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Verification and Analytical Validation of a Virtual Shooting Performance System. Comparing Accuracy and Shot Location Estimates

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Abstract

The introduction of decimal scoring in Olympic 10-m air rifle shooting has increased the need for highly precise shot-location measurement. Although the SCATT MX-02 is widely used to assess aiming behavior and estimate virtual shot locations, its validity against certified electronic scoring targets remains unclear. Therefore, this study examined inter-sensor agreement between 2 co-mounted SCATT MX-02 units and agreement between SCATT-derived virtual shot locations and SIUS-measured impact coordinates.

For inter-sensor agreement, 2 identically configured SCATT MX-02 sensors were mounted on the same rifle during 20 shots. For analytical validation, 3540 synchronized shots from 46 air-rifle athletes across 177 sessions were analyzed. SCATT-derived shot locations were compared with SIUS coordinates using a sequential workflow including custom shot detection, linear extrapolation, and ballistic forward simulation.

The 2 co-mounted sensors showed high agreement, with intraclass correlation coefficients of .994 and .999 for the horizontal and vertical axes, respectively, and a mean absolute error of 0.266 mm. However, SCATT-derived virtual shot locations did not achieve practical agreement with SIUS under any processing step. Linear extrapolation produced lower error than ballistic forward simulation, but the best mean validation error remained 0.99 mm, exceeding the predefined threshold of 0.25 mm. Sensitivity analyses indicated that velocity-related inputs were a major source of error.

These findings indicate that the SCATT MX-02 provides highly consistent aiming-trajectory data and is suitable for process-oriented training analysis. However, SCATT-derived virtual shot locations should not be considered interchangeable with certified measurements of actual shot impact.

Introduction

Performance in Olympic 10 m air rifle shooting has advanced steadily since the discipline's inclusion in the Olympic Games, increasing the demand for highly precise measurement systems capable of distinguishing among elite athletes. In response to the frequent occurrence of perfect scores under the former integer-based system, the International Shooting Sport Federation (ISSF) introduced decimal scoring in 2013, with shot values expressed in 0.1-point increments up to a maximum of 10.9 according to radial distance from the target centre [1]. This degree of resolution requires highly accurate electronic target systems. In official competition, shot-location measurement is therefore based on ISSF-certified electronic targets, with SIUS serving as the reference standard in Olympic shooting settings [2, 3].

Shooting performance reflects a complex interaction of ballistic and motor-control processes. From a ballistic perspective, projectile behaviour is influenced by internal and external factors, including variation in muzzle velocity and aerodynamic effects such as drag and wind [4–6]. From a motor-control perspective, the shooter–rifle system moves in six degrees of freedom, which are projected as horizontal and vertical fluctuations on the target plane. To quantify these fluctuations and provide technical

feedback, aiming-point analysis systems have become integral tools in elite shooting training. These systems combine optoelectronic sensing and inertial measurement to record the rifle's aiming trajectory and estimate a virtual shot location. Among these systems, SCATT is one of the most widely used worldwide [7]. In addition to trajectory visualization, SCATT-derived parameters have been used to characterize stability of hold, cleanness of triggering, aiming accuracy, and timing [8, 9], and the system generates a virtual shot coordinate based on a simplified ballistic model [10].

Despite its widespread practical and scientific use, SCATT's shot output remains a modeled estimate rather than a direct measurement of projectile impact. Nevertheless, many studies have used SCATT-derived virtual shot locations as performance outcome measures [11–21]. This widespread application contrasts with the limited number of validation studies and with repeated skepticism regarding the accuracy of SCATT and comparable systems [22–26]. To date, only one study appears to have examined the relationship between SCATT-estimated and real shot locations, and that investigation focused on pistol shooting using older infrared-based sensors that were susceptible to environmental influences such as lighting and reflective surfaces [25]. Systematic validation of the camera-based SCATT MX-02 against an ISSF-certified reference system in 10 m air rifle is currently lacking.

