Quiet Eye Duration and Gun Motion in Elite Shotgun Shooting

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ABSTRACT

CAUSER, J., S. J. BENNETT, P. S. HOLMES, C. M. JANELLE, and A. M. WILLIAMS. Quiet Eye Duration and Gun Motion in Elite Shotgun Shooting. *Med. Sci. Sports Exerc.*, Vol. 42, No. 8, pp. 1599–1608, 2010. **Introduction**: No literature exists to document skill-related differences in shotgun shooting and whether these may be a function of eye movements and control of gun motion. We therefore conducted an exploratory investigation of the visual search behaviors and gun barrel kinematics used by elite and subelite shooters across the three shotgun shooting subdisciplines. **Methods**: Point of gaze and gun barrel kinematics were recorded in groups of elite (n = 24) and subelite (n = 24) shooters participating in skeet, trap, and double trap events. Point of gaze was calculated in relation to the scene, while motion of the gun was captured by two stationary external cameras. Quiet eye (final fixation or tracking gaze that is located on a specific location/object in the visual display for a minimum of 100 ms) duration and onset were analyzed as well as gun motion profiles in the horizontal and vertical planes. **Results**: In skeet, trap, and double trap disciplines, elite shooters demonstrated both an earlier onset and a longer relative duration of quiet eye than their subelite counterparts did. Also, in all three disciplines, quiet eye duration was longer and onset earlier during successful compared with unsuccessful trials for elite and subelite shooters. Kinematic analyses indicated that a slower movement of the gun barrel was used by elite compared with subelite shooters. **Conclusions**: Overall, stable gun motion and a longer quiet eye duration seem critical to a successful performance in all three shotgun disciplines. **Key Words:** EXPERTISE, TARGET SHOOTING, VISUAL BEHAVIOR, KINEMATICS

In target sports such as golf, archery, and billiards, the ability to accurately select the correct parameters for movement is crucial for successful performance. Access to pertinent visual stimuli and the effective processing of information are essential in these sports. Whereas performance in these sports is based on aiming at a stationary target, shotgun shooting requires competitors to hit a target that is moving away from or across them at speeds up to 100 km·h^{-1}. Consequently, the event requires less of a focus on aiming and is more akin to an interceptive task, with the shooter trying to intercept the clay with the shot. To date, there have been no attempts to examine visual search or gun barrel kinematics in such targeting tasks or to examine how these factors interact with expertise. Our aim in this study was to explore how visual search and gun barrel movement characteristics differ between skilled and less skilled shooters across successful and unsuccessful shots. The intention was to identify the key factors that contribute to expert performance in the three shotgun subdisciplines (i.e., skeet, trap, and double trap), providing insight into the visual and kinematic process underpinning expert performance in the sports.

Most previous researchers have focused their efforts on how objects moving toward an athlete are tracked. These include the penalty kick in soccer (22), receiving serve in volleyball (27), attempting to strike baseball pitches (23), and batting in cricket (13). Vickers (26) identified three gaze control phases for interceptive actions: object recognition, object tracking, and object control. During the object recognition phase, fixations and pursuit tracking are used to determine the trajectory and movement parameters of the target. The object tracking phase involves smooth pursuit tracking to keep the target in the fovea (the center of the retina where there is close pairing of ganglion cells to photoreceptors, thereby permitting greatest visual acuity) to ensure that any changes in trajectory are detected. Finally, in the object control phase, fixations and tracking behaviors are used to stabilize the eyes as the target is successfully intercepted.

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In recent years, researchers investigating interceptive tasks have focused on a visual phenomenon known as the "quiet eye" (QE) period. The QE was defined by Vickers (24) as the final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace within 3° of the visual angle for a minimum of 100 ms. It has been reported that the onset of the QE period occurs earlier and its duration is longer in the elite compared with the subelite athletes in sports, such as golf (25), basketball (9), ice hockey (20), billiards (30), and rifle shooting (11,28). Moreover, several researchers have identified a longer QE period on successful compared with unsuccessful trials across several tasks (19,24,30). It has been argued that during the QE period, performers set the final parameters of the movement, process appropriate environmental cues, and synchronize motor strategies (14). The key principle is that QE is associated with the amount of cognitive programming required for a successful action (30).

Previously, researchers who have considered shooting sports have focused on the rifle (12,29,31) and pistol (8,15,21) disciplines. These tasks involve relatively small gun movements to a stationary target. However, shotgun shooting produces a much large variability between shots and greater uncertainty with respect to the target. In shotgun shooting, there are three main subdisciplines: skeet, trap, and double trap. In each subdiscipline, shooters attempt to align accurately their gun in preparation for the clay(s) and then anticipate the release of the target(s). Once released, shooters must track the moving target with the gun barrel before pulling the trigger at an optimal time. Abernethy and Neal (1) reported that, in clay shooting, an ability to detect rapidly and reliably the target on release and to track the target accurately seems critical to a successful performance. However, differences in gaze behaviors are likely to be evident across each shooting discipline because of the varying task constraints and subsequent demands of each shot.

In skeet shooting, two towers (high and low) are situated on the left and right of the layout, and targets are released horizontally across the shooter from either one or both of the trap houses simultaneously. The shooter has one shot per target to break the clays and shoots 25 targets from eight different positions per round. In trap shooting, the target is released from a "trap" concealed in a trench 15 m in front of the shooting stations. The targets can be released from one of three traps that propel the clays in different directions: the left trap throws targets to the right (up to 45° from the center), the central trap throws straightaway targets (±15° from the center), and the right trap throws targets to the left (up to 45° from the center). Shooters are allowed two shots to hit the target and shoot 25 targets from five different stations per round. In the double trap, two targets are released simultaneously from the three most central traps. The left–center trap throws targets to the right (up to 5° from the center), the center–center trap throws straightaway targets, and the right–center trap throws targets to the left (up to 5° from the center). Shooters are allowed one attempt per target and shoot 25 pairs from five different stations per round. In both trap and double trap disciplines, the target is moving away from the shooter at speeds of up to 65 mph, ensuring that the probability of hitting the target reduces as the shot cluster becomes more dispersed and that the targets' representation on the retina decreases.

