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Section I – Kinesiology

Hierarchical and Corrective Organization of Postural Control in Ballroom Dance: Associations with Dance Condition and Expertise

by
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This study examined how dance condition (female, male, couple), and expertise influence the hierarchical organization and corrective dynamics of postural control in ballroom dancers performing the standardized contra check position. The study included 30 dancers: 14 professionals (7 dance couples) and 16 novices (8 dance couples). Center of pressure (COP) data were collected during quiet standing (QS) and under contra check conditions (solo and partnered). Postural control was analyzed using rambling-trembling (RM-TR) decomposition, sample entropy (SampEn), and a trend change index (TCI) derived from MACD to quantify correction frequency, amplitude, and velocity. During QS, no between-group differences were found in global sway velocity or correction frequency. However, professionals exhibited higher rambling velocity and greater signal complexity (SampEn). In the contra check, female participants showed the highest sway velocity as well as corrective amplitude and velocity. Professionals demonstrated condition-dependent redistribution between RM and TR components and modulated corrective amplitude and velocity without increasing correction frequency. The partnered condition was associated with relatively greater TR contribution along with reduced corrective amplitude and velocity. Entropy did not differ between task conditions. The results indicate condition-related differences in postural control variables and greater modulation across conditions in professionals compared to novice dancers.

Keywords: *rambling-trembling decomposition; sample entropy; trend change index (TCI); partner interaction; center of pressure*

Introduction

Dance combines artistic expression with high motor demands, developing efficient and precise postural control mechanisms through years of training (Casabona et al., 2016; Janura et al., 2019). Traditional, linear metrics of stability (e.g., velocity or center of pressure (COP) path length) often fail to capture subtle differences in expert athletes' performances (Isableu et al., 2017; Powell and Williams, 2015). Conventional postural sway measures can also respond differently to visual perturbations: Najafabadi et al. (2025) reported increased anterior–posterior sway excursion and variability under accelerating and returning tilted virtual environments, whereas anterior–posterior maximum sway velocity and the sway area did not change significantly. Therefore, contemporary biomechanics utilizes advanced COP signal analyses, such as rambling (RM), trembling (TR) decomposition, and nonlinear measures (e.g., sample entropy [SampEn]), which allow for the assessment of the flexibility and complexity of movement control in dancers. Understanding these mechanisms is crucial not only for optimizing dance training, but also for analysing specific motor interactions, such as partnering in ballroom dancing, where two independent

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postural systems must synchronize into a single, coordinated unit. To investigate these interactions under standardized yet ecologically valid conditions, the present study focused on the contra check position. The contra check is one of the most technically demanding and highly standardized positions in International Standard ballroom dance, requiring precise whole-body coordination while maintaining stability despite a pronounced displacement of the center of mass beyond the base of support (Zhang et al., 2021). Moreover, because the position is performed in close partnership, it involves continuous mechanical and sensory interaction between dancers, making it a particularly suitable experimental model for investigating both postural control and partner-dependent sensorimotor coordination.

The RM-TR method is based on the biomechanical assumption that maintaining an upright body posture results from the superposition of two processes (Zatsiorsky and Duarte, 2000). The COP signal is divided into an RM component, obtained by interpolating the instantaneous equilibrium points (IEP-moments when horizontal forces are zero), and a TR component, representing the difference between the raw COP signal and the RM trajectory. The RM component has been interpreted as reflecting supraspinal processes involved in shifting the reference point around which the body is stabilized, whereas the TR component is thought to be associated with peripheral mechanisms, including spinal reflex activity and the mechanical properties of muscles and joints. However, it should be emphasized that this interpretation remains theoretical, and RM-TR decomposition provides only indirect insight into the neural organization of postural control (Zatsiorsky and Duarte, 1999). The method is very sensitive to age-related changes and specific sensory deficits (Degani et al., 2017; Gerber et al., 2022; Yamagata et al., 2019). Analysis of the RM-TR components indicates that in dancers, especially under partnering conditions, there is a shift in postural control from the RM level toward peripheral and reflex mechanisms (TR) (Michalska et al., 2023). The increased TR contribution, accompanied by a relative decrease in RM, may reflect a shift toward more automated and potentially more efficient balance regulation, particularly in contexts requiring enhanced somatosensory adaptation, such as partner contact (Richer and Lajoie, 2020). Importantly, elevated TR values in professional dancers should not be interpreted as reduced stability per se, but rather as indicative of a more responsive and adaptable postural system capable of rapid and precise adjustments (Michalska et al., 2026).

SampEn is a non-linear method that evaluates the temporal structure of the signal, not its amplitude. SampEn measures the regularity and predictability of data series by analyzing the probability of specific patterns to be repeated (Richman and Moorman, 2000). High entropy means low predictability and is interpreted as a characteristic of a healthy, complex system, capable of adaptation. A decrease in entropy (an increase in regularity) often accompanies aging or diseases (e.g., Parkinson's), suggesting a "loss of complexity" and reduced plasticity of the system (Costa et al., 2002; Degani et al., 2017). Professional dancers (ballet and ballroom) exhibit higher SampEn values than untrained or novice individuals, suggesting a more automated postural system less dependent on conscious control (Janura et al., 2019; Michalska et al., 2018). Training increases the complexity and irregularity of the COP signal (higher entropy), which, from a nonlinear biomechanics perspective, is interpreted as a manifestation of a flexible, adaptive, and highly efficient balance control system that does not require constant attentional engagement (Pálya and Kiss, 2024; Stins et al., 2009).

