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Impaired Mediolateral Postural Control at the Ankle in Healthy, Middle-Aged Adults

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RESEARCH ARTICLE

Impaired Mediolateral Postural Control at the Ankle in Healthy, Middle-Aged Adults

Cédric T. Bonnet, Marie Mercier, Sébastien Szaffarczyk

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ABSTRACT. Elderly adults sway more than young adults. Based on the literature, the authors expected the mediolateral ankle postural control mechanism to be affected before age 60 years. Twelve healthy young adults (24.21 ± 2.50 years) and 12 middle-aged adults (51.13 ± 6.09 years) participated in the study. To challenge mediolateral stance, the conditions modified the mediolateral distance among the feet (narrow and standard distances), mandibular position (rest position, left and right laterality occlusion positions), and the occlusion with clenching (intercuspal occlusion, left and right maximal voluntary clenches). As we expected, middle-aged adults exhibited significantly reduced contribution of the ankle mechanism. It was so both in narrow and standard stances. A second objective was to show a greater contribution of the 2 mechanisms in narrow than in standard stances. The results confirmed our hypothesis. As we expected, mandibular conditions only had a significant effect on center of pressure sway. Unexpectedly, middle-aged adults did not increase their range of center of pressure sway in narrow stance. They may have overconstrained their sway because of their ankle impairments. On the practical level, our results suggest that older adults should increase their stance width to relieve their hip and ankle control mechanisms and to stabilize their mediolateral posture.

Keywords: age-related impairments, center of pressure sway, mediolateral axis, postural control mechanisms, stance width

In stance, individuals sway all the time because of internal and external constraints (e.g., organ movement, gravity). Hence, postural control mechanisms have to work continuously to maintain postural stability (Winter, 1995). These mechanisms act conjointly and predominantly around the ankle and hip joints in the anteroposterior (AP) axis (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Nashner & McCollum, 1985) and mediolateral (ML) axis (Winter, Prince, Frank, Powell, & Zabjek, 1996; Winter, Prince, Stergiou, & Powell, 1993). In the ML axis, Winter et al. (1996; 1993) identified an ankle-based mechanism (center of pressure change [COP_c]) and a hip-based mechanism (center of pressure vertical COP_v).

For subjects in quiet stance with a spontaneously chosen stance width (i.e., standard stance), COP_v and COP_c were shown to be the prime mechanisms involved in controlling ML and AP COP displacement, respectively (e.g., Winter et al., 1996; Winter et al., 1993). In the ML axis, COP_c was subsequently found to have a significant secondary role in controlling COP displacement in standard stance (Gatev, Thomas, Kepple, & Hallett, 1999; Termoz et al., 2008). Only Termoz et al. analyzed age-related changes in both ankle and hip postural control mechanisms. Their comparative study of young adults (M age = $27.1 \pm$ years) and elderly adults (M age = $60.4 \pm$ years) did not highlight any significant age-related differences in either COP_v or COP_c .

In the literature, adults over age 60 years have been found to show (a) significantly higher body sway amplitudes (Maurer & Peterka, 2005) and velocities (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996) and (b) significantly lower body sway frequencies (McClenaghan et al., 1995), relative to young adults. All these effects were particularly pronounced in the ML axis (Maki, Holliday, & Topper, 1994; McClenaghan et al., 1995). Therefore, the finding that postural control mechanisms withstand the effects of aging (Termoz et al., 2008) is unexpected—especially for the ML axis. One would expect the greater ML postural sway in elderly adults to be due to significant impairment in at least one postural control mechanism (Maurer & Peterka, 2005). One significant shortcoming of Termoz et al.'s study was the instruction given to participants to move as little as possible during the trials. This requirement may have masked age-related changes in body stiffness (Cenciari, Loughlin, Sparto, & Redfern, 2010; Maurer & Peterka, 2005) and other physiological impairments at the ankles in particular (Barr, Browning, Lord, Menz, & Kendig, 2005; Gilling et al., 1995). Indeed, Fitzpatrick, Taylor, and McCloskey (1992) reported that standing as steadily as possible can influence reflex muscle stiffness. Another shortcoming of Termoz et al.'s study relates to the fact the researchers did not vary the difficulty of the stance conditions in the ML axis. It can be hypothesized that use of more difficult ML stance conditions would reveal age-related differences in COP_v or COP_c .

One way of challenging ML postural control is to shorten the stance width when these feet are side by side (Day, Steiger, Thompson, & Marsden, 1993; Mouzat, Dabonneville, & Bertrand, 2004). In the literature, Gatev et al. (1999) analyzed ankle and hip mechanisms in narrow and standard stances in seven healthy male subjects (M age = $42.3 \pm$ years). The researchers compared the stances in terms of the center of mass, the COP, angular motions, and electromyography activities and performed cross-correlation analyses of the time-series. Their results showed that ankle and hip mechanisms made significantly greater contributions to ML body sway control in narrow stance than in standard stance. Another way of challenging ML postural control is to perform lateral modifications of the masticatory system (e.g., left and right laterality occlusion positions and lateral occlusion with clenching). This type of challenge may alter the stomatognathic system, which relays vestibular and visual information of importance for postural control

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(Buisseret-Delmas, Compoin, Delfini, & Buisseret, 1999). Gangloff and Perrin (2002) showed that in quiet stance with the eyes open, anesthesia of the trigeminal nerve increased the area of COP displacement. One can consider that performing intentional, lateral modifications of the masticatory system as a secondary task may destabilize the participants to some extent or is at least very unlikely to increase their stability.