There are few previous reports of shotgun shooting performance. Abernethy and Neal (1) used a battery of standardized visual tests in a laboratory environment to determine differences in visual function between skill groups. No differences were evident for shooters in rapid tachistoscopic detection and coincidence timing selection compared with a control sample. In contrast, Czigler et al. (4) found that shooters demonstrated more efficient attentive processing, with faster and more accurate responses, than a control group in a visual discrimination task that required fast information processing. Di Russo et al. (6) reported similar findings when measuring visual scanning behavior in high-level target shooters in relation to a control sample. Shooters were found to have shorter saccadic latency to targets in both a simple reaction task and a discrimination task. Morrillo et al. (18) also found that trained shooters have shorter saccadic latency, as well as shorter antisaccadic latency in both gap (fixation point removed at time of target presentation) and overlap (fixation point always present) conditions. In consideration of the underlying mechanisms, Di Russo et al. (5) examined the effect of practice on the brain activity of clay target shooters using self-paced flexion movements of either the right or the left index finger. The data suggest that the Bereitschaftspotential (BP) and negative slope latencies were longer for shooters, indicating an extended duration of domain-specific motor preparation. BP amplitudes were smaller compared with a control group but only for the right, triggering finger. No group differences were found for motor potential and reafferent positivity. On the basis of these findings, the authors concluded that motor task execution is performed more economically and at a lower metabolic cost as domain-specific experience increases. Overall, the results identify several discriminating variables in shooting performance across a variety of skill levels. Although such psychophysiological evidence is indeed compelling, overt perceptual–cognitive aspects of performance as well as the movement kinematics used by the shooters may also account for important additional variance that discriminates between skill groups and across shot outcome.

A biomechanical analysis of shotgun shooting was conducted by Bourne et al. (3) to identify common performance characteristics across the three shotgun subdisciplines. The kinematic profile of the body segments and gun barrel in relation to each shooter's center of pressure was recorded. It was concluded that a common approach is taken to the maintenance of the center of pressure and movement across the shooting subdisciplines, with hip rotation accounting for the majority of the horizontal displacement of the gun barrel.

No literature exists to document skill-related differences in shotgun shooting and whether these may be a function of eye movements and control of gun motion. In the current article, we explored the visual search behaviors and gun barrel kinematics used by elite and subelite shooters across the three different shooting subdisciplines. Key performance variables were analyzed in an attempt to identify the factors that discriminate shooters at elite and subelite levels of the sport. The QE characteristics, gun barrel kinematics, and the relationship between the final fixation on the clay (QE period), alongside the onset of the QE period and shot outcome, were examined in elite and subelite shooters as they shot in skeet, trap, and double trap subdisciplines. According to a previous work (e.g., [24]), elite shooters should exhibit both an earlier onset of QE and a longer final fixation on the clay compared with subelite shooters. Moreover, when a within-group analysis is used, longer QE durations and earlier onsets of QE have been reported on successful compared with unsuccessful trials (19,24,30). We hypothesized that the same effect will be evident across all disciplines of shotgun shooting. Owing to the nature of the task in the current study, we adopted the definition of QE cited in Vickers (24) to encompass the current task constraints and demands. In the present study, QE is defined as the final tracking gaze that is located on the moving target for a minimum of 100 ms.

Given the paucity of previous research on the kinematics of shotgun shooting, our approach is largely descriptive but is rooted in established conceptual notions forwarded in traditional (7) and contemporary (10) notions of skill learning. These theories advocate that elite performers exhibit more efficient and consistent action production than subelite or novice performers. Because the position of the barrel in relation to the clay determines whether the shot is successful or unsuccessful, movement of the gun to get to this final position was assumed to be crucial to a successful performance. The techniques that are used for moving the gun to the final shot position were expected to differ between elite and subelite shooters in each of the subdisciplines. Differences in gun motion were predicted between elite and subelite shooters across each of the shooting disciplines. Although differences in gun barrel kinematics between elite and subelite shooters (12,15,29) have been reported in other shooting disciplines (i.e., pistol, rifle), fundamental differences in the specific nature of these tasks prevent clear predictions from being articulated. We report several kinematic measures and provide a descriptive analysis of the variables in relation to the respective shooting disciplines; this is essential to identify fundamental differences between skill level and shot outcome and to better design training programs to enhance performance in shooters.

MATERIALS AND METHODS

Participants

Forty-eight shooters provided written informed consent before participating. Shooters were categorized according to their specialized subdiscipline (skeet, trap, or double trap), and then each subdiscipline was subdivided into two groups on the basis of their skill level (elite or subelite). For skeet, the elite group comprised eight shooters from the Great Britain (GB) squad (age = 29.3 ± 9.0 yr) with an average of 11.4 yr of experience in shooting. All shooters were ranked in the top 10 in the country at the time of testing. The subelite group (age = 30.1 ± 7.2 yr) consisted of eight recreational shooters with an average of 7.25 yr of shooting. The elite group in trap comprised eight members of the GB squad (age = 30.6 ± 10.5 yr) who had an average of 11.1 yr of experience in shooting. All shooters were ranked in the top 10 in the country at the time of testing. The subelite group (age = 32.0 ± 8.5 yr) consisted of eight recreational shooters with an average of 6.9 yr of shooting. The double trap elite group comprised eight shooters currently in the top 10 GB rankings (age = 26.9 ± 4.8 yr) who had an average of 9.8 yr of experience in shooting. The subelite group (age = 36.2 ± 12.1 yr) consisted of eight recreational shooters with an average of 5.5 yr of shooting. All shooters had normal or corrected-to-normal visual acuity. Participants used their own personal shotguns and wore their normal shooting attire. Approval for the study was gained via the ethics committee of the lead institution, and participants were free to withdraw from testing at any stage.

Measures

Visual search behaviors. Visual search behaviors were recorded using a mobile corneal reflection system (Model ASL Mobile Eye II; Applied Science Laboratories, Waltham, MA). This mobile system uses a method known as "dark pupil tracking" in which the relationship between two eye features, the pupil and a reflection from the cornea, is computed to locate gaze within a scene. The mobile eye has a system accuracy of 0.5° of visual angle, a resolution of 0.10° of visual angle, and a visual range of 50° horizontal and 40° vertical.