An additional analytical approach involves adapting financial signal-processing algorithms, particularly the Moving Average Convergence/Divergence (MACD) indicator, to detect biomechanically meaningful trend changes in COP trajectories (Wodarski et al., 2022). The intersection of exponential moving averages identifies discrete postural correction events, from which variables such as the number of corrections (TCI), inter-correction time (TCI_dT), displacement amplitude (TCI_dS), and correction velocity (TCI_dV) can be derived (Wodarski, 2023). This method allows for differentiation between increased sway resulting from more frequent corrections and this resulting from greater corrective amplitudes. Unlike standard methods (e.g., Fourier transform) which focus on periodic movements, stock market indicators enable the detection of transient, non-cyclic, and chaotic

changes that are crucial for assessing stability strategies in healthy individuals. TCI-based analysis has demonstrated high reliability and sensitivity in clinical populations (Wodarski et al., 2023); however, it has not yet been applied to professional dance performance.

These methods complement each other. While SampEn tells us about the overall condition of the system, the RM-TR decomposition helps distinguish between the relative contributions of central and peripheral mechanisms of postural control, and TCI provides precise data on the dynamics and the number of specific repair responses. By integrating hierarchical signal decomposition (RM-TR) with event-based corrective analysis (TCI), the present approach bridges physiological mechanism and behavioral output, enabling multilevel characterization of postural regulation beyond conventional stabilographic metrics. The aim of the study was to investigate how a dance condition (female solo, male solo, partnered contra check) and the expertise level would influence the hierarchical organization and corrective dynamics of postural control in the standardized contra check dance position. We hypothesized that the dance condition would significantly modulate postural control. Specifically, reduced sway was expected in the partnered contra check condition compared to solo positions in both professional and novice dancers. Furthermore, it was hypothesized that professional dancers would demonstrate greater condition-dependent redistribution between RM and TR components compared to novice dancers. In addition, professional dancers were expected to show more pronounced modulation of corrective amplitude and velocity adjustments.

Methods

Participants

A total of 30 dancers were enrolled in the study, comprising both professional and novice performers. The professional cohort included 14 competitive ballroom dancers who held an international-level dance classification (Table 1). The novice cohort consisted of 16 university students who had completed a three-month intensive ballroom dance program within their field of academic specialization. Eligibility criteria for the professional group included: being at least 18 years of age, holding a minimum national A-class ranking in International Standard ballroom dance, and having at least three years of experience in dancing in a fixed partnership. For the novice group, inclusion criteria were: age ≥18 years and completion of a three-month Standard ballroom dance specialization course. Participants from both groups were excluded if they had sustained a serious musculoskeletal injury requiring surgical treatment within the previous two years. The participants provided written informed consent to take part in the study voluntarily. All of them satisfied the inclusion criteria and completed the experiment successfully. All procedures were performed in accordance with the Declaration of Helsinki and relevant institutional guidelines. The study was approved by the Institutional Bioethics Committee of The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland (protocol code: 3/2014; approval date: 05 December 2014). No adverse events occurred during testing.

Design and Procedures

Postural control was assessed using a force plate (60 cm × 90 cm × 9 cm; BP600900, Watertown, MA, USA), which recorded ground reaction forces and moments at a sampling rate of 100 Hz. The antero-posterior (AP) and medio-lateral (ML) directions were defined with respect to the pelvic coordinate system. The testing protocol included a quiet standing (QS) test and one position characteristic of International Standard ballroom dance, namely the contra check. During the QS trials, participants stood barefoot on the force plate with their feet positioned hip-width apart and their arms relaxed alongside their bodies. They were instructed to maintain an upright and stable posture while keeping their gaze fixed on a reference point located 3 m directly in front of them. All contra check trials were performed while participants wore their standard training ballroom dance shoes to preserve the sport-specific characteristics of the task. The contra check dance positions were staged twice—while standing solo and while standing with a partner. Under the partnered contra check condition, both dancers stood simultaneously on the same force plate. Consequently, the recorded center-of-pressure signal represented the global COP of the dancing couple rather than that of an individual dancer. On the force plate, male dancers performed a forward lunge with pronounced knee flexion, while female

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dancers stepped back with the opposite leg, creating a strong and elongated body line (Figure 1). Novice dancers completed a 13-week ballroom dance training program consisting of one supervised 90-min session per week focused primarily on the technique of the International Standard dances. None of the participants had previous ballroom dance experience before enrollment in the program. Each novice dancer trained with the same partner throughout the intervention to ensure consistent motor learning conditions. Partner allocation was based on anthropometric compatibility. The assumption of the assessed position was preceded by a short dance sequence, which served solely to allow the dancers to naturally assume the contra check position. The preceding movement phase was neither recorded nor analyzed. Once the dancers had stabilized the required position, they were instructed to maintain the contra check position for 30 s while posturographic data were collected. Data recording commenced once the dancers had stabilized the required position, which typically occurred within approximately 1–5 s after assuming the position. If the dancers stopped the movement outside the force plate area, the trial was repeated. Each dance position was performed twice, with a 2-min rest interval between trials, and the mean values obtained from the two valid trials were used for further statistical analyses. Prior to data collection, participants were familiarized with the experimental protocol and were given the opportunity to rehearse the procedure, including controlled termination of movement within the designated force plate area. The contra check position was executed in accordance with the 2001 guidelines of the Imperial Society of Teachers of Dancing (ISTD).