In the present study, our primary objective was to demonstrate significant, age-related differences in ML postural control mechanisms in general and at the ankle in particular. We included both middle-aged (under 60 years) adults and young adults because we expected to see the onset of significant changes in ML COP_c (but not in COP displacements) to occur in the under 60-year-old adults (Maurer & Peterka, 2005). Middle-aged adults usually show greater postural stability than adults over the age of 60 (Abrahamova & Hlavacka, 2008; Era et al., 2006). In order to detect age-related changes in the contributions of the two ML postural control mechanisms (ankle and hip), we deliberately modified the difficulty of ML stance by changing (a) the stance width and (b) the side on which jaw position or clenching was maintained. We assumed that more challenging experimental conditions would better reveal age-related impairments in ML COP_c. For young adults (control data), we expected to reproduce the literature findings for standard stance, that is to say a high contribution of the hip mechanism, a low but nevertheless significant contribution of the ankle mechanism (Gatev et al., 1999; Termoz et al., 2008) and no cooperation between the ankle and hip mechanisms (Winter et al., 1996; Winter et al., 1993). To elaborate on earlier findings regarding postural control mechanisms, our secondary objective was to highlight significant changes in these mechanisms under conditions that challenged ML postural control. We expected that narrow stance would increase the contribution of both ML ankle and hip mechanisms in all the participants, at least in terms of higher cross-correlation coefficients between time-series (Gatev et al., 1999). However, this effect was expected to be much greater for ML COP_c than for ML COP_v, because ML COP_v versus COP_{net} cross-correlation is already very high in healthy adults in standard stance (Termoz et al., 2008; Winter et al., 1996; Winter et al., 1993). For all the participants, we expected to find that ML COP displacement was significantly influenced by jaw conditions, as shown by certain literature studies (for a review, see Amat, 2009; Cuccia & Caradonna, 2009). However, we did not expect to see a significant effect of the different jaw conditions on the postural control mechanisms. Indeed, postural control mechanisms are known to vary little under circumstances that do not threaten postural stability (Termoz et al., 2008).

Methods

Participants

Twelve students (6 women) from the Universities of Lille 1 and Lille 2 and 12 middle-aged adults (8 women) participated

in this study. The mean age, bodyweight, and height were 24.21 ± 2.50 years, 61.75 ± 8.58 kg, and 173.25 ± 10.65 cm for the young adults, respectively, and 51.13 ± 6.09 years, 70.05 ± 16.72 kg, and 166.17 ± 9.32 cm for the middle-aged adults. Exclusion criteria were a history of neurological or musculoskeletal disease, vestibular problems, recurrent dizziness, any kind of surgery in the preceding six months, any known or treated disabilities at the ankles and hips, previous craniofacial trauma or surgery or signs and/or symptoms of temporomandibular disorders (joint or muscle pain or signs or previous treatment of temporomandibular luxation). Previous or current orthodontic treatment and dentition were not chosen to be part of the selection criteria. The participants gave their written, informed consent to participation.

Apparatus

A dual-top force platform (AMTI, Watertown, MA, USA) was used to record COP displacement with a 100 Hz sampling frequency. The platform was placed 1.50 m from a wall. In all trials, the participants faced the wall and looked at a black dot (visual angle: 1°) placed at eye height in front of them.

Conditions

The study combined four independent variables: age (young vs. middle-aged adults), stance width (narrow vs. standard stance), mandibular position (rest position and left and right laterality occlusion positions), and occlusion with clenching (intercuspal occlusion and left and right maximal voluntary clenches). Stance width, mandibular position, and occlusion with clenching were modified specifically to challenge ML stance. In the narrow stance condition, the participants placed their feet close together, with one foot on each platform. In the standard stance condition, the participants freely chose the most comfortable foot position. We did not impose the foot position because it can lead the participants to feel uncomfortable (Kapteyn, Bles, Njiokiktjien, Kodde, & Massen, 1983; McIlroy & Maki, 1997). However, we controlled the influence of foot position in supplementary analyses (see Results). In the mandibular rest position, the teeth were not in contact with each other (as is the case after swallowing). In the left and right laterality occlusion positions, the participants had to shift their jaw as far to the left or to the right as possible (without experiencing pain) and maintain the mandibular position for the duration of the trial. In the intercuspal occlusion, the participants had to clench their teeth throughout the trial. In the left and right clenching conditions, the participants again clenched their teeth but put more pressure on the left or right side of the jaw, respectively. In all trials, the participants were told to hold their hands by the side of the body. This important instruction was repeated several times.

Procedure

Before the first trial, the foot positions (in bare feet) were marked on a piece of paper taped to each platform. The

210 experimenter explained the different trial conditions and checked that the participants were able to comply with the instructions.

215 The experiment consisted of two trials per condition, giving a total of 24 trials (each lasting 35 s). The trials were run in blocks, to avoid confusion for subtle changes between conditions. Four condition blocks (mandibular position and clenching in standard and narrow stances) were performed successively and were counterbalanced for half the participants. In the four blocks, the order of the mandibular and clenching conditions was randomized. All participants in both groups performed the same trials. To aid relaxation, 220 the participants were instructed to sit down after 12 trials and at any time if needed. The instruction to relax during trials was repeated several times.

Variables and Analyses

Stance Width and Stance Angle

225 Stance width was defined as the distance between the heel centers. Stance angle was defined as the angle between the lines going through the middle of the big toe and the middle of the heel for each foot (cf. McIlroy & Maki, 1997).

Postural Control Mechanisms

230 To investigate postural control mechanisms, we used Winter et al.'s (1993) equations:

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

$$COP_c(t) = COP_l(t) \times 0.5 + COP_r(t) \times 0.5 \quad (2)$$

$$COP_v(t) = COP_{net}(t) - COP_c(t) \quad (3)$$

235 In these equations, $COP_l(t)$, $COP_r(t)$, $R_{vl}(t)$, and $R_{vr}(t)$ correspond to the COP displacement and the vertical reaction forces under the left and right feet, respectively.