Gun barrel kinematics. Video data were collected to calculate the coordinates of the gun barrel to provide a more comprehensive understanding of the shooting action. Two digital video cameras (XM2; Canon, Lake Success, NY) sampling at 50 Hz and with a shutter speed of 1/150 were used. Each camera was positioned 4.0 m in front of the shooting station at an angle of 50° relative to the center of the range, one camera on the left side of the range and the other on the right, at a height of 0.9 m. The cameras were connected to a central computer by two FireWire cables (Belkin, Playa Vista, CA), and the camera shutters were synchronized using a signal sent from the central computer. The cameras filmed simultaneously during each shooting trial. The shooting area was calibrated using a 12-point, three-dimensional frame.

Procedures

Participants only shot in their own specialized subdiscipline (skeet/trap/double trap). All trials took place from the

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central shooting station in the range. An International Shooting Sport Federation shooting range is designed to accommodate all three Olympic shooting events. In each of the disciplines, the central shooting station is located at the same position in the range (station 3 for double trap andtrap and station 4 for skeet). In skeet, shooters were positioned at station 4, shooting the high target first. For trap, the central trap was used with the target projected directly away from the shooter, and in the double trap, targets were released from the left and central traps. Participants were required to take 20 shots from the shooting station. During all trials, the shooters were required to follow the normal rules of their discipline as stipulated by the International Shooting Sport Federation.

Before collecting data from each participant, a 25-mm-diameter expanded polystyrene marker was attached to the underside of the gun barrel by a cable tie to enable digitization of the gun barrel for kinematic analysis. The marker was not visible to the shooters during their routine. Participants were fitted with the mobile eye system, which was then calibrated using reference points in the shooting range. The calibration was conducted while participants were in their "normal" shooting stance. Before each shot, the video cameras were activated to record the movement and outcome of the shot. The mobile eye system recorded data for the entire duration of the test session, although the accuracy of the calibration was checked periodically. The intertrial interval was 60 s.

Statistical Analysis

A total of four hit and four miss shots were identified for each shooter for further analysis. For skeet and double trap, a miss was defined as a successful shot on the first clay but missing the second. This was because of the low miss frequency for the first target in each of the disciplines. After each trial, participants were asked to state whether the shot was a "good" or "bad" trial, irrelevant of outcome. For analysis, only hits that were seen to be good shots and misses that were seen to be bad shots were selected. This ensured that only the best and worst shots were analyzed. Coaches often use this technique to make a qualitative judgment about the shot on the basis of the individualized quality criteria. For each trial, the saved kinematic video files were imported into the SIMI Motion 6 (SIMI Reality Motion Systems, Unterschleissheim, Germany) analysis software. To increase accuracy, the marker placements were measured using three Qualysis cameras (Gothenburg, Sweden). An average calibration error of 0.76% of screen size was found, which is in the acceptable range recommended by SIMI software (between 0% and 3%) for an accurate analysis. The gun barrel marker was manually tracked in both video recordings for five frames before the initiation of the movement, and the following five frames after the completion of the shot were digitized.

Visual search behavior data were analyzed frame by frame using Gamebreaker software (Sportstec, Camarillo, CA). Relative QE duration, QE onset, and shot time were analyzed. Relative QE was defined as the percentage of QE duration relative to the shot time. In trap, total shot time was defined as the moment of clay appearance to shot release, and for skeet and double trap, this was the time from shot 1 to shot 2. Relative QE was used because of the variances in shot times. Onset of QE was determined as the time from shot 1 until QE initiation in skeet and double trap and as the time from clay release until QE initiation in trap. Eye movements were logged manually from the video recordings, and QE characteristics were determined by frame counts. The objectivity of the eye movement data was established using intraobserver (97.2%) and interobserver (95.8%) agreement methods. For the kinematic data, peak velocity, time from peak velocity to shot, total movement time, individual shot movement times (skeet/double trap), and gun barrel displacements in the horizontal and vertical axes were analyzed. Peak velocity characteristics enable elements of the shooting technique to be identified (i.e., are the shooters tracking the clay until the barrel "catches up" with the target or accelerating ahead of the target and then waiting for the clay to reach the gun barrel?). A two-way mixed-design ANOVA was used to examine the effect of skill (elite/subelite) and shot outcome (hit/miss) on all of the individual variables with repeated measures on the last factor. The effect sizes were calculated using partial eta squared values (η_p^2) and Cohen *d* as appropriate. The α level for significance was set at 0.05. If the sphericity assumption was violated, the Huynh–Feldt correction was used.

RESULTS

Skeet

Relative quiet eye duration. There were significant main effects for skill, $F_{1,14} = 27.269$, $P < 0.05$, $\eta_p^2 = 0.66$, and outcome, $F_{1,14} = 77.000$, $P < 0.05$, $\eta_p^2 = 0.85$. The elite shooters displayed a longer relative duration of quiet eye on both hits (mean = 65.0% ± 1.7% vs 56.4% ± 4.0%) and misses (mean = 60.1% ± 2.5% vs 52.9% ± 3.8%) compared with the subelite shooters. The results are presented in Figure 1. There was no significant interaction between skill × outcome, $F_{1,14} = 2.063$, $P > 0.05$, $\eta_p^2 = 0.13$.

Onset of quiet eye. There were significant main effects for skill, $F_{1,14} = 23.750$, $P < 0.05$, $\eta_p^2 = 0.63$, and outcome, $F_{1,14} = 33.333$, $P < 0.05$, $\eta_p^2 = 0.71$. The elite shooters displayed significantly earlier onset of quiet eye (mean = 220.8 ± 16.7 ms) compared with subelite shooters (mean = 255.5 ± 19.5 ms). An earlier quiet eye onset was observed on hits (mean = 228.8 ± 25.7 ms) compared with misses (mean = 247.5 ± 21.2 ms). The results are presented in Figure 2. The interaction between skill × outcome was not significant ($F_{1,14} = 2.096$, $P > 0.05$, $\eta_p^2 = 0.13$).

