

Comparative Analysis of Bullet Trajectories in Rifled and Smoothbore Firearms: Implications for Forensic Angle-of-Fire Estimation

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Abstract

Original Research Article

Forensic reconstruction of shooting incidents routinely assumes that a projectile travels in a straight line between its entry and exit wounds. This study tested that assumption experimentally by comparing bullet trajectories from rifled and smoothbore firearms within calibrated ballistic gelatine. Three handguns representing the principal archetypes encountered in South Asian casework were used: an Indian Ordnance Factory 7.65 mm rifled semi-automatic pistol, an Indian Ordnance Factory .32" rifled break-open revolver, and a country-made 7.65 mm smoothbore pistol. Six analytical shots (two per firearm, each into a fresh block) were fired from a fixed muzzle-to-target distance of 1.07 m into 12.5% w/w Type-A 250-Bloom porcine gelatine blocks, calibrated to a penetration depth of 8.5–9.5 cm. Preset vertical angles were +15° elevation for the smoothbore pistol, 0° for the semi-automatic pistol and –10° decline for the revolver, with the firing bench rotated 10° to the right of the laboratory baseline. Blocks were sectioned along the sagittal midline and the internal wound track was measured directly. Both rifled firearms produced parabolic wound tracks with perpendicular deviations of 0.3–1.6 cm from the entry–exit chord, and straight-line angle estimation returned errors of 7° and 13°; in the revolver case a bullet fired at a 10° decline yielded an apparent 3° elevation, reversing the sign of the reconstructed angle. The smoothbore pistol produced linear tracks with estimation errors of 1°, within measurement tolerance, but wound channels an order of magnitude wider (10–70 mm against a uniform 11.7–13.2 mm for the rifled firearms) and markedly non-uniform. Horizontal deviation was ≤1° for all firearms. These observations indicate that the straight-line method retains validity for smoothbore weapons but can be substantially misleading for rifled weapons at close range, and that firearm type should be established before a trajectory reconstruction method is selected. Given the small sample, the findings are reported as a controlled demonstration requiring confirmation at larger scale.

Keywords: Bullet Trajectory, Rifled Firearms, Smoothbore Firearms, Country-Made Firearms, Forensic Ballistics, Angle-Of-Fire Estimation, Ballistic Gelatine, Shooting Incident Reconstruction.

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1. INTRODUCTION

1.1 Background on Ballistic Trajectory Analysis

Forensic reconstruction of a shooting incident depends on an accurate understanding of the path taken by the projectile. The technique most widely used to estimate the angle of fire connects the entry and exit wounds with a straight line and extends that line rearward to approximate the position of the shooter [1, 2]. The method — variously described as the string-and-pin, probing or rod method — is favoured for its simplicity, its minimal equipment requirement and the speed with which it can be applied at a scene [3].

The linear assumption is nevertheless an approximation. A bullet follows a three-dimensional path from muzzle to rest. Gravity imposes continuous downward acceleration, so that even short trajectories

curve; Kerkhoff *et al.*, quantified the resulting systematic error in the vertical component of handgun trajectory reconstructions and proposed 20 m and 30 m as conservative distances beyond which the straight-line model should not be applied to subsonic and supersonic handgun bullets respectively [5, 6]. Aerodynamic drag decelerates the projectile and alters the energy available for transfer to the target [32, 33].

Within the target the situation is more complex still. Rifled barrels impart gyroscopic spin, which stabilises the bullet in air but does not guarantee stability on entry into a denser medium. The abrupt deceleration at the air–tissue interface can initiate yaw and precession, and the resulting asymmetric resistance produces a curved rather than a straight internal track [7–11]. Smoothbore barrels impart no spin; projectiles leaving

them are aerodynamically unstable and tend to yaw or tumble soon after exit, so that their flight is less predictable and their effective range short [26, 27].

1.2 Rifled and Smoothbore Firearms in Casework

The distinction matters in practice because both classes of weapon are encountered in the same jurisdictions. In India and comparable jurisdictions across South Asia, parts of Africa and Latin America, tightly regulated factory-made rifled handguns coexist with a large population of illicitly manufactured smoothbore weapons, known regionally as country-made or improvised firearms [26-29]. These are typically single-shot steel-tube constructions produced without rifling, headspace control or dimensional tolerance, and their examination has become a routine component of ballistic casework in the region [26-30]. A forensic examiner confronted with a wound track therefore cannot assume a single ballistic model, and the choice of reconstruction method may itself depend on which class of weapon was used.