This gap is important because disagreement between SCATT-derived virtual shots and SIUS-measured impact coordinates may arise from multiple sources. One possible source is hardware-level measurement variability between SCATT units. Another is temporal bias in shot-moment detection, if the internally identified shot event occurs earlier or later than the true projectile release. Further discrepancies may arise from the simplified flight-simulation approach used to project shot location from the recorded aiming trajectory [10], or from velocity estimates derived from two-dimensional aiming-point data that may not adequately represent the underlying three-dimensional rifle and muzzle dynamics. Because the projectile reaches the target approximately 57 ms after release and SCATT does not directly observe pellet flight or all relevant initial conditions, even small errors in timing, position, or velocity estimation may propagate into meaningful spatial discrepancies at the target plane. Accordingly, validation of SCATT cannot be reduced to a single comparison between virtual and real shot coordinates, but instead requires a stepwise investigation of which components contribute most strongly to disagreement with a certified reference system.

Therefore, the purpose of this study was twofold. First, we aimed to verify the agreement of two identically configured SCATT MX-02 sensors mounted on the same rifle under identical shooting conditions, thereby establishing whether hardware-level interchangeability could be assumed. We hypothesized that co-mounted SCATT MX-02 sensors would demonstrate high agreement. Second, we aimed to analytically validate SCATT-derived virtual shot locations against SIUS-measured impact coordinates in 10 m air rifle using a sequential exploratory strategy designed to minimize the discrepancy between both systems. Specifically, we examined whether disagreement could be reduced by successive refinements in shot detection and shot-location modeling, progressing from native SCATT processing to custom shot detection, to physics-based ballistic forward simulation, and finally to diagnostic analyses isolating the contribution of velocity information. For this analytical validation

component, we did not formulate a single directional hypothesis across all refinement steps. Instead, we explored which processing stage most effectively reduced disagreement with the SIUS reference standard and which source of error primarily limited agreement.

Methods

Study Design

This study followed the EVIDENCE Publication Checklist for Studies Evaluating Connected Sensor Technologies [27] to support transparent reporting of study design, connected-sensor implementation, reference standards, data handling, and statistical analysis. The investigation comprised 2 complementary components aligned with verification and analytical validation logic. First, a controlled single-subject design was used to verify intersensor agreement between 2 co-mounted SCATT MX-02 units operating under identical conditions. Second, a multi-athlete, multi-session design was used to evaluate agreement between SCATT-derived virtual shot locations and SIUS-measured impact coordinates under standardized 10 m air-rifle conditions. For this analytical validation component, a sequential exploratory workflow was used to progressively identify and reduce sources of disagreement between both systems.

Participants

Two independent cohorts contributed to the study. For the intersensor agreement component, 1 trained male 10 m air-rifle athlete completed 20 competition-style shots in a single laboratory session. For the analytical validation component, 46 active 10 m air-rifle athletes contributed routine diagnostic sessions between April 2022 and December 2024, yielding 3540 shots across 177 sessions. Competitive level ranged from national-team athletes to Olympic medalists. Inclusion criteria were current rifle athletes classified between Talent-3 and Mastery within the Foundations, Talent, Elite and Mastery (FTEM) framework [28], use of personal competition equipment, and recent national or international training or competition exposure. Exclusion criteria were acute injury or illness and FTEM levels below Talent-3.

All procedures were approved by the ethics committee of the national shooting federation and were conducted in accordance with the Declaration of Helsinki and its later amendments [29]. All participants, or legal guardians in the case of minors, provided written informed consent.

Apparatus and Software

Aiming-point trajectories were recorded using the SCATT MX-02 system [7], and real shot impacts were measured using a SIUS LS10 electronic scoring target [3]. The SCATT MX-02 records the projected aiming trajectory at 100 Hz using combined optical sensing and inertial measurement. The SIUS LS10 served as the criterion reference because ISSF-certified electronic targets represent the competition standard for 10 m air rifle [2]. According to ISSF regulations, approved electronic scoring targets must determine shot location with a precision of at least one-half of one decimal scoring ring in Olympic air rifle [1].

For the intersensor agreement component, 2 identically configured SCATT MX-02 sensors were mounted on the same rifle and connected to a single computer running 2 parallel SCATT Professional instances. For the analytical validation component, 1 SCATT MX-02 unit was used per session, while the SIUS LS10 simultaneously provided impact coordinates and official scores. A custom software solution was used to synchronize and register SCATT and SIUS data through the local range network [30]. Native SCATT shot files were exported to text format using a publicly available exporter [31] for offline analysis in MATLAB [32].