Peak velocity for shot 2. Significant main effects were observed for skill, $F_{1,14} = 14.117$, $P < 0.05$, $\eta_p^2 = 0.50$,

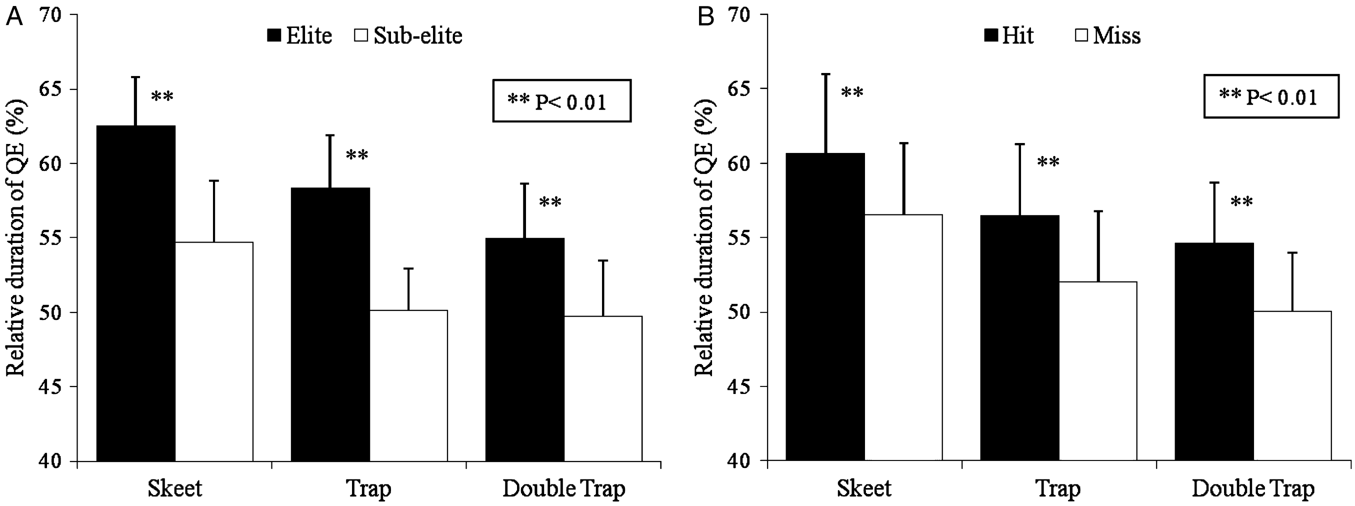

FIGURE 1 —Mean relative QE duration (%) in each subdiscipline between elite and subelite shooters (A) and between successful and unsuccessful trials (B).

and outcome, $F_{1,14}$ = 4.769, P < 0.05, η_p^2 = 0.25. The elite shooters displayed significantly lower peak velocity (mean = 0.79 ± 0.11 m·s^{-1}) compared with subelite shooters (mean = 1.01 ± 0.15 m·s^{-1}). The mean peak velocity values were lower on hits (mean = 0.87 ± 0.18 m·s^{-1}) compared with those on misses (mean = 0.94 ± 0.16 m·s^{-1}). The interaction between skill × outcome was not significant, $F_{1,14}$ = 0.062, P > 0.05, η_p^2 = 0.00.

Time from peak velocity to shot 2. There was a significant main effect for skill, $F_{1,14}$ = 23.282, P < 0.05, η_p^2 = 0.62, and outcome, $F_{1,14}$ = 4.741, P < 0.05, η_p^2 = 0.25. The elite shooters displayed a significantly shorter period from peak velocity to taking the shot (mean = 283.8 ± 53.8 ms) compared with subelite shooters (mean = 455.0 ± 69.5 ms). This period was significantly shorter on hits (mean = 350.0 ± 98.7 ms) compared with misses (mean = 388.8 ± 102.7 ms). No interaction effects were apparent between skill and outcome, $F_{1,14}$ = 0.400, P > 0.05, η_p^2 = 0.03.

Total movement time. There were no significant main effects for skill, $F_{1,14}$ = 1.087, P > 0.05, η_p^2 = 0.07, or outcome, $F_{1,14}$ = 2.403, P > 0.05, η_p^2 = 0.15, and no skill × outcome interaction, $F_{1,14}$ = 3.380, P > 0.05, η_p^2 = 0.19.

Movement time for shot 1. There were no significant main effects for skill, $F_{1,14}$ = 1.908, P > 0.05, η_p^2 = 0.12. However, there was a significant main effect for outcome, $F_{1,14}$ = 15.295, P < 0.05, η_p^2 = 0.52, and a significant interaction between skill and outcome, $F_{1,14}$ = 9.718, P < 0.05, η_p^2 = 0.41. The mean movement time for shot 1 of subelite shooters did not differ between hits and misses (d = 0.39), whereas the elite shooters used significantly shorter movement times on hits compared with misses (d = 1.63).

Movement time for shot 2. There were no significant main effects for skill, $F_{1,14}$ = 0.634, P > 0.05, η_p^2 = 0.04, or outcome, $F_{1,14}$ = 0.443, P > 0.05, η_p^2 = 0.03, and no significant interaction, $F_{1,14}$ = 0.391, P > 0.05, η_p^2 = 0.03.

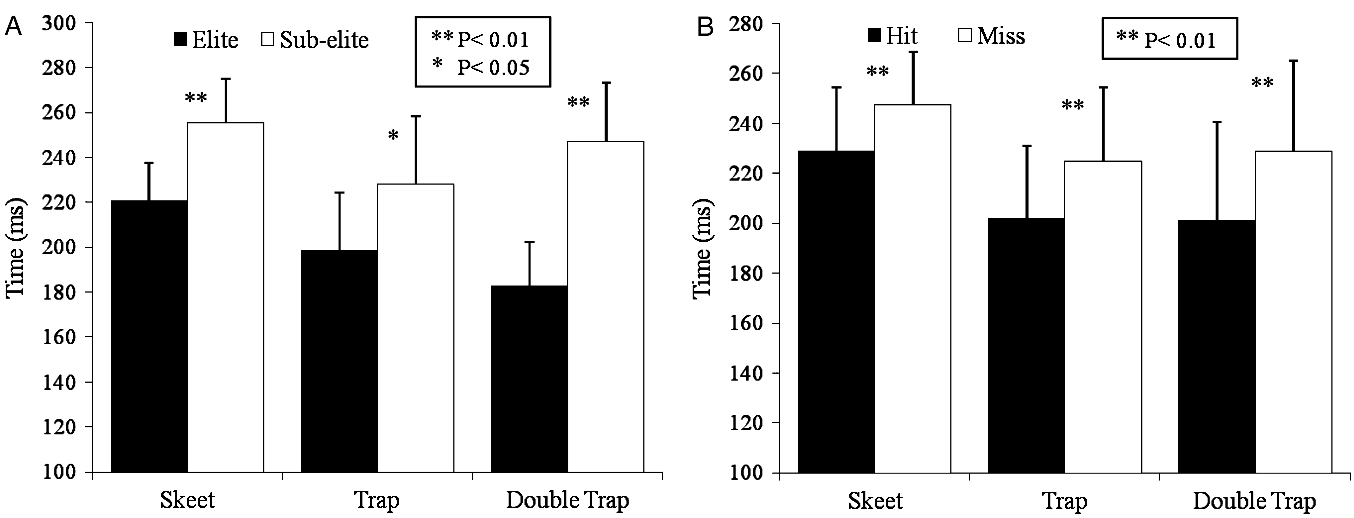

FIGURE 2 —Mean onset of QE (ms) in each subdiscipline between elite and subelite shooters (A) and between successful and unsuccessful trials (B).