1.3 Ballistic Gelatine as a Tissue Simulant

Ballistic gelatine is the internationally accepted surrogate for human soft tissue in wound ballistics research, on account of its density, its elasticity and its optical transparency [9-36]. Jussila reviewed the preparation variables and proposed a standard method, noting that concentration is of secondary importance provided the medium is validated against a reference penetration function [18]. Subsequent work has characterised storage and preservation effects [19], contrast enhancement [20], the influence of the supporting counterfort [21], and bullet deceleration measured by high-speed video [22].

In the present study, blocks were prepared at 12.5% w/w rather than the more common 10%. The higher concentration increases mechanical strength and allows the block to retain its geometry during sectioning and repeated measurement, which is essential when the wound track itself is the measurand rather than the penetration depth. Every block was nevertheless calibrated against the FBI reference protocol before use, so that comparability with the wider literature is preserved [24, 25].

1.4 Prior Work on Trajectory Deflection within Tissue Simulants

The question addressed here is not new, and a body of quantitative work exists against which the present observations should be read. Riva *et al.*, modelled bullet deflection due to gelatine perforation and reported that deflection angles are approximately constant for a given gelatine depth, finding no significant influence of previously fired tracks or of the block side [13]. Kerkhoff *et al.*, measured pistol bullet deflection through soft tissue simulants under different incidence and exit angles [14], and Riva *et al.*, extended the analysis to rifle bullets [15]. Later contributions

examined the influence of bullet type and muzzle-to-target distance [16], and of an interposed skin simulant [17].

Two observations follow. First, deflection within a soft tissue simulant is a documented and measurable phenomenon rather than an artefact, which supports the plausibility of the curvature reported below. Second, that literature is concerned almost exclusively with factory-made rifled ammunition; it does not address country-made smoothbore weapons, and it does not directly compare the two classes under a common protocol. The present study is positioned in that gap.

1.5 Objectives

This study had three objectives:

- To characterise the internal trajectory of bullets fired from rifled and from country-made smoothbore handguns into calibrated ballistic gelatine, in terms of track shape, perpendicular deviation from the entry–exit chord, and wound-channel geometry;
- To quantify the error incurred when the conventional straight-line angle-of-fire method is applied to each class of firearm, by comparing the reconstructed angle against the preset firing angle; and
- To derive firearm-specific recommendations for trajectory reconstruction practice in jurisdictions where both classes of weapon are encountered.

1.6 Significance

Forensic protocols commonly apply a single linear reconstruction model irrespective of firearm type. If rifled projectiles curve appreciably within tissue at close range while smoothbore projectiles do not, then a uniform protocol will be accurate for one class and misleading for the other, and the direction of the resulting error will not be apparent to the examiner. Establishing firearm type early in an examination would then be not merely descriptive but methodologically decisive, with direct consequences for shooter positioning, for the interpretation of shooting dynamics and for the weight properly attached to ballistic evidence in court [2-42].

2. MATERIALS AND METHODS

2.1 Experimental Design

The study was designed as a controlled comparison in which barrel type and preset vertical firing angle were varied while all other parameters were held constant: firing distance, target medium, block preparation, ambient temperature, measurement instrumentation and observer protocol. Materials and tools were selected for general availability, so that the protocol can be replicated in laboratories with limited resources. Where competing international standards exist, the more widely referenced was adopted to maximise comparability [25-41].

2.2 Firearms and Ammunition

Three handguns representing the principal archetypes of licit and illicit short arms in the region were used. The country-made 7.65 mm smoothbore pistol was a single-shot, non-rifled steel-tube weapon of the type described by Pal and Pratihari and by Dhaka *et al.*, [26, 27], two analytical rounds were discharged at +15° elevation, simulating the upward trajectory typical of chest-level assaults. The Indian Ordnance Factory 7.65 mm semi-automatic pistol has a 114 mm barrel with six right-hand grooves and a nominal muzzle velocity of 315 ± 5 m/s; two analytical rounds were fired horizontally (0°), replicating an across-room engagement. The Indian Ordnance Factory .32" break-open revolver (Field Gun

Factory MK-III) has a 100 mm barrel rifled one turn in 200 mm and a nominal muzzle velocity of 290 ± 10 m/s; two analytical rounds were fired at -10° decline, representing downward trajectories such as those encountered in stairwell or self-inflicted scenarios.