Data Processing

Raw data were processed offline using MATLAB software (MathWorks, Natick, MA, USA). Initially, all signals were subjected to low-pass filtering with a fourth-order Butterworth filter, applying a cut-off frequency of 7 Hz to reduce high-frequency noise. Subsequently, the COP variables were computed from the filtered force and moment data. To calculate the correction of the COP signal, the algorithm that enables the calculation of the MACD index was used. The MACD line was obtained by subtracting two exponential moving averages (EMAs) of lengths of samples 12 and 26. A signal line was then computed as a 9-sample EMA of the MACD line. At a sampling frequency of 100 Hz, these variables corresponded to temporal windows of 0.12 s, 0.26 s, and 0.09 s, respectively. This standard MACD parameterization had previously been adapted for COP signal analysis and enabled detection of physiologically meaningful trend changes while reducing the influence of short-lived fluctuations and measurement noise (Wodarski, 2023). Points where the MACD and signal lines intersected marked trend changes, and their count defined the trend change index (TCI) (Wodarski, 2023). Next, the time intervals between successive trend-change points formed the MACD_dT vector, and the mean of these intervals was defined as TCI_dT. Displacements between these points yielded MACD_dS, with its mean defining TCI_dS. The ratio of corresponding values in MACD_dS and MACD_dT produced MACD_dV, and its mean provided TCI_dV. All indicators could be calculated separately for AP and ML directions. Richman and Moorman's (2000) algorithm for sample entropy and Zatsiorsky and Duarte's (1999, 2000) method for RM and TR decomposition were used. For RM-TR decomposition, the RM trajectory was reconstructed by identifying all instantaneous equilibrium points (IEPs), defined as time points at which the horizontal forces were equal to zero. These points were subsequently interpolated using cubic spline functions to obtain a smooth RM trajectory, whereas the TR trajectory was calculated as the difference between the original COP signal and the reconstructed RM trajectory. Sample entropy was calculated using an embedding dimension of m = 3 and a tolerance of $r = 0.2 \times$ the standard deviation of the time series. The analysis was performed on the complete 30-s recording (3000 samples at 100 Hz). Because the tolerance was expressed relative to the signal standard deviation, no additional normalization procedure was applied.

The following variables were further analysed: COP velocity (cm/s) (v COP), RM velocity (v RM) (cm/s), and TR velocity (v TR) (cm/s) to assess dancers' postural sway. The regularity and temporal complexity of the COP time series were quantified using SampEn. To determine the relative contribution of the RM and TR components to the COP signal, the indices

vRM/COP and vTR/COP were calculated. The characteristics of COP signal corrections were expressed using the following variables: TCI_per s (number of corrections per second), TCI_dT (s), TCI_dS (mm), and TCI_dV (mm/s).

Statistical Analysis

Descriptive statistics were calculated for all variables. Normality was assessed using the Shapiro-Wilk test. Variables that violated the assumption of normality under the quiet standing condition were analyzed using non-parametric tests, whereas variables satisfying this assumption were analyzed using parametric methods. Between-group differences in quiet standing were analyzed using independent samples *t*-tests or Mann-Whitney *U* tests, depending on distribution. Effect sizes were reported as Cohen's *d* or rank-biserial correlation (r_{pb}). For the contra check position, a two-way mixed-design ANOVA was conducted with the group (professional vs. novice) as the between-subject factor and the condition (female solo, male solo, partnered contra check) as the within-subject factor. When sphericity was violated, the Greenhouse-Geisser correction was applied. Effect sizes were expressed as eta squared (η^2). To assess the relative contribution of rambling (RM) and trembling (TR), a two-way repeated-measures ANOVA was performed separately within each group, with the component (RM vs. TR) and the condition as within-subject factors. Owing to the interdependence of partner performance during the contra check position, the dance pair rather than the individual dancer was considered the experimental unit for all mixed-model analyses. Pearson correlations were computed to examine associations between TR contribution and SampEn, separately for each plane and group. Additionally, a pooled correlation analysis was performed using data combined across all experimental conditions. Statistical significance was set at $p \leq 0.05$. All analyses were performed using Statistica v.13.3.

Results

The Shapiro-Wilk test indicated that variables obtained during quiet standing violated the assumption of normality and were therefore analyzed using non-parametric tests. All variables obtained during the contra check condition met the assumptions for parametric analyses.

Quiet Standing

The Mann-Whitney *U* test did not reveal statistically significant differences in mean v COP values (cm/s) in either the AP ($U = 70$, $p = 0.09$, $r_{pb} = 0.37$) or ML ($U = 112$, $p = 0.99$, $r_{pb} = 0.00$) planes between professional and novice dancers. No between-group differences were observed for any TCI-derived variables ($p > 0.05$). Following signal decomposition, a significant between-group difference was found only for the v RM variable in the AP plane. Professional dancers exhibited greater rambling component velocity compared to novice dancers ($t = -2.32$, $p = 0.03$, $d = 0.85$). Additionally, SampEn values were significantly higher in professional than in novice dancers ($U = 52$, $p = 0.01$, $r_{pb} = 0.53$).

Contra Check Dance Position

Postural Sway

In the AP plane, the condition significantly affected all sway velocity variables (v COP, v RM, v TR), with moderate to large effect sizes ($\eta^2 = 0.19–0.27$). Values were generally highest under the female solo condition and lower under the male solo and partnered conditions (Table 2). No main effect of the group was found; however, significant group × condition interactions were observed for all AP variables ($\eta^2 = 0.06–0.16$). Post hoc analysis indicated that differences were most consistent between the female solo and partnered conditions, particularly for vCOP and vRM (Figure 2).

In the ML plane, the condition significantly influenced all sway velocity variables, with large effect sizes ($\eta^2 = 0.20–0.33$). Significant group effects were found for vCOP and vRM ($\eta^2 = 0.12–0.15$) (Table 2). Interactions were significant for vCOP and vTR. Post hoc comparisons showed that differences were primarily observed between the female solo and partnered conditions, both in professional and novice dancers (Figure 3).

Postural Correction

In the AP plane, TCI_per_s and TCI_dT were not significantly affected by the condition or the group. In contrast, TCI_dS and TCI_dV showed significant condition effects ($\eta^2 = 0.10–0.15$) and significant group × condition interactions ($\eta^2 = 0.15–0.22$), with higher values generally recorded under the female solo condition (Table 3). Post hoc analysis indicated that significant differences were

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primarily present within the professional group, particularly between the female solo and the other conditions. Across analyses, the female solo condition showed the largest condition-related effects (Figure 4).

In the ML plane, no significant effects were found for TCI_per_s or TCI_dT. TCI_dS showed significant condition and interaction effects (η^2 = 0.11–0.14), while TCI_dV demonstrated a significant interaction only (η^2 = 0.14) (Table 3). In both cases, significant pairwise differences were mainly limited to the professional group and involved the female solo condition (Figure 4).