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TABLE 1. Mean and SD for kinematic variables for elite and subelite skeet shooters on hit and miss trials.

	Elite		Subelite	
Skeet	Hit	Miss	Hit	Miss
Peak velocity ($m \cdot s^{-1}$)	0.756 ± 0.12	0.834 ± 0.10	0.979 ± 0.16	1.041 ± 0.15
Time from peak velocity to shot (ms)	270.0 ± 56.3	297.5 ± 50.9	430.0 ± 90.3	480.0 ± 83.2
Total movement time (ms)	2163.8 ± 70.0	2281.3 ± 69.4	2261.3 ± 118.6	2251.3 ± 110.6
Shot 1 movement time (ms)	937.5 ± 36.6	1015.0 ± 56.3	992.5 ± 26.1	1001.3 ± 18.1
Shot 2 movement time (ms)	1226.3 ± 65.2	1266.3 ± 51.3	1268.75 ± 96.00	110.1 ± 110.1
Horizontal displacement (m)	17.1 ± 2.4	18.6 ± 2.7	28.5 ± 5.1	32.9 ± 5.4
Vertical displacement (m)	3.2 ± 0.8	3.4 ± 0.9	2.2 ± 0.7	1.8 ± 0.5

Displacement of gun shot 2 (horizontal axis). There was a significant main effect for skill, $F_{1,14}$ = 86.539, P < 0.05, $\eta_p{}^2$ = 0.86 (Table 1). The elite shooters displayed a significantly shorter gun displacement in horizontal axis (mean = 17.8 ± 5.6 cm) compared with subelite shooters (mean = 30.7 ± 2.4 cm). There was no main effect for outcome, $F_{1,14}$ = 3.780, P > 0.05, $\eta_p{}^2$ = 0.21, and no skill × outcome interaction, $F_{1,14}$ = 0.889, P > 0.05, $\eta_p{}^2$ = 0.06.

Displacement of gun shot 2 (vertical axis). There was a significant main effect for skill, $F_{1,14}$ = 9.932, P < 0.05, $\eta_p{}^2$ = 0.42. The elite shooters displayed a significantly larger gun displacement in the vertical axis (mean = 3.3 ± 0.9 cm) compared with subelite shooters (mean = 2.0 ± 0.6 cm). There were no main effects for outcome, $F_{1,14}$ = 0.094, P > 0.05, $\eta_p{}^2$ = 0.01, and no skill × outcome interaction, $F_{1,14}$ = 0.441, P > 0.05, $\eta_p{}^2$ = 0.03.

Trap

Relative duration of quiet eye. There were significant main effects for skill, $F_{1,14}$ = 55.199, P < 0.05, $\eta_p{}^2$ = 0.80, and outcome, $F_{1,14}$ = 227.554, P < 0.05, $\eta_p{}^2$ = 0.94. The elite shooters displayed significantly longer relative duration of quiet eye (mean = 58.4% ± 3.5%) compared with subelite shooters (mean = 50.1% ± 2.8%). Significantly longer quiet eye durations were evident on hits (mean = 56.5% ± 4.8%) compared with misses (mean = 52.2% ± 4.8%). The results are presented in Figure 1. The interaction between skill and outcome interaction was not significant, $F_{1,14}$ = 0.380, P > 0.05, $\eta_p{}^2$ = 0.03.

Onset of quiet eye. There were significant main effects for skill, $F_{1,14}$ = 5.453, P < 0.05, $\eta_p{}^2$ = 0.28, and outcome, $F_{1,14}$ = 62.618, P < 0.05, $\eta_p{}^2$ = 0.82. As depicted in Figure 2, the elite shooters displayed significantly earlier onset of quiet eye (mean = 198.8 ± 25.4 ms) compared with subelite shooters (mean = 228.3 ± 30.0 ms). Earlier quiet eye onset was observed on hits (mean = 202.0 ± 29.2 ms) compared with misses (mean = 225.0 ± 29.6 ms). The interaction between skill and outcome was not significant, $F_{1,14}$ = 1.266, P > 0.05, $\eta_p{}^2$ = 0.08.

Peak velocity. Significant main effects were observed for skill, $F_{1,14}$ = 17.339, P < 0.05, $\eta_p{}^2$ = 0.55, and outcome, $F_{1,14}$ = 6.095, P < 0.05, $\eta_p{}^2$ = 0.30 (Table 2). The elite shooters displayed significantly lower peak velocity (mean = 0.51 ± 0.05 $m \cdot s^{-1}$) compared with subelite shooters (mean = 0.66 ± 0.13 $m \cdot s^{-1}$). Significantly lower peak velocities were also observed on hits (mean = 0.55 ± 0.12 $m \cdot s^{-1}$) compared with misses (mean = 0.64 ± 0.15 $m \cdot s^{-1}$). The interaction was not significant, $F_{1,14}$ = 3.016, P > 0.05, $\eta_p{}^2$ = 0.18.

Time from peak velocity to shot. A significant main effect was observed for skill, $F_{1,14}$ = 762.961, P < 0.05, $\eta_p{}^2$ = 0.98. The elite shooters displayed a significantly shorter period from peak velocity to the shot (mean = 24.0 ± 3.1 ms) compared with subelite shooters (mean = 170.0 ± 20.5 ms). There was no main effect for outcome, $F_{1,14}$ = 1.230, P > 0.05, $\eta_p{}^2$ = 0.08, and no skill × outcome interaction, $F_{1,14}$ = 1.060, P > 0.05, $\eta_p{}^2$ = 0.07.

