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To freeze or not to freeze? Affective and cognitive perturbations have markedly different effects on postural control

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ABSTRACT

Similar effects have been reported for diverting attention from postural control and increased anxiety on the characteristics of center-of-pressure (COP) time series (decreased excursions and elevated mean power frequency). These effects have also received similar interpretations in terms of increased postural stiffness, suggesting that cognitive and affective manipulations have similar influences on postural control. The present experiment tested this hypothesis by comparing postural conditions involving manipulations of attention (diverting attention from posture using cognitive and motor dual tasks) and anxiety (standing at a height), and by complementing posturography with electromyographic analyses to directly examine neuromuscular stiffness control. Affective and cognitive manipulations had markedly different effects. Unlike the height condition, diverting attention from balance induced smaller COP amplitudes and higher sway frequencies. In addition, more regular COP trajectories (lower sample entropy) were found in the height condition than the dual-task conditions, suggesting elevated attentional investment in posture under the affective manipulation. Finally, based on an analysis of the cross-correlation function between anterior–posterior COP time series and enveloped calf muscle activity, indications of tighter anticipatory neuromuscular control of posture were found for the height condition only. Our data suggest that affective and cognitive perturbations have qualitatively different effects on postural control, and thus are likely to be associated with different control processes, as

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evidenced by differences in neuromuscular regulation and attentional investment in posture.

1. Introduction

In days gone by, postural control was viewed as a largely automatic process, governed by sensory information and reflex loops. In contrast, more recent literature on posture-cognition dual-tasking strongly suggests that postural control synergies are also sensitive to cognitive manipulations (e.g., Mitra, 2003; Teasdale, Bard, LaRue, & Fleury, 1993). Encouraging participants to focus attention on postural sway appears to interfere with automatic control processes (Hunter & Hoffman, 2001; Vuillerme & Nafati, 2007), whereas diverting attention from one's own balance (e.g., by using a secondary task) enhances automatic control processes, putatively leading to balance that has greater "efficacy" (Huxhold, Li, Schmiedek, & Lindenberger, 2006), is more "effective" (McNevin & Wulf, 2002; Vuillerme & Nafati, 2007), or more "efficient" (Donker, Roerdink, Greven, & Beek, 2007; Riley, Baker, & Schmit, 2003). Beneficial effects on posture when attention is diverted from postural control are typically evidenced by smaller center-of-pressure (COP) excursions (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Fraizer & Mitra, 2008), accompanied by increased higher-frequency components (McNevin & Wulf, 2002), as indicated by reduced COP variability (standard deviation) and elevated mean power frequency (MPF), respectively.

The COP characteristics accompanying quiet standing when attention is diverted from balance regulation have been attributed to a stiffening of posture. For example, McNevin and Wulf (2002) found higher-frequency components in COP trajectories when participants were instructed to stand still while minimizing the movements of a loosely hanging sheet touched with their fingertips ("external focus of attention") compared to instructions to minimize finger movements ("internal focus") and a baseline (no touch) condition. McNevin and Wulf (2002) suggested that participants minimized sheet movements by increasing joint/muscle stiffness. This suggestion was motivated from the modeling work of Winter, Patla, Prince, Ishac, and Gielo-Perczak (1998), which established the relationship between the effective stiffness of an inverted pendulum balancing system and the frequencies in the resultant COP spectrum. An external focus arguably resulted in more automatic (or "reflex-like") postural control (McNevin & Wulf, 2002). Increased ankle joint stiffness has also been proposed by Vuillerme and Vincent (2006) and Vuillerme and Nafati (2007) to account for the observed effects of attention on balance, although in the latter study the increased stiffness was linked to an internal attention focus, in contrast to the findings and interpretation of McNevin and Wulf (2002).

Stiffening of the ankle joint has also been proposed as a mechanism to explain effects of anxiety on postural performance. When participants are required to maintain balance when standing at the edge of an elevated surface (inducing a postural threat) similar markers of ankle stiffening are observed in the posturogram (e.g., Brown, Polych, & Doan, 2006; Carpenter, Frank, & Silcher, 1999; Carpenter, Frank, Silcher, & Peysar, 2001) as in the dual-tasking situations, i.e., increased COP MPF and reduced COP displacements. Carpenter et al. (2001) and Brown et al. (2006) additionally recorded muscular activity, and suggested that the changes in muscular activity in the postural threat condition reflect increased ankle stiffening via a mechanism of co-contraction. Interestingly, comparable COP characteristics have been observed in patients with phobic postural vertigo, which have also been attributed to increased co-activation of ankle muscles resulting in increased postural stiffness (Krafczyk, Schlamp, Dieterich, Haberhauer, & Brandt, 1999). These stiffening responses bear close resemblance to what ethologists refer to as "freezing behavior" when confronted with an imminent threat, with signs of "immobility" (reduced displacements) and "rigidity" (increased MPF) in the COP trajectories (e.g., Azevedo et al., 2005; see also Facchinetti, Imbiriba, Azevedo, Vargas, & Volchan, 2006).

As outlined above, there seem to be marked similarities between studies that examine cognitive effects on posture (using dual-tasking paradigms) and studies that examine effects of anxiety on posture, both in terms of empirical posturographic findings (decreased COP excursions and increased MPF) and proposed theoretical interpretations (freezing, or stiffening of the ankle joint). However, close reading of the literature also suggests subtle but important differences in the way stiffness is conceived. According to McNevin and Wulf (2002; see also Wulf, McNevin, & Shea, 2001) increased MPF results from changes in ankle stiffness, and represents a marker of an external focus of attention, which promotes the use of more automatic control processes, i.e., a release of cognitive resources. In a similar vein, Dault, Frank, and Allard (2001) interpreted increased MPF in the COP trajectories during a working memory task as a result of participants adopting a less attention-demanding co-contraction mode. However, within the literature on anxiety and balance, stiffness is usually conceived as a protective mechanism (e.g., to prevent a fall), caused by "tighter control" of balance supporting muscles. In this context, stiffness control indicates close monitoring by the actor of the position of one's own body (Huffman, Horslen, Carpenter, & Adkin, 2009), i.e., heightened awareness, and thus reduced automaticity of postural control (for a comparable distinction, see Schmid, Conforto, Lopez, & D'Alessio, 2007).