The displacement of COP_{net} corresponds to the displacement of the COP under each foot, taking into account the weight under each foot (Equation 1). The contribution of COP_c to COP_{net} was calculated by eliminating the contribution of COP_v (Equation 2). The contribution of COP_v to COP_{net} was then calculated by subtracting the contribution of COP_c from COP_{net} (Equations 1 and 3). It should be recalled that COP_{net} relates to COP displacement, whereas COP_v and COP_c relate to the contribution of the hip and ankle mechanisms. COP_v and COP_c correspond to the parts of COP displacement that are controlled by the ankle and hip mechanisms, respectively. An example of COP_{net} , COP_v , and COP_c time series is shown in Figure 1. To test our hypotheses, the computation was performed in the ML axis but not in the AP axis. Moreover, the computation of COP_v (load-unload) in the AP axis may not be right, as a single platform under each foot cannot measure the extent to which the anterior and posterior parts of the foot load and unload, respectively (i.e., two platforms under each foot would be required). If AP COP_v is not measured objectively, then it may not be differentiated from AP COP_c .

As in Termoz et al. (2008), root mean square (RMS) COP_v and RMS COP_c were computed with respect to RMS COP_{net} (in percentage). The higher the RMS of COP displacement explained by one of the mechanisms, the higher the amplitude contribution of that mechanism. As in previous studies (Lafond, Corriveau, & Prince, 2004; Termoz et al., 2008; Winter et al., 1996; Winter et al., 1993), normalized cross-correlations with zero lag were analyzed for three relationships: COP_v versus COP_{net} , COP_c versus COP_{net} , and COP_v versus COP_c . The higher the cross-correlation coefficient between one mechanism and COP_{net} is, the more active that mechanism is (i.e., the longer its action to control COP_{net}). Both analyses are complementary to calculate the contribution of the two mechanisms to control COP displacement. Indeed, the contribution of one mechanism may be significant if the amplitude contribution is sufficiently great relative to RMS COP_{net} and if the active contribution is also

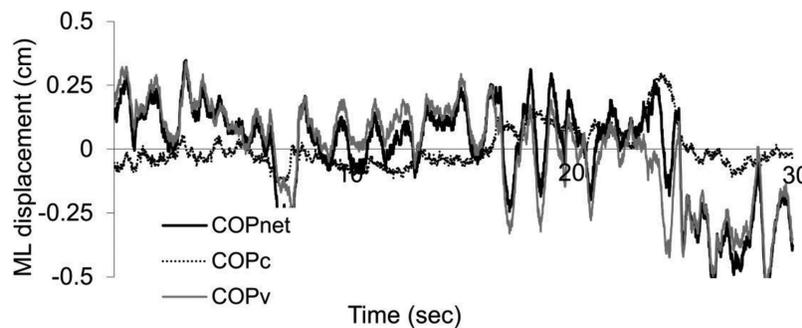


FIGURE 1. Representation of the time-series for net center of pressure (COP_{net}), center of pressure change (COP_c), and center of pressure vertical (COP_v) in one trial recorded in standard stance (cm) in the mediolateral (ML) axis. Thirty seconds of data are shown.

275 sufficiently high. If the amplitude contribution were very large with no significant active contribution, the mechanism would not control COP displacement. In other words, the more similar the time series of the COP_c or COP_v and of COP_{net} , the better the contribution of that mechanism to control COP displacement. The similarity is analyzed both in
280 terms of amplitude and phase. Supplementary information about the model is available in former manuscripts (Lafond et al., 2004; Termoz et al., 2008; Winter et al., 1996; Winter et al., 1993).

COP Displacement

285 As in other studies in which the stance width was modified, we used the mean velocity, standard deviation, and range to analyze COP displacement (e.g., Day et al., 1993; Kirby, Price, & MacLeod, 1987; Mouzat et al., 2004). These variables are also those typically used to compare body sway in
290 young adults versus elderly adults (e.g., Maurer & Peterka, 2005; Prieto et al., 1996).

Analyses

In order to eliminate transitory behavior at the start of the trials, the first 5 s of data were not analyzed (Kinsella-Shaw, Harrison, Colon-Semenza, & Turvey, 2006). Each variable was calculated as the average of the two trials per condition. Repeated measures analyses of variance (ANOVA) with four factors (age, stance width, mandibular position, and clenching position) were performed on the dependent variables with
300 a threshold for statistical significance set to $p < .05$. In secondary analyses, one-sample t tests were used to compare the amplitudes of the cross-correlation coefficients with zero. For these analyses, the threshold for statistical significance was set to $p < .025$ after Bonferroni adjustment.

Results

Amplitude Contribution of the Postural Control Mechanisms

RMS COP_c /RMS COP_{net}

310 The ANOVA showed a significant main effect of stance width only, $F(1, 22) = 4.72$, $\eta_p^2 = .15$, $p < .052$. The RMS COP_c /RMS COP_{net} was significantly greater in standard stance than in narrow stance (Figure 2, Table 1).

RMS COP_v /RMS COP_{net}

315 There was a significant main effect of stance width only, $F(1, 22) = 4.85$, $\eta_p^2 = .15$, $p < .052$. The RMS COP_v /RMS COP_{net} was significantly greater in standard stance than in narrow stance (Figure 2, Table 1).