Total movement time. Significant main effects were apparent for skill, $F_{1,14}$ = 17.039, P < 0.05, $\eta_p{}^2$ = 0.55, and outcome, $F_{1,14}$ = 7.001, P < 0.05, $\eta_p{}^2$ = 0.33. The elite shooters displayed a significantly shorter total movement time (mean = 623.1 ± 94.0 ms) compared with subelite shooters (mean = 815.0 ± 111.2 ms). Moreover, movement time was shorter on hits (mean = 685.6 ± 126.4 ms) compared with misses (mean = 752.5 ± 128.9 ms). There was no skill × outcome interaction, $F_{1,14}$ = 0.006, P > 0.05, $\eta_p{}^2$ = 0.00.

Displacement of gun (horizontal axis). There were significant main effects for skill, $F_{1,14}$ = 16.607, P < 0.05, $\eta_p{}^2$ = 0.54, and outcome, $F_{1,14}$ = 5.993, P < 0.05, $\eta_p{}^2$ = 0.30. The elite shooters displayed a significantly shorter gun displacement in the horizontal axis (mean = 1.3 ± 0.5 cm) compared with subelite shooters (mean = 2.2 ± 0.6 cm). Lower displacement scores were apparent on hits (mean = 1.5 ± 0.6 cm) compared with misses (mean = 2.1 ± 0.7 cm). The elite shooters displayed a shorter displacement on both hits (mean = 1.1 ± 0.4 cm) and misses (mean = 1.5 ± 0.5 cm) compared with the subelite shooters hits (mean = 1.8 ± 0.6 cm) and misses (mean = 2.7 ± 0.4 cm). The differences in displacement increased proportionately for each skill

TABLE 2. Mean and SD for kinematic variables for elite and subelite trap shooters on hit and miss trials.

	Elite		Subelite	
Trap	Hit	Miss	Hit	Miss
Peak velocity ($m \cdot s^{-1}$)	0.501 ± 0.03	0.527 ± 0.07	0.590 ± 0.15	0.744 ± 0.12
Time from peak velocity to shot (ms)	23.8 ± 3.4	24.2 ± 3.1	165.0 ± 25.7	175.8 ± 13.1
Total movement time (ms)	588.8 ± 82.5	657.5 ± 97.1	782.5 ± 132.0	847.5 ± 105.5
Horizontal displacement (cm)	1.1 ± 0.4	1.5 ± 0.5	1.8 ± 0.6	2.7 ± 0.4
Vertical displacement (cm)	11.8 ± 1.0	12.0 ± 0.6	16.1 ± 3.3	17.1 ± 4.1

TABLE 3. Mean and SD for kinematic variables for elite and subelite double trap shooters on hit and miss trials.

	Elite		Subelite	
Double Trap	Hit	Miss	Hit	Miss
Peak velocity ($m \cdot s^{-1}$)	0.31 ± 0.05	0.35 ± 0.07	0.40 ± 0.04	0.37 ± 0.05
Total movement time (ms)	932.5 ± 53.9	955.3 ± 73.0	1521.3 ± 76.1	1577.5 ± 72.1
Shot 1 movement time (ms)	202.5 ± 64.8	211.3 ± 74.3	340.0 ± 18.5	371.3 ± 29.0
Shot 2 movement time (ms)	730.0 ± 47.5	744.0 ± 47.8	1181.25 ± 61.8	1206.25 ± 51.0
Shot 1 horizontal displacement (cm)	0.4 ± 0.1	0.4 ± 0.1	1.1 ± 0.2	1.1 ± 0.3
Shot 1 vertical displacement (cm)	1.9 ± 0.3	1.4 ± 0.4	3.3 ± 0.5	3.6 ± 0.7
Shot 2 horizontal displacement (cm)	7.0 ± 1.3	7.6 ± 0.9	7.6 ± 0.7	9.6 ± 1.7
Shot 2 vertical displacement (cm)	6.2 ± 2.4	6.8 ± 2.5	7.2 ± 1.2	8.2 ± 0.9

level from hits to misses. There was no significant skill × outcome interaction, $F_{1,14} = 0.878$, $P > 0.05$, $\eta_p^2 = 0.06$.

Displacement of gun (vertical axis). A significant main effect for skill was observed, $F_{1,14} = 23.306$, $P < 0.05$, $\eta_p^2 = 0.63$. The elite shooters displayed a significantly shorter gun displacement in vertical axis (mean = 11.9 ± 0.8 cm) compared with subelite shooters (mean = 16.6 ± 3.6 cm). There was no significant main effect for outcome, $F_{1,14} = 6.487$, $P > 0.05$, $\eta_p^2 = 0.03$, and no skill × outcome interaction, $F_{1,14} = 0.153$, $P > 0.05$, $\eta_p^2 = 0.01$.

Double Trap

Relative duration of quiet eye. Significant main effects were evident for skill, $F_{1,14} = 13.610$, $P < 0.05$, $\eta_p^2 = 0.49$, and outcome, $F_{1,14} = 141.087$, $P < 0.05$, $\eta_p^2 = 0.91$. The elite shooters displayed significantly longer relative duration of quiet eye (mean = 55.0% ± 3.7%) compared with subelite shooters (mean = 49.7% ± 3.8%). A longer mean relative duration of quiet eye was apparent on hits (mean = 54.6% ± 4.0%) compared with misses (mean = 50.1% ± 3.9%). The results are presented in Figure 1. There was no interaction between skill and outcome, $F_{1,14} = 3.460$, $P > 0.05$, $\eta_p^2 = 0.20$.

Onset of quiet eye. There were significant main effects for skill, $F_{1,14} = 55.041$, $P < 0.05$, $\eta_p^2 = 0.80$, and outcome, $F_{1,14} = 58.155$, $P < 0.05$, $\eta_p^2 = 0.81$. The elite shooters displayed significantly earlier onset of quiet eye (mean = 182.8 ± 19.7 ms) compared with subelite shooters (mean = 247.0 ± 26.2 ms). An earlier mean onset of quiet eye was evident on hits (mean = 201.1 ± 39.4 ms) compared with misses (mean = 228.8 ± 36.2 ms). The skill × outcome interaction was not significant, $F_{1,14} = 1.353$, $P > 0.05$, $\eta_p^2 = 0.09$. The results are presented in Figure 2.

