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Postural Control 2-1 s Before Firing as a Marker of Low-Score Risk in Elite Women's 25 m Pistol Shooting

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Abstract

Background

Postural control is important for precision shooting, but absolute center of pressure values may reflect individual strategies. This study examined whether shot-specific deviations from each athlete's usual postural control before firing were associated with shot score and low-score risk in elite women's 25 m pistol shooting.

Methods

Thirteen elite shooters completed two simulated matches, providing 778 Precision Stage shots. Shot score and aiming variables were recorded using an optoelectronic system, while center of pressure variables, including ellipse area (EA), were obtained from a plantar pressure plate. Signed deviation scores were calculated for the final 1–0 s and preceding 2–1 s window. Fixed effects, mixed effects, and generalized estimating equation models examined shot score and athlete-specific low-score thresholds.

Results

The 2–1 s model showed modestly better fit than the 1–0 s model. Deviations during the final 1–0 s were not clearly associated with shot score. In contrast, larger-than-usual EA during the 2–1 s window was associated with lower shot score in fixed effects models (β = −0.364, 95% CI − 0.615 to − 0.113, p = 0.008) and mixed effects models (β = −0.360, 95% CI − 0.599 to − 0.121, p = 0.003). Each 1 SD increase in EA deviation was associated with 1.155 to 1.260 times higher odds of low-score shots. Predicted probability increased by 3.57 to 7.28 percentage points from 0 SD to + 2 SD.

Conclusions

Larger than usual EA during the 2–1 s window before firing was associated with poorer outcomes, supporting an individualized approach to interpreting postural control in pistol shooting.

1 Introduction

Women's 25 m pistol is an Olympic shooting event that requires highly precise coordination among postural regulation, aiming stability, and trigger execution[1–3]. Prior shooting research has also linked postural balance, aiming behavior, and performance[4, 5]. In the qualification phase, athletes complete both a Precision Stage and a Rapid Fire Stage. During the Precision Stage, shots are fired at a 25 m target, where the diameter of the 10 ring is only 50 mm[6]. The shooter holds the pistol with the shooting arm extended while maintaining an upright stance. Under these conditions, small disturbances in body

orientation or balance may affect the alignment among the shooter, pistol, and target, thereby influencing shot accuracy[7–9].

Postural control is an established component of skilled shooting performance[10–12]. Experienced and elite shooters generally show better postural stability and more effective regulation of body sway before firing[3, 13]. Accordingly, center-of-pressure and body-sway measures are commonly used to quantify the stability of the support system during aiming and shot execution[3]. This evidence has largely supported an absolute stability interpretation, in which reduced sway is considered favorable for shooting performance. However, sway–performance relationships may differ across athletes and may be stronger within athletes than between athletes[4]. The same absolute COP value may therefore have different performance meanings for different shooters.

Elite shooters may develop distinct yet stable postural control strategies through prolonged training[12, 14, 15]. Consequently, the same absolute COP value may represent a habitual pattern for one athlete but an atypical fluctuation for another. When raw COP values are analysed without separating stable between-athlete differences from shot-to-shot variation within athletes, individual characteristics may obscure the fluctuations most relevant to immediate performance and make a common “less sway is better” criterion misleading[16, 17]. This limitation is particularly important in elite shooting, where performance differences are small and detecting subtle departures from an athlete’s established preparation pattern may be more informative than comparing athletes against a single absolute standard.

On this basis, the present study examined whether shot-to-shot departures from an athlete’s own postural control pattern before firing were related to performance in elite women’s 25 m pistol shooting. Athlete-specific deviation scores were calculated for the final 1–0 s and preceding 2–1 s windows to determine whether their performance relevance differed across the period before firing. We then examined whether deviations in the more informative window were associated with shot score after adjustment for key aiming-related covariates and with low-score risk defined within each athlete’s own performance distribution. We hypothesized that larger positive deviations from an athlete’s usual control pattern before firing would be associated with lower shot score and higher low-score risk.

2 Methods

2.1 Participants

Thirteen elite female 25 m pistol shooters voluntarily participated in this study (age 20.00 ± 2.74 years, body mass 60.77 ± 6.50 kg, training experience 8.85 ± 2.44 years). All athletes regularly competed at the international level and had extensive high-level competitive experience. On average, the athletes fired more than 25,000 shots per year. Data were collected during the 2025 season at an elite training camp using two simulated matches separated by one day. All participants were informed of the aims and procedures before testing and provided written informed consent. All procedures were conducted in

accordance with the Declaration of Helsinki and were approved by the Sports Science Experiment Ethics Committee of Beijing Sport University (approval no. 2025617H).

