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Different neuromuscular control mechanisms regulate static and dynamic balance: A center-of-pressure analysis in young adults

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ABSTRACT

The analysis of the center of pressure (CoP) trajectory, derived from force platforms, is a widely accepted measure to investigate postural balance control. The CoP trajectory could be analyzed as a physiological time-series through a general stochastic modeling framework (i.e., Stabilogram Diffusion Analysis (SDA)). Critical point divides short-term from long-term regions and diffusion coefficients reflect the level of stochastic activity of the CoP. Sample Entropy (SampEn) allows quantifying the CoP complexity in terms of regularity. Thus, this study aimed to understand whether SDA and SampEn could discriminate the neuromuscular control mechanisms underpinning static and dynamic postural tasks. Static balance control and its relationship with dynamic balance control were investigated through the CoP velocity (Mean Velocity) and the area of the 95th percentile ellipse (Area95). Balance was assessed in 15 subjects (age: 23.13 ± 0.99 years; M = 9) over a force platform under two conditions: static (ST) and dynamic, both in anterior-posterior (DAP) and medio-lateral (DML) directions. During the DAP and DML, subjects stood on an unstable board positioned over a force platform. Short-term SDA diffusion coefficients and critical points were lower in ST than in DAP and DML ($p < 0.05$). SampEn values resulted greater in ST than in DAP and DML ($p < 0.001$). As expected, lower values of Area95 ($p < 0.001$) and Mean Velocity ($p < 0.001$) were detected in the easiest condition, the ST, compared to DAP and DML. No significant correlations between static and dynamic balance performances were detected. Moreover, differences in the diffusion coefficients were detected comparing DAP and DML ($p < 0.05$). In the anterior-posterior direction, the critical point occurred at relatively small intervals in DML compared to DAP ($p < 0.001$) and ST ($p < 0.001$). In the medio-lateral direction, the critical point differed only between DAP and DML ($p < 0.05$). Overall, SDA analysis pointed out a less tightly regulated neuromuscular control system in the dynamic tasks, with closed-loop corrective feedback mechanisms called into play at different time intervals in the three conditions. SampEn results reflected more attention and, thus, less automatic control mechanisms in the dynamic conditions, particularly in the medio-lateral task. The different neuromuscular control mechanisms that emerged in the static and dynamic balance tasks encourage using both static and dynamic tests for a more comprehensive balance performance assessment.

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1. Introduction

Posture and balance control are essential to safely achieve daily living activities and motor tasks in general (Paillard, 2017). Postural regulation could never be considered totally automatic (Jacobs & Horak, 2007; Paillard, 2017). Traditionally, literature differentiates between static and dynamic balance conditions. Static balance is referred to quiet standing under unperturbed environments in which the subject is mainly unaware of the continuous automatic adjustments of tonic muscles (Macpherson & Horak, 2013). Conversely, when dynamic tasks are performed (i.e., base of support displacements or external mechanical stimuli), the continuous changes in the surrounding environment and acting forces lead to a higher involvement of the cognitive process to achieve goal-directed movements (Takakusaki et al., 2017). Both automatic and cognitive processes of postural control are based on somatosensory, visual, and vestibular information that take action in different areas of the central nervous system, depending on the level of automatization of the motor process (Takakusaki et al., 2017).

Since several cognitive, sensory, and motor control mechanisms are mirrored in the CoP trajectory, analyzing the CoP behavior in dynamic conditions should deserve attention. Indeed, computational methods such as Stabilogram Diffusion Analysis (SDA) and Sample Entropy (SampEn) allow for investigating the amount of automatic or voluntary regulation invested in postural balance tasks.

The SDA aims to quantify the stochastic behavior of the CoP trajectory (Collins & De Luca, 1993; Doyle et al., 2008). Critical point coordinates quantify the spatial and temporal characteristics of switching from short-term to long-term regions. The short-term region is characterized by open-loop control schemes, while long-term region by closed-loop feedback mechanisms. Diffusion coefficients reflect the level of stochastic activity of the CoP (Collins & De Luca, 1993). Over the last 25 years, SDA has been proposed as a reliable method to explore better the control mechanisms of static balance in several fields of application, such as Parkinson's disease (Mitchell et al., 1995), fallers (Melzer et al., 2010), older adults (Laughton et al., 2003), and even ultramarathon runners (Marcolin et al., 2016). Remarkably, SDA has never been applied to the CoP trajectory during dynamic balance tasks.

Differently, SampEn allows quantifying the complexity of a time series in terms of regularity (Richman & Moorman, 2000), and it has already been applied to CoP variability (Rizzato et al., 2018; Yamagata et al., 2017). A loss in the complexity of physiological and behavioral systems occurs when their structural components are reduced. The smaller the SampEn value, the lower the complexity or greater the regularity of a time series. In particular, CoP regularity was found to be positively related to the amount of attention invested in postural control (Donker et al., 2007; Roerdink et al., 2011). The degree of cognitive investment (i.e., voluntariness) is greater when the attentional demand is higher. For instance, Ramdani and colleagues showed that lower SampEn values were significantly associated with eyes-closed (i.e., higher attentional demand) than eyes-opened conditions in quiet standing (Ramdani et al., 2009). To the best of our knowledge, only one study was conducted on dynamic postural tasks (i.e., reaching sine-wave targets), showing that the CoP complexity in older adults was higher than in young individuals (Ko & Newell, 2016).