Peak velocity for shot 2. There were no significant main effects for skill, $F_{1,14} = 2.001$, $P > 0.05$, $\eta_p^2 = 0.13$, or outcome, $F_{1,14} = 0.121$, $P > 0.05$, $\eta_p^2 = 0.01$, and there was no interaction, $F_{1,14} = 0.696$, $P > 0.05$, $\eta_p^2 = 0.05$.

Total movement time. There were significant main effects for skill, $F_{1,14} = 361.258$, $P < 0.05$, $\eta_p^2 = 0.96$, and outcome, $F_{1,14} = 8.391$, $P < 0.05$, $\eta_p^2 = 0.38$ (Table 3). The elite shooters displayed a significantly shorter total movement time (mean = 943.9 ± 63.1 ms) compared with subelite shooters (mean = 1549.4 ± 77.2 ms). Shorter movement times were observed on hits (mean = 1226.9 ± 210.6 ms) compared with misses (mean = 1266.4 ± 258.5 ms). The skill × outcome interaction was not significant, $F_{1,14} = 1.509$, $P > 0.05$, $\eta_p^2 = 0.10$.

Movement time for shot 1. Significant main effects were observed for skill, $F_{1,14} = 35.741$, $P > 0.05$, $\eta_p^2 = 0.72$, and outcome, $F_{1,14} = 6.411$, $P > 0.05$, $\eta_p^2 = 0.31$. The elite shooters displayed a significantly shorter total movement time (mean = 206.9 ± 67.5 ms) compared with subelite shooters (mean = 355.6 ± 28.5 ms). There were also significant differences between hits (mean = 271.3 ± 84.6 ms) and misses (mean = 291.3 ± 89.6 ms). The interaction was not significant $F_{1,14} = 2.029$, $P > 0.05$, $\eta_p^2 = 0.13$.

Movement time for shot 2. A significant main effect for skill was observed, $F_{1,14} = 369.106$, $P < 0.05$, $\eta_p^2 = 0.96$. The elite shooters displayed a significantly shorter movement time (mean = 737.0 ± 46.6 ms) compared with the subelite shooters (mean = 1193.8 ± 56.2 ms). There was no significant main effect for outcome, $F_{1,14} = 3.191$ $P > 0.05$, $\eta_p^2 = 0.19$, and no skill × outcome interaction, $F_{1,14} = 0.254$, $P > 0.05$, $\eta_p^2 = 0.02$.

Displacement of gunshot 1 (horizontal axis) There was a significant main effect for skill, $F_{1,14} = 70.302$, $P < 0.05$, $\eta_p^2 = 0.83$. The elite shooters displayed a significantly smaller gun displacement (mean = 0.4 ± 0.2 cm) compared with subelite shooters (mean = 1.1 ± 0.2 cm). The main effect for outcome was not significant, $F_{1,14} = 0.153$, $P > 0.05$, $\eta_p^2 = 0.01$, and the skill × outcome interaction was not significant as well, $F_{1,14} = 0.153$, $P > 0.05$, $\eta_p^2 = 0.01$.

Displacement of gunshot 1 (vertical axis). There was a significant main effect for skill, $F_{1,14} = 32.524$, $P < 0.05$, $\eta_p^2 = 0.70$. The means revealed that the elite shooters displayed a significantly smaller gun displacement (mean = 1.7 ± 0.6 cm) compared with the subelite shooters (mean = 3.5 ± 0.6 cm). There was no main effect for outcome, $F_{1,14} = 0.498$, $P > 0.05$, $\eta_p^2 = 0.03$, and no skill × outcome interaction, $F_{1,14} = 2.497$ $P > 0.05$, $\eta_p^2 = 0.15$.

Displacement of gunshot 2 (horizontal axis). Significant main effects were noted for skill, $F_{1,14} = 7.515$, $P < 0.05$, $\eta_p^2 = 0.35$, and outcome, $F_{1,14} = 11.624$, $P < 0.05$, $\eta_p^2 = 0.45$. The elite shooters displayed a significantly smaller gun displacement (mean = 7.3 ± 1.1 cm) compared with the subelite shooters (mean = 8.6 ± 1.6 cm). A smaller gun displacement was evident on hits (mean = 7.3 ± 1.0 cm) than on misses (mean = 8.6 ± 1.7 cm). The interaction between skill and outcome was not significant, $F_{1,14} = 2.975$, $P > 0.05$, $\eta_p^2 = 0.18$.

Displacement of gunshot 2 (vertical axis). There were no significant main effects for skill, $F_{1,14} = 3.263$, $P > 0.05$, $\eta_p^2 = 0.19$, or outcome, $F_{1,14} = 1.335$, $P > 0.05$, $\eta_p^2 = 0.09$, and there was no interaction, $F_{1,14} = 0.077$, $P > 0.05$, $\eta_p^2 = 0.01$.

DISCUSSION

Although research has been undertaken using static aiming and interceptive tasks with approaching objects, limited attention has been devoted to tasks where the target travels away from the participant and is intercepted by an external object, as is the case in shotgun shooting. In this article, we analyzed key performance variables in an attempt to identify the factors that discriminate shooters at elite and subelite levels across the three shotgun subdisciplines. On the basis of previous works (9,24,28), we predicted that elite shooters would exhibit both an earlier onset of QE and a longer final fixation on the clay compared with subelite shooters, as well as an earlier onset of QE on successful compared with unsuccessful shots across all subdisciplines. It was also predicted that there would be differences in gun motion between elite and subelite shooters across each of the shooting subdisciplines.

Quiet eye. As predicted, relative QE duration was significantly longer for elite compared with subelite shooters, supporting previous findings in other sport tasks (9,11,25). Longer relative QE periods were also recorded on successful compared with unsuccessful shots, regardless of skill level. The latter finding supports previous work (19,24,30) and reinforces the view that the QE duration is an important factor in a successful performance across a multitude of aiming tasks. Our findings illustrate the importance of the QE period in a novel, externally paced, interceptive task, with the target moving away from the participant. This evidence advances the research on QE by identifying how it influences performance in sports that require unique orienting and visual control skills.