General Procedures

All measurements were collected on the same indoor 10 m range under ISSF-compliant standing air-rifle conditions. Target distance, target type, target height, and illumination followed ISSF regulations. Environmental conditions were stable across sessions, and athletes used their own rifles and ammunition.

Data collection was conducted at the national performance centre by sport scientists and coaches routinely trained in the operation of SCATT and SIUS systems. Before each diagnostic block, athletes received a brief reminder of the measurement procedure. Standard SIUS feedback was available to the athletes during shooting, whereas the measurement computer display was visible only to study staff. No coaching was provided during data collection.

Intersensor Agreement Procedures

For the verification component, 2 SCATT MX-02 sensors with identical firmware and matched sensitivity settings were mounted in close proximity on the same rifle barrel with minimal spacing and near-identical angular alignment. Calibration followed the standard SCATT single-shot procedure. After sighting shots at the athlete’s discretion, 20 competition-style shots were recorded. Manual post hoc alignment of virtual and real shot locations during the 20 analyzed shots was intentionally avoided to prevent introducing sensor-specific offsets. This setup yielded directly comparable aiming trajectories from 2 nominally identical sensors under identical motor and ballistic conditions.

Analytical Validation Procedures

For the analytical validation component, athletes completed standardized diagnostic shooting blocks while SCATT and SIUS recorded synchronized data. The protocol resembled ISSF competition procedures with 3 modifications: a SCATT sensor was attached to the rifle before preparation and sighting, athletes stood on force plates for other diagnostics not analyzed here, and the shooting block consisted of 20 shots rather than a full 60-shot competition. Target height was adjusted so that the aiming angle remained comparable to standard standing shooting, and total available shooting time was reduced proportionally to 25 minutes.

For each shot, SCATT recorded the aiming trajectory from 0.5 seconds before to 0.1 seconds after shot release at 100 Hz, while SIUS recorded impact coordinates and decimal scores. Sessions containing dry-

fire shots or missing SIUS records that prevented unambiguous one-to-one pairing between SCATT and SIUS were excluded. The final dataset comprised 177 sessions and 3540 matched SCATT–SIUS shot pairs.

Analytical validation followed a sequential exploratory workflow. First, shot location was estimated at the detected shot moment (T0), which served as the initial reference point for SCATT-based prediction. Second, because prediction accuracy at T0 was insufficient, the temporal reference point for the estimation was systematically varied in 10-ms increments from 70 ms before to 40 ms after T0 to examine the sensitivity of prediction accuracy to analysis timing and to identify the best-performing analysis time point. Third, linear extrapolation and physics-based ballistic modeling were compared at that time point. Fourth, because prediction error remained substantial, an additional diagnostic analysis examined the contribution of velocity information to model performance.

For each session, shots 1 to 10 formed a calibration subset, and shots 11 to 20 formed a validation subset. Model parameters were optimized on calibration shots and evaluated on validation shots.

Data Processing

Intersensor Agreement

All processing was performed in MATLAB 2024b [32]. For each of the 20 shots, trajectories from both SCATT sensors were temporally synchronized with shot release defined as time zero. The analysis window extended from 4.5 seconds before to 0.3 seconds after shot release.

To remove systematic differences caused by minor mounting offsets and isolate agreement between sensors, a rigid spatial transformation was applied using the Kabsch algorithm [33]. After alignment, pointwise radial error between the 2 trajectories was calculated. Mean absolute error (MAE) was used as the primary absolute agreement metric. Coordinate-specific agreement was additionally quantified for the horizontal and vertical axes using intraclass correlation coefficients (ICC 3,1). Bland–Altman analyses were performed to estimate mean bias and 95% limits of agreement for both axes.

Custom Shot Detection

For the analytical validation component, a custom shot-moment detection procedure was implemented in MATLAB. The algorithm operated on the SCATT position time series for each shot. Jerk magnitude was derived from repeated numerical differentiation of the horizontal and vertical coordinate traces. To refine SCATT's internal timing, the search was restricted to a narrow window of ± 50 ms around SCATT's native shot-detection point. Within this window, the time of maximum radial jerk was identified, and the final sample preceding this peak was defined as the detected shot moment (T0).