Thus, changes in frequency and/or sway magnitude may not always be indicative of the amount of attentional investment in the regulation of balance. A potentially fruitful way to assess the attentional investments in posture is to complement conventional measures of posturographic performance with measures of the dynamic structure of COP fluctuations. Measures indexing the regularity of COP fluctuations, such as sample entropy, approximate entropy, and recurrence quantification analysis, have been successfully applied to study the influence of attention on posture. Schmit, Regis, and Riley (2005) and Stins, Michielsen, Roerdink, and Beek (2009) found less regular COP fluctuations in balance experts than controls. In a similar vein, less regular COP excursions are observed when attention is experimentally withdrawn from posture (Cavanaugh, Mercer, & Stergiou, 2007; Donker et al., 2007; Roerdink et al., 2006; Stins, Michielsen et al., 2009). These results suggest more irregular COP fluctuations with reduced attentional involvement in the regulation of posture, or in other words, greater automaticity. Other studies have shown more regular COP fluctuations in balance-impaired groups than controls (e.g., Cavanaugh et al., 2006; Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Roerdink, Geurts, de Haart, & Beek, 2009; Roerdink et al., 2006; Schmit et al., 2006; Stins, Ledebt, Emck, van Dokkum, & Beek, 2009), which by the same token points to greater attentional involvement in the regulation of posture in these groups, i.e., decreased automaticity. Thus, complementing conventional posturography by an assessment of sway regularity may be instrumental in the examination of the attentional investment in posture.

The aim of the present study was to identify possible differences and commonalities in postural control during attentional distraction from posture using a dual-task paradigm (viz. mental arithmetic, or holding a cup filled with liquid), and during the maintenance of posture in an anxiety-provoking situation (viz. standing at the edge of a cliff). Postural control was assessed in terms of (a) conventional sway parameters (related to frequency, variability, and body lean), (b) the attentional investment in posture (by examining the regularity of COP trajectories), and (c) the neuromuscular regulation of balance. With respect to the latter, we recorded muscular activity of important leg muscles to examine whether postural changes are also accompanied by changes in stiffness. The literature suggests that two complementary neuromuscular mechanisms are available to stiffen posture: increased muscular co-contraction and a tighter anticipatory (or feedforward) control. The former can be controlled via appropriate tonic neural commands to muscles surrounding the ankle joint (e.g., Sasagawa, Ushiyama, Masani, Kouzaki, & Kanehisa, 2009; Winter et al., 1998). The latter type of control is based on a suitable internal model, predicting the postural dynamics. This anticipatory control must at least accompany postural stiffness through co-contraction (Morasso & Sanguineti, 2002; Morasso & Schieppati, 1999), as evidenced by the fact that rectified EMG activity of calf muscles is significantly correlated with AP COP and COM motions, with an anticipation of about 250–300 ms (Borg, Finell, Hakala, & Herrala, 2007; Gatev, Thomas, Kepple, & Hallett, 1999; Schieppati, Hugon, Grasso, Nardone, & Galante, 1994). In fact, simulations by Morasso and Sanguineti (2002) suggest that these two stabilizing mechanisms contribute about equally to the restoring forces necessary to prevent falling in normal participants, whereas with aging and pathology this balance in control is often shifted towards increased postural stiffness via exaggerated and energetically expensive co-activation of antagonistic ankle muscles (Morasso & Sanguineti, 2002). Therefore, we examined both co-contraction in muscles surrounding the ankle and the "tightness" of the coupling between COP and muscular activity time series in order to test whether our dual-tasking and affective manipulations would induce postural stiffening.

Our main hypotheses were that (a) dual tasking and anxiety conditions would lead to reduced COP excursions and increased COP MPF relative to baseline, (b) anxiety would promote attentional investment in posture (cf. Huffman et al., 2009), whereas dual tasking would promote an external focus of attention, leading to more regular COP fluctuations in the height than dual-tasking conditions, and (c) anxiety would lead to an increase in postural stiffness relative to dual tasking via elevated co-contraction and/or a tighter anticipatory control.

2. Methods

2.1. Participants

Eighteen healthy subjects participated (6 males, 12 females, mean age 26 years, *SD* 5 years) in the experiment. The study was approved by the ethics committee of the Faculty of Human Movement Sciences of VU University Amsterdam and performed in full compliance with the Declaration of Helsinki. All participants signed an informed consent form prior to testing.

2.2. Procedure

During all trials participants stood on a custom-made force plate (dimensions 1×1 m; sampling frequency 100 Hz; resolution 0.28 N/bit; resonance frequency 30 Hz), with the arms hanging relaxed alongside the body. Testing took place in a brightly lit hall. The force plate was positioned approximately 5 m from a wall. Prior to testing EMG electrodes were attached bilaterally to the muscle bellies of (1) m. rectus femoris (RF), (2) m. vastus medialis (VAS), (3) m. gastrocnemius (GS), (4) m. tibialis anterior (TA), and (5) m. extensor digitorum longus (ED). The interelectrode distance between ED and TA electrode pairs was always greater than 2 cm to minimize "cross-talk" between the muscles' EMG signals (cf. Schieppati et al., 1994). EMG was recorded at a sampling frequency of 2000 Hz and filtered online using a 5–400 Hz bandpass filter. A trigger signal was used to allow for offline alignment of EMG and force plate data.

The experiment consisted of four blocks of four trials (each trial lasting 60 s), with each trial pertaining to one of four conditions: (1) baseline, (2) cognitive dual task, (3) motor dual task, and (4) height. Conditions were presented in a random order within each block, with the restriction that identical conditions were never presented in direct succession. During the baseline condition participants stood on the force plate and fixated their gaze at the wall in front of them. During the cognitive dual-task condition participants were given a number (300, 301, 302, or 303) and they were asked to count silently backwards in steps of 7. At the end of the trial participants reported verbally how far back they had counted. In the motor dual-task condition participants were handed a cup and saucer with the cup filled to the rim with a cold dark liquid. Participants had to hold the saucer with their preferred hand close to their body, adopting a flexed elbow posture, and they were instructed not to spill any liquid. During the experiment no liquid was spilled. In the height condition the force plate was raised to a height of 1 m on the top of a heavy metal table. In all conditions participants stood with their toes nearly touching the edge of the force plate, so that in the height condition participants were facing a 1 m deep "cliff". Foot position was marked using a piece of paper (cf. Carpenter et al., 1999, 2001) and throughout all conditions the same foot placement was used.