The displacement of the center of pressure (CoP), derived from force platforms, is a widely accepted measure to investigate static balance control. The amplitude and the velocity of the CoP displacement are the most-employed parameters to quantify the postural performance objectively. However, although global CoP parameters have been demonstrated to change in static balance assessments with aging (Pajala et al., 2008), fatiguing physical exercise (Marcolin et al., 2019; Nardone et al., 1997), surrounding environment (Marinho-Buzelli et al., 2017), and coexistent pathologies (Błaszczyk, 2016), CoP behavior over dynamic balance control has not been investigated with the same assiduity. Thus, dynamic balance assessment mainly occurred through functional tests lacking to consider the CoP behavior as in the static balance assessment. For instance, Granacher and colleagues (Granacher et al., 2011) found a weak correlation between stride-to-stride gait variability and CoP displacement in static standing. Conversely, Muehlbauer and colleagues showed no correlations between quiet bipedal stance and proactive (i.e., Timed Up & Go test and Functional Reach test) and reactive (i.e., perturbed standing) balance (Muehlbauer et al., 2012). Similarly, no performance correlations were detected between global CoP parameters in static upright standing and a dynamic balance index derived from an oscillating computerized platform (Rizzato et al., 2021). To the best of our knowledge, only one study (Sell, 2012) examined the relationship between static (i.e., single-leg stance) and dynamic (i.e., single-leg landing) postural stability over a force platform. However, though no significant correlations were found, the dynamic test proposed by the authors did not properly fall within the above definition of dynamic balance (Paillard, 2019; Petró et al., 2017).

Given the importance of dynamic postural control and the still-debated relationship between static and dynamic balance performance (Granacher et al., 2011; Muehlbauer et al., 2012; Rizzato et al., 2021), we first aimed to understand whether the SDA and SampEn could discriminate the neuromuscular control mechanisms underpinning static and dynamic postural tasks. Then, based on the global CoP outputs derived from a force platform, we investigated the relationship between static and dynamic balance performance. We hypothesized that SDA and SampEn revealed useful tools to highlight the levels of voluntariness and attention in different balance tasks. Moreover, we expected no relationship between static and dynamic balance performances.

2. Methods

2.1. Subjects

Fifteen healthy subjects volunteered for the study (M = 9, F = 6; mean ± SD: 23.13 ± 0.99 years; 71.67 ± 12.37 kg; 1.77 ± 0.082 m). Subjects with no history of (i) orthopedic injuries in the last year, (ii) neurological diseases, and (iii) sight, hearing, or vestibular disorders were eligible for inclusion.

2.2. Experimental design

The experimental protocol received approval from the Human Ethical Committee of the Department of Biomedical Science of the University of Padova (n° HEC-DSB/08–18) and adhered to the principles of the Declaration of Helsinki. Subjects were informed about the methods and aims of the study, gave their written informed consent, and were free to renounce the study at any stage. The week before testing, researchers organized a familiarization session explaining the scheduled program to guarantee the correct execution.

We outlined a cross-sectional design in which postural balance control was tested under two conditions: static and dynamic, both in anterior-posterior (DAP) and medio-lateral (DML) directions (Fig. 1). Static postural balance (ST) was assessed on a force platform (AMTI BP400600, Watertown, MA, USA), where subjects had to hold the same static upright posture. In particular, they were instructed to stand with extended legs and place their arms naturally along their sides. The feet position on the force platform was standardized using a V-shaped frame, keeping a 7-cm distance between the heels and a wide-open position of the tips of 30° between them, according to the international society of posturography recommendations (Kapteyn et al., 1983).

During the dynamic tasks (i.e., DAP and DML conditions), subjects had to stand with parallel feet on an unstable square board (length: 50 cm; width: 50 cm; height: 8.5 cm), which rotated along a single axis. A marine plywood semicylinder allows the board to rotate 16 deg. in both directions. Subjects were asked to maintain the board parallel to the ground as much as possible without moving the feet from their original position. Subjects kept their hands on hips for the whole test duration to avoid counterbalance actions. The unstable board was positioned over the force platform to record the CoP trajectory. Trials were performed in both DAP and DML conditions, separately. During the DAP condition, the subjects' sagittal axis was parallel to the rotational axis of the unstable board, while, during the DML condition, the subjects' sagittal axis was perpendicular to the rotational axis. During static and dynamic tasks, subjects were barefooted and gazed at a thin green line vertically placed in front of them on a white wall at 80 cm. Overall, subjects performed ten trials in ST, DAP, and DML conditions. The static test, that required the subject being quiet and relaxed, was always performed before the dynamic conditions. Indeed, static balance performance could be altered immediately after physical exercise (Zemkovà & Hamar, 2014). Conversely, the dynamic tests (i.e., DAP and DML) were randomly administered to subjects. The duration was set to 30 s for all trials, according to Scoppa and colleagues' guidelines for stabilometric tests over force platforms (Scoppa et al., 2013). The rest between trials was set to 60 s.