Commercially available ammunition was used throughout. Both 7.65 mm pistols were loaded with .32 ACP 71 gr full metal jacketed cartridges; the revolver used .32 S&W Long 98–100 gr lead round-nose ammunition. All ammunition was conditioned for 48 h at 20 °C and 45% relative humidity before use [25-41]. Full specifications are given in Table 1.

Table 1: Specifications of the firearms and ammunition used in the study

Firearm	Barrel type	Barrel length (mm)	Calibre	Rifling	Ammunition	Bullet mass (gr)	Nominal muzzle velocity (m/s)
Country-made pistol	Smoothbore	≈110	7.65 mm	None	.32 ACP FMJ	71	≈310 (est.)
IOF semi-automatic pistol	Rifled	114	7.65 mm	6 RH grooves, 1:200 mm	.32 ACP FMJ	71	315 ± 5
IOF MK-III break-open revolver	Rifled	100	.32"	1 turn in 200 mm	.32 S&W Long LRN	98–100	290 ± 10

FMJ, full metal jacket; LRN, lead round nose; RH, right-hand; IOF, Indian Ordnance Factory. Nominal muzzle velocity is the manufacturer specification; the country-made pistol has no manufacturer specification and the figure given is estimated from comparable published measurements [26,27].

2.3 Ballistic Gelatine Preparation and Calibration

2.3.1 Preparation

Blocks were prepared at 12.5% w/w from Type-A 250-Bloom porcine gelatine powder. Exactly 1,000 g of powder was sprinkled gradually over 7,000 g of de-ionised water at 15 °C in a stainless steel vessel and left to hydrate for 90 min. The hydrated mixture was heated to 40 °C on an electric hotplate with continuous gentle stirring; the temperature ceiling was observed strictly, since excess heat degrades the mechanical properties of the finished block [18].

2.3.2 Degassing, Moulding and Conditioning

The dissolved gelatine was degassed under vacuum at 25 inHg for 10 min using a glass-coil manifold, which minimises entrained air and improves the visibility of the wound channel [18-20]. The clarified

solution was poured immediately into transparent polycarbonate moulds measuring $38 \times 16.5 \times 14.5$ cm, sealed with foil-lined rubber stoppers to prevent surface dehydration, and refrigerated at 4 °C for 24 h. On the day of firing each block was equilibrated to 30 ± 1 °C for 2 h to ensure uniform density through the volume [19].

2.3.3 Calibration

Each batch was calibrated with a 9 mm NATO 124 gr FMJ round fired at 365 ± 3 m/s in accordance with the FBI and ENFSI protocols [24, 25]. Blocks whose calibration penetration depth fell outside the 8.5–9.5 cm acceptance window were discarded and remade. Calibration parameters and outcomes are given in Table 2; a representative block during preparation is shown in Fig. 2.

Table 2: Ballistic gelatine block specification and calibration outcome

Parameter	Value	Reference / basis
Gelatine type	Type-A, 250 Bloom, porcine	Manufacturer specification
Concentration	12.5% w/w	This study; cf. 10% FBI standard [24]
Water temperature at mixing	15 °C	Jussila [18]
Hydration time	90 min	Jussila [18]
Dissolution temperature	40 °C	Jussila [18]
Degassing	10 min at 25 inHg	This study
Mould dimensions	$38 \times 16.5 \times 14.5$ cm	Measured
Setting	24 h at 4 °C	Mattijssen <i>et al.</i> , [19]
Pre-firing equilibration	2 h at 30 ± 1 °C	This study

Parameter	Value	Reference / basis
Calibration projectile	9 mm NATO 124 gr FMJ	FBI / ENFSI protocol [24,25]
Calibration velocity	365 ± 3 m/s	Chronograph
Acceptable penetration depth	8.5–9.5 cm	FBI / ENFSI protocol [24,25]
Measured penetration depth	9.1 cm (range 8.8–9.3 cm)	All blocks within acceptance
Block mass after setting	7,900–8,000 g	Measured to ± 1 g
Calculated block density	1.04–1.06 g/cm ³	From mass and volume

Every block used for trajectory analysis passed calibration; no block was retained after a failed calibration shot.

