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Original Scientific Article

Kinematic Characteristics Associated with Hit and Miss Outcomes in Elite Skeet Shooters: An Exploratory Study

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Purpose: This exploratory study investigated kinematic characteristics associated with successful (hit) and unsuccessful (miss) outcomes in elite Chinese skeet shooters, aiming to identify movement strategies that contribute to shooting success.
Methods: Video data were collected from five finalists of the Chinese national skeet team during internal qualification competitions for the Paris Olympics. Three cameras (50 Hz) recorded double-target trials at station 3. Each athlete contributed three successful and three unsuccessful trials. Four critical time points were analyzed: initiation of gun movement (T1), gun stock contact with the cheek (T2), first shot (T3), and second shot (T4). Variables included gun muzzle displacement and velocity, center of mass (COM) velocity, joint angles (shoulder, elbow, hip, knee), and stability/balance angles.
Results: At T2, hit shots exhibited significantly smaller gun displacement compared with missed shots (19.555±1.526cm vs. 22.496±2.375cm, $P<.001$, Cohen's d=-1.474), including both horizontal (17.279±1.266cm vs. 19.400±2.388cm, $P=.004$, Cohen's d=-1.110) and vertical components (9.081±1.480cm vs. 11.292±1.524cm, $P<.001$, Cohen's d=-1.427). Vertical velocity was also reduced (.247±.104m/s vs. .284±.099m/s, $P=.033$, Cohen's d=-.355). In addition, hit shots demonstrated a greater rear stability angle (13.580±1.841° vs. 13.100±1.750°, $P=.009$, Cohen's d=.267) and a smaller right elbow angle (70.840±3.363° vs. 72.937±2.710°, $P=.026$, Cohen's d=-.686). At T4, hit shots were characterized by a larger right knee angle (165.319±6.516° vs. 162.019±4.446°, $P=.032$, Cohen's d=.592) and a smaller right elbow angle (62.552±6.025° vs. 66.878±3.609°, $P=.013$, Cohen's d=-.871). Other joint angles and COM velocity showed no significant differences, though some variables indicated small to moderate effect sizes.
Conclusions: Effective skeet shooting is closely associated with reduced gun displacement and vertical velocity at T2, accompanied by a greater rear stability angle and a smaller right elbow angle. At T4, a larger right knee angle and a smaller right elbow angle further distinguished hit shots from misses. These findings highlight the importance of muzzle control, trunk posture, and upper limb configuration in enhancing shooting stability and mitigating recoil effects.

Keywords: skeet, shooting, gun motion, expertise, kinematics.

Introduction

Skeet shooting is an Olympic discipline that demands high levels of technical stability, psychological regulation, and performance in real-time[1]. Competitors must quickly track and intercept small, rapidly moving clay targets by executing coordinated actions, such as gun mounting, gun movement, firing, and follow-through, within a very brief timeframe[2]. Due to the targets' diminutive size and high initial velocity, skeet shooting necessitates extraordinary motor control and reaction speed from athletes[3,4]. Physiological tremor, as shown in studies of elite athletes, can serve as a sensitive marker of neuromuscular fatigue and motor control disruption, highlighting the importance of monitoring underlying neuromuscular mechanisms during high-precision sports [5]. Unlike static shooting disciplines such as pistol, rifle, or archery, skeet shooting is inherently dynamic, involving coordinated movements of the upper limbs, lower limbs, and trunk, while simultaneously maintaining balance and motion stability to effectively intercept swiftly moving targets [6]. From a broader sports biomechanics perspective, research on such high-performance, dynamic tasks aims not only to optimize movement efficiency and competitive success but also to reduce injury risk by improving movement quality and load distribution across the kinetic chain [7]. Previous studies have shown that minimizing unnecessary body and barrel movements enhances shooting precision, optimizes posture, and increases success rates [8,9].Consequently, examining the kinematic characteristics of athletes during the shooting phase in skeet provides valuable theoretical and practical insights into the biomechanical determinants of successful performance. Such knowledge can contribute to evidence-based technique refinement and support the development of targeted training strategies aimed at both performance enhancement and long-term athlete health.

Several studies have employed biomechanical approaches to analyze the movement characteristics of shooting sports and their relationship to performance from different perspectives. For example, Puglisi, et al. [10] used force platforms to collect six posture-related measures (center of pressure, COP) from skeet shooters of varying skill levels, including the standard deviation of COP in the medio-lateral (ML) and anterio-posterior (AP) directions, COP path length, and average sway velocity of COP. Their findings showed that elite shooters exhibited a significantly smaller 95% confidence ellipse area while maintaining posture, suggesting superior postural balance; good balance was associated with improved shooting performance. Similarly, Broďáni, et al. [11]highlighted that an optimal state of balance and stability helps reduce unwanted sway caused by holding and aiming the gun, resulting in a smoother and more stable sequence of actions (stance-gun mounting-aiming-firing). In addition, for static shooting disciplines like pistol and rifle, research has consistently shown that elite shooters demonstrate smaller body sway amplitudes during quiet standing and shooting tasks. This further supports the crucial role of postural balance in enhancing shooting precision [12-15].

Some scholars have examined the technical aspects of skeet shooting athletes to understand how technique influences performance. Hrybovskyy, et al. [16] created specialized hardware and software for athlete training and identified key indicators for practice, such as the distance from the aiming point to the target center, including horizontal and vertical components, along with relative and absolute velocity measures. Their research systematically established important metrics for evaluating skeet shooting technique. Causer, et al. [6] explored differences in gaze behavior and body kinematics across various shotgun disciplines (skeet, trap, and double trap), comparing elite and sub-elite shooters and successful and unsuccessful shots. They found that elite shooters demonstrated more controlled gun movements, with slower muzzle velocity, smaller displacement, and better timing strategies. Additionally, Guo, et al. [3] showed that skeet shooters who completed a six-week sport vision training (SVT) program experienced notable performance gains, including reduced peak velocity on the second shot, less gun displacement at that moment, and shorter reaction times. These results shed light on the technical traits of top-level athletes. Despite these insights, most research emphasizes external indicators like gun kinematics and lacks a comprehensive analysis of athletes' body movements. Also, many studies focus on general-level shooters rather than systematically studying international elite athletes. Furthermore, although empirical evidence linking technical performance to competition outcomes in real match scenarios remains limited, it should be noted that the data in the present study were collected during internal evaluation competitions rather than official international events. Importantly, these competitions directly determined athlete selection for the Chinese national skeet shooting team for the Paris Olympic Games, thereby representing a high-stakes selection context conducted under substantial competitive pressure and performance relevance.