2.2 Measures

Shooting Technique and Performance Measures

We used an optoelectronic shooting training device (SCATT MX-W2, 34 × 35 × 60 mm) to measure shooting technique parameters and scores (Lang & Zhou, 2024). The SCATT device was mounted below the pistol barrel using a specialized bracket (total weight 56 g). It recorded each shot's score as a decimal ring value as well as various aiming trace parameters, and it connected wirelessly to a computer via Wi-Fi (2.4 GHz, 20 MHz bandwidth). Shot score was analysed as the decimal ring value exported from the SCATT system and used as a continuous performance outcome. All data were stored in the SCATT Expert software and were later exported for analysis.

Postural Control Measures

A Footscan pressure plate system (Footscan 1.0, RSscan, Belgium) was used to measure postural control variables (Lang & Zhou, 2024). The system was used to compute COP metrics from plantar pressure data, including COP ellipse area (EA), the minor-to-major axis ratio of the fitted COP ellipse, and COP path length in the perpendicular, shooting, and total directions. COP data were extracted for the 1–0 s and 2–1 s windows before each shot. EA was calculated from the fitted COP trajectory within each window, and COP path length was calculated as the cumulative length of the COP trajectory[18]. The x axis represented the direction perpendicular to shooting, whereas the y axis represented the shooting direction. A sensitive microphone was placed in the shooting area to capture the sound of each shot. The audio signal was visually inspected to identify the firing timestamp. SCATT and Footscan recordings were aligned to this timestamp. All analysis windows were defined relative to the firing timestamp.

2.3 Design and Procedures

The protocol consisted of two simulated qualification matches performed on separate days. Under ISSF rules, the Women's 25 m pistol qualification event comprises 30 shots in the Precision Stage and 30 shots in the Rapid Fire Stage. In the present study, only Precision Stage shots from the two simulated matches were included. The protocol was designed to obtain 60 Precision Stage shots per athlete (30 shots per match), corresponding to 780 planned shots in total. After excluding two shots lost because of device recording failure, 778 valid shots were retained for analysis. All testing was conducted on an indoor 25 m range in accordance with the official ISSF rules and regulations for the Women's 25 m pistol event.

2.4 Statistical Analysis

All analyses were performed in R. Continuous variables are presented as mean ± standard deviation. For descriptive purposes, intraclass correlation coefficients were calculated using random intercept null models to quantify the proportion of variance attributable to differences between athletes, with the

remaining variance interpreted as shot-to-shot variation within athletes[19]. To quantify deviation from each athlete's habitual control pattern, postural control variables were expressed as athlete-specific deviation scores:

ICC = σ²_between-athlete / (σ²_between-athlete + σ²_within-athlete)

Xdev_ij = X_ij - $\bar{X}$_i

where X_ij is the value of a given postural control variable for shot j in athlete i, and $\bar{X}$_i is that athlete's mean value for the same variable across all valid shots (Marineau et al., 2024; Nakagawa et al., 2017).

Technical covariates were selected using athlete fixed effects linear models with shot score as the dependent variable. Candidate covariate sets included aiming-related variables, the distance between the firing point and the mean aiming point (DA) and aiming time (T). Aim10 was defined as the proportion of aiming time spent inside the 10-ring during the final 1–0 s before firing. Models were compared using AIC, BIC, adjusted R^2, parsimony, and sport-specific interpretability. The final technical adjustment set was then applied consistently in subsequent models.

To compare the relative informativeness of the two windows before firing, window-specific fixed effects models were fitted using a symmetric modelling structure. The Window 1 model included EA1dev, sp1dev, COP1dev, the retained technical covariates, and athlete fixed effects. The Window 2 model included EA2dev, sp2dev, COP2dev, the retained technical covariates, and athlete fixed effects. Window 1 was defined as the final 1–0 s before firing, and Window 2 was defined as the preceding 2–1 s before firing. Window selection was based on model fit indices and interpretability. If one window showed clearly superior model fit, that window was prioritized for the primary analysis; if the differences were modest, both windows were retained and interpreted as window-specific analyses.

Associations between postural control deviations and continuous shot score were estimated using athlete fixed effects linear models with cluster robust standard errors at the athlete level. In the continuous shot score models, postural deviation variables and technical covariates were entered in their original units; therefore, coefficients are interpreted in the units shown in Table 1. For the retained or window-specific models, the postural control deviation variables were entered together with the retained technical covariates and athlete fixed effects. Because the number of athlete clusters was limited (n = 13), corresponding linear mixed effects models with athlete as a random intercept were fitted to examine whether the direction and magnitude of the estimates were consistent under an alternative repeated measures modelling framework[20].

R_ij = β_0 + β_1EAdev_ij + β_2spdev_ij + β_3COPdev_ij + β_4Aim10_ij + β_5DA_ij + β_6T_ij + α_i + ε_ij

where R_ij denotes the decimal shot score for shot j in athlete i, alpha_i denotes athlete fixed effects, and epsilon_ij is the residual error term. Window-specific models used the corresponding Window 1 or Window 2 deviation variables.