2.3. Data analysis

2.3.1. Posturography

Anterior–posterior [AP] COP time series were low-pass filtered (2nd order zero-lag Butterworth filter, 15 Hz cutoff frequency); we focused on the AP component in view of the expectations regarding body lean, and because muscular activity of the selected lower-leg muscles mainly affects COP excursions in the AP direction. The first and last 2.5 s were removed from the filtered time series. Five posturographic measures were determined: (1) mean AP COP position (in mm, with higher values representing greater forward lean), (2) variability of AP COP (in mm, expressed as the *SD* of COP time series), (3) mean power frequency (MPF) of AP COP (in Hz), estimated from power density spectrum according to Welch's method, partitioned in seven segments with 50% overlap (Hanning window, mean and linear trends removed; cf. Vieira, Oliveira, & Nadal, 2009), (4) 95% power frequency (F95) which indexes the frequency below which 95% of the total power is found, thus providing an estimate of the "broadness" of the power spectrum, and (5) sample entropy of detrended AP COP (dimensionless, greater values indicating more irregular AP COP time series; template length $M = 3$, tolerance range $TR = .04$, parameter choice based on optimization procedure described by Lake, Richman, Griffin, and Moorman (2002)). In brief; sample entropy is the negative natural logarithm of an estimate of the conditional probability that subseries (epochs) of length M that match pointwise within a specific tolerance range (TR) also match at the next point. Lower sample entropy values imply a greater likelihood that sets of matching epochs in a time series will be followed by another match within a certain tolerance. For a more formal and detailed treatment, see Lake et al. (2002) and Richman and Moorman (2000). For TR and M parameter optimization in the context of COP time series, see Roerdink, Hlavackova, and Vuillerme (2011).

2.3.2. EMG

EMG time series were offline bandpass filtered with cutoffs at 10 and 400 Hz. Next, the signals were full-wave rectified and enveloped using a moving average filter (window size corresponding to 1 s and corrected for the induced shift). Similar to the COP time series, the first and last 2.5 s were excluded. Per muscle, mean EMG activity was determined. Relative change in mean EMG activity between ankle flexors and extensors was quantified by the ratio of TA over GS mean EMG activity (cf. Brown et al., 2006). In addition, TA and GS envelop curves were cross-correlated to determine whether antagonistic ankle muscles were acting in-phase or out of phase, indicating co-contraction or reciprocal activation patterns, respectively (cf. Carpenter et al., 2001). A similar analysis was performed for the second pair of antagonistic ankle muscles, i.e., ED and GS muscles.

2.3.3. Coupling between COP and EMG

The coupling between COP positions and EMG activity was examined across and within trials. With regard to the former, Pearson correlation coefficients were calculated between mean AP COP positions and mean EMG activity of the five upper and lower-leg muscles (averaged over left and right side). This relationship can be used to identify muscles that contribute most to changes in forward or backward across-trial lean (cf. Carpenter et al., 2001). With regard to the latter, the within-trial co-evolution of AP COP position and EMG activity envelopes of each muscle was examined via cross-correlation, for the left and right leg separately (cf. Borg et al., 2007; Gatev et al., 1999; Schieppati et al., 1994). To this end, EMG time series were first downsampled by a factor 20 to match the number of data points to that of the COP time series. The value of the maximum (positive or negative) correlation between both signals was determined, as well as the corresponding time shift. A range of positive and negative time shifts was adopted (±100 samples) with a positive time shift corresponding to EMG preceding the COP signal. Hence, maximum correlations in the positive time-shift region imply that EMG "drives" the COP (cf. Borg et al., 2007; Gatev et al., 1999).

2.3.4. Statistics

The five posturographic measures were averaged over the four repetitions of each condition and entered into a one-way repeated measures analysis of variance (ANOVA) with condition (baseline, cognitive dual task, motor dual task, and height) as within-subject factor. EMG outcome measures were also averaged over repetitions. Side (left or right leg) was included as a within-subject factor in the ANOVAs, which were conducted separately for each muscle pair in the case of mean EMG activity. Fisher's z-transformed correlation values and time shifts corresponding to the within-trial coupling of EMG activity and COP position were also entered in a side (left and right leg) by condition (baseline, cognitive dual task, motor dual task, and height) repeated measures ANOVA. Significant effects were further explored using paired-samples t-tests. We adopted a p-value of .05 for all analyses. Effect sizes (ES) of main and interaction effects were expressed as partial eta squared.

3. Results

Fig. 1 shows COP traces and EMG traces of m. gastrocnemius and m. tibialis anterior of a representative participant, during a trial in the baseline condition (panels A and B) and the height condition (panels C and D). The figure suggests the following effects (which are also corroborated by the statistical analyses): first, the overall position of COP during the height condition is somewhat lower (i.e., closer to the center of the force plate) than during the baseline condition, which is suggestive of a backward lean away from the edge. Second, the height condition is characterized by elevated TA activity and decreased GS activity, relative to baseline. Third, there is a marked