The shooting outcome (hit versus miss) functions as a valuable grouping variable within kinematic analyses, facilitating the identification of potential technical causes and movement patterns that contribute to missed targets [17]. By comparing athletes' kinematic characteristics at key temporal points under both hit and miss conditions, it becomes feasible to more directly ascertain detailed factors that influence accuracy, thereby providing targeted insights for training enhancement. Although pistol-shooting studies have reported differences in barrel kinematics between elite and sub-elite shooters [15,18,19], such findings are difficult to translate to shotgun shooting because the fundamentally different task dynamics limit cross-discipline comparisons. This study conducted a descriptive analysis of several kinematic variables related to both the firearm and the athletes. Such analysis proves valuable in identifying fundamental differences underlying shooting outcomes and, consequently, in designing more effective training strategies to enhance athletic performance.

Materials and Methods

Participants

Kinematic analyses were conducted on five male elite Chinese skeet shooters (mean age: 26.0±3.0 years; height: 182.4±3.8 cm; body mass 97.4±11.4 kg; personal best qualification score over 125 targets: 122.0±.5). All athletes were members of the Chinese national skeet team with 10.0±3.7 years of professional training experience and practiced at least five times per week. Information regarding the athletes' birthdates, height, and personal best scores was obtained from the publicly accessible International Shooting Sport Federation [20] website. The inclusion criteria required that participants were active national team shooters competing in Olympic-level qualification events. Exclusion criteria included acute musculoskeletal injuries, overload syndromes, or medical conditions that could interfere with safe shooting performance. Athletes with a history of shoulder, elbow, or knee injuries that could influence gun stability and posture were also excluded. The video data analyzed were recorded during three internal evaluation competitions held in 2024 by the Chinese national skeet shooting team in Putian, Fujian Province. For each athlete, three successful double-target shots (both targets hit) and three unsuccessful shots (first target hit, second target missed) from station 3 were analyzed. Second-target misses were chosen because first-target misses were rare among elite shooters, consistent with previous reports [6], and they represent the most common failure mode, reflecting breakdowns in rapid transition and follow-through. Findings are therefore specific to second-target failures.

Data Collection

All data collection adhered to the procedures outlined by Causer, et al. [6]. Two fixed video cameras (Lumix GH5, Panasonic Corporation, Osaka, Japan; 50 Hz; shutter speed: 1/1000 s; ISO: 2000-4000; resolution: 1920×1080 pixels) were strategically positioned on the right side (Camera 1) and in front (Camera 2) of the shooting stand, each at a distance of 5 m and a height of 1.05 m (Figure 1A). Additionally, one video camera (FDR-AX700, Sony Corporation, Tokyo, Japan) was installed on the left side of the shooting stand to record whether each shot resulted in a hit or miss, thereby verifying the actual outcomes during the competition. All three cameras recorded synchronously for each shooting trial. Prior to and immediately after the competition, a rigid three-dimensional calibration frame containing 28 control points (Figure 1C D) was placed at the shooting stand to calibrate the camera system. During testing, the athletes donned standard shooting attire and protective eyewear and performed double-target shooting (both left and right targets) from station 3 in accordance with competition rules. To minimize potential bias caused by variations in shooting sequence, only the specific sequence of shooting the low target first, followed by the high target, was analyzed; this sequence is unique to the final round and presents a higher level of difficulty. The five participants in this study were all elite Chinese skeet shooters, among whom missed targets occurred far less frequently than hits. To ensure the balance of the dataset, video recordings of missed targets were collected by monitoring three internal team evaluation competitions, resulting in an equal number of miss trials for each athlete.

Data Analysis

Video files from Cameras 1 and 2 were imported into SIMI-Motion (version 9.2.2, Simi Reality Motion Systems GmbH, Germany). All video data were digitized once by a single operator following a standardized digitization protocol. To

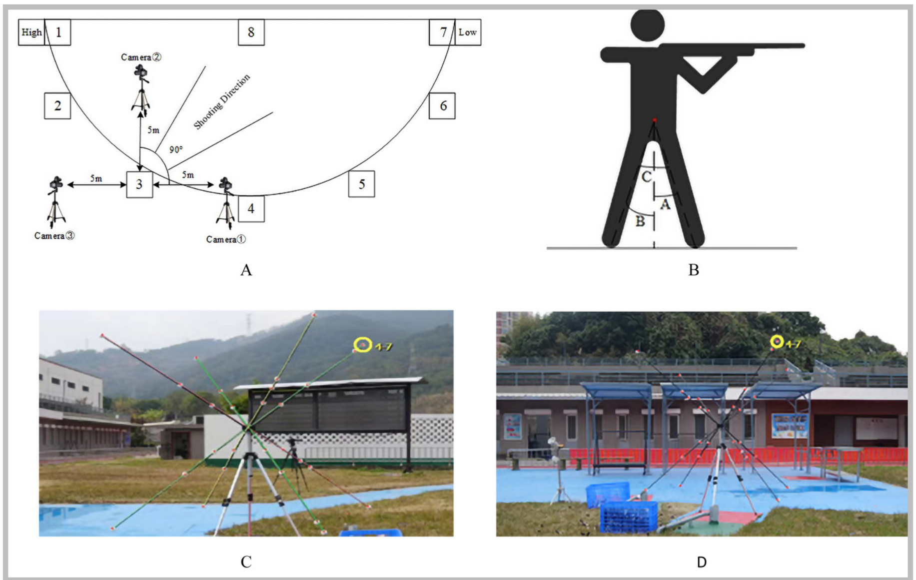

Figure 1. On-site shooting and data analysis workflow.

synchronize the two camera views, an event synchronization technique was applied, aligning four key moments of the shooting action: the initiation of gun movement [T1], the moment the stock contacted the cheek [T2], the first shot[T3], and the second shot[T4] (Figure 2). All video files were processed using the points-over-frame method [21]. Following the approach of Hanavan [22], a full-body model was constructed with 15 rigid segments; an additional two rigid segments were added to represent the shotgun. The digitized points included: the center of the head; the left and right shoulder, elbow, wrist, and metacarpophalangeal joints; the left and right hip, knee, ankle, and metatarsophalangeal joints; as well as the muzzle tip and rear end of the shotgun barrel. The digitization process covered every frame from T1 to T4, plus an additional five frames before T1 and five frames after T4 to serve as a buffer during filtering. Raw coordinate data were smoothed using a low-pass digital filter with a cut-off frequency of 6 Hz, following Kaiser, et al. [23]. The choice of 6 Hz was based on the relatively slow movement characteristics of the upper limb and firearm during skeet shooting, and is consistent with previous studies employing cut-off frequencies between 5-10 Hz for similar kinematic analyses[6]. Finally, three-dimensional coordinates were reconstructed from the x and y image coordinates of the two camera views using the Direct Linear Transformation (DLT) algorithm[24].