Postural Control

Given the significant group × condition interactions observed in previous analyses, the relationship between component structure and entropy was examined separately in professional and novice dancers.

Professional Dancers

In the AP plane, a significant main effect of the decomposition component (RM vs. TR) was found (F(1,13) = 248.02, p < 0.001, η^2 = 0.788), with RM exceeding TR across conditions. The main effect of the condition was not significant (F(2,26) = 1.53, p = 0.235), but a significant component × condition interaction was observed (F(2,26) = 9.72, p < 0.001), indicating position-dependent modulation of the RM-TR relationship. Post hoc analysis showed that TR differed between the male solo and partnered conditions (p < 0.006; Figure 5).

In the ML plane, a significant main effect of the component was also present (F(1,13) = 438.78, p < 0.001, η^2 = 0.932), with RM consistently higher than TR. Both the main effect of the condition (F(2,24) = 9.25, p = 0.001) and the interaction (F(2,24) = 29.70, p < 0.001) were significant. Post hoc comparisons indicated higher TR values under the male solo condition than under the female solo and partnered conditions, with lower TR under the partnered relative to the female solo condition (Figure 5). When data were pooled (N = 42) across conditions, TR was negatively correlated with SampEn in both the AP (r = −0.86, p < 0.001) and ML planes (r = −0.71, p < 0.001). No significant associations were observed within individual conditions.

Novice Dancers

In the AP plane, a significant main effect of the component was observed (F(1,14) = 142.75, p < 0.001, η^2 = 0.678), with higher RM than TR values. The main effect of the condition was not significant (F(2,28) = 0.16, p = 0.852), although a significant interaction was detected (F(2,28) = 6.19, p = 0.006). Post hoc tests revealed no significant between-condition differences for either component.

In the ML plane, only the main effect of the component was significant (F(1,14) = 117.44, p < 0.001, η^2 = 0.786), confirming RM dominance. No significant condition effects and interactions with SampEn were observed (p < 0.05). When data were pooled (N = 48) across conditions, TR was negatively correlated with SampEn in both the AP (r = −0.96, p < 0.001) and ML planes (r = −0.76, p < 0.001). No significant correlations were detected within individual conditions.

Table 1. Physical characteristics of participants.

	Professional			Novice		
			Mdn (min–max)			Mdn (min–max)
Variable	Male (n = 7)	Female (n = 7)		Male (n = 8)	Female (n = 8)	
Age [years]	23 (20–27)	22 (19–28)	23.5 (19.5–27.5)	21.5 (21–24)	21 (21–22)	21.5 (21–22.5)
Body height [cm]	173 (170–186)	164 (158–18)	168.5 (165.5–182)	181 (177–188)	166.5 (162–179)	175.5 (169.5–179.5)
Body mass [kg]	67 (55–70)	54 (52–62)	59.5 (54–66)	80* (70–105)	66* (53–79)	76* (64.5–85.5)
Individual/as a pair* experience [years]	11 (5.5–16)	13 (11–17)	5 (2–14)	–	–	–

*Mdn: median; * significant differences between professional and amateur (female, male, and couple) dancers in body mass values p < 0.05*

Table 2. Effects of a dance condition (female solo, male solo, partnered contra check) and the expertise level (professionals vs. novices) on the COP, RM, and TR velocities in the AP and ML planes.

Plane	Variable	Group	Female (M ± *SD*)	Male (M ± *SD*)	Partnered (M ± *SD*)	Effect	*F*	*p*	η^2
AP	vCOP	P	3.28 ± 1.00	2.25 ± 0.61	2.20 ± 0.43	Condition	14.89	**< 0.001**	0.251
		N	2.46 ± 0.51	2.39 ± 0.74	1.62 ± 0.52				
						Group	2.35	0.149	0.071
						Interaction	4.01	**0.03**	0.068
AP	vRM	P	2.65 ± 0.80	1.82 ± 0.49	1.70 ± 0.40	Condition	17.44	**< 0.001**	0.272
		N	1.92 ± 0.38	1.87 ± 0.59	1.20 ± 0.42				
						Group	3.21	0.097	0.091
						Interaction	4.07	**0.029**	0.063
AP	vTR	P	2.04 ± 0.76	1.27 ± 0.43	1.43 ± 0.28	Condition	5.67	**0.009**	0.191
		N	1.55 ± 0.29	1.52 ± 0.50	1.09 ± 0.34				
						Group	0.82	0.383	0.013
						Interaction	4.75	0.017	0.16
ML	vCOP	P	20.95 ± 0.56	1.97 ± 0.41	2.04 ± 0.53	Condition	22.9	**< 0.001**	0.329
		N	2.27 ± 0.37	0.95 ± 0.67	1.30 ± 0.47				
						Group	5.35	0.038	0.124
						Interaction	4.07	**0.029**	0.059
ML	vRM	P	2.56 ± 0.53	1.73 ± 0.33	1.72 ± 0.45	Condition	22.88	**< 0.001**	0.325
		N	1.91 ± 0.40	1.60 ± 0.58	1.06 ± 0.42				
						Group	6.6	**0.023**	0.152
						Interaction	2.82	0.078	0.04
ML	vTR	P	1.12 ± 0.32	0.61 ± 0.20	00.95 ± 0.35	Condition	10.85	**< 0.001**	0.197
		N	1.10 ± 0.28	0.89 ± 0.41	0.59 ± 0.34				
						Group	0.08	0.778	0.003
						Interaction	6.99	**0.004**	0.127

P: professional; N: novice; AP: antero-posterior; v: velocity; COP: center of pressure; RM: rambling; TR: trembling; ML: medio-lateral. Bold values indicate statistically significant results ($p < 0.05$)

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Table 3. Effects of a dance condition (female solo, male solo, partnered contra check) and the expertise level (professionals vs. novices) on TCI variables in the AP and ML planes.