2.3. Data analysis

The CoP trajectory was calculated through the ground reaction forces recorded from the computerized force platform at a sampling frequency of 100 Hz. According to the manufacturer's guidelines, the platform was zeroed before recording each trial. The platform employed in the study has an average CoP accuracy of <0.2 mm, crosstalk values typically ±0.05% of the applied load, and a measurement accuracy typically ±0.1% of the applied load (with a minimum applied load of 22.6 kg).

2.4. Stabilogram diffusion analysis

The SDA was developed by Collins and De Luca (Collins & De Luca, 1993). The mean square displacement $<\Delta r^2>$, as a function of time interval Δt (spanning m data intervals) for a CoP trajectory of N data point was calculated through the following equation.

$$<\Delta r^2>_{\Delta t} = \frac{\sum_{i=l}^{N-m} (\Delta r_i)^2}{(N-m)}$$

The same equation was applied for $<\Delta y^2>$ and $<\Delta x^2>$. The incremental values of Δt ranged from 0.01 to 10 s with a step of 0.01 s. The planar stabilogram diffusion plot is represented by the mean square displacements over Δt (Fig. 2). The CP was defined by the intersection of the lines fitted to the two regions (i.e., short-term region and long-term region) of the plot considering the x axis (Δt_{xCP}, $<\Delta x^2>_{CP}$), the y axis (Δt_{yCP}, $<\Delta y^2>_{CP}$), and the combination of the two (Δt_{rCP}, $<\Delta r^2>_{CP}$). Then, the diffusion coefficients were computed from the slopes of the lines fitted to the short-term and long-term regions along the x axis (*Dfxs* and *Dfxl,* respectively), the y

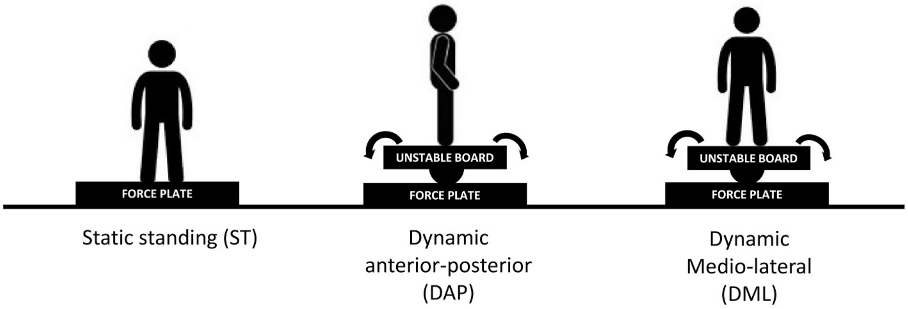

Fig. 1. Graphical representation of the experimental protocol.

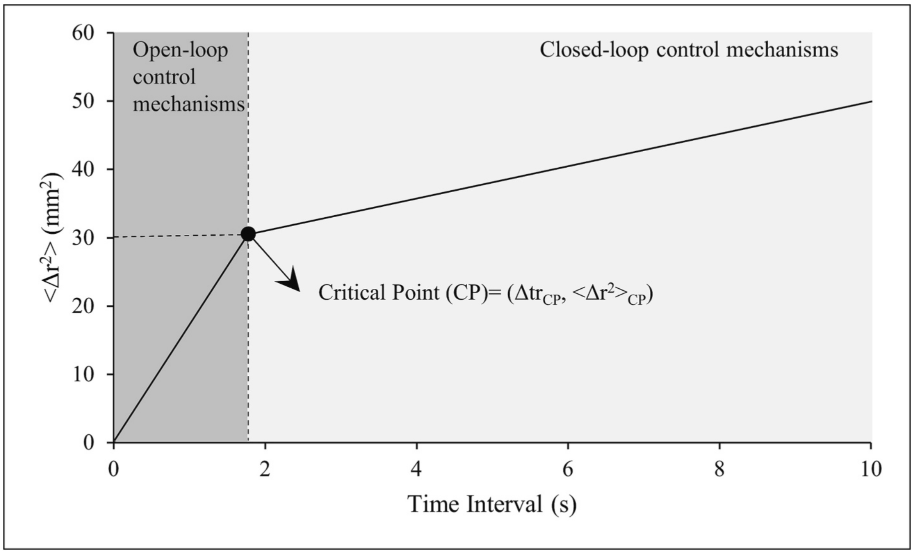

Fig. 2. Typical resultant planar stabilogram diffusion plot represented by the mean square displacements ($<\Delta r^2>_{CP}$ vs Δt_{rCP}) from a CoP time series.

axis (*Dfys* and *Dfyl,* respectively), and the combination of the two (*Dfxr*^{2} and *Dfyr*^{2}*,* respectively). The analysis tool was developed with MATLAB R2016b (The MathWorks, Inc., MA, USA).

2.5. Sample entropy

The SampEn was calculated in the frontal and sagittal planes (SampEn X and SampEn Y, respectively) for each experimental condition: ST, DAP, and DML. In the present study, the SampEn computation followed the procedure of Ramdani and colleagues (Ramdani et al., 2009) already presented elsewhere (Rizzato et al., 2018) and was calculated for each CoP time series as follows:

$$\mathrm{SampEn}(m,r,N) = -lnCP(m,r)$$

Given an *N* time points, SampEn is determined as the negative of the natural logarithm of conditional probability, which is a sequence of data points repeated within a tolerance *r* for a window length *m* (Pincus et al., 1991). In the present study, the proper values of *m* and *r* for the SampEn computation followed the procedure presented elsewhere (Ramdani et al., 2009). Hence, we used $m = 3$ for the error curve, and $r = 0.35$. The SampEn analysis tool was developed with MATLAB R2016b (The MathWorks, Inc., MA, USA).