Low-score risk was analysed using generalized estimating equation logistic models with athlete-specific thresholds[21]. For each athlete, low-score shots were defined as scores equal to or below the individual mean minus 0.50, 0.75, 1.00, 1.25, or 1.50 within athlete standard deviations. These thresholds were used to examine whether the association was consistent across increasingly stringent definitions of relatively poor shots within each athlete's own score distribution. Athlete identity was specified as the clustering variable, and an independence working correlation structure was used as the primary specification.

$LowScore_{ijk} = 1$ if $R_{ij} \leq \bar{R}_i - k \times SD_i(R)$, and 0 otherwise

$k \in \{0.50, 0.75, 1.00, 1.25, 1.50\}$

In the primary GEE models, EA2dev, sp2dev, COP2dev, Aim10, DA, and T were included as predictors. All predictors were standardized in the main models, and odds ratios were reported per 1 standard deviation increase in EA2dev. To aid practical interpretation, EA2dev was additionally modelled in its original unit while the remaining covariates were standardized; odds ratios were expressed per 0.05, 0.10, and 0.15 mm^2 increases in EA2dev. These unit-specific odds ratios were derived from the same EA2dev coefficient within each threshold model.

$$\text{logit}[P(LowScore_{ijk} = 1)] = \beta_0 + \beta_1 EA2dev_{ij} + \beta_2 sp2dev_{ij} + \beta_3 COP2dev_{ij} + \beta_4 Aim10_{ij} + \beta_5 DA_{ij} + \beta_6 T_{ij}$$

$$OR_{\Delta} = \exp(\beta_{EA2dev} \times \Delta)$$

Model estimated low-score probabilities were calculated across representative EA2dev levels from − 1 standard deviation to + 2 standard deviations, with other standardized covariates held at their sample means. The absolute change in estimated probability from 0 standard deviations to + 2 standard deviations was used to describe the risk gradient associated with increasing EA above each athlete's habitual level during the 2–1 s window.

$$\Delta p = p(EA2dev = +2\ SD) - p(EA2dev = 0\ SD)$$

For the low-score analyses, robustness was examined using leave-one-athlete-out refitting, alternative GEE working correlation structures, and model specification sensitivity analyses. These analyses were used to assess whether the direction and magnitude of the EA2dev estimate were consistent given the limited number of athlete clusters. The model specification analyses compared EA2dev-only models, technically adjusted models including Aim10, DA, and T, and full Window 2 models including EA2dev, sp2dev, COP2dev, Aim10, DA, and T. Results were interpreted based on effect direction, magnitude, confidence intervals, and consistency across model specifications. Two-sided P values were reported, with $P < 0.05$ considered statistically significant (Liang & Zeger, 1986).

3 Results

3.1 Descriptive Statistics

The testing protocol was designed to include 780 Precision Stage shots in total. Two shots were lost because of device recording failure during data acquisition. Therefore, a total of 778 valid shots from 13 elite female 25 m pistol shooters were retained for the final analyses. Descriptive statistics for all performance, technical, and postural control variables are presented in Table 1.

Table 1
Descriptive statistics of the study variables (N = 778)

Component	Variable	Mean ± SD	ICC	Between athlete variance, %	Within athlete variance, %
Performance	R (decimal score)	9.957 ± 0.590	0.075	7.5	92.5
Time	T (s)	6.339 ± 2.423	0.443	44.3	55.7
Aiming related variables	Aim9a0 (proportion)	0.988 ± 0.054	0.067	6.7	93.3
Aiming related variables	Aim10a0 (proportion)	0.827 ± 0.165	0.308	30.8	69.2
Aiming related variables	Aim10.5a0 (proportion)	0.388 ± 0.176	0.267	26.7	73.3
Aiming related variables	DA (mm)	22.477 ± 16.422	0.112	11.2	88.8
Aiming related variables	Aim10 (proportion)	0.517 ± 0.275	0.176	17.6	82.4
Aiming related variables	Aim10.5 (proportion)	0.171 ± 0.161	0.108	10.8	89.2
Postural control during 1–0 s before firing	EA1 (mm²)	0.068 ± 0.225	0.020	2.0	98.0
Postural control during 1–0 s before firing	(s/p)1	0.494 ± 0.197	0.074	7.4	92.6
Postural control during 1–0 s before firing	COPx1 (mm)	0.450 ± 0.500	0.133	13.3	86.7
Postural control during 1–0 s before firing	COPy1 (mm)	0.220 ± 0.420	0.094	9.4	90.6
Postural control during 1–0 s before firing	COP1 (mm)	0.549 ± 0.620	0.116	11.6	88.4
Postural control during 2–1 s before firing	EA2 (mm²)	0.096 ± 0.223	0.631	63.1	36.9
Postural control during 2–1 s before firing	(s/p)2	0.479 ± 0.191	0.073	7.3	92.7

Component	Variable	Mean ± SD	ICC	Between athlete variance, %	Within athlete variance, %
Postural control during 2–1 s before firing	COPx2 (mm)	0.490 ± 0.530	0.114	11.4	88.6
Postural control during 2–1 s before firing	COPy2 (mm)	0.200 ± 0.230	0.065	6.5	93.5
Postural control during 2–1 s before firing	COP2 (mm)	0.556 ± 0.547	0.115	11.5	88.5

Variable definitions are provided in the Methods section.