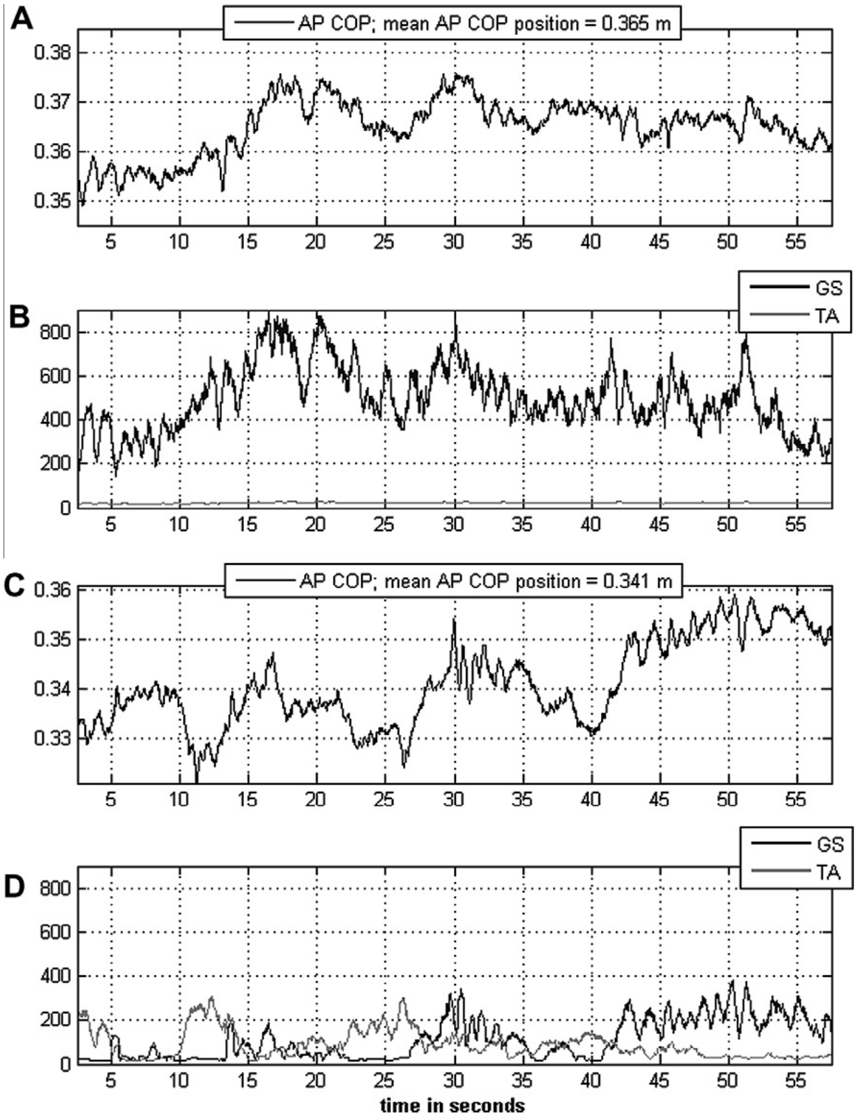

Fig. 1. Traces of the COP in the AP direction (COP AP) and traces of m. gastrocnemius (GS) and m. tibialis anterior (TA) EMG activity of a representative participant during a trial in the baseline condition (panel A: COP activity; panel B: EMG activity) and the height condition (panel C: COP activity; panel D: EMG activity). COP displacements are shown in m.

similarity between the waveforms of the COP and GS in both conditions, albeit with a small time shift between the two signals, suggesting that m. gastrocnemius is largely responsible for subsequent changes in COP activity.

Table 1
F-ratios, *p*-values and effect sizes (*ES*, using partial eta squared) for main effects of condition for each posturographic and EMG outcome measure.

	$F(3, 51)$	p	*ES*
Posturographic measures			
Mean position	3.192	<.05	.16
Sway variability	8.060	<.001	.32
Mean power frequency	5.175	<.05	.23
95% power frequency	3.776	<.05	.18
Sample entropy	10.47	<.001	.38
EMG measures			
Mean RF EMG activity	3.437	<.05	.17
Mean VAS EMG activity	2.487	.071	.13
Mean TA EMG activity	4.768	<.01	.22
Mean GS EMG activity	3.792	<.05	.18
Mean ED EMG activity	2.496	.070	.13
TA/GS ratio	6.402	<.01	.27
TA-GS cross-correlation	0.397	*N.S.*	.02
ED-GS cross-correlation	0.551	*N.S.*	.03
AP-COP – GS time shift	5.083	<.01	.23

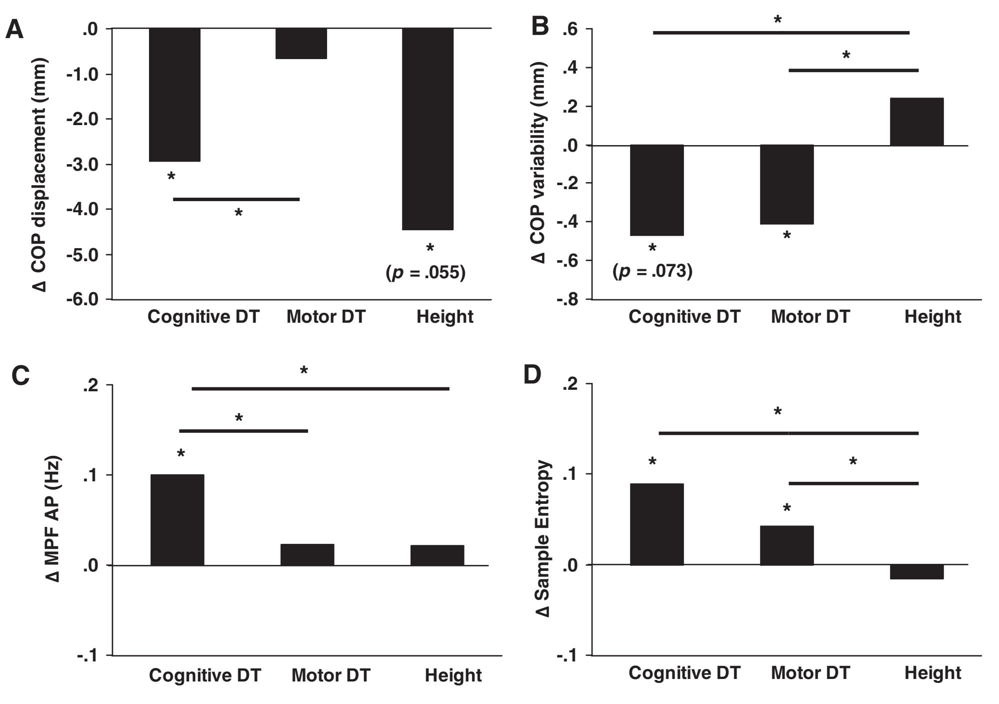

Fig. 2. Change in posturographic values relative to baseline for (A) mean COP position, (B) COP variability, (C) mean power frequency (MPF), and (D) sample entropy, separately for the cognitive dual-task (Cognitive DT), motor dual-task (Motor DT), and height conditions. Asterisks either denote a significant difference relative to baseline, or a significant difference between the conditions.

3.1. Posturography

Significant main effects of condition were observed for all posturographic measures (see Table 1 for an overview). Fig. 2 shows condition effects relative to baseline. Post hoc comparisons are described below.