Active Contribution of the Postural Control Mechanisms

COP_v versus COP_{net}

320 There was a significant main effect of stance width only, $F(1, 22) = 35.0$, $\eta_p^2 = .38$, $p < .053$. The COP_v versus COP_{net}

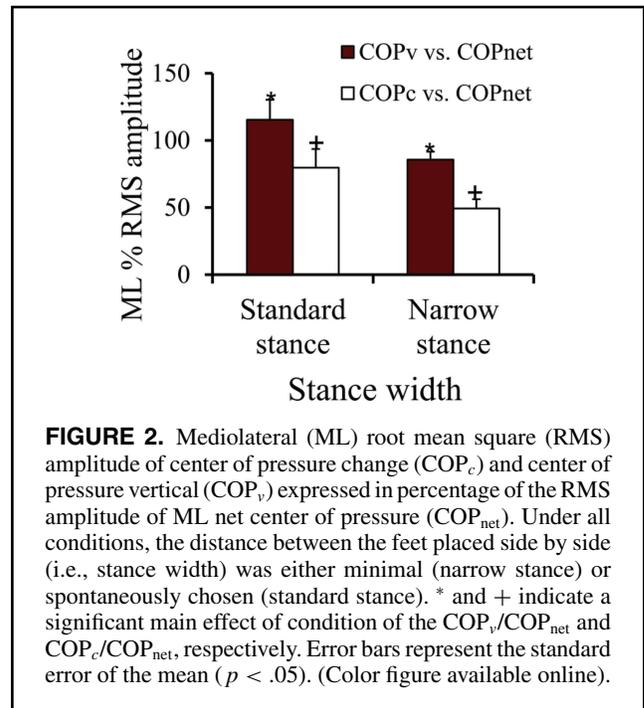


FIGURE 2. Mediolateral (ML) root mean square (RMS) amplitude of center of pressure change (COP_c) and center of pressure vertical (COP_v) expressed in percentage of the RMS amplitude of ML net center of pressure (COP_{net}). Under all conditions, the distance between the feet placed side by side (i.e., stance width) was either minimal (narrow stance) or spontaneously chosen (standard stance). * and + indicate a significant main effect of condition of the COP_v/COP_{net} and COP_c/COP_{net} , respectively. Error bars represent the standard error of the mean ($p < .05$). (Color figure available online).

was significantly greater in narrow stance than in standard stance (Figures 3A and 3B, Table 1).

COP_c versus COP_{net}

325 There were significant main effects of stance width, $F(1, 22) = 226.14$, $\eta_p^2 = .48$, $p < .053$, and group, $F(1, 22) = 5.12$, $\eta_p^2 = .16$, $p < .053$. The COP_c versus COP_{net} was significantly greater in narrow stance than in standard stance and significantly greater in young adults than in middle-aged adults (Figures 3A and 3B, Table 1). 330

COP_v versus COP_c

335 There were significant main effects of stance width, $F(1, 22) = 348.94$, $\eta_p^2 = .48$, $p < .053$, and group, $F(1, 22) = 4.34$, $\eta_p^2 = .14$, $p < .053$. The COP_v versus COP_c was significantly greater in narrow stance than in standard stance and significantly greater in young adults than in middle-aged adults (Figure 3A and 3B, Table 1).

The three analyses did not reveal any significant effect of mandibular or clenching position ($p = ns$).

COP Displacement

COP Standard Deviation

340 The ANOVA showed a significant main effect of stance width only, $F(1, 22) = 123.92$, $\eta_p^2 = .46$, $p < .054$. The COP standard deviation was significantly greater in narrow stance than in standard stance (Figure 4A, Table 1). 345

TABLE 1. Statistics of the Behavioral Dependent Variables as a Function of the Group (Young and Middle-Aged Adults) and the Stance Width (Standard and Narrow Stances)

| Dependent variables | Young adults | | Middle-aged adults | |
|--|------------------------------|------------------------------|------------------------------|------------------------------|
| | Standard stance | Narrow stance | Standard stance | Narrow stance |
| COP sway | | | | |
| SD | 0.15 ± 0.04 ^a | 0.55 ± 0.19 ^a | 0.15 ± 0.06 ^a | 0.42 ± 0.10 ^a |
| Range | 0.82 ± 0.20 ^{a,b,c} | 2.73 ± 0.78 ^{a,b,c} | 0.80 ± 0.04 ^{a,b,c} | 0.79 ± 0.05 ^{a,b,c} |
| M velocity | 1.37 ± 0.17 ^a | 1.64 ± 0.15 ^a | 1.25 ± 0.21 ^a | 1.55 ± 0.21 ^a |
| Postural control mechanisms | | | | |
| COP _v vs. COP _{net} | 0.97 ± 0.01 ^a | 0.99 ± 0.00 ^a | 0.96 ± 0.01 ^a | 0.99 ± 0.00 ^a |
| COP _c versus COP _{net} | 0.23 ± 0.06 ^{a,b} | 0.93 ± 0.02 ^{a,b} | 0.06 ± 0.08 ^{a,b} | 0.82 ± 0.05 ^{a,b} |
| COP _v versus COP _c | 0.03 ± 0.07 ^{a,b} | 0.89 ± 0.02 ^{a,b} | -0.16 ± 0.09 ^{a,b} | 0.76 ± 0.05 ^{a,b} |
| RMS COP _v /RMS COP _{net} | 113.47 ± 17.26 ^a | 77.39 ± 5.26 ^a | 117.31 ± 26.80 ^a | 94.03 ± 9.52 ^a |
| RMS COP _c /RMS COP _{net} | 83.13 ± 20.80 ^a | 46.73 ± 3.27 ^a | 76.28 ± 21.21 ^a | 51.86 ± 13.48 ^a |

Note. The dependent variables were the standard deviation; the range and mean velocity of center of pressure (COP) sway; the cross-correlation coefficients of COP_v versus COP_{net}, COP_c versus COP_{net}, and COP_v versus COP_c; and the root mean square (RMS) amplitude of COP_v and COP_c relative to the RMS of COP_{net}. The mean values ± the standard deviations of the dependent variables are given. COP_c = center of pressure change; COP_{net} = center of pressure net; COP_v = center of pressure vertical.