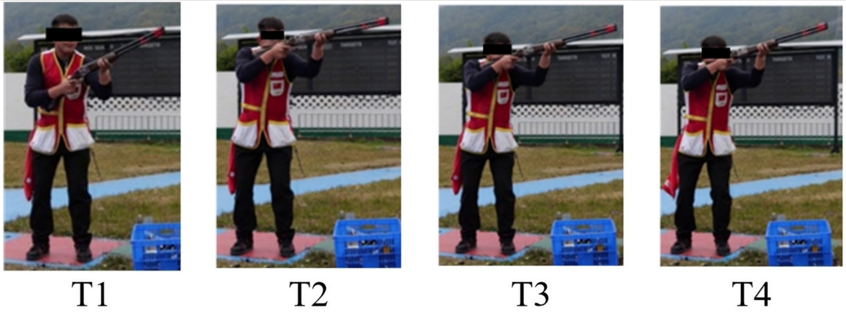

Figure 2. Skeet shooting technique phase diagram.
Notes. The initiation of gun movement (T1), contact of the gun stock with the cheek (T2), the first shot (T3), and the second shot (T4).

For subsequent analyses, three-dimensional coordinates-whether digitized or computed-were projected onto a two-dimensional sagittal plane utilizing only the anteroposterior and vertical coordinates. While specific analyses, such as sagittal-plane joint angles or projected COM-based balance angles, utilize two-dimensional projections for interpretability, all underlying kinematic data were derived from fully three-dimensional measurements. The center of mass (COM) position was estimated employing the rigid body segment parameter model introduced by Hanavan [22], and the COM velocity was subsequently derived from this data. Kinematics of the gun barrel, including movement velocity and displacement, were calculated from the positional data of the anterior endpoint of the barrel (i.e., the sight). Joint angles were defined and calculated as follows, utilizing the built-in functions of SIMI-Motion: the shoulder angle, formed by the line connecting the elbow, shoulder, and hip joints in the frontal plane; the elbow angle, formed by the line connecting the wrist, elbow, and shoulder joints in the sagittal plane; the hip angle, formed by the line connecting the shoulder, hip, and knee joints in the sagittal plane; and the knee angle, formed by the line connecting the hip, knee, and ankle joints in the sagittal plane. Additionally, three angles related to balance were computed: the front stability angle (A), which is the angle between the vertical projection line of the COM and the line connecting the COM to the anterior edge of the base of support (the tip of the left foot); the rear stability angle (B), which is the angle between the vertical projection line of the COM and the line connecting the COM to the posterior edge of the base of support (the tip of the right foot); and the overall balance angle (C), which is the sum of angles A and B (A + B)(Figure 1B).

Angles A and B were calculated using the following formula:

$$A^\circ = \arccos\left(\frac{z_{\mathrm{COM}} - z_L}{\sqrt{(x_L - x_{\mathrm{COM}})^2 + (z_L - z_{\mathrm{COM}})^2}}\right) \times \frac{180}{\pi}$$

$$B^{\circ} = \arccos\left(\frac{z_{\mathrm{COM}} - z_R}{\sqrt{(x_R - x_{\mathrm{COM}})^2 + (z_R - z_{\mathrm{COM}})^2}}\right) \times \frac{180}{\pi}$$

Where (xCOM, zCOM) denote the coordinates of the Centre of Mass (COM) within the sagittal plane, and (xL, zL) along with (xR, zR) represent the sagittal coordinates of the left and right toe tips, respectively. A larger front stability angle (A) signifies that the COM is situated further posteriorly relative to the anterior boundary (left toe), implying enhanced forward stability. Conversely, a smaller rear stability angle (B) indicates that the COM is positioned more anteriorly relative to the posterior boundary (right toe), which may suggest diminished backward stability.

Statistical analysis

All statistical analyses were conducted using Python 3.11 (Python Software Foundation, USA). Descriptive statistics (Mean ± SD) were summarized for each kinematic variable (e.g., front stability angle, rear stability angle, and balance angle) at four time points (T1-T4) under both hit and miss conditions. The normality of each variable was assessed using the Shapiro-Wilk test. Paired-sample t-tests were performed to compare hit and miss outcomes at each time point, accounting for within-subject repeated measures. Effect sizes for paired comparisons were quantified using Cohen's d. Temporal trends of kinematic variables under both conditions were visualized using bar charts. Due to the small sample size, all analyses were exploratory. Statistical significance was set at *P*<.05, and post-hoc statistical power was calculated for each paired comparison based on the observed effect size (Cohen's d), sample size, and an alpha level of .05 using G*Power.

Results

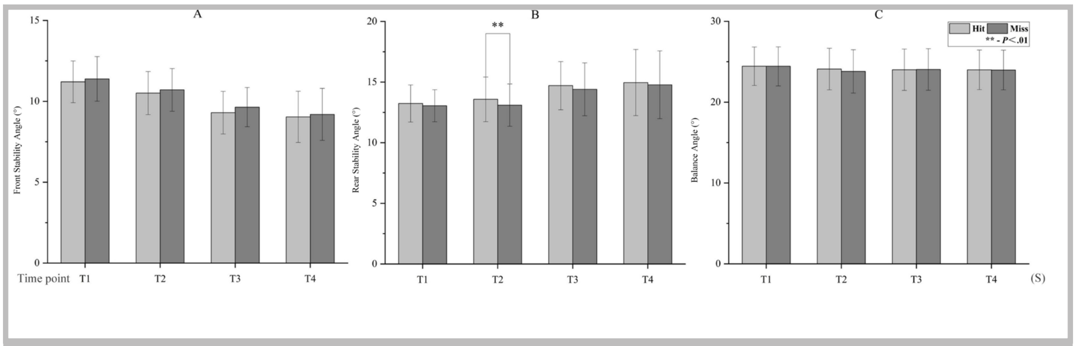

Figure 3. Kinematic parameters in skeet shooting, for front stability (A), rear stability (B), and balance (C) across T1-T4 time points.

The front stability angle (Figure 3A), rear stability angle (Figure 3B), and balance angle (Figure 3C) remained generally stable across T1-T4, with particularly small fluctuations observed in the balance angle. At T2, the rear stability angle under the hit condition was significantly greater than that under the miss condition (*P*<.01), while no significant differences were found at the other time points. The left (Figure 4A) and right (Figure 4B) knee joint angles remained relatively stable across T1-T4. The right knee angle was significantly greater in the hit condition than in the miss condition at T4 (*P*<.05). The left (Figure 4C) and right (Figure 4D) elbow joint angles increased during T2-T3 and decreased at T4. The right elbow angle was significantly smaller in the hit condition than in the miss condition at both T2 and T4 (*P*<.05). The left (Figure 4E) and right (Figure 4F) hip joint angles remained stable across T1-T4, with no significant differences between conditions. The left (Figure 4G) and right (Figure 4H) shoulder joint angles showed a marked increase at T2 and remained relatively stable from T2 to T4, with no significant differences between conditions.