3.1.1. Mean AP COP position

Participants exhibited a backward lean compared to baseline in the cognitive dual-task and height conditions, although the latter was only marginally significant, $t(17) = 2.963$, $p < .01$ and $t(17) = 2.056$, $p = .055$, respectively. In addition, mean AP COP position differed significantly between cognitive and motor dual-task conditions, $t(17) = 2.160$, $p < .005$. Change scores are shown in Fig. 2A.

3.1.2. Variability of AP COP

The average *SD* of AP COP in the baseline condition was 3.9 mm. The *SD* was significantly lower in the motor dual-task condition than baseline $t(17) = 2.900$, $p < .01$, and marginally significantly lower in the cognitive dual-task condition than baseline, $t(17) = 1.909$, $p = .073$. In addition, the *SD* was significantly lower in cognitive and motor dual-task conditions than the height condition, $t(17) = 3.478$, $p < .01$ and $t(17) = 2.507$, $p < .05$, respectively (see Fig. 2B).

3.1.3. Mean power frequency and F95

The average MPF of AP COP fluctuations in the baseline condition was 0.51 Hz. MPF of the cognitive dual-task condition was significantly higher than baseline, $t(17) = 4.200$, $p < .001$, motor dual-task, $t(17) = 2.435$, $p < .05$, and height, $t(17) = 2.247$, $p < .05$, conditions (see Fig. 2C). F95 was significantly higher in the cognitive dual-task condition (1.76 Hz) than in the baseline condition (1.44 Hz), $t(17) = 2.968$, $p < .01$), and marginally higher than in the other two conditions ($p = .065$ in both cases).

3.1.4. Sample entropy

The average value of sample entropy in the baseline condition was 0.86. Cognitive and motor dual-task conditions resulted in significantly higher sample entropy values than baseline, $t(17) = 4.411$, $p < .001$, and $t(17) = 2.159$, $p < .05$, respectively, and height conditions, $t(17) = 4.699$, $p < .001$, and $t(17) = 2.610$, $p < .05$, respectively) (see Fig. 2D).

3.2. EMG

3.2.1. Mean EMG activity

For none of the muscles significant main or interaction effects involving side were observed. Significant condition effects were observed for mean EMG activity of RF, TA, and GS muscle pairs (see Table 1

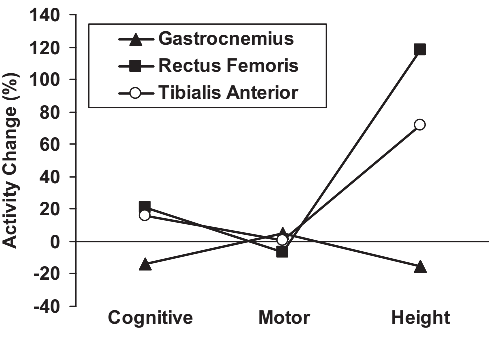

Fig. 3. Percentage-wise activity change in muscular activity relative to baseline, separately for the cognitive dual-task, motor dual-task, and height conditions.

for statistics). Post hoc analyses showed that RF and TA mean EMG activity was significantly higher for the height condition than the baseline condition, $t(17) = 2.111$, $p < .05$ and $t(17) = 2.509$, $p < .05$, respectively. Mean TA EMG activity was also significantly increased in the height condition compared to the motor dual-task condition, $t(17) = 2.389$, $p < .05$. The main effect of mean GS EMG activity was due to a significant decrease in activity during cognitive dual-task and height conditions relative to the baseline condition, $t(17) = 2.205$, $p < .05$ and $t(17) = 2.431$, $p < .05$, respectively, and the motor dual-task condition, $t(17) = 2.305$, $p < .05$ and $t(17) = 2.430$, $p < .05$, respectively. For ED and VAS only a tendency for elevated activity during the height condition was observed (p-values .070 and .071, respectively, see Table 1). Fig. 3 presents percentagewise changes in EMG activity for RF, TA, and GS muscles relative to baseline.

3.2.2. TA/GS ratio

A significant main effect of condition was observed for ankle antagonistic muscle activity ratio (Table 1). The activity ratios were significantly higher for the cognitive dual-task and height conditions than for the baseline condition, $t(17) = 2.571$, $p < .05$ and $t(17) = 2.965$, $p < .01$, respectively, and the motor dual-task condition, $t(17) = 2.611$, $p < .05$ and $t(17) = 2.968$, $p < .01$, respectively (see also Fig. 3).