All subsequent position and velocity estimates were referenced to this detected event. The custom detection therefore served as the temporal reference point for all subsequent analytical steps.

Statistical Analysis

Intersensor Agreement

For the verification component, intersensor agreement was evaluated descriptively using mean absolute error (MAE), root mean square error (RMSE), intraclass correlation coefficients (ICCs), and Bland–Altman biases and limits of agreement (LoA). Because the purpose of this component was to determine whether hardware-level disagreement was sufficiently small to support interpretation of the subsequent analytical validation, emphasis was placed on the magnitude of disagreement and the presence or absence of systematic bias rather than on inferential testing. No formal a priori power calculation was performed for this verification component.

Analytical Validation

For the analytical validation component, shot-level radial error between SCATT-derived virtual shot locations and SIUS impact coordinates was the primary outcome. For each session and analytical condition, mean calibration error, mean validation error, and the generalization gap between both subsets were calculated.

Results were evaluated descriptively at the session level. For the timing analysis, mean validation error was summarized across sessions for each analysis time point from − 70 to + 40 ms relative to T0 in 10-ms increments, and the time point yielding the lowest mean validation error was selected for subsequent model comparison. For the model comparison, validation error from the linear extrapolation model and the ballistic model was compared descriptively at the best-performing analysis time point. For the diagnostic sensitivity analysis, validation error was summarized across sessions for the respective model and velocity conditions.

Across analyses, emphasis was placed on the magnitude and consistency of differences in validation error rather than on formal confirmatory hypothesis testing. No formal a priori power calculation was performed for the analytical validation component because the available sample was determined pragmatically by routine diagnostic use in the national performance centre.

Results

Participant Characteristics and Analysis Sample

For the analytical validation component (RQ2), 117 athletes registered at the national and regional performance centres were screened. Of these, 71 were not eligible because they specialized in non-rifle disciplines or did not have concurrent registration of real impact coordinates. The final analytical validation sample comprised 46 athletes who provided written informed consent and contributed 177 diagnostic sessions between April 2022 and December 2024. These sessions yielded 3540 synchronized SCATT–SIUS shot pairs for analysis. Athlete age was 24.0 ± 6.1 years (range 15–50 y), 30.4% were male,

and competitive level ranged from FTEM Talent 3 to Mastery. Mean shot score across athletes was 10.30 ± 0.16 (range 9.76–10.51). No matched shot pairs were excluded as outliers.

For the intersensor agreement component (RQ1), 1 trained near-elite male rifle shooter completed 20 competition-style shots during a single session. Both SCATT MX-02 sensors recorded complete aiming trajectories at 100 Hz for all shots. After synchronization and alignment, all 20 shots were available for analysis.

Verification: Intersensor Agreement (RQ1)

For the intersensor agreement component, 1 trained near-elite male rifle shooter completed 20 competition-style shots during a single session. Both SCATT MX-02 sensors recorded complete aiming trajectories at 100 Hz for all shots. After cropping to the predefined analysis window (− 4.5 s to + 0.3 s relative to shot release), all 20 shots with 480 paired samples per shot were available for analysis, yielding 9600 paired observations.

To account for residual mounting-related translation and rotation between the 2 co-mounted sensors, a single rigid 2-dimensional transformation was estimated at the session level and applied to all trajectories from Sensor 1 before agreement metrics were computed. This alignment reduced root mean square discrepancy from 0.845 mm before alignment to 0.330 mm after alignment. The estimated transformation corresponded to a rotation of 0.063 rad and a translation of 0.590 mm in the horizontal direction and 0.556 mm in the vertical direction.

After session-level alignment, pooled mean absolute error between sensors was 0.266 mm, and pooled root mean square error was 0.330 mm. At the shot level, mean absolute error was 0.266 ± 0.183 mm (95% CI, 0.180–0.351 mm), and root mean square error was 0.279 ± 0.181 mm (95% CI, 0.194–0.364 mm) (Table 1).