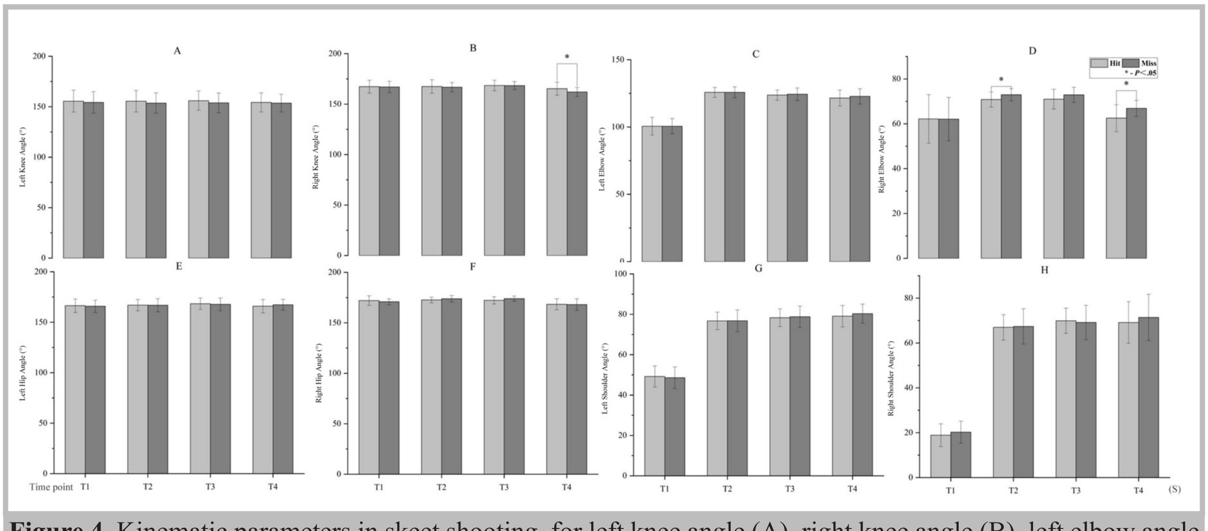

Figure 4. Kinematic parameters in skeet shooting, for left knee angle (A), right knee angle (B), left elbow angle (C), right elbow angle (D), left hip angle (E), right hip angle (F), left shoulder angle (G), and right shoulder angle (H) across T1-T4 time points.

Gun displacement (Figure 5A) and its horizontal (Figure 5B) and vertical (Figure 5C) components were significantly lower in the hit condition than in the miss condition at T2 (*P*<.01). Gun displacement and the horizontal component reached their maximum values at T4, whereas the vertical component decreased to its minimum at this time point. Gun velocity (Figure 6A) and its horizontal (Figure 6B) and vertical (Figure

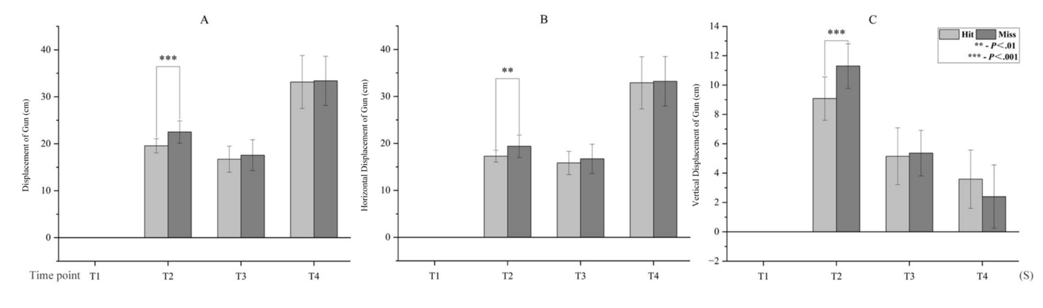

Figure 5. Kinematic parameters in skeet shooting, for displacement of the gun (A), horizontal displacement of the gun (B), and vertical displacement of the gun (C) across T1-T4 time points.

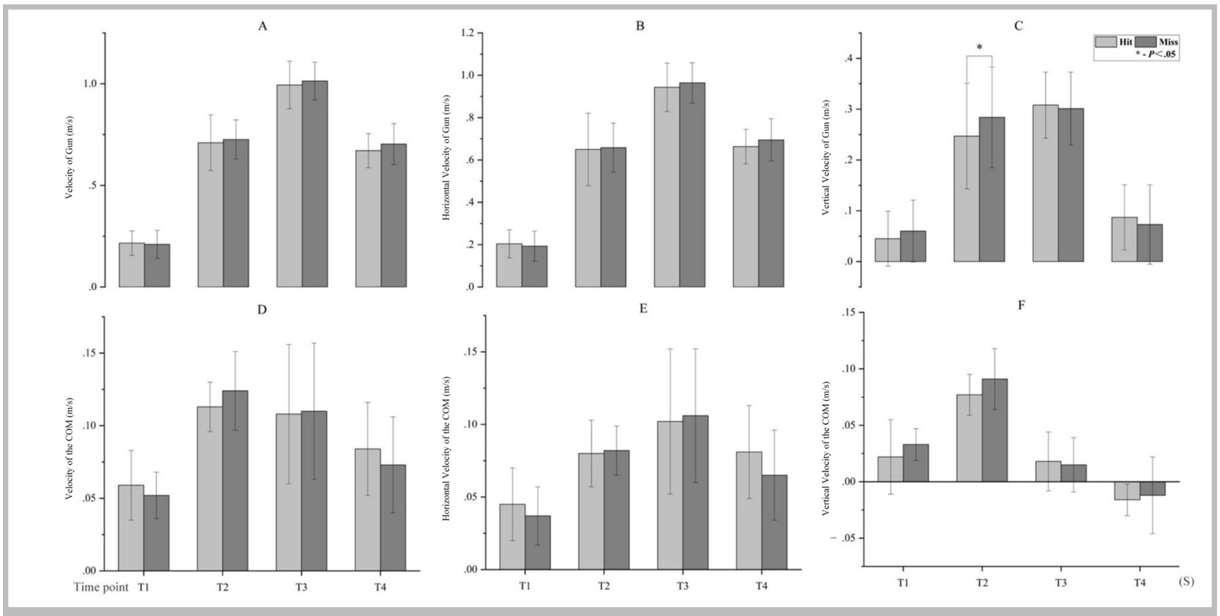

Figure 6. Kinematic parameters in skeet shooting, for velocity of the gun (A), horizontal velocity of the gun (B), vertical velocity of the gun (C), velocity of the center of mass (D), horizontal velocity of the center of mass (E), and vertical velocity of the center of mass (F) across T1-T4time points.

6C) components peaked during T2-T3. The vertical velocity was significantly lower in the hit condition than in the miss condition at T2 (*P*<.05), with no significant differences observed at the other time points. The velocity of the center of mass (Figure 6D) and its horizontal component (Figure 6E) were higher during T2-T3 and declined at T4. The vertical component (Figure 6F) reached a positive peak at T2, decreased at T3, and turned negative at T4, with no significant differences between conditions, where positive values indicate upward movement and negative values indicate downward movement.