The QE period is theorized to be used for cognitive processing during which the movement parameters for the task are programmed before action is executed (14). The longer QE in the current study could, therefore, enable the shooters to process the trajectory, direction, and speed of the clay in relation to the gun barrel more accurately before selecting the correct response characteristics. However, research is required to validate this assumption either by involving experimental manipulations to the task constraints or by embracing technological and theoretical advances in the neurosciences. Williams et al. (30) imposed time constraints on billiards shots to assess the impact of QE periods. The constraints led to a reduction in the preparatory phase of the movement, decreasing QE duration significantly in both skill levels. The QE period in the billiard task seems to reflect underlying cognitive processes that play a highly influential role in preparation of the movement. A similar method could be used in shooting to provide a greater understanding of the underlying mechanisms associated with the QE period.

Those examining the QE in sport have typically focused on self-paced tasks where the last fixation can be relatively long (e.g., basketball free throws [24], rifle shooting [11], billiards [30]). However, in shotgun shooting, the task is externally paced, and the shooter is under severe temporal pressure. As the target is moving away from the shooter, the probability of intercepting the shot lessens as the target size decreases. Consequently, delaying the shot could substantially reduce the chances of a successful outcome. It is possible that the elite shooters have developed a strategy to pull the trigger at an "optimal time," allowing the greatest probability of success, but enabling enough time before the shot to program accurately the action.

The earlier onset of QE that was evident with the elite shooters compared with the subelite shooters in the current study is consistent with previous researches in other aiming and interceptive tasks (9,11,20). It has been suggested that this strategy enables the shooters to process information about the flight of the clay earlier than the subelite shooters. Moreover, this finding suggests that the elite shooters are better at anticipating the release of the clay and attending to the most critical cues to initiate the correct response. As a result of the temporal constraints inherent in clay target shooting, shooters need to detect the clay early and then track it in an uninterrupted manner before pulling the trigger (1). An earlier onset of QE was found in trap and double trap in relation to skeet in both skill groups. This finding may be due to the different task constraints in each of the disciplines. The trap and double trap subdisciplines require early clay detection and that the trigger be pulled early to increase success probability because the clay is moving away, whereas skeet shooters do not require such a quick detection and onset of QE due to the clay moving across the layout with the image size of the target being relatively stable.

Gun barrel kinematics. As predicted, differences were found in all subdisciplines between skill groups and shot outcome in the gun motion. In skeet, the elite shooters demonstrated a lower gun barrel displacement in the horizontal axis but showed no differences in movement time on shot 2. This finding suggests that the elite (peak velocity = $0.79\ \text{m}\cdot\text{s}^{-1}$) shooters have a slower motion from picking up the target until the shot compared with their subelite (peak velocity = $1.01\ \text{m}\cdot\text{s}^{-1}$) counterparts. Analysis of the velocities in both skeet and trap shows that lower peak velocities are evident on hits compared with misses and that the velocities are significantly lower for elite compared with subelite shooters. This lower peak velocity apparently results in a more stable motion of the gun with no periods of high acceleration. The ability to keep the gun barrel stable throughout the shooting movement has been seen to be critical in rifle shooting using a running target task (17) as well as in air pistol shooting and other rifle studies with stationary targets (15,16). Although similar

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results are presented in the current study, the task constraints and complexities differ significantly. Both skill groups in skeet and trap demonstrated shorter movement times on hits compared with misses. A shorter movement time would enable more time to complete the second shot in skeet and decrease the distance traveled away from the shooter by the target in trap.

Two different strategies were determined in the skeet and trap subdisciplines. The elite shooters shoot at, or just after, their peak velocity, implying that the gun is increasing in speed as it catches up to the clay until the trigger is pulled. In contrast, the subelite shooters fire significantly later after the peak velocity of the gun. Further analysis showed that subelite shooters tended to accelerate early in the movement to get ahead of the clay and then decrease gun barrel speed until the target catches up before then pulling the trigger. This strategy leads to higher peak velocities initially to get ahead of the target. It also gives a reasonable explanation for why there are larger horizontal axis displacements in the subelite shooters.

A different strategy was used in the double trap because of the more severe temporal constraints. The elite shooters pulled the trigger significantly earlier on both shots compared with the subelite shooters and, therefore, had a lower total movement time. This strategy gives the elite shooters greater opportunity to hit the targets because they have not traveled as far away from the trap. The subelite shooters had a tendency to spend an increased period on shot 1, reducing their chances of a successful second shot. When the subelite shooters hit the second target, they demonstrated a significantly lower movement time for shot 1. The elite shooters also demonstrated lower horizontal axis displacement on the second shot. This latter finding is likely a consequence of taking the shot earlier, and in doing so, the angular displacement of the clays is smaller than when the subelite shooters pull the trigger. The elite shooters also demonstrated a surprisingly small gun barrel displacement from target release to shot 1. The elite shooters' greater task knowledge and experience in the discipline likely enables them to anticipate more accurately the clay appearance and to line up the gun barrel to allow a quick and efficient shot.

Although a seminal investigation, our findings may have important implications for sport-specific training and performance enhancement. We have highlighted several variables that affect performance across the different subdisciplines of shotgun shooting. We have examined the performance strategies used by truly elite performers *in situ*, identifying a multitude of discriminating performance measures that directly affect shot outcome and differentiate across skill levels in shotgun shooting. The results can be used to improve the perceptual–cognitive skills of shooters by using video analysis and feedback techniques in the shooting environment. For example, Adolphe et al. (2) used video feedback of gaze behavior to train elite volleyball players' performance accuracy in passing to the area occupied by the setter. On-court sessions to improve ball detection, tracking, and forearm passing skills were used. Significant pretest to posttest improvements were found in tracking onset, tracking duration, and the ability to maintain a stable gaze on the contact point during step corrections. Feedback and training of gaze behaviors could similarly be developed to improve performance and the knowledge bases of both elite and subelite shooters.

In conclusion, completion of this project extended knowledge of QE and its application using a novel sporting task and world-class athletes. The key performance characteristics that discriminate elite from subelite shotgun shooters were identified using both kinematic and point of gaze data. Longer relative QE and earlier onset of QE, coupled with a smaller gun barrel displacement and a more efficient timing strategy, seemed to be the most important factors mediating expert performance. Also, different spatial and temporal strategies were identified between elite and subelite shooters, which were evident across all three subdisciplines of shotgun shooting. The elite shooters modified their shooting strategy to increase the probability of a successful shot outcome on the basis of the specific task constraints of the subdisciplines, allowing a more efficient and effective movement.

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