Table 1
Metrics for intersensor agreement analysis

Metric	Value
MAE, mm	0.266 ± 0.183
MAE 95% CI, mm	0.180 to 0.351
RMSE, mm	0.279 ± 0.181
RMSE 95% CI, mm	0.194 to 0.364
ICC x-axis	0.994
ICC y-axis	0.999
Bias x, mm	−0.000
LoA x, mm	−0.574 to 0.574
Bias y, mm	−0.000
LoA y, mm	−0.300 to 0.300

Coordinate-specific agreement was high. ICC (3,1) was .994 for the horizontal axis and .999 for the vertical axis. Bland–Altman analyses showed negligible mean bias on both axes (x: −0.000 mm; y: −0.000 mm), with 95% limits of agreement of − 0.574 to 0.574 mm horizontally and − 0.300 to 0.300 mm vertically. Thus, the 2 co-mounted SCATT MX-02 sensors showed very high relative agreement and minimal systematic bias after session-level alignment, but residual absolute disagreement remained above 0.25mm.

Analytical Validation: SCATT Versus SIUS (RQ2)

Step 1: Linear Extrapolation

Linear extrapolation produced lower error than the ballistic model across the analyzed time points. Using the calibration-validation split across 177 sessions, validation error for the linear model ranged from 0.84 mm at T_minus = − 0.01 s to 1.20 mm at T_minus = + 0.04 s, with an overall validation mean of 0.99 ± 0.65 mm. Calibration error averaged 0.78 ± 0.58 mm, yielding a mean generalization gap of + 0.21 mm. The lowest validation errors occurred close to trigger release, whereas error increased when estimates were based on earlier pre-shot positions or on postshot positions affected by recoil.

Across all analyzed time points, validation error remained well above the predefined practical accuracy threshold of 0.25 mm. Accordingly, Step 1 did not satisfy the criterion for practical agreement with SIUS.

Step 2: Custom Shot Detection

The custom jerk-based shot-detection procedure was implemented to examine whether reducing temporal bias in shot-moment identification improved agreement under the same linear extrapolation framework. In the full analytical workflow, this step served to isolate the contribution of shot-detection timing while keeping the shot-location model unchanged. The resulting comparisons informed selection of the shot-detection approach for subsequent analyses. However, the available linear-model results remained above the predefined 0.25-mm threshold, indicating that refinement of shot timing alone was insufficient to achieve practical equivalence with SIUS.

Step 3: Ballistic Forward Simulation

The ballistic forward model did not improve agreement relative to linear extrapolation. Validation error ranged from 0.98 mm at T_minus = − 0.03 s to 2.66 mm at T_minus = + 0.01 s, with an overall validation mean of 1.61 ± 1.42 mm. Calibration error averaged 1.38 ± 1.34 mm, resulting in a mean generalization gap of + 0.23 mm. Error increased markedly around and after trigger release, indicating that SCATT-derived initial conditions in this interval were not sufficient to support accurate ballistic forward simulation.

Optimized ballistic parameters also showed values that were not physically plausible for 10 m air-rifle shooting, including mean forward velocity estimates of 191.6 ± 4.2 m/s, gravitational acceleration of 9.602 ± 0.716 m/s², and drag coefficient estimates of 0.764 ± 0.022. These parameter patterns suggest compensatory fitting rather than accurate recovery of underlying projectile dynamics. As with the linear model, validation error remained well above the predefined 0.25-mm threshold.

Comparison of Linear and Ballistic Models

A linear mixed-effects model fitted to validation data showed a significant main effect of simulation approach, $F_{1,42300} = 6221.6$, $P < .001$, indicating that ballistic simulations produced larger radial errors than linear extrapolation. The fixed-effect estimate showed that ballistic predictions exceeded linear-model error by 0.834 mm (SE = 0.0106; 95% CI [0.813, 0.854]). There was also a significant interaction between simulation approach and analysis time, $F_{1,42300} = 2573.6$, $P < .001$, indicating that ballistic-model performance deteriorated more strongly as analysis time approached and exceeded trigger release.

Variance decomposition showed that 1.9% of variance was attributable to between-athlete differences, 7.4% to between-session differences, and 90.7% to residual variance. At the mean T_minus value, estimated marginal means were 1.00 mm for the linear model and 1.62 mm for the ballistic model, a difference of − 0.62 mm (95% CI [− 0.64, − 0.60]; $P < .001$). Thus, across the validation dataset, linear extrapolation consistently outperformed ballistic forward simulation.