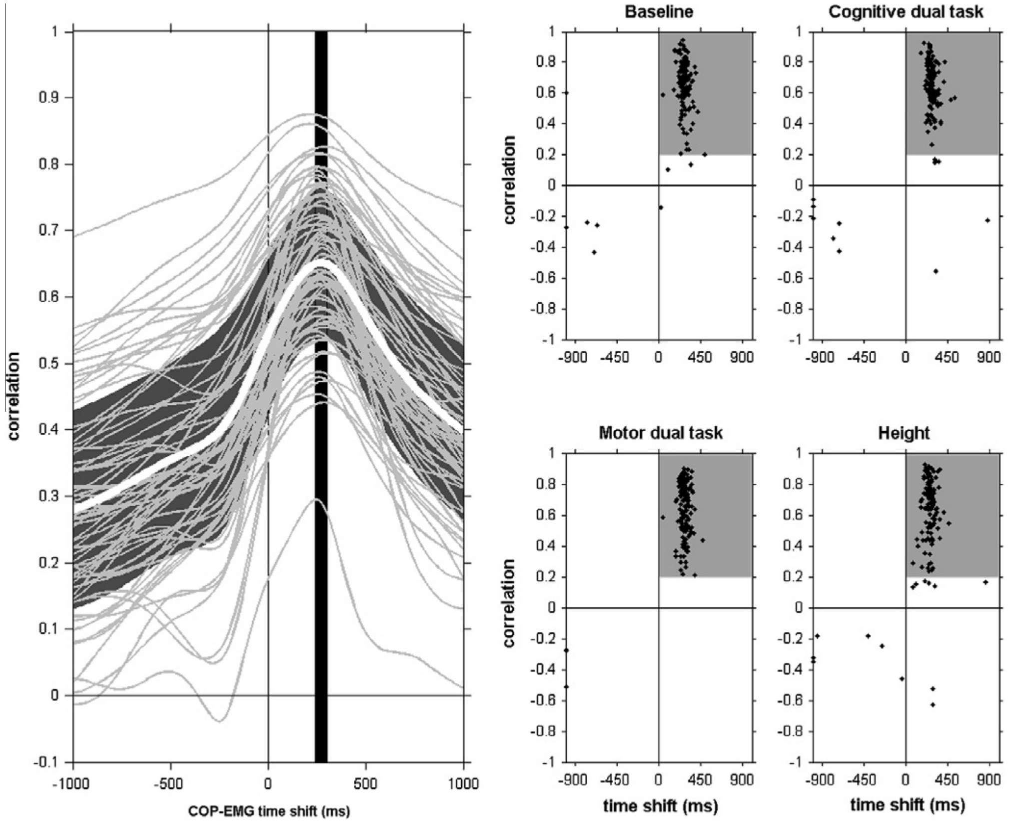

Fig. 4. Correlation between GS activity and COP AP fluctuations. Left panel: each line represents an individual correlation function, averaged over leg and trial repetition. The thick white line represents the grand averaged correlation function; the shaded area corresponds to the ±1-*SD* interval; the vertical thick black line represents the grand averaged time-shift values (±1-*SD*). Right panels: peak correlation by time-shift values. Each dot represents a single trial. Valid observations (as defined in the text) fall within the shaded areas. Note that the correlation functions shown on the left are based on valid observations only.

3.2.3. Cross-correlation between antagonistic ankle muscle activity

No significant main or interaction effects of condition and side were observed for the cross-correlation between TA and GS and ED and GS envelope curves (all *F*'s < 0.9). On average, TA and ED activity were positively correlated with GS activity ($r = .262$; $SE = .043$ and $r = .273$; $SE = .044$), suggesting moderate levels of co-contraction for all conditions (cf. Carpenter et al., 2001).

3.3. Coupling between COP and EMG

3.3.1. Correlation between mean AP COP position and mean EMG activity

The analysis of the across-trials coupling revealed significant correlations between mean AP COP position and mean EMG activity of RF ($r = -.344$) and VAS ($r = -.218$) muscles, indicating that EMG activity of these quadriceps femoris muscles increased with backward lean. Mean EMG activity of GS, TA, and ED muscles was not significantly correlated with mean AP COP position.

3.3.2. Cross-correlation between AP COP and EMG envelope time series

Preliminary analyses of within-trial co-evolution revealed that only GS EMG activity was consistently related to COP displacement. Hence, the presentation of the results is limited to the GS muscle. Fig. 4 (left panel) depicts mean and individual cross-correlation functions between the two signals, showing that GS EMG was strongly coupled to AP COP displacement. Peak correlations were found at time shifts of about 250–300 ms, indicating that GS activity "drives" the COP (cf. Borg et al., 2007; Gatev et al., 1999).

Correlation by time-shift distributions are depicted for each condition in Fig. 4 (right panels) (each data point represents a separate trial for each leg). Based on inspection of these distributions, only data points with a positive time shift and with a peak correlation greater than .20 were included for further statistical analysis (i.e., shaded area), excluding 39 out of 576 observations (6.8%). The resultant peak correlations and time shifts were averaged per condition and side. Note that the condition by side repeated measures ANOVA was not jeopardized because this treatment of the data did not result in missing values. No significant main or interaction effects of side and condition were observed for the peak correlations: *r* was .64 on average. In contrast, a significant main effect of condition was observed for the associated time shifts; time shifts were significantly lower in the height condition (257 ms) than in cognitive (278 ms; $t(17) = 3.715$, $p < .01$) and motor (278 ms; $t(17) = 3.126$, $p < .05$) dual-task conditions, whereas the difference between height and baseline conditions (257 and 274 ms, respectively) was only marginally significant ($t(17) = 1.980$, $p = .064$).

4. Discussion

The present experiment was conducted to examine whether cognitive and affective states have similar or differential effects on balance regulation in general and on postural stiffening in particular. The focus on the latter aspect was motivated from findings in the literature that both diversion of attention (McNevin & Wulf, 2002; Vuillerme & Vincent, 2006) and experimentally induced or pathological postural anxiety (e.g., Carpenter et al., 1999, 2001; Krafczyk et al., 1999) lead to increased COP MPF and reduced COP amplitudes. These characteristics were interpreted to reflect an increase in ankle stiffness for both cognitive and affective manipulations. However, this suggestion was never tested using direct neuromuscular estimates of postural stiffness across various psychological manipulations. In the present study we therefore compared the effects of cognitive and affective interventions on the COP and EMG time series.

In line with previous research, we found reduced COP amplitudes and increased sway frequencies (MPF and F95) when attention was experimentally diverted from postural control (i.e., holding a cup filled with liquid or performing mental arithmetic) relative to baseline, although overall the results were stronger for the latter dual-tasking condition. Similar amplitude and MPF results were expected for the height condition relative to baseline. However, no significant differences were observed between height and baseline conditions. In other words, we found no evidence for "immobility" and "rigidity" in the posturogram (cf. Azevedo et al., 2005; Facchinetti et al., 2006) when standing at the edge of a cliff compared to baseline. A possible reason for this null effect might be that only moderate levels of anxiety were induced, resulting in minimal postural adaptations. For example, in the study of Adkin, Campbell, Chua, and Carpenter (2008) the platform was raised to 3.2 m, which arguably constitutes a greater postural threat than our 1 m setup. In addition, we did not score subjective anxiety ratings, so that we do not know how much anxiety was actually experienced. An alternative reason for our null effect is that it could be that participants were more variable in their reaction to the height manipulation compared to the secondary tasks. This interpretation is supported, for example, by the borderline significance in backward lean, despite the greatest absolute values. Another possibility could be that our baseline condition was somehow not adequately controlled for in terms of attentional investment (see also Fraizer & Mitra, 2008).