^aSignificant main effect of condition ($p < .05$).

^bSignificant main effect of group ($p < .05$).

^cSignificant main effect of group by condition interaction ($p < .05$).

COP Range

There were significant main effects of group, $F(1, 22) = 62.59, \eta_p^2 = .43, p < .05$; and stance width, $F(1, 22) = 76.05, \eta_p^2 = .44, p < .05$; and a significant group by stance

width interaction, $F(1, 22) = 77.18, \eta_p^2 = .44, p < .054$. Only in young adults, the range of COP displacement was significantly greater in narrow stance than in standard stance (Figure 4B, Table 1).

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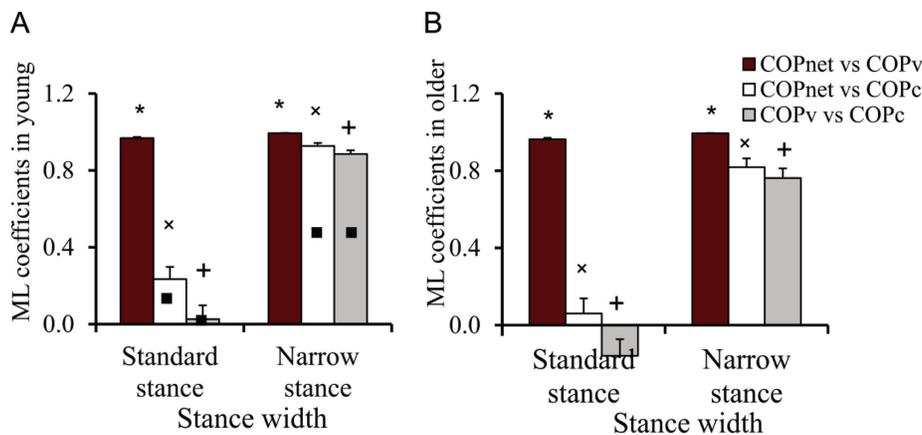


FIGURE 3. Mediolateral (ML) cross-correlation coefficients in young adults (A) and middle-aged adults (B). Black: Cross-correlation between the integrated displacement of the center of pressure (COP) under the left and right foot (COP_{net}) and the COP displacement under the control of the hip mechanism (COP_v vs. COP_{net}). White: Cross-correlation between COP_{net} and the COP displacement under the control of the ankle mechanism (COP_c vs. COP_{net}). Gray: Cross-correlation between COP_v and COP_c (COP_v vs. COP_c). Under all conditions, the distance between the feet placed side by side (i.e., stance width) was either minimal (narrow stance) or spontaneously chosen (standard stance). x, *, and + indicate a significant main effect of condition of the COP_v versus COP_{net}, COP_c versus COP_{net}, and COP_v versus COP_c relationships, respectively. ■ indicates a main effect of group. Error bars represent the standard error of the mean ($p < .05$). (Color figure available online).