3.2 Technical and Window Screening

Model fit comparison of candidate technical covariate sets showed that models including Aim10 and DA consistently provided favourable fit statistics. The model including Aim9a0, Aim10, DA, and T showed the lowest AIC among the representative candidate sets (AIC = 1106.420, BIC = 1185.590, adjusted R^2 = 0.317), whereas the model including Aim9a0, Aim10, and DA showed a similar AIC and the lowest BIC (AIC = 1106.560, BIC = 1181.060, adjusted R^2 = 0.316). The more parsimonious model including Aim10, DA, and T retained comparable fit (AIC = 1109.370, BIC = 1183.880, adjusted R^2 = 0.313) while avoiding additional overlap among aiming-related variables. Therefore, based on model fit, parsimony, and sport-specific interpretability, Aim10 + DA + T was retained as the common technical adjustment set for subsequent models. The full technical covariate screening results are provided in Supplementary Table S1.

Using the retained technical adjustment set, two symmetric window-specific fixed effects models were compared to evaluate the relative informativeness of the final 1–0 s window and the preceding 2–1 s window before firing. The Window 2 model showed lower AIC and BIC values and a slightly higher adjusted R^2 than the Window 1 model. Specifically, the Window 2 model showed AIC = 1104.890, BIC = 1193.370, and adjusted R^2 = 0.320, compared with AIC = 1112.790, BIC = 1201.270, and adjusted R^2 = 0.313 for the Window 1 model. Because the model fit difference was modest but consistently favoured Window 2, Window 2 was prioritized for the primary analyses, while Window 1 was retained as a window-specific comparison in the continuous shot score analyses.

Table 2
Model-fit comparisons for technical covariate screening and pretrigger windows Panel A. Representative technical covariate sets

Predictors	AIC	BIC	Adjusted R^2
Aim9a0 + Aim10 + DA + T	1106.42	1185.59	0.317
Aim9a0 + Aim10 + DA	1106.56	1181.06	0.316
Aim10 + DA + T	1109.37	1183.88	0.313
Aim10 + DA	1110.58	1180.43	0.312
Aim10.5 + DA + T	1160.01	1234.52	0.267
Aim10.5a0 + DA + T	1263.50	1338.01	0.163
Aim10a0 + DA + T	1266.47	1340.98	0.160
Panel B. Window-specific postural control models			

Window specific model	AIC	BIC	Adjusted R^2
Window 1, during 1–0 s before firing	1112.79	1201.27	0.313
Window 2, during 2–1 s before firing	1104.89	1193.37	0.320

AIC = Akaike information criterion; BIC = Bayesian information criterion.

3.3 Window-Specific Associations Between Postural Control Deviations and Shot Score

The Window 1 fixed effects model showed that postural control deviation variables during the final 1–0 s before firing were not significantly associated with shot score after adjustment for the retained technical covariates and athlete fixed effects. EA1dev was not associated with shot score (β = 0.110, 95% CI: -0.260 to 0.481, p = 0.529). Similarly, sp1dev (β = 0.072, 95% CI: -0.218 to 0.362, p = 0.599) and COP1dev (β = 0.009, 95% CI: -0.156 to 0.174, p = 0.909) showed no significant associations with shot score. Among the retained technical covariates, Aim10 was positively associated with shot score, whereas DA was negatively associated with shot score. T did not reach statistical significance.

The corresponding linear mixed effects model produced similar estimates and effect directions. EA1dev remained not significantly associated with shot score (β = 0.110, SE = 0.109, 95% CI: -0.103 to 0.324, p = 0.313). sp1dev (β = 0.074, SE = 0.111, 95% CI: -0.143 to 0.291, p = 0.504) and COP1dev (β = 0.011, SE = 0.047, 95% CI: -0.082 to 0.103, p = 0.821) also remained not significantly associated. These findings indicate that deviations from each athlete's habitual control pattern during the final 1–0 s window were not clearly associated with shot score. The full Window 1 estimates are presented in Table 3.