2.4 Indoor Range and Firing Stand

Firings were conducted in a purpose-built indoor range of $10 \times 4 \times 4$ m with concrete walls, incorporating a mild steel bullet trap for calibration rounds and a 3 m cotton-lined chamber for projectile recovery. Ambient temperature and relative humidity were recorded at the start and end of each session with a digital thermo-hygrometer.

A tubular steel bench measuring 2.5×0.8 m fitted with a padded breech clamp secured each firearm.

Trigger actuation was by rigid steel linkage, permitting remote discharge from behind a 10 mm polycarbonate barrier. The bench was rotated 10° to the right of the laboratory baseline so that the projectile entered along the midline of the block. Vertical pitch was preset at $+15^\circ$ for the smoothbore pistol, 0° for the semi-automatic pistol and -10° for the revolver. Muzzle-to-block distance was fixed at 1.07 m (3.5 ft) and verified twice before each session. The layout is shown schematically in Fig. 1.

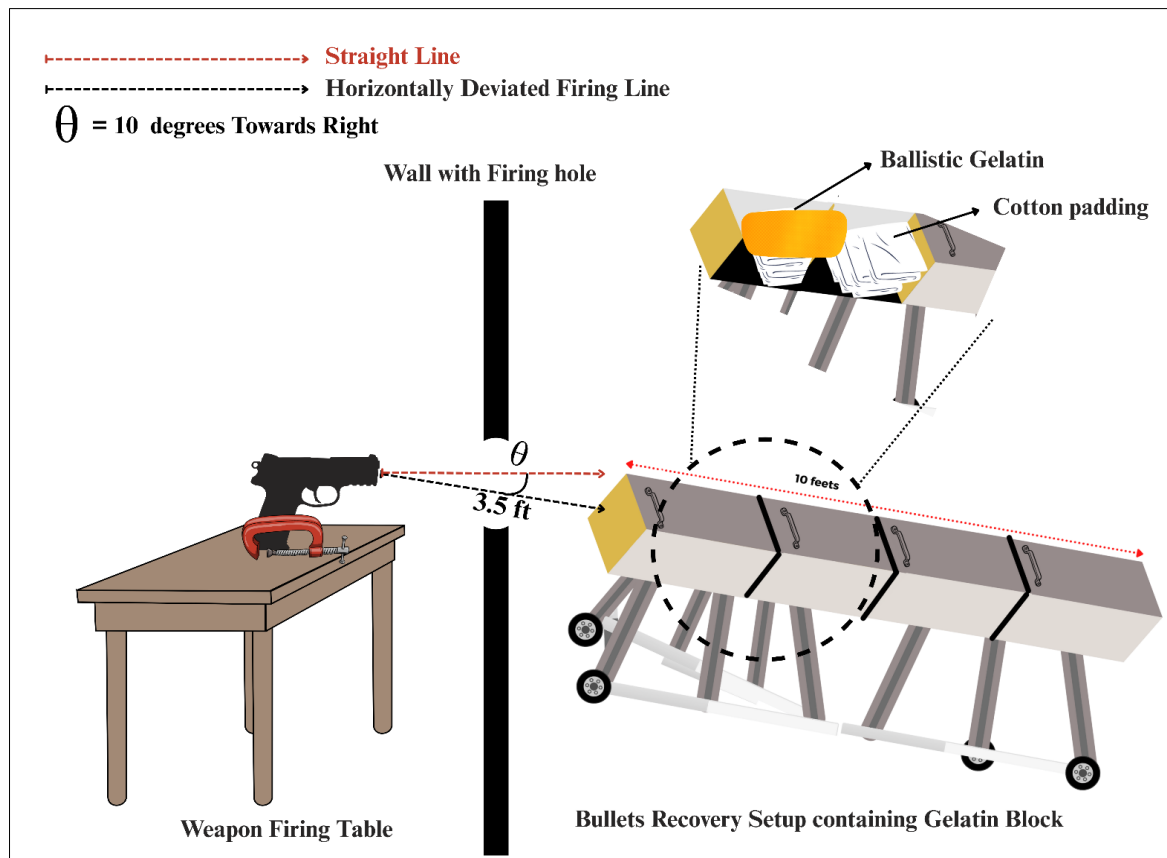


Fig. 1: Schematic of the experimental indoor firing range. The layout shows the firing bench and stabilising clamp, the polycarbonate safety barrier, the position and orientation of the ballistic gelatine block at 1.07 m from the muzzle, the 10° rightward horizontal offset of the firing line from the laboratory baseline, and the cotton-lined bullet recovery chamber. All components are labelled to allow reproduction of the measurement geometry