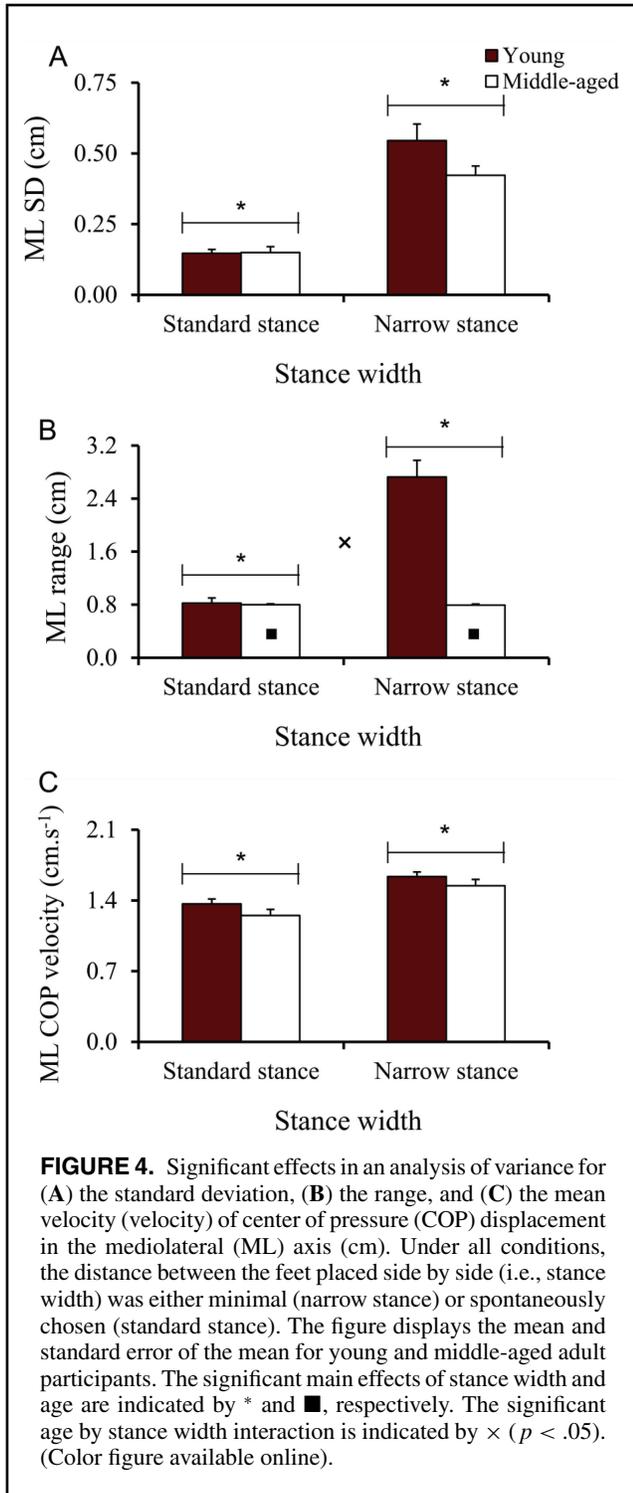


FIGURE 4. Significant effects in an analysis of variance for (A) the standard deviation, (B) the range, and (C) the mean velocity (velocity) of center of pressure (COP) displacement in the mediolateral (ML) axis (cm). Under all conditions, the distance between the feet placed side by side (i.e., stance width) was either minimal (narrow stance) or spontaneously chosen (standard stance). The figure displays the mean and standard error of the mean for young and middle-aged adult participants. The significant main effects of stance width and age are indicated by * and ■, respectively. The significant age by stance width interaction is indicated by × ($p < .05$). (Color figure available online).

COP Mean Velocity

355 The ANOVA showed significant main effects of clenching, $F(1, 22) = 5.91, \eta_p^2 = .17, p < .05$ (Figure 5), and stance width, $F(1, 22) = 69.66, \eta_p^2 = .43, p < .054$. The COP mean velocity was significantly faster in occlusion with clenching (1.46 ± 0.17) than in mandibular position (1.44 ± 0.18). This

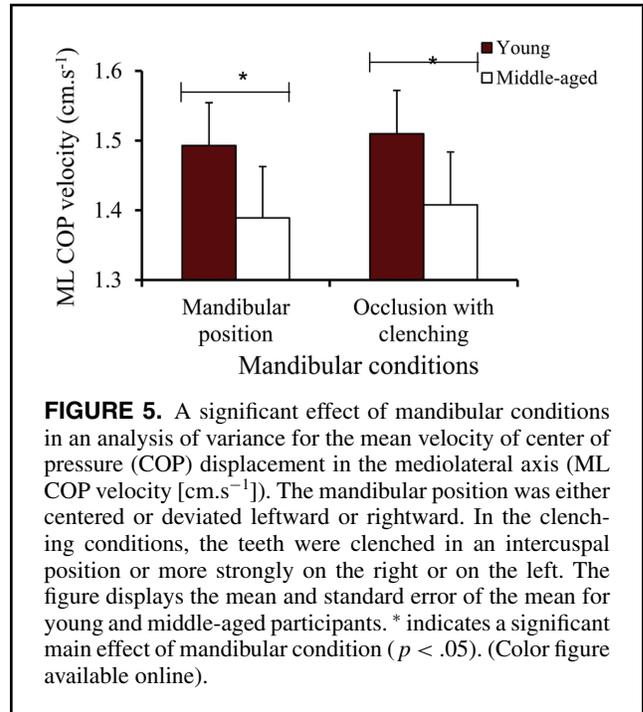


FIGURE 5. A significant effect of mandibular conditions in an analysis of variance for the mean velocity of center of pressure (COP) displacement in the mediolateral axis (ML COP velocity [$\text{cm}\cdot\text{s}^{-1}$]). The mandibular position was either centered or deviated leftward or rightward. In the clenching conditions, the teeth were clenched in an intercuspal position or more strongly on the right or on the left. The figure displays the mean and standard error of the mean for young and middle-aged participants. * indicates a significant main effect of mandibular condition ($p < .05$). (Color figure available online).

significant effect may seem surprising because the means are quite similar (Figure 4C). However, it should be noted that the partial eta squared was much smaller than in other analyses. The COP mean velocity was also significantly faster in narrow stance than in standard stance (Table 1).

Significance of the Active Contribution

Above, the mandibular positions and clenches conditions did not lead to any significant effect. On this basis, only the stance width factor was included in the new analyses. One-sample t tests were used to compare only those correlation coefficients that were close to zero (i.e., ML COP_c vs. COP_{net} and ML COP_v vs. COP_c in both groups in standard stance). These t tests showed that ML COP_c versus COP_{net} in standard stance was significantly greater than zero in young adults only, $t(11) = 3.67, p < .025$ (Figures 3A and 3B, Table 1). This is an important finding relative to our main objective. The ML COP_v versus COP_c values did not differ from zero in either of the two groups, $t_s(11) < 1.86, p > .025$.

Analyses Controlling for the Foot Position, Height, Weight, and Age

The two groups were compared in terms of stance width and stance angle (Figure 6) in standard and narrow stances. Independent t tests did not show any significant inter-group differences, $t_s(22) < 1.45, p > .05$.

To further control for the influence of foot position (stance width, stance angle) and also height, weight and age on the dependent variables, we used the normalization procedure already adopted by Chiari, Rocchi, and Cappello (2002) and

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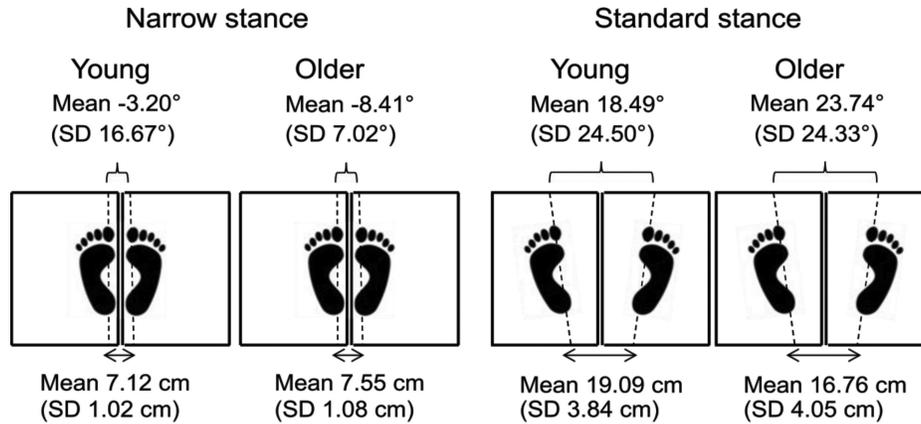


FIGURE 6. Representation of the foot positions adopted by the participants in the two stance width conditions (narrow and standard stances). The mean values and standard deviations of the stance width and stance angle are given for each stance condition. (Color figure available online).

recommended by O'Malley (1996). This procedure consists of removing the influence of a confounding variable without changing the units and range of the data. These variables were controlled in each age group separately. The main analyses (ANOVAs) were redone with the normalized variables.