Table 3
Window 1 models for shot score

Predictor	Fixed-effects model			Linear mixed-effects model				
	β	95% CI	p value	β	SE	df	95% CI	p value
EA1dev	0.110	-0.260 to 0.481	0.529	0.110	0.109	764.334	-0.103 to 0.324	0.313
sp1dev	0.072	-0.218 to 0.362	0.599	0.074	0.111	763.794	-0.143 to 0.291	0.504
COP1dev	0.009	-0.156 to 0.174	0.909	0.011	0.047	764.225	-0.082 to 0.103	0.821
Aim10	0.940	0.743 to 1.137	< 0.001	0.930	0.069	732.903	0.794 to 1.066	< 0.001
DA	-0.009	-0.013 to -0.006	< 0.001	-0.009	0.001	776.353	-0.012 to -0.007	< 0.001
T	-0.016	-0.038 to 0.007	0.152	-0.010	0.009	307.957	-0.027 to 0.007	0.244

In contrast, the Window 2 fixed effects model showed that EA2dev was negatively associated with shot score after adjustment for sp2dev, COP2dev, Aim10, DA, T, and athlete fixed effects (β = -0.364, 95% CI: -0.615 to -0.113, p = 0.008). COP2dev was positively associated with shot score (β = 0.100, 95% CI: 0.025 to 0.175, p = 0.013), whereas sp2dev was not significantly associated with shot score (β = 0.033, 95% CI: -0.151 to 0.217, p = 0.701). Among the retained technical covariates, Aim10 was positively associated with shot score, whereas DA was negatively associated with shot score. T did not reach statistical significance.

The Window 2 linear mixed effects model produced similar estimates and effect directions. EA2dev remained negatively associated with shot score (β = -0.360, SE = 0.122, 95% CI: -0.599 to -0.121, p = 0.003), and COP2dev remained positively associated with shot score (β = 0.101, SE = 0.044, 95% CI: 0.014 to 0.187, p = 0.023). sp2dev was not significantly associated with shot score (β = 0.035, SE = 0.113, 95% CI: -0.186 to 0.257, p = 0.754). These consistent estimates supported the robustness of the Window 2 findings under an alternative repeated measures modelling framework. The full Window 2 estimates are presented in Table 4.

Table 4
Window 2 models for shot score

Predictor	Fixed-effects model			Linear mixed-effects model				
	β	95% CI	p value	β	SE	df	95% CI	p value
EA2dev	-0.364	-0.615 to -0.113	0.008	-0.360	0.122	758.560	-0.599 to -0.121	0.003
sp2dev	0.033	-0.151 to 0.217	0.701	0.035	0.113	758.300	-0.186 to 0.257	0.754
COP2dev	0.100	0.025 to 0.175	0.013	0.101	0.044	758.160	0.014 to 0.187	0.023
Aim10	0.931	0.729 to 1.132	< 0.001	0.921	0.069	735.010	0.786 to 1.057	< 0.001
DA	-0.010	-0.014 to -0.006	< 0.001	-0.010	0.001	769.930	-0.012 to -0.007	< 0.001
T	-0.018	-0.041 to 0.005	0.111	-0.012	0.009	333.400	-0.029 to 0.005	0.166

Sensitivity analyses were consistent with the primary Window 2 findings. Leave-one-athlete-out analyses showed that the negative association between EA2dev and shot score and the positive association between COP2dev and shot score were preserved after excluding each athlete in turn. The window-by-deviation interaction analysis suggested a stronger negative EAdev association in Window 2 than in Window 1, although the interaction was marginal and did not reach conventional statistical significance. No meaningful interaction was observed for spdev or COPdev. Full sensitivity results are provided in Supplementary Tables S2-S5.

3.4 Window 2 Deviation From Habitual Control Pattern and Low-Score Risk

The standardized GEE models showed that greater EA2dev was consistently associated with higher low-score odds defined within each athlete's own score distribution across all threshold definitions (Fig. 1A). Each 1 SD increase in EA2dev was associated with 1.155 to 1.260 times higher odds of low-score shots. This association was statistically significant across all thresholds, with ORs of 1.155 for k = 0.50, 1.256 for k = 0.75, 1.243 for k = 1.00, 1.211 for k = 1.25, and 1.260 for k = 1.50.

To facilitate interpretation in the original measurement scale, EA2dev was additionally expressed as raw unit increments (Fig. 1B). Across threshold definitions, each 0.05 mm² increase in EA2dev was associated with 1.050 to 1.070 times higher odds of low-score shots. When expressed per 0.10 mm² and 0.15 mm² increases, the corresponding odds ratios ranged from 1.090 to 1.150 and from 1.140 to 1.240, respectively. These associations remained statistically significant across all threshold definitions.

Model estimated low-score probabilities further demonstrated a graded increase across EA2dev levels (Fig. 1C). At 0 SD, the estimated low-score probability ranged from 6.8% to 24.5%, depending on the threshold definition. When EA2dev increased to + 2 SD, the corresponding probability increased to 10.3% to 30.2%. Compared with the 0 SD reference level, + 2 SD EA2dev was associated with an absolute increase of 3.57 to 7.28 percentage points in estimated low-score probability. The largest absolute increase was observed at k = 0.75, where the estimated probability increased from 16.5% at 0 SD to 23.8% at + 2 SD.