Table 1 presents discrete spatial angle variables for the hit and miss outcomes at key time points (T1-T4). Regarding the front stability angle, no significant differences were observed (all *P*>.05). However, the most significant effect was noted at T3 (Cohen's d=-.269, *P*=.071), where the hit condition exhibited slightly lower values. Conversely, the rear stability angle was significantly higher in the hit condition at T2 (13.580±1.841° vs 13.100±1.750°; t=3.038, *P*=.009, Cohen's d=.267), with

Table 1. Comparison of discrete spatial angle variables (Mean ± SD) between hit and miss outcomes at key time points (T1–T4), with effect sizes (Cohen's d) and t-test results.

Variable	Time point	Outcome	Mean	SD	Cohen's d	t	*P*	*Post-hoc Power*	CI 95%	
Front stability angle(°)	T1	Hit	11.207	1.289	-.135	-1.036	.318	.056	-2.526	2.166
		Miss	11.387	1.381						
	T2	Hit	10.513	1.331	-.146	-1.202	.249	.058	-2.520	2.132
		Miss	10.707	1.318						
	T3	Hit	9.300	1.318	-.269	-1.954	.071	.076	-2.562	1.882
		Miss	9.640	1.210						
	T4	Hit	9.040	1.584	-.096	-.700	.495	.053	-2.954	2.648
		Miss	9.193	1.606						

Rear stability angle(°)	T1	Hit	13.233	1.532	.130	1.256	.230	.056	-2.326	2.698
		Miss	13.047	1.321						
	T2	Hit	13.580	1.841	.267	3.038	.009	.076	-2.674	3.634
		Miss	13.100	1.750						
	T3	Hit	14.706	1.984	.144	2.040	.061	.057	-3.363	3.963
		Miss	14.406	2.183						
	T4	Hit	14.960	2.731	.065	.831	.420	.052	-4.670	5.030
		Miss	14.780	2.793						
Balance angle(°)	T1	Hit	24.440	2.383	.003	.037	.971	.050	-4.206	4.220
		Miss	24.433	2.415						
	T2	Hit	24.093	2.575	.109	1.515	.152	.054	-4.331	4.903
		Miss	23.807	2.682						
	T3	Hit	24.007	2.555	-.016	-.220	.829	.050	-4.546	4.466
		Miss	24.047	2.577						
	T4	Hit	24.000	2.447	.011	.156	.878	.050	-4.281	4.335
		Miss	23.973	2.460						
Left knee angle(°)	T1	Hit	155.543	10.880	.120	.807	.433	.055	-17.617	20.211
		Miss	154.246	10.661						
	T2	Hit	155.517	10.644	.181	1.137	.275	.062	-16.337	20.099
		Miss	153.636	10.098						
	T3	Hit	156.011	9.634	.225	1.446	.170	.068	-14.887	19.271
		Miss	153.819	9.818						
	T4	Hit	154.314	9.447	.082	.517	.613	.052	-15.276	16.772
		Miss	153.566	8.792						
Right knee angle(°)	T1	Hit	167.281	6.477	.042	.177	.862	.051	-10.355	10.859
		Miss	167.029	5.570						
	T2	Hit	167.492	6.703	.121	.523	.609	.055	-9.436	10.838
		Miss	166.791	4.660						
	T3	Hit	168.474	5.220	.019	.088	.931	.050	-8.071	8.245
		Miss	168.387	3.990						
	T4	Hit	165.319	6.516	.592	2.383	.032	.177	-6.495	13.095
		Miss	162.019	4.446						
Left elbow angle(°)	T1	Hit	100.577	6.593	-.002	-.011	.992	.050	-10.776	10.754
		Miss	100.588	5.630						
	T2	Hit	125.729	3.755	-.008	-.029	.977	.050	-6.909	6.849
		Miss	125.759	4.074						
	T3	Hit	123.697	3.798	-.169	-.680	.508	.060	-8.120	6.698
		Miss	124.408	4.602						
	T4	Hit	121.523	5.968	-.213	-.936	.365	.066	-11.475	8.991
		Miss	122.765	5.683						

Right elbow angle(°)	T1	Hit	62.191	10.836	.010	.079	.938	.050	-17.951	18.151
		Miss	62.091	9.692						
	T2	Hit	70.840	3.363	-.686	-2.490	.026	.220	-7.460	3.266
		Miss	72.937	2.710						
	T3	Hit	71.008	4.389	-.492	-2.108	.054	.138	-8.774	4.930
		Miss	72.930	3.345						
	T4	Hit	62.552	6.025	-.871	-2.831	.013	.322	-13.046	4.394
		Miss	66.878	3.609						
Left hip angle(°)	T1	Hit	166.388	6.648	.083	.845	.412	.053	-10.648	11.708
		Miss	165.858	6.070						
	T2	Hit	166.976	5.642	.016	.094	.927	.050	-10.589	10.781
		Miss	166.880	6.498						
	T3	Hit	168.397	5.615	.101	.584	.569	.054	-9.881	11.083
		Miss	167.796	6.304						
	T4	Hit	165.963	6.669	-.228	-1.950	.071	.069	-12.017	9.259
		Miss	167.342	5.379						
Right hip angle(°)	T1	Hit	172.047	4.784	.291	1.059	.308	.080	-5.783	8.081
		Miss	170.898	2.878						
	T2	Hit	172.697	2.879	-.383	-1.442	.171	.103	-6.413	4.115
		Miss	173.846	3.112						
	T3	Hit	172.303	3.570	-.543	-1.655	.120	.157	-7.133	3.761
		Miss	173.989	2.550						
	T4	Hit	168.410	5.432	.054	.299	.769	.051	-9.545	10.157
		Miss	168.104	5.783						
Left shoulder angle(°)	T1	Hit	49.216	5.234	.114	.596	.560	.055	-8.651	9.849
		Miss	48.617	5.301						
	T2	Hit	76.750	4.324	-.007	-.041	.968	.050	-8.628	8.558
		Miss	76.785	5.403						
	T3	Hit	78.315	4.392	-.105	-.686	.504	.054	-9.062	8.042
		Miss	78.825	5.306						
	T4	Hit	79.104	5.343	-.246	-1.267	.226	.072	-10.090	7.610
		Miss	80.344	4.718						
Right shoulder angle(°)	T1	Hit	18.910	5.058	-.251	-1.076	.300	.073	-10.135	7.441
		Miss	20.257	4.951						
	T2	Hit	66.983	5.667	-.058	-.378	.711	.051	-12.430	11.630
		Miss	67.383	7.858						
	T3	Hit	69.936	5.628	.117	.640	.533	.055	-11.009	12.575
		Miss	69.153	7.650						
	T4	Hit	69.136	9.280	-.229	-1.974	.068	.069	-19.479	14.985
		Miss	71.383	10.319						

Notes. Values are presented as mean ± SD. Cohen's d represents the effect size for paired comparisons between hit and miss outcomes. Post-hoc power was calculated based on the observed effect size, sample size, and an alpha level of .05. T1 = initiation of gun movement; T2 = gun stock contact with the cheek; T3 = first shot; T4 = second shot.