Plane	Variable	Group	Female (M ± *SD*)	Male (M ± *SD*)	Partnered (M ± *SD*)	Effect	F	*p*	η^2
AP	TCI_per_s	P	4.01 ± 0.42	3.69 ± 0.39	3.68 ± 0.46	Condition	2.09	0.144	0.049
		N	3.80 ± 0.30	3.76 ± 0.46	3.73 ± 0.47				
						Group	0.03	0.865	0.001
						Interaction	1	0.383	0.023
AP	TCI_dT	P	0.25 ± 0.03	0.27 ± 0.03	0.27 ± 0.03	Condition	2.32	0.119	0.054
		N	0.26 ± 0.02	0.27 ± 0.04	0.27 ± 0.04				
						Group	0.02	0.9	< 0.001
						Interaction	0.69	0.513	0.016
AP	TCI_dS	P	0.54 ± 0.07	0.33 ± 0.08	0.35 ± 0.06	Condition	5.43	**0.011**	0.096
		N	0.36 ± 0.14	0.41 ± 0.17	0.35 ± 0.18				
						Group	0.39	0.541	0.015
						Interaction	8.69	**0.001**	0.153
AP	TCI_dV*	P	1.80 ± 0.55	0.88 ± 0.25	0.92 ± 0.22	Condition	7.54	**0.003 †**	0.151
		N	0.96 ± 0.37	1.15 ± 0.46	0.94 ± 0.53				
						Group	1.29	0.276	0.034
						Interaction	10.79	**<0.001 †**	0.216
ML	TCI_per_s	P	3.47 ± 0.37	3.31 ± 0.22	3.67 ± 0.48	Condition	2.51	0.101	0.073
		N	3.15 ± 0.33	3.25 ± 0.36	3.35 ± 0.39				
						Group	2.84	0.116	0.093
						Interaction	0.91	0.417	0.026
ML	TCI_dT	P	0.29 ± 0.03	0.30 ± 0.02	0.27 ± 0.03	Condition	2.16	0.135	0.063
		N	0.32 ± 0.03	0.31 ± 0.03	0.30 ± 0.03				
						Group	2.99	0.107	0.1
						Interaction	0.72	0.495	0.021
ML	TCI_dS	P	0.56 ± 0.10	0.39 ± 0.12	0.32 ± 0.10	Condition	6.67	**0.005**	0.139
		N	0.39 ± 0.17	0.47 ± 0.23	0.34 ± 0.11				
						Group	0.12	0.738	0.004
						Interaction	5.29	**0.012**	0.11
ML	TCI_dV*	P	1.40 ± 0.22	0.91 ± 0.30	0.81 ± 0.32	Condition	3.1	**0.062**	0.083
		N	0.89 ± 0.33	1.25 ± 0.84	0.84 ± 0.36				
						Group	0.08	0.786	0.003
						Interaction	5.04	**0.014**	0.135

*P: professional; N: novice; *: Greenhouse-Geisser correction applied; †: GG-corrected p reported in output; AP: antero-posterior; ML: medio-lateral; TCI_per_s: trend change index per second; TCI_dT: mean value of time between successive trend changes; TCI_dS: mean value of displacement between successive trend changes; TCI_dV: mean velocity of the COP displacement between successive trend changes. Bold values indicate statistically significant results (p < 0.05)*

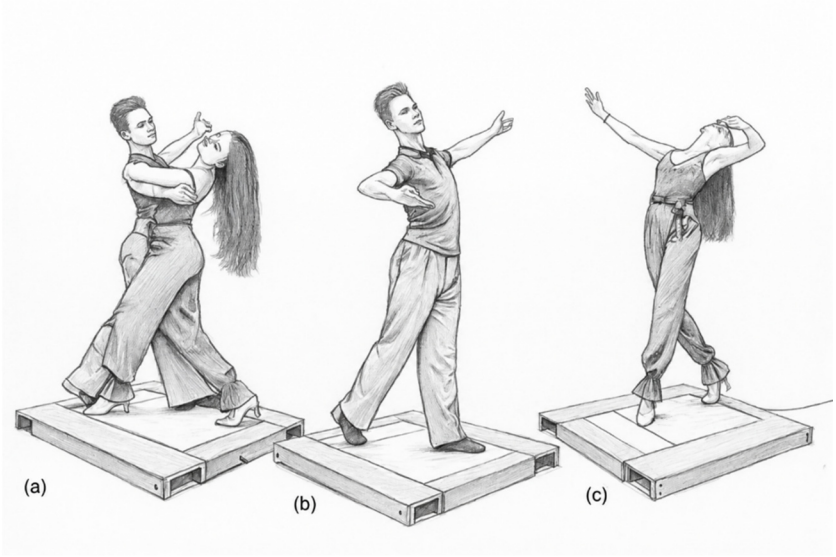


Figure 1. The experimental procedure on the force plate of the contra check position.
(a) standing with a partner, with the foot of the supporting leg perpendicular to the long axis of the force plate; (b) male solo standing, with the foot of the supporting leg parallel to the long axis of the force plate; (c) female solo standing, with the foot of the supporting leg parallel to the long axis of the force plate