Step 4: Diagnostic Sensitivity Analysis

The diagnostic sensitivity analysis examined whether model disagreement was driven primarily by velocity-related inputs. In the ballistic framework, disabling speed estimation reduced mean validation error from 1.61 ± 1.42 mm to 1.05 ± 0.67 mm, corresponding to an improvement of − 0.56 mm (− 34.9%).

In contrast, disabling drag and gravity optimization had negligible effect on error (+ 0.01 mm). The interaction between speed condition and drag/gravity condition was not significant, $F_{1,84776} = 0.776$, P = .378.

These results indicate that velocity-related information, rather than gravity or drag parameterization, was the dominant contributor to error in the ballistic model. Even under the improved speed-off condition, however, error remained above the predefined 0.25-mm threshold. Thus, none of the tested processing variants yielded practical equivalence between SCATT-derived virtual shot locations and SIUS-measured impact coordinates.

Summary of Main Findings

The verification component showed that 2 co-mounted SCATT MX-02 units provided nearly identical aiming trajectories, with all predefined intersensor agreement criteria satisfied. In contrast, the analytical validation component showed that SCATT-derived virtual shot locations did not achieve practical agreement with SIUS-measured shot coordinates under any tested processing approach. Linear extrapolation outperformed ballistic forward simulation, and diagnostic analyses indicated that velocity-related inputs were a major source of disagreement. Across all evaluated approaches, mean radial error remained substantially above the predefined threshold of 0.25 mm.

Discussion

The purpose of this study was 2-fold: first, to verify agreement between 2 identically configured SCATT MX-02 sensors mounted on the same rifle under identical shooting conditions; and second, to analytically validate SCATT-derived virtual shot locations against SIUS-measured impact coordinates in 10 m air rifle using a sequential exploratory strategy. The main findings were that hardware-level agreement between co-mounted SCATT MX-02 units was very high, whereas SCATT-derived virtual shot locations did not achieve practical agreement with SIUS-measured impact coordinates under any tested processing approach. Across the analytical validation steps, linear extrapolation consistently outperformed ballistic forward simulation, and diagnostic analyses indicated that velocity-related inputs were a major source of disagreement.

The present findings indicate that both sensors provide highly consistent representations of the underlying aiming trajectory, as reflected by near-perfect ICC values. This suggests that relative metrics describing movement dynamics can be interpreted interchangeably across sensors. However, absolute agreement was substantially lower, with residual pointwise discrepancies in the submillimeter range. Given the fine spatial resolution relevant for decimal scoring, these differences are not negligible. Thus, while the sensors can be considered equivalent for relative analyses, their interchangeability for absolute performance metrics such as shot location appears limited.

This distinction highlights that high reliability does not imply sufficient absolute agreement for performance-level interpretation. In practical terms, the sensors can be used interchangeably when

analyzing movement structure or temporal dynamics, but caution is required when interpreting absolute spatial outcomes such as shot placement.

The analytical validation component showed that this second requirement was not met. Even the best-performing approach remained clearly above the predefined practical threshold of 0.25 mm radial error relative to SIUS. Thus, SCATT-derived virtual shot locations could not be regarded as practically interchangeable with SIUS-measured impact coordinates. This result is important because SCATT virtual shots are frequently used in both applied settings and scientific studies as indicators of shooting performance. The present findings suggest that such use should be interpreted with caution when the research question depends on accurate reconstruction of actual pellet impact location rather than on characteristics of the aiming process itself [11–14, 18–20, 34, 35].

Among the tested processing approaches, linear extrapolation outperformed ballistic forward simulation. This result may initially seem counterintuitive because a physics-based ballistic model should, in principle, more closely resemble true projectile flight than a simplified linear approximation. However, the superiority of a more realistic physical model depends on the quality of the initial conditions supplied to that model. In the present context, those initial conditions were derived from SCATT-based aiming-point data, that is, from a 2-dimensional representation of rifle motion projected onto the target plane. Such data may be sufficient to support simple extrapolation over a short interval, but they appear insufficient to reliably recover the 3-dimensional state variables required for accurate ballistic simulation. As a consequence, the added model complexity did not improve accuracy and instead amplified the effects of uncertainty in the model inputs.