2.6. Global CoP parameters

The CoP signal was analyzed with the software Balance Clinic 1.4.2 (AMTI, Watertown, MA, USA). We calculated the following global CoP parameters for all the experimental conditions: Area95 (the area of the 95th percentile ellipse measured in cm^2) and Mean Velocity (the path length per time unit, i.e., the average velocity in cm/s). In each condition, global CoP parameters were averaged among the ten trials.

2.7. Statistical analysis

An a priori power analysis (G*Power 3.1.9.2 software) showed that a sample size of 15 participants and a moderate effect size of 0.35 would provide a statistical power of 0.8. The mean value among the ten trials performed by each subject was considered for statistical analysis. The D'Agostino-Pearson test was employed to check the data normality distribution. A one-way ANOVA was employed to assess differences in SDA and SampEn parameters among ST, DAP, and DML conditions. The effect size of the different variables was measured through the partial eta squared (η_p^2). The same statistical test was employed to assess differences in the global CoP parameters among ST, DAP, and DML conditions. In case of statistically significant differences, we performed the Bonferroni post hoc analysis. Pearson's correlation was used to correlate Area95 and Mean Velocity between static and dynamic conditions. The strength of the correlation was interpreted as follows: weak ($r \leq 0.35$), moderate ($0.36 < r < 0.67$), high ($0.68 < r < 0.90$), and very high ($r \geq 0.90$), (Taylor, 1990). Statistical analysis was performed using the software package JASP for Windows (Version 0.11.1, Amsterdam), and results were presented as mean ± standard deviation (SD). The significant level for differences was set to $p < 0.05$.

3. Results

3.1. Stabilogram diffusion analysis

Results of the SDA parameters in the ST, DAP, and DML conditions are reported in Table 1 and Table 2. The one-way ANOVA for repeated measures showed significant differences for the $Dfsr^2$ ($p < 0.001$; $\eta_p^2 = 0.631$), $Dflr^2$ ($p < 0.001$; $\eta_p^2 = 0.638$), *Dfxs* ($p < 0.01$; $\eta_p^2 = 0.465$), *Dfxl* ($p < 0.05$; $\eta_p^2 = 0.351$), *Dfys* ($p < 0.001$; $\eta_p^2 = 0.863$), and *Dfyl* ($p < 0.001$; $\eta_p^2 = 0.779$). Results of the Bonferroni post-hoc analysis are reported in Table 1. For what concern CP results, a graphical representation is given in Fig. 3. The one-way ANOVA for repeated measures showed significant differences for the Δt_{rCP} ($p < 0.05$; $\eta_p^2 = 0.128$), $<\Delta r^2>_{CP}$ ($p < 0.001$; $\eta_p^2 = 0.566$), Δt_{xCP} ($p < 0.01$; $\eta_p^2 = 0.282$) $<\Delta x^2>_{CP}$ ($p < 0.001$; $\eta_p^2 = 0.488$), Δt_{yCP} ($p < 0.001$; $\eta_p^2 = 0.592$), and $<\Delta y^2>_{CP}$ ($p < 0.001$; $\eta_p^2 = 0.779$). Table 2 reports the results of the Bonferroni post-hoc analysis.

3.2. Sample entropy

Fig. 4 shows the SampEn X and SampEn Y results. Specifically, the one-way ANOVA for repeated measures showed significant differences between ST, DAP and DML conditions considering the SampEn X ($p < 0.001$; $\eta_p^2 = 0.775$) and the SampEn Y ($p < 0.001$; $\eta_p^2 = 0.915$) values. Bonferroni post-hoc analysis revealed significantly higher ($p < 0.001$) SampEn X values for ST (1.355 ± 0.027) than DAP (0.982 ± 0.140) and DML (0.785 ± 0.250). In addition, SampEn X values were significantly ($p < 0.05$) higher in DAP than DML condition. The SampEn Y showed significantly higher ($p < 0.001$) values for the ST (1.380 ± 0.033) condition compared to DAP (0.822 ± 0.172) and DML (0.874 ± 0.117) conditions.

3.3. Global CoP parameters

The one-way ANOVA analysis showed a statistically significant difference for the Area95 ($p < 0.001$; $\eta_p^2 = 0.719$) and Mean Velocity ($p < 0.001$; $\eta_p^2 = 0.706$) parameters when comparing the ST, DAP and DML conditions. For the Area95, Bonferroni post-hoc analysis (Fig. 5) revealed significantly lower ($p < 0.001$) values for the ST (1.215 ± 0.833 cm^2) condition with respect to DAP (16.436 ± 5.402 cm^2) and DML (24.189 ± 13.000 cm^2) conditions. Similarly, the Mean Velocity (Fig. 5) showed significantly lower ($p < 0.001$) values for the ST (3.088 ± 0.432 cm/s) condition compared to DAP (6.852 ± 1.305 cm/s) and DML (8.160 ± 2.075 cm/s) conditions. Pearson's coefficient did not show any statistically significant correlations between static and dynamic conditions for all the global CoP parameters (namely, Area95 and Mean Velocity).