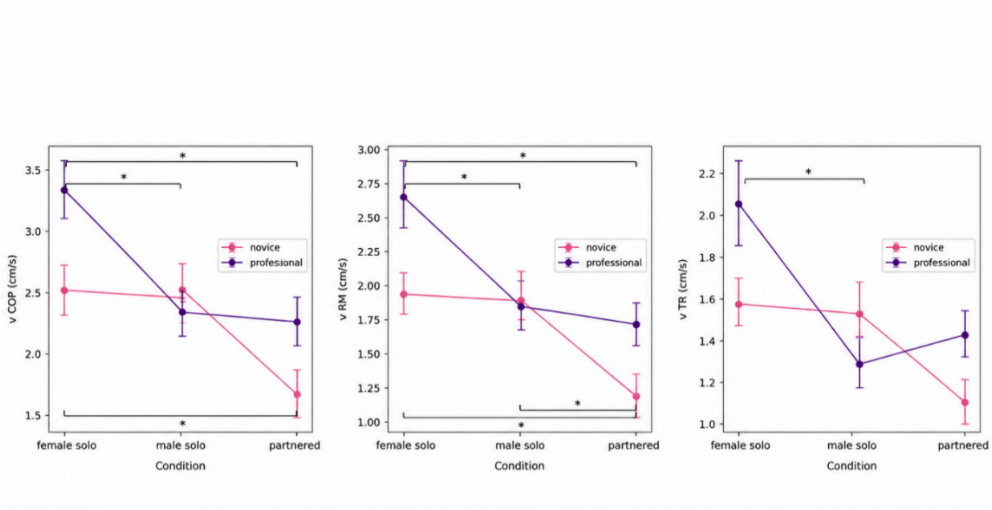


Figure 2. Mean values of v COP, v RM, v TR (standard errors marked as error bars) in the AP plane.
Thin solid line: significant differences $p < 0.05$; AP: antero-posterior; v: velocity; COP: center of pressure; RM: rambling; TR: trembling

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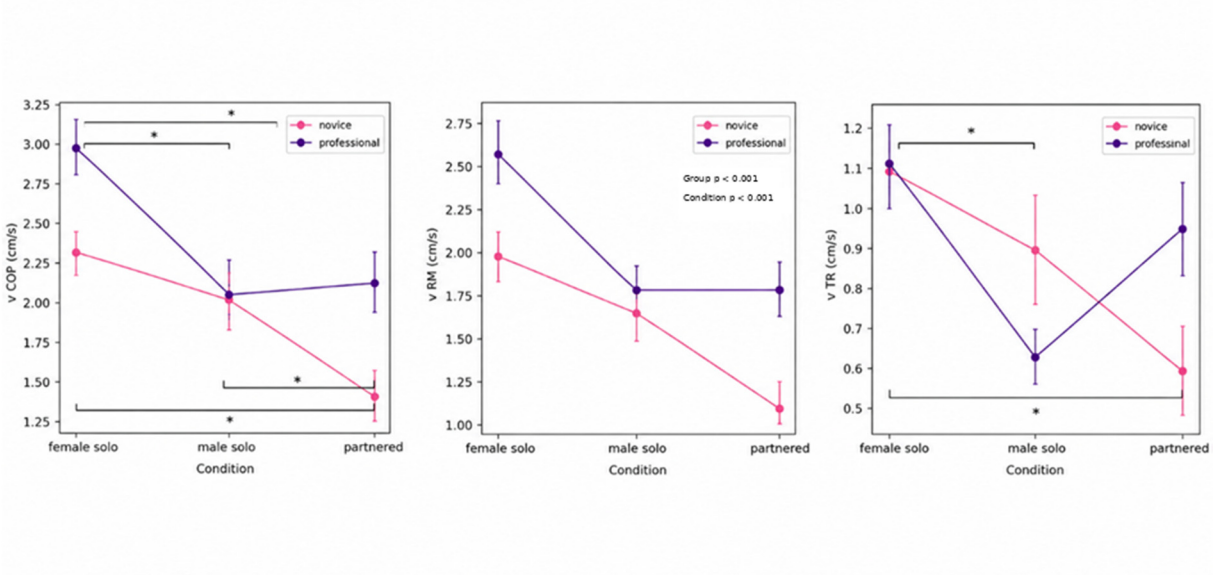


Figure 3. Mean values of v COP, v RM, v TR (standard errors marked as error bars) in the ML plane.
Thin solid line: significant differences at p < 0.05; V: velocity; COP: center of pressure; RM: rambling; TR: trembling, ML: medio-lateral

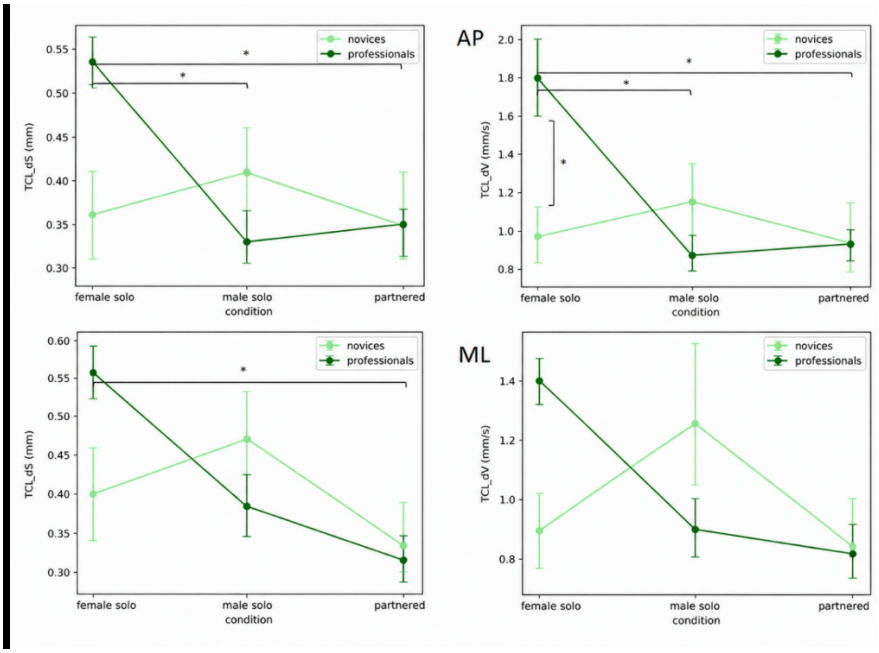


Figure 4. Mean values of TCI_dS and TCI_dV for the AP and ML planes.
Standard errors marked as error bars; thin solid line: significant differences at p < 0.05; V: velocity; COP: center of pressure; RM: rambling; TR: trembling, ML: medio-lateral