Second, we found that the cognitive and motor manipulations had marked effects on the regularity of COP fluctuations, which – as argued in the Introduction – is related to attentional involvement in balance. Sample entropy was significantly higher in the postural and non-postural secondary task conditions than in the baseline condition which, according to the proposed relation between COP regularity and the amount of attention invested in posture (Donker et al., 2007; Donker et al., 2008; Roerdink et al., 2006; Roerdink et al., 2009; Stins, Michielsen, Roerdink, & Beek, 2009), indicates that attention was successfully shifted somewhat from controlling posture to performing the secondary task. We had also expected that COP time series would be more regular for standing at the edge of a cliff than in the baseline condition, as suggestive of greater attentional involvement, mediated by postural anxiety, but no such effect was found. However, the direct comparison between the secondary task conditions and the height condition, with significantly lower sample entropy values in the latter condition, suggests different postural control processes for affective and cognitive manipulations that appear to be related to attentional investment. This interpretation is in line with the study of Quant, Adkin, Staines, Maki, and McIlroy (2004), who studied perturbation-evoked cortical potentials during posture, quantifying attentional changes in supraspinal processing of task-specific afferent sensory information via the so-called N1 response (see also Dietz, Quintern, Berger, & Schenck, 1985). The magnitude of this response, which is evoked by unpredictable postural perturbations and which occurs approximately 100–200 ms after perturbation onset (Dietz et al., 1985), represents the relative degree of cerebral engagement. Quant et al. (2004) found that the N1 response amplitudes were attenuated when attention was diverted from postural control, thereby supporting the aforementioned sample entropy interpretation in terms of attentional investments in posture in secondary task conditions.

We expected differences in the neuromuscular regulation of balance between affective and cognitive manipulations. First of all, we found increased muscular activity in RF and TA muscles and decreased activity in the GS muscle for the height condition (Fig. 3), and consequently an increased TA/GS ratio. These results are consistent with those of previous studies (Brown et al., 2006; Carpenter et al., 2001). However, they should probably not be interpreted as signatures of increased stiffness because under those conditions a concomitant protective backward lean was present that correlated significantly across trials with quadriceps activity. Second, we assessed co-contraction by cross-correlating TA and ED activity with GS activity (cf. Carpenter et al., 2001) and we found moderate positive correlations that did not differ between conditions. Hence, ankle stiffness in terms of the level of co-activation of antagonistic lower-leg muscles was comparable for affective and cognitive manipulations. Third, the within-trial correlation analysis revealed a substantial positive time shift of about 270 ms between the GS EMG activity and AP COP displacements. This finding is in agreement with the results of Schieppati et al. (1994; see also Borg et al., 2007; Gatev et al., 1999), who found that soleus muscle activity consistently preceded COP displacement, although in that study the relatively low sampling frequency precluded analysis of the time lags over conditions. Our cross-correlation analysis revealed that the time lag between the signals was task-dependent as it was significantly smaller in the height condition than in the other three conditions. This result may be indicative of a somewhat tighter anticipatory postural control when standing at the edge of the cliff. Therefore, on an electromyographic level of analysis, postural control in an anxiety-provoking context seems to be characterized by close monitoring and controlling of the position of the own body. This is in line with a recent study of Huffman et al. (2009), where participants reported more conscious control and a greater concern about their own posture when standing at the edge of a high cliff. In a similar vein, Adkin et al. (2008) found that the abovementioned N1 response amplitudes intensified when standing at the edge of a cliff. Taken together, these interpretations are in line with our hypothesis of a close monitoring of the body position of the actor under postural threat, putatively resulting in a "tighter" anticipatory postural control.

In conclusion, we demonstrated that postural control was influenced within a participant by affective and cognitive interventions in terms of attentional investments and tightness of neuromuscular control. With respect to standing at the edge of a cliff, we found some evidence of stiffening, manifested by a tighter anticipatory control, accompanied by evidence of greater attentional involvement in the regulation of balance. With respect to posture-cognition dual-tasking, we found no support for the interpretation of McNevin and Wulf (2002) and Vuillerme and Vincent (2006) that increased ankle stiffness accounts for the utilized efficient automatic postural control. In fact, ankle stiffness can be increased by an increased co-activation of lower-leg muscles or by a tighter neuromuscular control (and of course, by a combination of both components). Given the present set of results, the interpretation that increased ankle stiffness accounts for the utilized efficient automatic postural control seems unlikely in view of the fact that increased co-activation is energetically inefficient (Morasso & Sanguineti, 2002) and that a tighter anticipatory control is attention-demanding. Increased stiffness regulation thus seems not to occur when attention is experimentally withdrawn from controlling posture. However, increased stiffness shows up in numerous other instances, such as when postural control is impaired (Melzer, Benjuya, & Kaplanski, 2001; Morasso & Sanguineti, 2002), threatened (Carpenter et al., 1999; Carpenter et al., 2001), or when individuals are presented with highly salient emotion-provoking images (Azevedo et al., 2005; Facchinetti et al., 2006), but at an energetic and attentional cost.

References

Adkin, A. L., Campbell, A. D., Chua, R., & Carpenter, M. G. (2008). The influence of postural threat on the cortical response to unpredictable and predictable postural perturbations. *Neuroscience Letters, 435*, 120–125.

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin, 58*, 135–139.

Azevedo, T. M., Volchan, E., Imbiriba, L. A., Rodrigues, E. C., Oliveira, J. M., Oliveira, L. F., et al (2005). A freezing-like posture to pictures of mutilation. *Psychophysiology, 42*, 255–260.

Borg, F., Finell, M., Hakala, I., & Herrala, M. (2007). Analyzing gastrocnemius EMG-activity and sway data from quiet and perturbed standing. *Journal of Electromyography and Kinesiology, 17*, 622–634.

Brown, L. A., Polych, M. A., & Doan, J. B. (2006). The effect of anxiety on the regulation of upright standing among younger and older adults. *Gait and Posture, 24*, 397–405.

Carpenter, M. G., Frank, J. S., & Silcher, C. P. (1999). Surface height effects on postural control: Hypothesis for a stiffness strategy for stance. *Journal of Vestibular Research, 9*, 277–286.

Carpenter, M. G., Frank, J. S., Silcher, C. P., & Peysar, G. W. (2001). The influence of postural threat on the control of upright stance. *Experimental Brain Research, 138*, 210–218.

Cavanaugh, J. T., Guskiewicz, K. M., Giuliani, C., Marshall, S., Mercer, V. S., & Stergiou, N. (2006). Recovery of postural control after cerebral concussion: New insights using approximate entropy. *Journal of Athletic Training, 41*, 305–313.