The controlled analyses provided two new significant findings. After controlling for the age difference in each group, the group by stance width interaction effect was significant for the standard deviation of COP displacement (young adults standard stance: 0.15 ± 0.04 cm, narrow stance: 0.55 ± 0.19 cm; middle-aged adults standard stance: 0.15 ± 0.05 cm, narrow stance: 0.42 ± 0.08 cm). After controlling for height, a main effect of age was found for the velocity of COP displacement (young adults: 1.57 ± 0.18 $\text{cm}\cdot\text{s}^{-1}$; middle-aged adults: 1.43 ± 0.25 $\text{cm}\cdot\text{s}^{-1}$). Otherwise, most of these results showed a slightly greater partial eta squared with the normalized variables. Importantly, the main effect of age in the ANOVA for the cross-correlation COP_c versus COP_{net} was much stronger for each controlled variable than before the normalization ($.45 < \eta_p^2 < .46$). Overall therefore, the foot position and physical characteristics of the participants were confounding variables in the sense that they limited the amount of significant findings and the strength of the results.

Discussion

Our study featured four main findings. First, the active contribution of ML postural control mechanisms at the ankle is significantly lower in middle-aged (i.e., nonelderly) adults than in young adults. Second, the role of ML ankle postural control mechanism is much greater than has previously been found—especially for narrow stance. Third, narrow stance increased the overall contribution of the two mechanisms, but not as much as expected. Fourth, the different mandibular positions and clenching conditions significantly changed the

characteristics of COP displacement but not the contributions of COP_c and COP_v .

Age-Related Changes in Postural Control Mechanisms

The study results confirmed our expectation that the ankle mechanism contributes significantly less to ML COP displacement control in middle-aged adults than it does in young adults. Indeed, middle-aged adults exhibited significantly lower ML COP_c active contribution than young adults did (Figures 3A and 3B, Table 1). In other terms, the result means that the active contribution of the ankle mechanism was less efficient in middle-aged adults than in young adults. Furthermore, the active contribution of ML COP_c was null in middle-aged adults but significantly positive in young adults (Figures 3A and 3B, Table 1). It means that the ankle mechanism had no significant role in ML postural control in middle-aged adults in standard stance while it did have a significant role in young adults. These two effects may be significantly diminished the collaboration between ML COP_v and ML COP_c seen in middle-aged adults, relative to young adults (Figures 3A and 3B, Table 1). This is a striking finding because it relates to a main effect of age and was not solely observed in ML-challenging conditions (Figures 3A and 3B, Table 1). Also, the effect was much stronger after controlling for foot positions and/or physical characteristics of the participants (see Results). Our healthy, middle-aged participants may thus have shown preclinical signs of future ML postural instability. Indeed, impairments in postural control mechanisms should subsequently translate into increased postural sway (Maurer & Peterka, 2005). Our results differed from those reported by Termoz et al. (2008) probably because we did not instruct our participants to remain as steady as possible during the trials. Thus, when seeking to understand age-related or disease-related increases in ML

sway, it may be more appropriate to test participants under
455 natural conditions.

Age-Related Changes in COP Displacement

Middle-aged adults did not exhibit greater or more rapid
ML COP displacement than young adults did under any of our
experimental conditions (Figures 4A, 4B, and 4C, Table 1).
460 This result was expected, as middle-aged adults are usually
found to sway either as much as young adults do or signif-
icantly slightly more (Abrahamova & Hlavacka, 2008; Era
et al., 2006). However, our analyses showed that middle-aged
adults exhibited a significantly lower range of ML COP dis-
465 placement than young adults did (Figure 4B, Table 1). As ex-
emplified by Figure 4B, middle-aged adults did not increase
their range of COP displacement in narrow stance, whereas
young adults clearly did. This result was unexpected, since
previous studies mostly found that COP displacement and/or
470 postural sway were greater in narrow stance than in wider
stance (Day et al., 1993; Kirby et al., 1987; Mouzat et al.,
2004). Our other results (standard deviation and the mean
velocity of COP displacement) were in line with literature
findings (Figures 4A and 4C, Table 1). We therefore suppose
475 that middle-aged adults controlled their narrow stance in an
unexpected manner by constraining the maximum amplitude
of their ML oscillation. In this difficult stance condition, they
may have increased their ankle stiffness as an alternative con-
trol mechanism to compensate for putative impairments in
480 the ML ankle postural control mechanism (Figure 3A, Ta-
ble 1). This interpretation is supported by Benjuya, Melzer,
and Kaplanski (2004), who showed an age-related increase
in ankle muscle cocontraction (i.e., greater electromyogra-
phy activities of the peripheral muscles) in narrow stances.
485 Overall, our study results cannot confirm our initial hypoth-
esis whereby impairments in ML COP_c appear earlier in life
than any changes in ML COP displacement. However, we
found that healthy adults under the age of 60 can have a
significant impairment in ML postural control.