4. Discussion

4.1. Neuromuscular control mechanisms

4.1.1. Stabilogram diffusion analysis

The interpretation of the CoP stabilogram from a motor control perspective through the Area95 and the Mean Velocity is limited because it ignores the dynamic characteristics of the stabilogram (Collins & De Luca, 1993). SDA is a general stochastic modeling framework to interpret CoP time series that can reveal at least two different neuromuscular control mechanisms: open-loop control mechanisms over short-term intervals and closed-loop control mechanisms over long-term intervals. Diffusion coefficients quantify postural instability with high values representing a less tightly regulated control system (Collins & De Luca, 1993). Our results showed significantly greater diffusion coefficients in the dynamic conditions compared to the static ones. These values are in accordance with the global CoP parameters, confirming a greater postural instability in the most challenging dynamic tasks. Interestingly, diffusion coefficients presented the highest values along the axis where the unstable board allowed the major degree of freedom. That is, *Dfxs* resulted higher in DML than in DAP and *Dfys* in DAP compared to DML. Similar behavior was observed for the long-term coefficients where *Dfxl* resulted higher in DML than in DAP and *Dfyl* in DAP compared to DML. Thus, we can speculate that controlling the unstable board was more complex and thus, balance was less tightly regulated along the direction where the participants could move (i.e., y axis in DAP and x axis in DML). Conversely, balance was easily managed (i.e., lower diffusion coefficients) along the non-rotational axis of the unstable board (i.e., x axis in DAP and y axis in DML). This behavior was more evident for the medio-lateral x axis where the

Table 1
Diffusion coefficients in the static (ST), dynamic anterior-posterior (DAP), and dynamic medio-lateral (DML) conditions. Data are presented as mean ± standard deviation (SD). * Different from ST ($p < 0.05$); # Different from DAP ($p < 0.05$).

	ST	DAP	DML
$Dfsr^2$	29.84 ± 77.71	278.52 ± 88.69*	399.81 ± 278.04*
$Dflr^2$	3.52 ± 4.45	17.23 ± 6.01*	16.61 ± 8.84*
Dfxs	15.46 ± 50.84	86.63 ± 37.89*	267.27 ± 251.30* #
Dfxl	1.07 ± 2.78	3.49 ± 1.68*	8.96 ± 8.68 *#
Dfys	14.37 ± 27.06	191.88 ± 62.66*	132.53 ± 50.42*#
Dfyl	2.44 ± 1.90	13.74 ± 5.70*	7.64 ± 2.97*#

Table 2

Transition points (Δt_{rCP}, Δt_{xCP}, Δt_{yCP}) and critical displacements ($<\Delta r^2>_{CP}$, $<\Delta x^2>_{CP}$, and $<\Delta y^2>_{CP}$) in the static (ST), dynamic anterior-posterior (DAP), and dynamic medio-lateral (DML) conditions. Data are presented as mean ± standard deviation (SD). * Different from ST ($p < 0.05$); # Different from DAP ($p < 0.05$).

	ST	DAP	DML
Δt_{rCP}	0.93 ± 0.31	0.76 ± 0.17	0.75 ± 0.11
$<\Delta r^2>_{CP}$	18.37 ± 15.80	414.62 ± 166.62*	607.34 ± 498.6*
Δt_{xCP}	0.85 ± 0.76	0.44 ± 0.10	0.90 ± 0.14 #
$<\Delta x^2>_{CP}$	3.67 ± 2.97	77.28 ± 40.46*	467.89 ± 455.04*#
Δt_{yCP}	1.01 ± 0.37	0.90 ± 0.19	0.50 ± 0.11*#
$<\Delta y^2>_{CP}$	15.35 ± 14.14	338.94 ± 152.05*	137.87 ± 69.81*#

average ratio between the short and long diffusion coefficients was 0.35. Conversely, the average ratio between the short and long diffusion coefficients was 0.62 for the anterior-posterior y axis. Since the board rotational axis and ankle joints were parallel in DAP, we speculate that the ankle strategy was the most employed to recover balance; thus, greater anterior-posterior CoP displacements were observed. The unstable board oscillations in DML did not easily allow ankle plantarflexion and dorsiflexion.

The critical point (Fig. 2) marks the transition of the postural control system from open-loop to closed-loop control mechanisms (Collins & De Luca, 1993). In this regard, the planar transition point Δt_{rCP} in ST (Fig. 3c) showed a larger short-term region (≃ 22%) compared to DAP and DML. The behavior of the transition point in DAP and DML deserves attention, considering the medio-lateral and anterior-posterior components separately (Fig. 3a and b). From a neurophysiological point of view, in DAP and DML, the postural control system switched from an open-loop to a closed-loop control earlier compared to ST only when considering the axis around which the board did not rotate (i.e., Δt_{xCP} in DAP and Δt_{yCP} in DML). Conversely, short-term regulation regions were comparable in ST and DAP considering Δt_{yCP}, and in ST and DML considering Δt_{xCP}. Thus, participants showed larger short-term regions with open-loop control mechanisms and higher diffusion coefficients along the axis where the greatest amount of CoP displacements was allowed.