Sensitivity analyses supported the stability of the low-score GEE findings. Leave-one-athlete-out analyses showed that the positive association between EA2dev and low-score odds was preserved across all threshold definitions. Alternative GEE working correlation structures produced directionally consistent estimates, except for one exchangeable model at k = 1.00 that showed numerical instability and was not interpreted. Model specification analyses showed that the EA2dev association was weakest when entered alone, became stronger after technical adjustment, and was most consistent in the full Window 2 model. Full sensitivity results are provided in Supplementary Tables S6-S10.

The individualized deviation approach is summarized conceptually in Fig. 2.

4 Discussion

The main finding of this study was that larger-than-usual EA during the 2–1 s window was associated with shooting performance in elite women's 25 m pistol shooters. Deviations during the final 1–0 s window before firing were not clearly related to shot score, whereas larger than usual EA during the preceding 2–1 s window was associated with lower shot score. Larger EA2dev was also associated with higher risk of low-score shots defined within each athlete's own performance distribution. These findings support the relevance of an individualized deviation framework for postural control before firing among elite pistol shooters.

The present results are consistent with previous evidence that postural stability contributes to shooting performance, but they also suggest that EA contains substantial variation across athletes[12]. Previous studies have generally shown that reduced body sway is associated with better shooting performance[3]. For example, Era et al. reported that experienced shooters were better able to stabilize posture during the final seconds before the shot[13], and Sundaram et al. showed that stability-related technical components are associated with shooting performance[3]. However, the large variance across athletes in EA2 observed in the present study suggests that absolute COP magnitude may partly reflect individualized postural control strategies rather than instability alone[15, 16]. This interpretation is consistent with Ball et al., who reported that the relationships among body sway, aim point fluctuation, and performance differed across elite pistol shooters[4]. Thus, in elite shooting, the functional meaning of postural sway may be specific to each athlete rather than uniform across all athletes.

Building on this athlete-specific perspective, EA2dev reflects deviation from each athlete's habitual EA pattern during the 2–1 s window. The association between EA2dev and both shot score and low-score

risk suggests that EA above each athlete's habitual level may be relevant to performance. One possible explanation is provided by functional movement variability theory, which suggests that variability in skilled movement is not merely noise or error, but may reflect structured, task-relevant adjustments[16, 22]. In shooting, a certain degree of COP fluctuation may contribute to fine regulation of the shooter, pistol, and target system[23]. Accordingly, positive EA2dev values indicate EA above the athlete's habitual 2–1 s level rather than absolute sway magnitude alone.

The window-specific pattern suggests that the performance relevance of postural control before firing may not be confined to the final moment before firing. One possible explanation is that the 2–1 s and 1–0 s windows reflect different functional demands within the shooting sequence[24]. The 2–1 s window may correspond to the establishment of a control state that is ready for execution, in which postural support, sight alignment, pistol stabilization, and trigger preparation are organized before shot release[2, 15]. A larger EA2dev may therefore indicate that the shooter enters the final execution phase with an EA pattern that differs from her habitual preparatory state. By contrast, the final 1–0 s window is closer to shot release, when the athlete executes the shot on the basis of the already established support and aiming condition. Related evidence supports this window-based interpretation[1]. Goodman et al. identified two phases in aiming-point trajectories before firing in rifle shooting[25], and Köykkä et al. also highlighted that variables assessed close to triggering may reflect both stability and execution-related processes[23]. These findings suggest that the final seconds before firing should not be treated as a homogeneous period of postural control, but as functionally distinct windows within the shooting sequence[5, 24]. Given the exploratory nature of this interpretation and the limited evidence specific to the Precision Stage of elite women's 25 m pistol shooting, future studies should verify whether this pattern is reproducible and clarify how postural support, aiming control, pistol stabilization, and trigger execution are coordinated across the final windows before firing.

The positive association between COP2dev and shot score should be interpreted cautiously. This finding does not imply that greater postural movement is necessarily beneficial for shooting performance. EA and COP path length reflect different aspects of postural control[18]. EA2dev represents the spatial dispersion of the COP trajectory, whereas COP2dev reflects the total COP path length during the same window[18]. A larger COP2dev, after accounting for EA2dev and covariates related to aiming, may therefore reflect movement within a relatively controlled spatial area rather than a broader spread of postural sway. In elite shooters, such movement may represent small active adjustments used to maintain the support, aim, and trigger preparation state[14]. However, this result remains exploratory. Because variables derived from COP are mechanically related and were entered into the same multivariable model[26], the positive COP2dev coefficient may also reflect shared variance or a suppression-like effect rather than a direct beneficial role of COP path deviation[18]. Future studies should examine COP directionality, temporal structure, aiming point trajectories, pistol motion, and trigger execution together to clarify the functional meaning of COP path deviation.

5 Limitations

Several limitations should be noted. First, the sample included a small number of elite shooters, which may limit generalizability. Second, the study examined only the Precision Stage under simulated match conditions; therefore, the findings may not extend to the Rapid Fire Stage or official competitions. Third, trigger force, pistol kinematics, fatigue, recovery status, and psychological pressure were not directly measured, so the proposed control mechanisms remain exploratory. Finally, the observational design does not allow causal conclusions. Future studies should validate this deviation-based approach across more athletes, training days, and competition settings, and integrate COP measures with aiming, pistol motion, trigger-execution and athlete-state variables.