Cavanaugh, J. T., Mercer, V. S., & Stergiou, N. (2007). Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: A methodological report. *Journal of NeuroEngineering and Rehabilitation, 4*, 42.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture, 14*, 110–116.

Dietz, V., Quintern, J., Berger, W., & Schenck, E. (1985). Cerebral potentials and leg muscle e.m.g. responses associated with stance perturbation. *Experimental Brain Research, 57*, 348–354.

Donker, S. F., Ledebt, A., Roerdink, M., Savelsbergh, G. J. P., & Beek, P. J. (2008). Children with cerebral palsy exhibit greater and more regular postural sway than typically developing children. *Experimental Brain Research, 184*, 363–370.

Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Experimental Brain Research, 181*, 1–11.

Facchinetti, L. D., Imbiriba, L. A., Azevedo, T. M., Vargas, C. D., & Volchan, E. (2006). Postural modulation induced by pictures depicting prosocial or dangerous contexts. *Neuroscience Letters, 410*, 52–56.

Fraizer, E. V., & Mitra, S. (2008). Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. *Gait and Posture, 27*, 271–279.

Gatev, P., Thomas, S., Kepple, T., & Hallett, M. (1999). Feedforward ankle strategy of balance during quiet stance in adults. *Journal of Physiology, 514.3*, 915–928.

Huffman, J. L., Horslen, B. C., Carpenter, M. G., & Adkin, A. L. (2009). Does increased postural threat lead to more conscious control of posture? *Gait and Posture, 30*, 528–532.

Hunter, M. C., & Hoffman, M. A. (2001). Postural control: Visual and cognitive manipulations. *Gait and Posture, 13*, 41–48.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69*, 294–305.

Krafczyk, S., Schlamp, V., Dieterich, M., Haberhauer, P., & Brandt, T. (1999). Increased body sway at 35–8 Hz in patients with phobic postural vertigo. *Neuroscience Letters, 259*, 149–152.

Lake, D. E., Richman, J. S., Griffin, M. P., & Moorman, J. R. (2002). Sample entropy analysis of neonatal heart rate variability. *The American Journal of Physiology – Regulatory, Integrative and Comparative Physiology, 283*, 789–797.
McNevin, N. H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science, 21*, 187–202.
Melzer, I., Benjuya, N., & Kaplanski, J. (2001). Age-related changes of postural control: Effect of cognitive tasks. *Gerontology, 47*, 189–194.
Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science, 22*, 253–270.
Morasso, P. G., & Sanguineti, V. (2002). Ankle muscle stiffness alone cannot stabilize balance during quiet standing. *Journal of Neurophysiology, 88*, 2157–2162.
Morasso, P. G., & Schieppati, M. (1999). Can muscle stiffness alone stabilize upright standing? *Journal of Neurophysiology, 82*, 1622–1626.
Quant, S., Adkin, A. L., Staines, W. R., Maki, B. E., & McIlroy, W. E. (2004). The effect of a concurrent cognitive task on cortical potentials evoked by unpredictable balance perturbations. *BMC Neuroscience, 5*, 8.
Richman, J. S., & Moorman, J. R. (2000). Physiological time-series analysis using approximate entropy and sample entropy. *The American Journal of Physiology – Heart and Circulatory Physiology, 278*, H2039–H2049.
Riley, M. A., Baker, A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin, 62*, 191–195.
Roerdink, M., Geurts, A. C. H., de Haart, M., & Beek, P. J. (2009). On the relative contribution of the paretic leg to the control of posture after stroke. *Neurorehabilitation and Neural Repair, 23*, 267–274.
Roerdink, M., de Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C., & Beek, P. J. (2006). Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. *Experimental Brain Research, 174*, 256–269.
Roerdink, M., Hlavackova, P., & Vuillerme, N. (2011). Center-of-pressure regularity as a marker for attentional investment in postural control: A comparison between sitting and standing postures. *Human Movement Science, 30*, 203–212.
Sasagawa, S., Ushiyama, J., Masani, K., Kouzaki, M., & Kanehisa, H. (2009). Balance control under different passive contributions of the ankle extensors: Quiet standing on inclined surfaces. *Experimental Brain Research, 196*, 537–544.
Schieppati, M., Hugon, M., Grasso, M., Nardone, A., & Galante, M. (1994). The limits of equilibrium in young and elderly normal subjects and in parkinsonians. *Electroencephalography and Clinical Neurophysiology, 93*, 286–298.
Schmid, M., Conforto, S., Lopez, L., & D'Alessio, T. (2007). Cognitive load affects postural control in children. *Experimental Brain Research, 179*, 375–385.
Schmit, J. M., Regis, D. I., & Riley, M. A. (2005). Dynamic patterns of postural sway in ballet dancers and track athletes. *Experimental Brain Research, 163*, 370–378.
Schmit, J. M., Riley, M. A., Dalvi, A., Sahay, A., Shear, P. K., Shockley, K. D., et al (2006). Deterministic center of pressure patterns characterize postural instability in Parkinson's disease. *Experimental Brain Research, 168*, 357–367.
Stins, J. F., Ledebt, A., Emck, C., van Dokkum, E. H., & Beek, P. J. (2009). Patterns of postural sway in high anxious children. *Behavioral and Brain Functions, 5*, 42.
Stins, J. F., Michielsen, M. E., Roerdink, M., & Beek, P. J. (2009). Sway regularity reflects attentional involvement in postural control: Effects of expertise, vision and cognition. *Gait and Posture, 30*, 106–109.
Teasdale, N., Bard, C., LaRue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research, 19*, 1–13.
Vieira, T. M. M., Oliveira, L. F., & Nadal, J. (2009). Estimation procedures affect the center of pressure frequency analysis. *Brazilian Journal of Medical and Biological Research, 42*, 665–673.
Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological Research, 71*, 192–200.
Vuillerme, N., & Vincent, H. (2006). How performing a mental arithmetic task modify the regulation of foot pressure displacements during bipedal quiet standing. *Experimental Brain Research, 169*, 130–134.
Winter, D. A., Patla, A. E., Prince, F., Ishac, M., & Gielo-Perczak, K. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology, 80*, 1211–1221.
Wulf, G., McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A*, 1143–1154.