4.1.2. *Sample entropy*

The SampEn quantifies the entropy of a time series, namely the regularity of the time series. The higher the SampEn value, the more irregular the time series (Richman & Moorman, 2000). From a neurophysiological perspective, the higher the regularity of the time series, the higher the efficiency of its control system (Goldberger et al., 2002). This algorithm has already been applied to the CoP trajectory to deepen postural control mechanisms (Donker et al., 2007; Rizzato et al., 2018; Roerdink et al., 2006). The comparison between static and dynamic balance revealed greater values in the first condition, considering both SampEn X and SampEn Y. These findings can be explained by the more attention the participants allocated to the dynamic balance tasks, which led to more regular CoP displacements and thus to lower SampEn values (Donker et al., 2007). As per the SDA, SampEn analysis identified a statistically significant difference between DAP and DML with a greater SampEn Y value in DAP. We can speculate that the control of the unstable board in DML was less straightforward than in DAP. The consequence was a less automatic response to the medio-lateral oscillations in DML, thus allocating more attention. This hypothesis is supported by studies on the modulation of electroencephalogram (EEG) activity in different postural tasks considering alpha and beta power at central electrode sites (Hülsdünker et al., 2016; Petrofsky & Khowailed, 2014; Slobounov et al., 2009). Indeed, it has been demonstrated that the medio-lateral component of postural sway is more complex to be controlled than the anterior-posterior component by a higher EEG cortical activity in the former (Slobounov et al., 2008).

4.2. *Global CoP parameters*

Results from global CoP parameters highlighted a considerable difference between the static and the dynamic conditions but no differences comparing DAP and DML conditions. Thus, being the Area95 an index of the overall postural performance and the Mean Velocity of the efficiency of the postural control system (Paillard & Noé, 2015), subjects obtained the highest performance and efficiency in the static task. These results were not surprising. Indeed, since dynamic tasks are generally more challenging, they usually induce higher body instability and thus greater CoP oscillations to counteract external destabilizations. This peculiarity makes dynamic tasks the best choice when static posturography fails to discriminate postural control performance alone (Petró et al., 2017).

On the relationship between static and dynamic balance performance, to the best of our knowledge this study compared for the first time the same global CoP parameters (i.e., Area95 and Mean Velocity) over static and dynamic conditions. Our results strengthened the body of the literature reporting no relationship between static and dynamic balance performance (Muehlbauer et al., 2012; Rizzato et al., 2021), though global CoP parameters from static posturography were compared to a dynamic stability index (Rizzato et al., 2021) or functional tests (Muehlbauer et al., 2012). Moreover, the age of the participants of the present study allows extending the findings that emerged in older adults to a population of young healthy subjects. Thus, we can speculate that the absence of relationship could be related not to aging per se but to the distinct contribution of the same anatomical structures (i.e., cerebral cortex, basal ganglia, cerebellum, brainstem, and spinal cord) in ruling different balance conditions (Takakusaki et al., 2017). Although postural regulation could never be considered fully automatic (Paillard, 2017), quiet bipedal standing represents an unperturbed and predictable context where postural regulation mainly occurs at brainstem-spinal levels through mostly automatic processes (Lajoie et al., 1993; Takakusaki et al., 2017). Conversely, DAP and DML conditions call into play more cognitive processes of postural control with a prevalence of supra-spinal postural strategies to achieve goal-directed movements (Lajoie et al., 1993). However, this lack of