490 Effects of Stance Width on the Postural Control Mechanisms

For young adults in standard stance, the results were con-
sistent with those reported by Termoz et al. (2008) and Gatev
et al. (1999; i.e., significant contributions of both ankle and
495 hip mechanisms to the control of ML COP displacement
(Figure 3A, Table 1). In the comparison between standard
and narrow stances, Figures 3A and 3B showed that the ac-
tive contribution was significantly greater in narrow stance
than in standard stance. This finding was expected based
500 on the study by Gatev et al. However, the findings for the
RMS amplitude of the mechanisms were not anticipated. In-
deed, Figure 2 showed that the amplitude contribution of the
mechanisms was significantly lower in narrow stance than
in standard stance. In comparison, the findings for the active
505 contribution were stronger ($\eta_p^2 > .38$) than the findings for

the amplitude contribution ($\eta_p^2 < .16$), thus confirming that
the overall contribution of ML COP_v and ML COP_c were
higher in narrow stance than in standard stance. In other
words, the two mechanisms were more active to modify the
510 position of COP displacement in narrow stance but did it with
less strength. Therefore, the overall contribution of postural
mechanisms to controlling COP displacement was weakly
increased, probably explaining why individuals sway more
in narrow stance than in standard stance (e.g., Day et al.,
515 1993; Kirby et al., 1987; Mouzat et al., 2004). In narrow
stance, the amplitude contribution may have been weaker
because the two reaction forces (one under each foot) were
closer to each other, thus shortening the lever arm to control
ML postural sway. Indeed, Winter et al. (1996) explained
520 that the wider the stance width is, the less muscle activation
required to maintain the same COP displacement.

In Gatev et al. (1999), seven healthy men stood in nar-
row and standard stance conditions with their eyes open
or closed. In narrow stance, Gatev et al.'s analyses showed
525 (a) less electromyography activity in the lower leg, (b) more
relationships between linear and angular motions at the hip,
(c) less correlation of body motions throughout the body,
and (d) a significant correlation between hip angular mo-
tions in the AP and ML axis. Based on these findings, the
researchers concluded that the hip mechanism contributed
530 more to the control of narrow stance than to the control
of standard stance. We additionally showed an unpublished
finding that the collaboration between COP_v and COP_c is
significantly greater in narrow stance than in standard stance
(Figures 3A and B, Table 1). As expected also, the difference
535 in the active contribution of COP_c between standard and nar-
row stances was much greater than the difference for COP_v
in these conditions (effect size in the ANOVAs = .48 and .38,
respectively). It is noteworthy that in narrow stance, the active
contribution of COP_c to ML postural control was almost as
540 great as the active contribution of COP_v (Figures 3A and 3B,
Table 1). Because elderly adults have been shown to naturally
adopt a significantly narrower quiet stance than young adults
(McIlroy & Maki, 1997), they may have more difficulty
controlling ML COP displacement in natural stance. This
545 is an important practical message, given the very high *F*
value found for the main effect of stance width on COP_c,
 $F(1, 22) = 226.14$.

550 Effects of Mandibular Position and Clenching on COP Displacement and Mechanisms

Some studies have shown that mandibular conditions can
significantly change the area of COP displacement (Gang-
loff, Louis, & Perrin, 2000; Gangloff & Perrin, 2002). Our
analyses with COP displacement variables did not confirm
555 these findings (at least for the ML axis) because there was no
significant effect of mandibular or clenching laterality. Al-
though the participants exhibited significantly more rapid ML
COP displacement in clenching conditions than in mandibu-
lar position conditions (Figure 5), this effect was probably

560 meaningless. Indeed, it was not clearly apparent on Figure 5
and the effect size was low. By clenching the teeth, the me-
chanical increased tension in the fascia system may have
spread to increase the participants' overall body stiffness,
which in turn would have reduced their COP displacement
565 velocity. This increase in body stiffness must have been slight
because it did not affect COP SD, COP range, or the con-
tributions of the two postural control mechanisms (COP_c
and COP_v). Overall, the mandibular conditions only had a
marginal effect on postural control, even in narrow stance.

570 Summary and Future Work

We are not aware of any literature reports of age-related im-
pairments in ankle and hip postural control mechanisms that
could explain the known, age-related increases in ML COP
amplitude and velocity (Maki et al., 1994; Prieto et al., 1996).
575 In the present study, we expected to find and indeed observed
an age-related impairment in the ML ankle postural control
mechanism in under 60-year-old adults (with no changes in
the ML hip mechanism). In practical terms, our study demon-
strates that ML postural control may already be compromised
580 before age 60 years—even though healthy middle-aged in-
dividuals did not exhibit significantly greater COP displace-
ment than young adults. Our study is limited in the sense that
the neuromuscular control at the ankle and hip is unknown.
However, based on our findings, future researchers should
585 be directed to search for physiological factors that may ex-
plain the lower age-related active contribution of ML COP_c:
these may include a lower threshold for sensing passive in-
version or eversion of the ankle (Gilsing et al., 1995) and a
general reduction in the somatosensory threshold at the feet,
590 ankles and legs (Menz, Morris, & Lord, 2005, 2006; Scott,
Menz, & Newcombe, 2007; Toledo & Barela, 2010). Mea-
sures of these physiological factors as well as measures of
electrophysiological factors (e.g., nerve conduction velocity
of lower leg muscles) will be relevant to better explain normal
595 and abnormal neuromuscular contributions of COP_c and
COP_v to control stance. Future researchers' work and prac-
tical efforts should also check whether improving the motor
performance or sensitivity of the inversion or eversion mech-
anism increases the contribution of COP_c and reduces ML
600 falls (which are significantly related to hip fractures; Hayes
et al., 1996; Rogers & Mille, 2003). Based on our present
results, it may be important to teach elderly and middle-aged
adults to increase their stance width to compensate for the
lower COP_c active contribution. Alternatively, older adults
605 could be taught to regularly check their ankle function on the
sensory and motor levels.

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