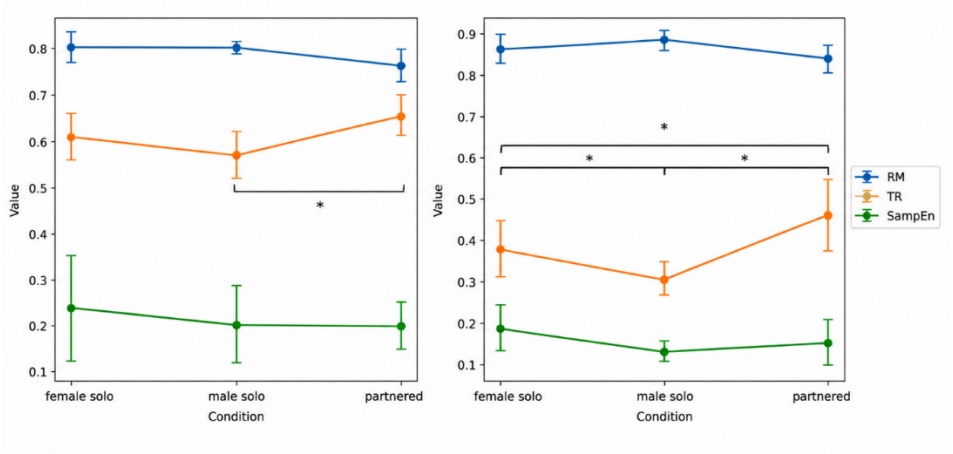


Figure 5. Mean values of RM, TR, and SampEn for AP and ML planes (standard errors marked as error bars) for professional dancers.
Thin solid line: significant differences at $p < 0.05$; AP: antero-posterior; ML: medio-lateral; RM: rambling; SampEn: Sample Entropy; TR: trembling

Discussion

Text text text text text text. Text text text text This study examined postural control during the contra check position in professional and novice ballroom dancers, focusing on task-related modulation and the relative contributions of the RM and TR components. The findings showed that the female solo position was associated with the highest sway velocity and corrective variables. Professionals exhibited greater task-dependent modulation than novice dancers, and variation in the RM-TR balance across dance positions was observed only in the professional group. When pooled across conditions, the TR component was negatively associated with SampEn in both the AP and ML planes.

During QS, no significant between-group differences were observed in global COP velocity or in any TCI-derived variables, indicating comparable sway magnitude and correction frequency between professional and novice dancers under low task demands. However, professionals exhibited greater rambling velocity in the AP plane and higher SampEn values. These findings suggest that expertise-related differences may be reflected primarily in the internal organization and temporal structure of postural control rather than in gross sway amplitude. Previous research indicates that professional dancers do not necessarily demonstrate superior static postural stability compared to non-dancers when assessed with traditional sway metrics under low task demands (Cicchella, 2021; Janura et al., 2019; Michalska et al., 2018). This is often interpreted as reflecting the limited sensitivity of simple, low-challenge tasks to reveal expertise-related adaptations in postural control. Although the present findings are generally consistent with these previous studies, direct comparison should be interpreted cautiously because important methodological differences exist. Previous investigations primarily examined ballet dancers or generic balance tasks performed individually, whereas the present study investigated ballroom dancers and additionally evaluated postural control during a standardized dance-specific

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position involving partner interaction. Consequently, the observed similarities likely reflect the limited sensitivity of quiet standing to detect expertise-related adaptations, whereas the contra check provides a more ecologically valid task for revealing sport-specific mechanisms of postural regulation.

In contrast to QS, the contra check represents a dance-specific, high-demand postural configuration characterized by asymmetric loading, pronounced COM displacement, and altered base-of-support conditions. Under these constraints, clear role- and expertise-dependent changes in the underlying mechanisms of postural control became apparent (Figure 2). Unlike the minimal demands of the quiet stance, the contra check required context-dependent adjustment of postural strategies, revealing differences in sway dynamics and in the relative contribution of RM and TR components that were not evident under low-challenge conditions. These findings support the concept that expertise-related adaptations in postural control become increasingly apparent as task complexity increases, particularly when balance regulation must be integrated with dance-specific biomechanical constraints and partner interaction. This task-specific perspective is also consistent with intervention-based evidence from aerobic gymnastics, where a sport-specific jumping interval training program produced significant adaptations in physical performance, with training frequency influencing the magnitude of some adaptations (Ma et al., 2025). The elevated sway observed under the female solo condition most likely reflects the greater mechanical demands of this posture rather than reduced postural stability *per se*. Although this observation differs from that reported by Michalska et al. (2026), the two studies are not directly comparable. The previous investigation examined the standard ballroom hold, whereas the present study focused on the contra check position, which is characterized by greater displacement of the center of mass, asymmetric loading, and substantially higher stabilization demands. Furthermore, the present study incorporated RM-TR decomposition and TCI analyses, enabling assessment of both the hierarchical organization of postural control and the dynamics of corrective responses beyond conventional stabilographic measures. The backward displacement of the COM, combined with trunk extension and a relatively constrained base of support, increases destabilizing torques and challenges postural equilibrium. The asymmetrical lower-limb configuration and elongated body alignment may further intensify the stabilization requirement (Błaszczyk and Fredyk, 2024). In contrast, the partnered contra check may modify postural control through additional tactile and proprioceptive information arising from physical contact (Vuillerme et al., 2007). However, because both dancers stood simultaneously on the same force plate, the recorded COP represented the global postural behavior of the couple. Consequently, the observed reductions in corrective amplitude and velocity may reflect not only enhanced sensory integration, but also biomechanical coupling and mechanical support between partners. Furthermore, the observed differences should not be attributed exclusively to partner contact, biological sex, or a dance role. The three tested conditions (male solo, female solo, and partnered contra check) also differed in body geometry, base-of-support characteristics, anthropometry, and mechanical interaction between partners, all of which may have contributed to the observed postural control responses. Therefore, the present findings should be interpreted as reflecting the combined influence of these task-specific characteristics rather than any single factor in isolation.