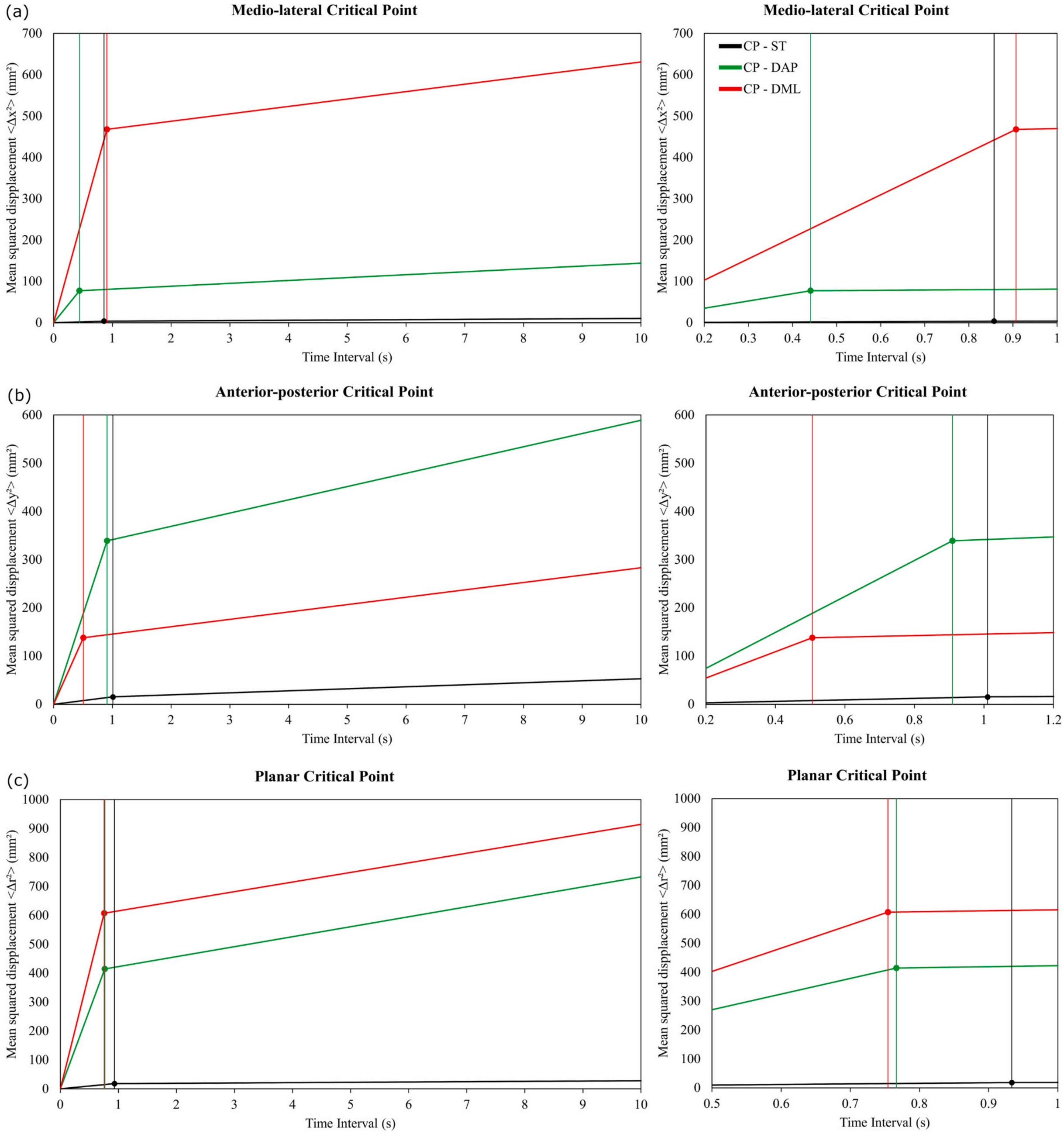

Fig. 3. Graphical representation of Medio-lateral (a), anterior- posterior (b), and planar (c) stabilogram diffusion plots (left side of the panel) with their zooms (right side of the panel) around critical points (dots). Vertical lines indicated the switch from open-loop to closed-loop control mechanisms. Static (ST), dynamic anterior-posterior (DAP), and dynamic medio-lateral (DML) conditions are represented with black, green, and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationship between static and dynamic balance performance needs to be confirmed with further studies over different populations with larger sample sizes.

The present study has some limitations. Due to the construction of the unstable board, which allows oscillations only around a single axis, it was not possible to collect anterior-posterior and medio-lateral oscillations within the same trial. The single radius of curvature of the unstable board represents another limitation. Although the used radius fit the tested population, the employment of an unstable board with a variable radius that would have allowed different difficulty levels could have strengthened the findings of the present study.