This interpretation is supported by the pattern of optimized ballistic parameters. Several estimated parameter values were physically implausible for 10 m air-rifle shooting, suggesting that the optimization procedure compensated for unmodeled or poorly estimated aspects of the problem rather than recovering meaningful ballistic constants. In other words, the ballistic model appeared to absorb error through parameter adjustment. This interpretation is also consistent with the marked deterioration in ballistic-model performance around and after trigger release, where recoil and transient rifle dynamics likely further reduce the validity of SCATT-derived initial conditions. Under these circumstances, a simpler linear approach was more robust than a more detailed ballistic simulation.

The diagnostic sensitivity analyses further support this conclusion. When velocity-related inputs were removed or constrained, prediction error in the ballistic framework decreased substantially, whereas changes to drag and gravity parameterization had negligible effect. This pattern indicates that the dominant source of error was not the omission or misspecification of basic external-ballistic forces over a 10 m flight distance, but the quality of the velocity information entering the model. This is plausible because SCATT estimates aiming motion from target-plane trajectories sampled at 100 Hz, whereas the actual shot outcome depends on the rifle's state at the instant of projectile release, including translational and rotational components that may not be fully represented by the available 2-dimensional

data. Over a flight time of approximately 57 ms, even small timing or velocity errors may propagate into meaningful spatial discrepancies at the target.

Taken together, these findings suggest that SCATT should not be viewed primarily as an impact-measurement system, but rather as a process-analysis system. The MX-02 appears highly capable of recording aiming trajectories reproducibly, and SCATT-derived variables related to stability, timing, and triggering may therefore remain highly valuable for training diagnostics and movement analysis. By contrast, the present data do not support treating SCATT-derived virtual shot coordinates as direct substitutes for impacts measured by an ISSF-certified electronic target system[2, 3]. This distinction is especially important for scientific studies in which virtual shot coordinates are used as outcome measures [11–14, 18–20, 34, 35]. If absolute shot-location accuracy is central to the research question, SIUS or another certified reference system should remain the preferred criterion measure.

The present results also help contextualize prior literature that relied on SCATT-derived virtual shot locations as performance outcomes. These studies may still provide meaningful insight into psychophysiological or technical correlates of shooting performance, particularly when the primary interest lies in within-athlete patterns or relative differences under comparable conditions. However, the current findings suggest that observed effects should not automatically be interpreted as precise changes in true impact location. More generally, the results emphasize the importance of distinguishing between measurement of the aiming process and measurement of the projectile outcome.

Several limitations should be considered. First, the verification component was based on a single athlete and a single session. Although this design was appropriate for isolating intersensor agreement under tightly controlled conditions, it limits generalization across rifles, athletes, and mounting configurations. Second, the analytical validation component was based on routine diagnostic data from a high-performance setting rather than on a prospectively balanced experimental design. This improves ecological validity, but sample structure was determined pragmatically by training-centre use. Third, the SIUS LS10 was treated as the criterion reference because it represents the certified competition standard, but manufacturer-level precision specifications for this exact system were not independently verified within the present study. Fourth, SCATT sampling was limited to 100 Hz, which may be insufficient to resolve the most critical dynamics around trigger release. Fifth, the ballistic model necessarily simplified some aspects of projectile behavior and rifle dynamics; however, the sensitivity analyses suggest that model-input limitations were more influential than omission of basic drag or gravity effects. Finally, the present findings apply specifically to 10 m air rifle and the tested SCATT MX-02 workflow and should not be generalized automatically to other shooting disciplines, distances, or sensor configurations.

In summary, this study shows that the SCATT MX-02 provides highly consistent aiming-trajectory measurements at the hardware level, but that SCATT-derived virtual shot locations do not achieve practical agreement with SIUS-measured impact coordinates under the tested processing approaches. Linear extrapolation was more accurate than ballistic forward simulation, and velocity-related inputs

emerged as a major source of estimation error. These findings support the use of SCATT for process-oriented training diagnostics, but not the assumption that its virtual shot coordinates are interchangeable with certified target-based measurements of true shot location.

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