no other time points demonstrating significance. Balance angle differences were negligible across all time points (all *P*>.05). Concerning knee angles, the right knee angle at T4 was significantly larger in the hit condition (165.319±6.516°) compared to the miss condition (162.019±4.446°; t=2.383, *P*=.032, Cohen's d=.592), whereas the differences in the left knee angles were not significant. Concerning elbow angles, the right elbow angle was significantly lower in the hit condition at T2 (t=-2.490, *P*=.026, Cohen's d=-.686) and T4 (t=-2.831, *P*=.013, Cohen's d=-.871), with a marginal difference observed at T3 (*P*=.054); differences in the left elbow angles were not significant. In terms of hip angles, no significant differences were detected, except for a trend toward a lower left hip angle in the hit condition at T4 (t=-1.950, *P*=.071). Shoulder angles remained statistically similar across conditions; however, a trend toward smaller right shoulder angles in the hit condition was observed at T4 (*P*=.068). Overall, notable differences primarily emerged for the rear stability angle at T2, the right knee angle at T4, and the right elbow angle at T2 and T4.

Table 2 presents the discrete spatial distance variables corresponding to hit and miss outcomes at the key time points (T1-T4). At T2, the displacement of the firearm was significantly lower in the hit condition (19.555±1.526cm) compared to the miss condition (22.496±2.375cm; t=-5.492, *P*<.001, Cohen's d=-1.474). Similarly, horizontal displacement at T2 was also significantly reduced in the hit condition (17.279±1.266cm) versus the miss condition (19.400±2.388cm; t=-3.409, *P*=.004, Cohen's d=-1.110). Vertical displacement at T2 followed the same pattern, being significantly lower in the hit condition (9.081±1.480cm) compared to the miss condition (11.292±1.524cm; t=-4.783, *P*<.001, Cohen's d=-1.472). At T3 and T4, no statistically significant differences were observed for total, horizontal, or vertical displacement between hit and miss conditions (all *P*>.05), although a slight nonsignificant trend toward higher vertical displacement in the hit condition was noted at T4 (*P*=.157). These findings suggest that differences in gun displacement, particularly at T2, may be associated with successful shooting performance.

Table 2. Comparison of discrete spatial distance variables (Mean ± SD) between hit and miss outcomes at key time points (T1–T4), with effect sizes (Cohen's d) and t-test results.

Variable	Time point	Outcome	Mean	SD	Cohen's d	t	*P*	*Post-hoc Power*	CI 95%	
Displacement of gun(cm)	T1	Hit	/	/	/	/	/	/	/	/
		Miss	/	/						
	T2	Hit	19.555	1.526	-1.474	-5.492	.000	.696	-6.446	.564
		Miss	22.496	2.375						
	T3	Hit	16.721	2.769	-.280	-1.445	.171	.078	-6.192	4.488
		Miss	17.573	3.291						
	T4	Hit	33.145	5.623	-.046	-.235	.818	.050	-9.791	9.295
		Miss	33.393	5.239						
Horizontal displacement of gun(cm)	T1	Hit	/	/	/	/	/	/	/	/
		Miss	/	/						
	T2	Hit	17.279	1.266	-1.110	-3.409	.004	.472	-5.477	1.235
		Miss	19.400	2.388						
	T3	Hit	15.843	2.476	-.315	-1.482	.161	.086	-5.814	4.046
		Miss	16.727	3.104						
	T4	Hit	32.905	5.559	-.058	-.290	.776	.051	-9.830	9.200
		Miss	33.220	5.274						
Vertical displacement of gun(cm)	T1	Hit	/	/	/	/	/	/	/	/
		Miss	/	/						
	T2	Hit	9.081	1.480	-1.472	-4.783	.000	.695	-4.849	.427
		Miss	11.292	1.524						
	T3	Hit	5.151	1.937	-.119	-.648	.527	.055	-3.289	2.871
		Miss	5.360	1.550						
	T4	Hit	3.588	1.984	.573	1.497	.157	.169	-2.448	4.824
		Miss	2.400	2.154						

Notes. Values are presented as mean ± SD. Cohen's d represents the effect size for paired comparisons between hit and miss outcomes. Post-hoc power was calculated based on the observed effect size, sample size, and an alpha level of .05. T1 = initiation of gun movement; T2 = gun stock contact with the cheek; T3 = first shot; T4 = second shot.

Table 3 presents the discrete velocity variables for the hit and miss outcomes at the critical time points (T1-T4). No significant differences were observed in the velocity of the gun across different time points (all *P*>.05), although at T4, there was a nonsignificant trend toward lower velocity in the hit condition (*P*=.258). Similarly, the horizontal velocity of the gun exhibited no significant differences (all *P*>.05), with minor adverse effects observed at T3 (Cohen's d=-.202) and T4 (Cohen's d=-.351). Notably, the vertical velocity of the gun at T2 was significantly lower in the hit condition (.247±.104m/s) compared to the miss condition (.284±.099m/s; t=-2.360, *P*=.033, Cohen's d=-.355), while differences at other time points were not statistically significant. Regarding the velocity of the center of mass (COM), no significant differences were detected (all *P*>.05). At T4, the hit condition demonstrated a marginally higher mean velocity (.084±.032 m/s) than the miss condition (.073±.033 m/s; t=1.437, *P*=.173, Cohen's d=.318), though this difference was not statistically significant. Similarly, the horizontal velocity of the COM revealed no significant differences, although a moderate positive effect was present at T4 (Cohen's d=.488, *P*=.081). For the vertical velocity of the COM, no significant differences were found across time points; however, at T2, there was a nonsignificant trend toward lower vertical velocity in the hit condition (t=-1.924, *P*=.075, Cohen's d=-.624). Overall, only the vertical velocity of the gun at T2 achieved statistical significance, indicating a potential association between reduced upward motion of the gun and successful shooting performance. Given the small sample size and exploratory design of the study, the statistical analyses were underpowered a priori, which limits the ability to detect small-to-moderate effects even when observable differences were present.

Table 3. Comparison of discrete velocity variables (Mean ± SD) between hit and miss outcomes at key time points (T1–T4), with effect sizes (Cohen's d) and t-test results.