The TCI analysis revealed an interesting pattern of expertise-related adaptations. Regardless of the group, the number of postural corrections did not change across the conditions (female solo, male solo, and partnered contra check). However, the amplitude (TCI_dS) and velocity (TCI_dV) of these corrections varied significantly in the professional group. Notably, correction velocity was significantly higher in professional female dancers compared to novice dancers, indicating faster execution of corrective responses (Michalska et al., 2026). According to Wodarski et al. (2024), a greater COP displacement amplitude combined with a constant inter-correction interval represents an effective control strategy, in which the system executes larger and more decisive corrective actions to prepare for a predictable perturbation. Professionals do not correct more frequently—they correct more efficiently. This finding suggests that expertise is

reflected in a more task-specific organization of corrective responses rather than an increased correction frequency. To our knowledge, this is the first study to apply TCI analysis in ballroom dancers; therefore, direct comparison with previous dance studies is currently not possible.

In both groups, the RM component had significantly higher values compared to the TR component, as determined by the calculation algorithm itself. However, only professional dancers demonstrated a condition-dependent redistribution between the RM and TR components. Task-related modulation of these components has previously been reported, suggesting that rambling and trembling are differentially affected by postural demands and control strategies (Celik et al., 2023; Shin et al., 2011). However, direct comparison with these studies should be interpreted cautiously because they primarily investigated quiet standing or clinical populations, whereas the present study examined a highly demanding, dance-specific posture requiring continuous adaptation to asymmetric loading and partner-related mechanical constraints. In particular, the male solo condition was characterized by the strongest RM dominance, while the partnered contra check condition showed a relatively greater TR contribution. The increase in TR contribution was strongly and negatively correlated with both correction TCI_dS and TCI_dV (Figures 1 and 2), suggesting that greater reliance on peripheral mechanisms may reduce the need for large, high-velocity corrective impulses. This interpretation is consistent with the notion that trembling reflects rapid, small-scale adjustments generated at the peripheral level (Zatsiorsky and Duarte, 2000). These findings further suggest that the relative contribution of central and peripheral control mechanisms is not fixed but adapts to the specific biomechanical demands of different dance roles and partner-related demands. SampEn did not differ across conditions and showed no consistent within-condition association with TR. Therefore, no robust task-dependent relationship between TR contribution and signal complexity was confirmed. From the perspective of motor control theory, entropy reflects the structural organization of variability rather than mere randomness (Costa et al., 2002; Huisinga et al., 2012), and its stability across conditions may indicate preserved global control architecture despite hierarchical redistribution between RM and TR components. Together, these findings indicate that RM-TR decomposition and SampEn provide complementary information about postural regulation, capturing different aspects of motor control that cannot be inferred from conventional COP measures alone.

From a practical perspective, the present findings suggest that ballroom dance training should emphasize the ability to adapt postural control strategies to different dance roles and partnering conditions rather than focusing solely on reducing postural sway. Professional dancers did not perform more frequent postural corrections but instead adjusted their amplitude and velocity according to task demands, indicating more efficient postural regulation. The greater postural demands observed in the female solo contra check position suggest that this role may require additional practice under dance-specific balance conditions, particularly in novice dancers. Furthermore, the distinct postural organization observed during partnered performance highlights the importance of incorporating partner-specific practice into regular training. This recommendation is consistent with intervention-based evidence showing that targeted balance training can improve dynamic postural control and sport-specific performance (Ibrahim et al., 2025). Finally, advanced stabilographic measures such as RM-TR decomposition, SampEn, and TCI may provide more sensitive tools for monitoring training adaptations than conventional COP measures alone, facilitating the development and evaluation of role-specific balance training programs.

Several limitations of the present study should be acknowledged. First, the sample size was relatively small. However, it should be noted that the examined group consisted of athletes representing the highest competitive dance class, which partially compensates for the small sample size by ensuring a high level of performance homogeneity and expertise. Nevertheless, the relatively small number of participating couples may limit the generalizability of the findings, and partner-specific training history may have influenced postural responses. Second, the comparison group consisted of novice dancers who had completed only a three-month ballroom

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dance training program. Therefore, the observed between-group differences should be interpreted as reflecting a comparison between highly experienced and novice dancers rather than successive stages of dance expertise. Third, biological sex and a dance role were inherently confounded in the study design. Consequently, the observed differences cannot be unequivocally attributed to either biological sex or role-specific demands, and anthropometric differences may also have contributed to the observed postural responses. Finally, the dancers were instructed to maintain the contra check position for 30 s during posturographic assessment. This duration represents a methodological compromise. Although maintaining the contra check for 30 s is physically demanding and does not fully reflect the dynamic nature of ballroom dance performance, shorter recordings would not have provided sufficient data for the reliable computation of SampEn and RM-TR decomposition. Consequently, the recording duration was selected to balance ecological validity with the methodological requirements of the applied signal analyses.

Conclusions

QS did not differentiate professionals from novice dancers in traditional stabilographic variables; however, professionals exhibited higher rambling velocity and greater signal complexity (SampEn), indicating a more flexible and internally organized control structure, even when overt sway amplitude remained comparable. In the dance-specific contra check position, clear condition- and expertise-dependent adaptations emerged. The female role imposed the highest postural demands, as evidenced by increased sway velocity and greater corrective amplitude and velocity. Importantly, professionals did not increase the frequency of corrections but instead modulated their amplitude and velocity, suggesting a more efficient and selective corrective strategy. The partnered condition was characterized by a relatively greater TR contribution and lower corrective amplitude and velocity. Entropy remained stable across task conditions, suggesting comparable regularity of the COP signal between conditions. From a practical perspective, the present findings suggest that balance training in ballroom dancers should consider the specific postural demands associated with different dance configurations. The greater postural demands observed in the female solo contra check suggest that this position may require additional emphasis during training, whereas the distinct postural-control characteristics of the partnered condition highlight the importance of incorporating both individual and partnered practice into regular training.

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