6 Conclusions and Practical Implications

In elite women's 25 m pistol shooters, larger-than-usual EA during the 2–1 s window before firing was associated with lower shot score and higher low-score risk. These findings support an individualized deviation framework for understanding postural control before firing in elite pistol shooting.

From a practical perspective, the present findings suggest that monitoring postural control before firing relative to each athlete's habitual control pattern may complement traditional assessments based on absolute sway magnitude[27]. In the models of low-score risk, larger positive EA2dev values during the 2–1 s window before firing were consistently associated with higher odds of low-score shots defined within each athlete's own performance distribution. Coaches may therefore benefit from establishing each athlete's own 2–1 s EA profile and monitoring shots or training sessions in which 2–1 s EA rises above the athlete's habitual level[28]. However, the applied use of EA2dev should be considered preliminary and should be validated across more athletes, training days, and competitive contexts before being used as a standalone monitoring metric[29].

Declarations

Ethics approval and consent to participate

The study was approved by the Sports Science Experiment Ethics Committee of Beijing Sport University (approval no. 2025617H). Written informed consent was obtained from all participants before participation.

Consent for publication

Not applicable.

Competing interests

The authors declare no conflicts of interest.

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Author Contribution

Author ContributionsY.W. conceived and designed the study. Y.W., M.W., R.L., and W.Y.W. contributed to data collection and data organization. Y.W. performed the data processing and statistical analysis and drafted the initial manuscript. M.W., R.L., and W.Y.W. contributed to interpretation of the findings and manuscript revision. Y.Z. and W.Q.W. supervised the study, acquired funding, provided methodological guidance, and critically revised the manuscript. All authors read and approved the final manuscript.

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Data Availability

All data have been included in the article or included as supplementary information.