2.5 Shot Matrix and Replication

Each analytical shot was fired into a fresh, previously unused block, so that no track could be influenced by a prior impact — a control indicated by Riva *et al.*, who examined precisely this potential

confounder [13]. Each analytical shot was preceded by a conditioning round of identical ammunition fired into the recovery chamber, to stabilise barrel temperature and fouling. The complete schedule is given in Table 3.

Table 3: Shot matrix: firearm, barrel type, preset vertical angle and replication

Firearm	Barrel type	Preset vertical angle	Analytical shots (n)	Conditioning shots (n)	Block ID prefix
Country-made 7.65 mm pistol	Smoothbore	+15° elevation	2	2	SB
IOF 7.65 mm semi-automatic	Rifled	0° (horizontal)	2	2	RF
IOF .32" MK-III revolver	Rifled	−10° decline	2	2	RV
Total	—	—	6	6	—

Analytical shots are experimental firings into gelatine used for trajectory analysis. Conditioning shots are preceding rounds of identical ammunition fired into the recovery chamber and excluded from analysis. Block identifiers follow the pattern SB-1, RF-2 and so on; laboratory records retain the full identifier including firearm, ammunition, angle and date.

2.6 External Impact Measurement

After each shot the entry and exit defects were located visually. A transparent metric rule was placed parallel to the relevant block face and an L-shaped steel square used to confirm perpendicularity to the block axis. Each defect diameter was measured three times with a Vernier caliper of 0.01 mm resolution and the mean recorded. Defect centres were mapped to ± 0.5 mm, providing the initial estimate of the entry–exit chord.

2.7 Sectioning and Internal Documentation

Each block was assigned a unique identifier recording firearm, ammunition, firing angle and test date, preserving chain of custody. Longitudinal sectioning along the sagittal midline was performed with a utility knife pre-warmed in water at 40 °C, in a single continuous cut passing through both defects, so as to

minimise deformation of the gelatine and preserve the cavity walls. Cut faces were blotted with lint-free wipes to remove condensation before imaging.

The exposed cavity was photographed at high resolution with a metric scale in frame. Maximum visible length, width and depth of the wound channel were measured with a transparent rule and Vernier caliper at defined stations along the track, each value logged against its position on the block. For smoothbore shots a linear regression was fitted to the extracted track coordinates; for rifled shots a second-order polynomial was fitted to capture curvature. Where transverse sectioning was additionally required, identical tools and documentation protocols were applied. Representative sections appear in Fig. 3, and the horizontal view in Fig. 4.

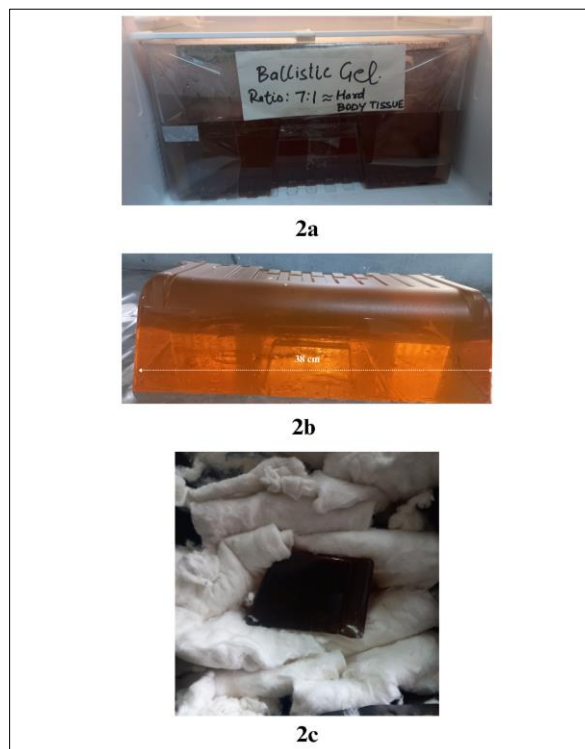


Fig. 2: Preparation of the ballistic gelatine blocks. (A) 12.5% w/w Type-A 250-Bloom porcine gelatine setting under refrigeration. (B) The same block after demoulding and equilibration at 30 °C. (C) Front view of the block installed in the bullet recovery box