Variable	Time point	Outcome	Mean	SD	Cohen's d	t	*p*	*Post-hoc Power*	CI 95%	
Velocity of gun(m/s)	T1	Hit	.216	.060	.091	.243	.812	.053	-.108	.120
		Miss	.210	.069						
	T2	Hit	.710	.137	-.134	-.457	.655	.056	-.224	.192
		Miss	.726	.096						
	T3	Hit	.994	.117	-.180	-.881	.393	.062	-.205	.167
		Miss	1.013	.093						
	T4	Hit	.671	.084	-.339	-1.179	.258	.091	-.195	.131
		Miss	.703	.101						
Horizontal velocity of gun(m/s)	T1	Hit	.204	.066	.164	.448	.661	.060	-.109	.131
		Miss	.193	.071						
	T2	Hit	.650	.171	-.055	-.219	.830	.051	-.265	.249
		Miss	.658	.116						
	T3	Hit	.943	.114	-.202	-1.058	.308	.065	-.205	.163
		Miss	.964	.095						
	T4	Hit	.663	.082	-.351	-1.225	.241	.094	-.193	.129
		Miss	.695	.100						
Vertical velocity of gun(m/s)	T1	Hit	.045	.054	-.253	-1.609	.130	.073	-.116	.086
		Miss	.060	.061						
	T2	Hit	.247	.104	-.355	-2.360	.033	.095	-.215	.141
		Miss	.284	.099						
	T3	Hit	.308	.065	.096	.306	.764	.053	-.113	.127
		Miss	.301	.072						
	T4	Hit	.087	.064	.198	.745	.468	.064	-.111	.139
		Miss	.073	.078						

Velocity of the COM(m/s)	T1	Hit	.059	.024	.323	.958	.354	.087	-.029	.043
		Miss	.052	.016						
	T2	Hit	.113	.017	-.454	-1.275	.223	.124	-.051	.029
		Miss	.124	.027						
	T3	Hit	.108	.048	-.034	-.157	.878	.050	-.085	.081
		Miss	.110	.047						
	T4	Hit	.084	.032	.318	1.437	.173	.086	-.046	.068
		Miss	.073	.033						
Horizontal velocity of the COM(m/s)	T1	Hit	.045	.025	.352	1.182	.257	.095	-.032	.048
		Miss	.037	.020						
	T2	Hit	.080	.023	-.093	-.237	.816	.053	-.038	.034
		Miss	.082	.017						
	T3	Hit	.102	.050	-.086	-.397	.698	.053	-.088	.080
		Miss	.106	.046						
	T4	Hit	.081	.032	.488	1.879	.081	.136	-.039	.071
		Miss	.065	.031						
Vertical velocity of the COM(m/s)	T1	Hit	.022	.033	-.463	-1.241	.235	.127	-.056	.034
		Miss	.033	.014						
	T2	Hit	.077	.018	-.624	-1.924	.075	.191	-.054	.026
		Miss	.091	.027						
	T3	Hit	.018	.026	.110	.327	.748	.054	-.041	.047
		Miss	.015	.024						
	T4	Hit	-.016	.014	-.136	-.444	.664	.057	-.050	.042
		Miss	-.012	.034						

Notes. Values are presented as mean ± SD. Cohen's d represents the effect size for paired comparisons between hit and miss outcomes. Post-hoc power was calculated based on the observed effect size, sample size, and an alpha level of .05. T1 = initiation of gun movement; T2 = gun stock contact with the cheek; T3 = first shot; T4 = second shot.

Discussion

This exploratory study examined the kinematic differences between successful (hit) and unsuccessful (miss) shots in skeet shooting, with a primary focus on gun displacement and velocity parameters, the velocity of the center of mass, and body joint angles. The increased rear stability angle observed under the hit condition at T2 indicates that the shooter's trunk is positioned more anteriorly [25], signifying a forward-leaning posture. This also accounts for the concurrently observed larger right knee angle: right-handed shooters typically adopt a stance with the left foot forward and the right foot positioned behind[26]. Consequently, leaning the trunk forward naturally leads to a reduction in right knee flexion. This forward lean shifts the center of mass anteriorly, augmenting rearward postural stability to better absorb the recoil generated at trigger release. Such a posture aids in stabilizing the firearm by establishing a more rigid support structure, effectively cushioning the kickback, and maintaining muzzle alignment during the recoil phase [27]. Evidence from biomechanics of shooting substantiates this interpretation. Sattlecker, et al. [28] demonstrated that reduced anteroposterior sway velocity, indicative of enhanced trunk stability, was associated with improved rifle stability and accuracy among standing shooters. Furthermore, Zemková, et al. [29] found that excessive body sway was correlated with greater deviations in barrel alignment and diminished shot precision. Beyond isolated trunk or knee mechanics, the interplay among multiple joints can critically influence postural stability and shooting performance. The joint-by-joint approach (JBJTA) posits that movement deficiencies at one joint often arise from compensatory actions across the kinetic chain, encompassing the trunk, hips, knees, ankles, and feet[30]. For example, limited hip mobility or ankle dorsiflexion may alter knee mechanics, affecting flexion angles and postural control, whereas trunk stability can propagate through the lower limbs to improve dynamic balance and recoil absorption.

Furthermore, the smaller right elbow angles observed under the hit condition at T2 and T4 may reflect more effective gun handling and refined upper limb control. Firstly, a smaller elbow angle generally indicates that the shooter maintains a firmer hold on the stock against the shoulder, resulting in more stable contact between the gun and shoulder and consequently enhanced stability during aiming and recoil absorption [31]. In skeet shooting, the movement of the gun is primarily driven by the dominant (right) hand, and maintaining a smaller right elbow angle suggests that the shooter actively guides and controls the gun's trajectory [32]. This pattern is biomechanically efficient and prevents an undesirable "dragging" motion, in which the gun's angular velocity exceeds that of the trunk and its inertia pulls the shooter forward, causing the gun to drive the body rather than be actively controlled. [4]. Secondly, a smaller right elbow angle also positions the upper limb closer to the trunk, thereby effectively reducing the moment of inertia of the system. In biomechanics, mass distributed farther from the axis of rotation increases the moment of inertia, making it more difficult to initiate or halt rotational movements compared to when the mass is situated closer [33]. By flexing the right elbow and keeping the arm nearer to the trunk, shooters reduce the rotational inertia of the upper body-gun system. This biomechanical configuration facilitates a faster and more coordinated execution of essential actions, including raising the gun, swinging, firing, and follow-through, ultimately enabling shooters to move the gun more responsively and efficiently along the target trajectory[34].

Regarding gun motion, the results demonstrated that at T2, the displacement of the gun, including both its horizontal and vertical components, was significantly lower under the hit condition. Furthermore, the vertical velocity of the gun was notably reduced in the hit condition at T2. The observed decrease in gun displacement and vertical velocity during this phase likely signifies a crucial role of gun stability in achieving successful shots. This finding is consistent with the research by Causer, et al. [6], who underscored the significance of gun stability for shooting efficacy. Notably, while Causer, et al. [6] did not report a significant main effect for gun displacement at shot two (corresponding to T4 in this study), the current investigation identified significant differences at T2, encompassing both horizontal and vertical components. Moreover, by examining gun velocity, this study introduces a novel insight into the reduced vertical velocity of the gun at T2 under the hit condition. The reduced muzzle displacement observed at T2 likely indicates a shorter duration of gun movement, thereby enabling shooters to allocate more time to redirect and track the second target, effectively reducing the shooting distance [3,6]. Additionally, diminished muzzle displacement suggests enhanced movement economy[35], with the muzzle trajectory more closely aligned to the target's actual flight path. These findings expand upon prior work and emphasize the significance of both temporal efficiency and trajectory optimization during the gun movement phase. Furthermore, the decreased vertical velocity of the muzzle at T2 indicates reduced vertical oscillation, resulting in a predominantly horizontal movement pattern. Prior research has demonstrated that reduced vertical oscillation facilitates a smoother alignment of the muzzle with the target trajectory [36]. Specifically, during standing shooting, the vertical acceleration of the muzzle immediately prior to trigger pull has been shown to negatively correlate with shooting performance, as measured by the distance of the hit point from the center of the target [37]. Collectively, these findings enrich previous studies by emphasizing the critical importance of gun motion characteristics, particularly during the T2 phase, for successful shooting performance.

