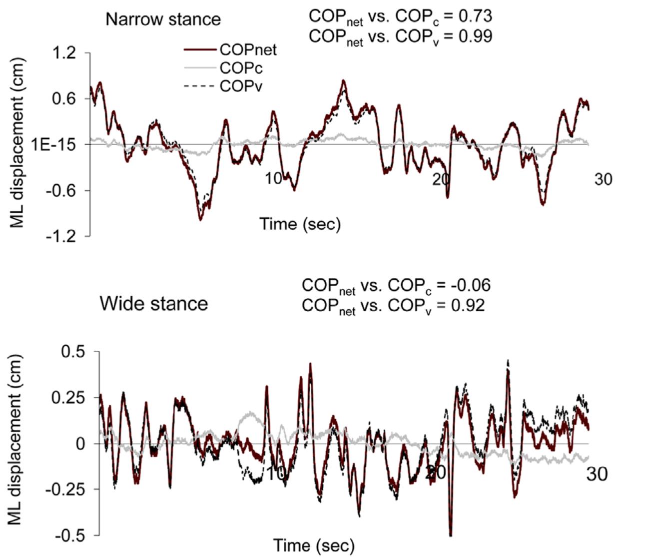

Fig. 4. Time-series for COP_{net}, COP_v and COP_c under wide stance and narrow stance conditions (units: cm) in the mediolateral (ML) axis. The mean cross-correlation coefficients for COP_{net} vs. COP_v and COP_{net} vs. COP_c are provided. See Fig. 2 for the definitions of these terms.

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

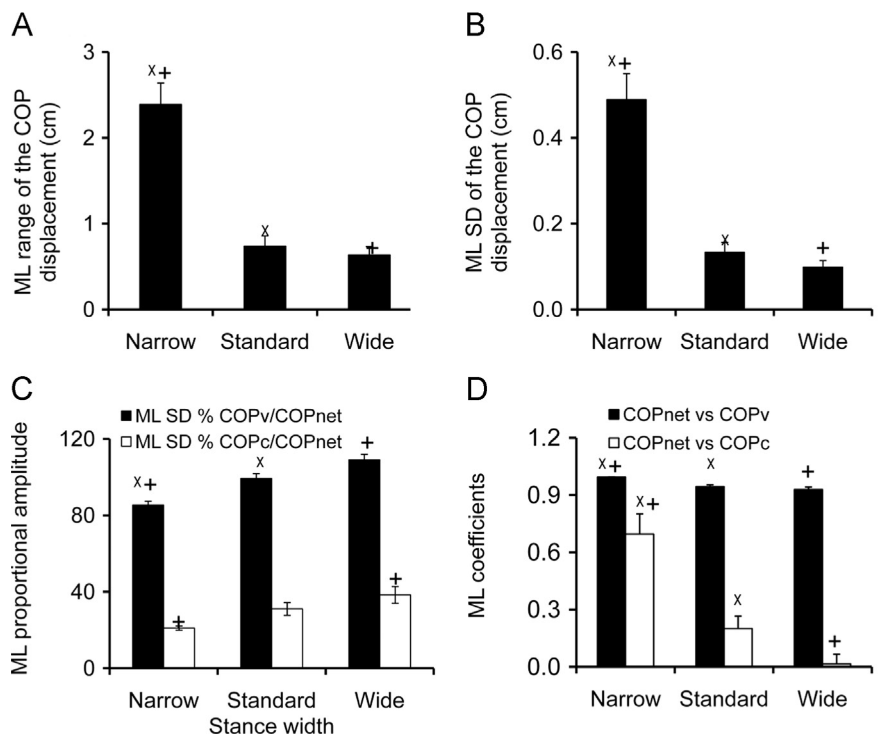

Fig. 5. Results of the repeated measures ANOVA and post-hoc Newman–Keuls analyses. The variables are (A) the range of the mediolateral (ML) center of pressure (COP) displacement; (B) the standard deviation (SD) of the ML COP displacement; (C) the SD amplitudes of ML COP_v (COP vertical) and ML COP_c (COP change) expressed in percentage of the SD amplitude of ML COP_{net} (weighted average of the COP displacement under both feet); and (D) the cross-correlation coefficient in two analyses: ML COP_v vs. COP_{net} and ML COP_c vs. COP_{net}. Averages ($\pm$ standard errors) under the three stance width conditions (narrow, standard and wide stances) are shown. The $^{+}$ and * show a significant difference between narrow and wide stances, and between narrow stance and standard stance, respectively ($p<0.017$).

COP_c under the three stance width conditions. As also reported by Termoz et al. (2008), the cross-correlation COP_c vs. COP_{net} was sufficiently high in standard stance, allowing COP_c to actively control the ML COP displacement under that foot condition ($p < 0.017$). These results confirmed the good use of the model.

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 COP_v 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 COP_v and COP_c, 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 ($\eta_p^2 = 0.38$ 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_c more than its amplitude contribution ($\eta_p^2 = 0.40$ vs. 0.29). Consequently, COP_c 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 COP_c significantly changed when the stance angle was modified (from -30° to 120°). Therefore, COP_c has an important role to adjust ML postural control to passive conditions challenging ML stance.

4.5. Concluding remarks

Surprisingly, ML SD % COP_v/COP_{net} was found to be greater than 100% in wide stance (109.10 ± 2.91; Fig. 5C). In practice, it means that the COP_v time-series exhibited larger fluctuations than the COP_{net} time-series in wide stance (Fig. 4). This finding is possible when COP_v and COP_c displacements are in anti-phase. Indeed, the two mechanisms have complementary effects to explain COP_{net} and under the wide stance condition, the two mechanisms should have had opposite effects on COP_{net} 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 COP_c 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 COP_v to explain COP_{net} but did not discuss how much the secondary role of COP_c 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 COP_c 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 COP_c. 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 COP_c, but not in the primordial ML COP_v, compared with controls.

Conflict of interest statement

There are no conflict of interests.

Acknowledgment

Nothing to declare.

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