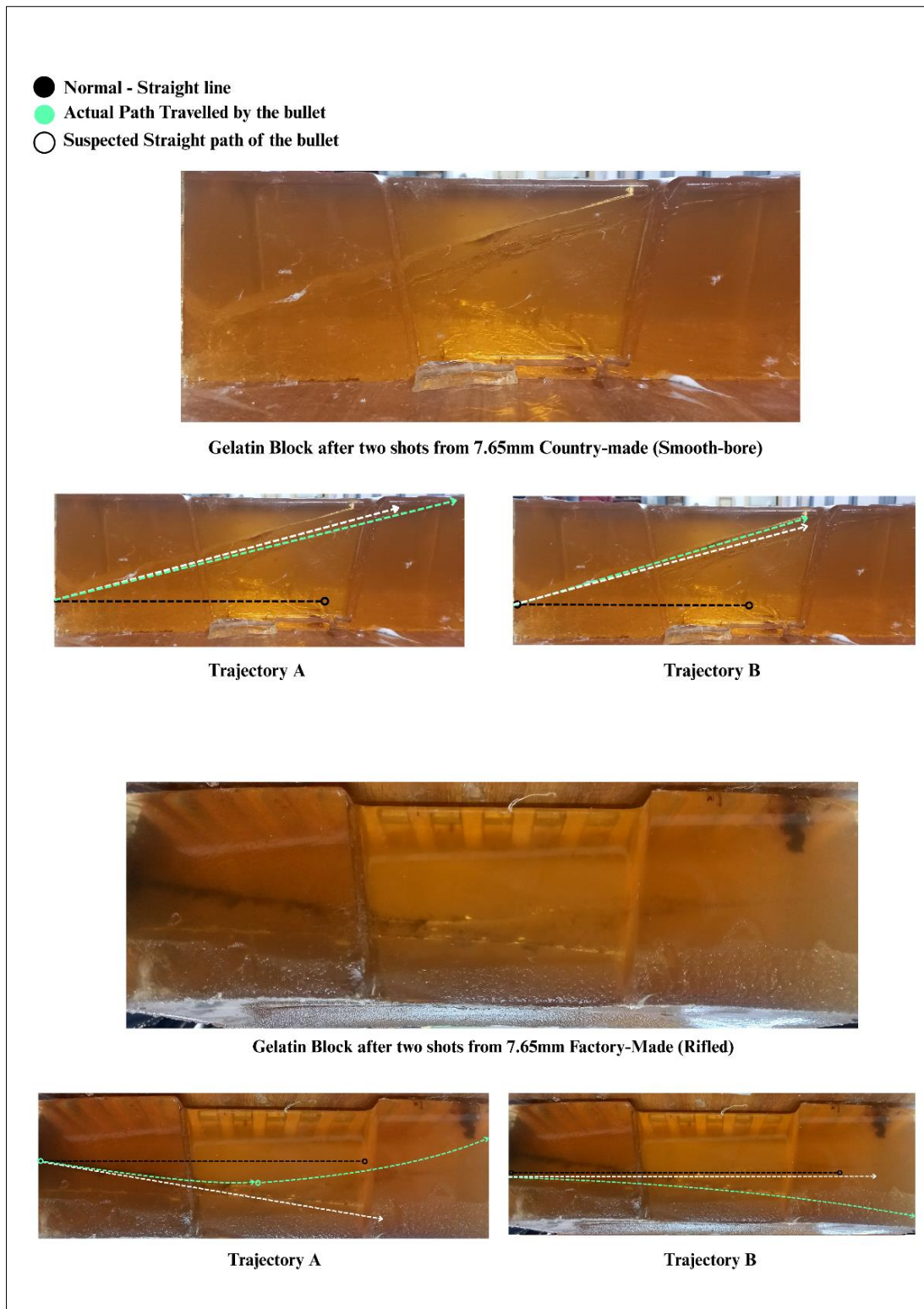


Fig. 3: Representative post-firing sections through the gelatine blocks, showing the linear track produced by the country-made smoothbore pistol alongside the parabolic track produced by the rifled firearms