Concerning the lack of significant differences in most joint angle and center of mass velocity variables between hit and miss conditions, several plausible explanations can be proposed. Firstly, from a sport psychology viewpoint, elite athletes generally develop highly consistent technical movement patterns through extensive and repetitive training, leading to inherently low movement variability [38]. For shooters, this technical consistency tends to be maintained across various performance outcomes, as errors in elite performers typically exhibit individual-specific characteristics rather than systematic deviations[35]. Secondly, athletes may adopt compensatory strategies to preserve performance; when an unexpected deviation occurs in one joint, minor adjustments in adjacent joints can aid in maintaining the overall movement pattern-a phenomenon known as motor equivalence [39]. Thirdly, shooting is intrinsically a precision task executed from a relatively static standing posture, which inherently results in low center of mass velocity; fluctuations in this measure are consequently unlikely to substantially impact shooting accuracy [36]. Finally, the relatively limited sample size in this preliminary investigation may have constrained the statistical power to identify smaller effect sizes in certain kinematic variables [40].Moreover, while kinematic analysis describes motion, it does not reveal underlying neuromuscular control. Future studies could therefore employ muscle synergy analysis to examine how neuromuscular control supports kinematic efficiency[41] , such as maintaining reduced elbow angles to minimize rotational inertia-thereby providing deeper insight into technical consistency and compensatory strategies during gun movement. In addition, tremor assessment has been successfully applied in other elite sports to evaluate movement stability and fine motor control, demonstrating the broader applicability of such neuromuscular measures in high-precision tasks [42].The consistently low post-hoc power values indicate that the present study was underpowered to detect small effects. Therefore, the absence of statistically significant differences should not be interpreted as evidence of no effect, but rather as a limitation related to the small sample size inherent in studies involving elite athletes.

Practical Applications

This exploratory study identified significant differences in muzzle displacement and vertical velocity at T2, indicating that coaching strategies should focus on training programs aimed at improving muzzle control and vertical stability, particularly during the critical phase from the initiation of gun movement to the moment when the stock contacts the cheek (T1-T2). Specific interventions might include utilizing marker-less motion capture systems combined with real-time biofeedback to assist athletes in monitoring and minimizing excessive muzzle displacement and vertical oscillations-factors shown to negatively influence shooting accuracy [6,35-37]. Moreover, the larger rear stability angle and smaller right elbow angle observed under the hit condition underscore the biomechanical importance of adopting a slightly forward-leaning posture and maintaining a compact upper limb configuration. Coaches could incorporate balance training-utilizing both loaded and unloaded conditions, as well as varied surfaces [43]-to aid athletes in stabilizing their trunk and reducing sway at crucial moments. Recoil simulation drills can further educate shooters to sustain this forward-leaning posture and ensure firm contact between the gun and shoulder during dynamic scenarios, thereby enhancing coupled control of the firearm and shooter [31]. Finally, these findings highlight the potential for developing advanced technological tools-such as wearable sensors or intelligent shooting analysis systems-to offer immediate feedback on muzzle stability, elbow positioning, and postural alignment, thereby facilitating personalized technique refinement.

This study presents several limitations. Firstly, the relatively small sample size and the fact that all participants were international-level athletes may restrict the applicability of the findings to less experienced or amateur shooters, and the use of a uniform low-pass cut-off frequency of 6 Hz for both body and gun barrel trajectories may have attenuated high-frequency components associated with rapid barrel motion and recoil. Secondly, the analysis was confined to a few key time points, lacking continuous dynamic evaluation throughout the entire shooting process. Thirdly, other potential influencing factors, such as psychological state and environmental conditions, were neither controlled nor measured. Future research could address these constraints through several approaches. Firstly, recruiting a larger and more diverse cohort of athletes increases the sample size and improves the generalizability of the results, and future studies may also consider adopting a dual-filtering strategy (e.g., 6 Hz for body and 12-15 Hz for gun) to better preserve high-frequency components associated with rapid barrel motion. Secondly, continuous dynamic and time-series analyses should be implemented instead of focusing solely on isolated time points, thereby capturing the comprehensive nature of the shooting process. Thirdly, systematically accounting for environmental factors-such as wind and lighting conditions-may impact the target's flight trajectory and consequently influence shooting performance. Lastly, future research could explore using emerging technologies, such as wearable sensors and artificial intelligence, to provide real-time feedback. These approaches may overcome the limitations of lab-based motion capture, allowing for more ecologically valid analysis of shooting technique and supporting skill improvement [44].

Conclusions

This exploratory study identified preliminary kinematic patterns that may distinguish successful from unsuccessful shots in skeet shooting. Specifically, smaller muzzle displacement and reduced vertical velocity at T2 were observed under the hit condition, suggesting that gun stability and controlled muzzle motion during the early gun movement phase could play a role in shooting success. Additionally, athletes tended to exhibit a larger rear stability angle and smaller right elbow angle under the hit condition, indicating that a slightly forward-leaning posture and compact upper limb configuration may be associated with enhanced postural stability and reduced rotational inertia. Although most joint angles and variables related to the velocity of the center of mass showed no statistically significant differences, this likely reflects the high degree of technical consistency and the employment of compensatory strategies characteristic of elite shooters. Overall, these findings provide preliminary insights into the biomechanics of shooting performance. They may inform future training approaches, for example by emphasizing muzzle control, trunk stability, and the potential use of real-time feedback technologies to support individualized technical refinement. Importantly, given the small sample size and exploratory nature of the study, all results should be interpreted cautiously and confirmed in larger cohorts.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Ethical Committee approval

The research involving human participants received approval from the Chinese Institute of Sport Science Ethics Committee (CISSEC), Beijing, China. The studies adhered to relevant local laws and institutional standards (Approval No. 2024.09.02).

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The authors declare no conflicts of interest.

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Author-s contribution

JP: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review and editing. TY: Formal analysis, Methodology, Writing - original draft, Writing - review and editing. YG: Conceptualization, Methodology, Software, Writing - review and editing. LJ: Formal analysis, Methodology Software, Writing - review and editing. PW: Conceptualization, Methodology, Writing -original draft, Writing - review and editing.

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