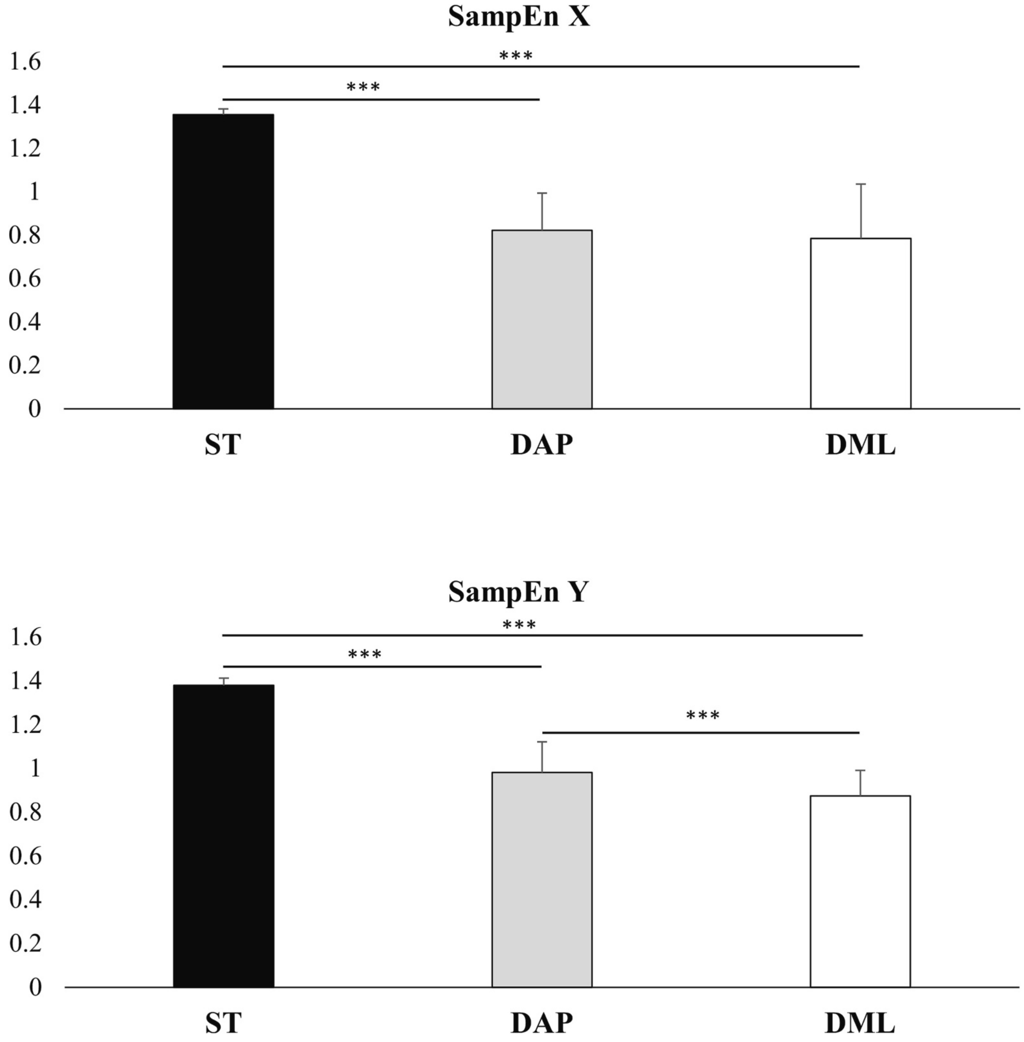

Fig. 4. Sample entropy results in the static (ST), dynamic anterior-posterior (DAP), and dynamic medio-lateral (DML) conditions. Data are presented as mean ± standard deviation (SD). ***$p < 0.001$.

5. Conclusions

The findings of the present study demonstrated that a significant amount of information could be retrieved from the CoP trajectory to describe static and dynamic postural control. SDA and SampEn were revealed as useful analysis tools to add information on the neuromuscular control mechanisms regulating static and dynamic balance, resulting more sensitive than global CoP parameters in the dynamic postural assessment. SDA diffusion coefficients found a less tightly regulated control system in the dynamic tasks above all along the directions where the unstable board allowed the greatest amount of motion. Moreover, the critical point analysis demonstrated differences in the switch from an open-loop to closed-loop control when comparing anterior-posterior and medio-lateral directions. Corrective feedback mechanisms were called into play earlier in the dynamic tasks than in the static condition. SampEn analysis confirmed a higher level of attention and, thus, less automatic control mechanisms in the dynamic tasks. Global CoP parameters clearly objectified the major oscillations in dynamic conditions compared to the static test but did not allow to detect differences between the two dynamic tasks. Furthermore, the lack of a relationship between static and dynamic balance performance warrants further research on the neuromuscular control mechanisms. The different neuromuscular control mechanisms that emerged in the static and dynamic balance tasks encourage using both static and dynamic tests for a more comprehensive balance performance assessment.

CRediT authorship contribution statement

Alex Rizzato: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Michael Benazzato:** Investigation, Data curation. **Matteo Cognolato:** Investigation, Data curation. **Davide Grigoletto:** Investigation.

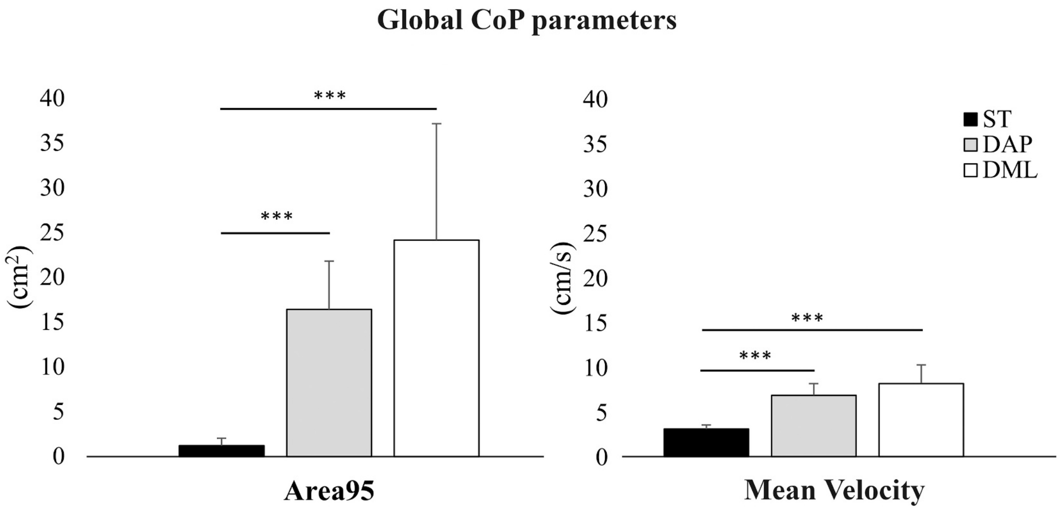

Fig. 5. Results of global CoP parameters (i.e., Area95 and Mean Velocity) in the static (ST), dynamic anterior-posterior (DAP), and dynamic medio-lateral (DML) conditions. Data are presented as mean ± standard deviation (SD). *** $p < 0.001$.

Antonio Paoli: Formal analysis, Resources, Writing – review & editing, Supervision. **Giuseppe Marcolin:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available on request.

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