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Figures

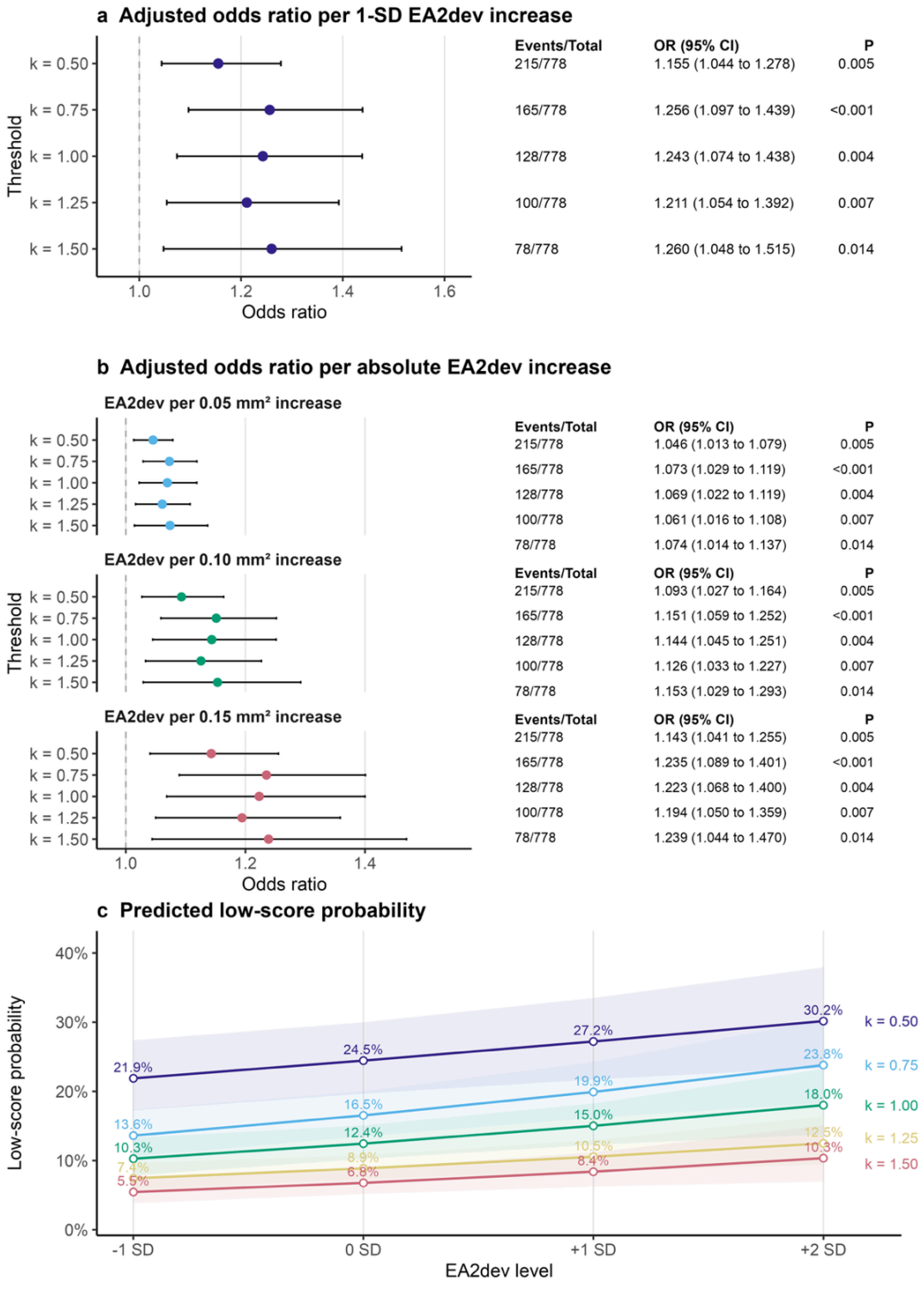


Figure 1

Odds-ratio estimates across thresholds and probabilities estimated from the model. Panel A shows standardized odds-ratio estimates for EA2dev, expressed per 1 SD increase. Panel B shows raw-unit odds-ratio estimates for EA2dev expressed per 0.05, 0.10, and 0.15 mm² increase. Panel C shows model-estimated probabilities of low-score shots across EA2dev levels from -1 SD to +2 SD, with other

standardized covariates held at their sample means. Thresholds for low-score shots were defined relative to each athlete's own score distribution.

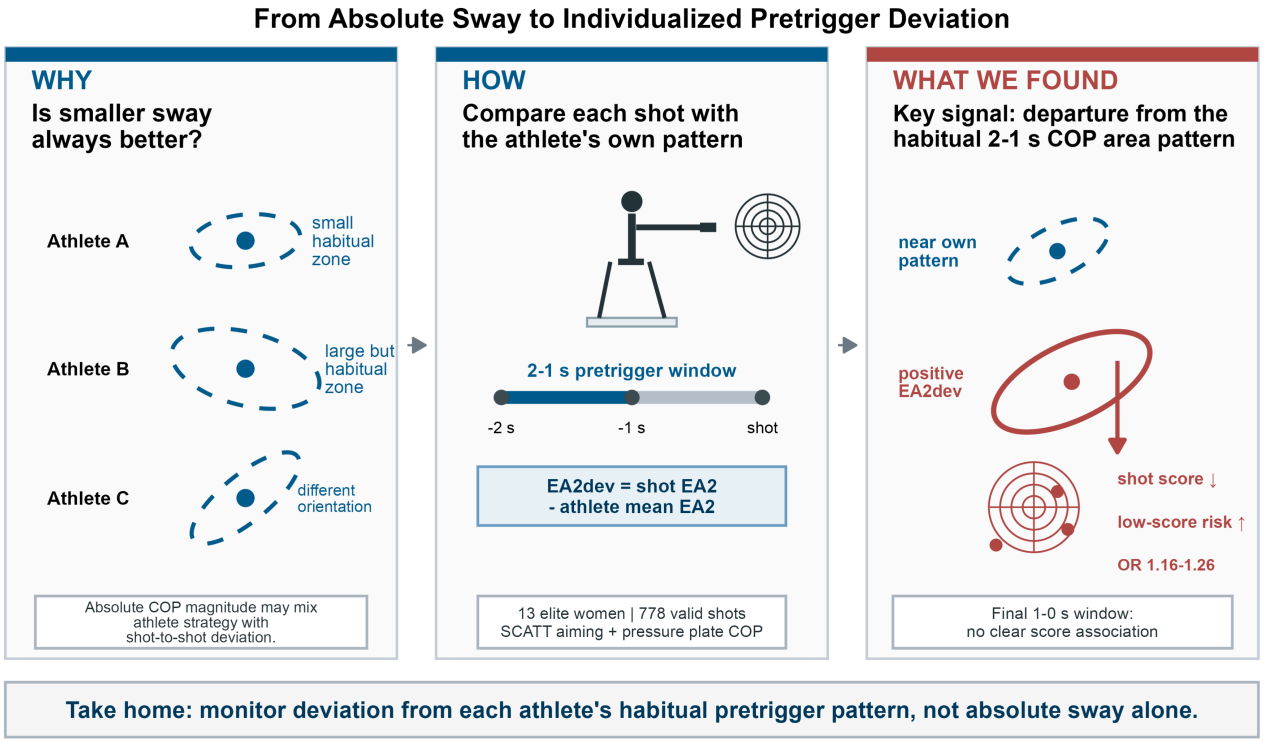


Figure 2

Conceptual framework of the individualized deviation approach. The figure summarizes why absolute sway magnitude may mix athlete-specific control strategies with shot-to-shot deviation, how EA2dev was calculated relative to each athlete's habitual EA pattern during the 2–1 s window, and how this deviation was related to shot score and low-score ris

Supplementary Files

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