2.8 Angle-Of-Fire Estimation and Error Calculation

The angle of fire was estimated by the conventional forensic method: the centres of the entry and exit defects on the sectioned face were joined by a straight line and the angle between that chord and the horizontal baseline of the block was measured with a protractor [1-3]. Where the internal track was visibly

parabolic, the straight-line construction was nevertheless applied, since the purpose of the study was precisely to assess the reliability of that construction across firearm types.

The preset firing angle was established before discharge by aligning the firearm and bench to a

measured vertical angle. The estimation error for each shot was taken as the difference between the preset angle and the reconstructed angle:

$$\varepsilon = \theta_{\text{set}} - \theta_{\text{obs}} \quad (1)$$

Where θ_{set} is the preset vertical firing angle and θ_{obs} the angle of the entry–exit chord, both measured positive for elevation. The magnitude reported in the Results is the absolute error $|\varepsilon|$. In addition, the maximum perpendicular displacement of the observed track from the chord was measured directly on the sectioned face:

$$d_{\text{max}} = \max_i |P_i - \text{proj}_{\text{chord}}(P_i)| \quad (2)$$

Where P_i denotes the track coordinates sampled along the channel. This quantity is reported in centimetres and is independent of the angular measurement, providing a second, geometrically distinct indicator of curvature.

All measurements were verified independently by a second observer. Discrepancies exceeding 1° for angles or 0.5 mm for linear dimensions were resolved by joint review and a consensus value recorded.

2.9 Data Recording and Management

Raw measurements — entry and exit defect diameters, inter-defect distance, channel length and all other recorded dimensions — were entered on paper worksheets at the time of measurement, each labelled with block code, firearm and ammunition details, firing angle and date. Completed sheets were checked for completeness before transcription to an electronic spreadsheet. Paired readings were compared where more than one observer or session was involved; discrepancies beyond tolerance were flagged and resolved as described above. Both paper records (scanned) and electronic files were backed up periodically to storage accessible only to the study team.

2.10 Quality Assurance and Calibration

Rules, L-squares and Vernier calipers were checked against a certified steel reference at the start of each measurement day and any instrument failing tolerance was withdrawn from service. Every instrument was inspected visually for wear or damage before use. Departures from the prescribed measurement or calibration schedule were recorded in the laboratory log together with a note on the likely effect on data quality. Procedures followed ISO/IEC 17025 principles for laboratory measurement, and firearm examination practice followed ENFSI and AFTE guidance [25-40].

2.11 Data Analysis

With two analytical shots per firearm, the design supports descriptive comparison but not inferential testing, and no significance tests were performed. Reporting a p-value from a sample of this size would convey a precision the data do not possess. Results are therefore given as individual observed values together with the arithmetic mean and range for each

firearm class, and the reader is directed to the magnitude of the differences and to their consistency across replicates rather than to a test statistic.

Two derived quantities are reported. The absolute angle estimation error $|\varepsilon|$ follows Eq. (1). The perpendicular deviation d_{max} follows Eq. (2). Track shape was classified as linear where a first-order fit accounted for the observed coordinates within measurement tolerance, and as parabolic where a second-order term was required. Wound-channel diameters originally recorded in inches have been converted to millimetres throughout for consistency; the converted values are the ones tabulated.

2.12 Safety, Legal and Ethical Compliance

All firings were conducted behind a polycarbonate barrier with personnel positioned outside the line of fire. The firing area was cleared before each discharge and only authorised, trained personnel operated firearms or handled fired blocks. Eye and ear protection were used in accordance with laboratory policy. Firearms and ammunition were acquired and handled strictly in accordance with the applicable national, regional and institutional licensing requirements, and all discharges were performed by certified examiners of the Forensic Ballistics Division, FSL Madhuban. The study involved no live animals, no human participants and no cadaveric tissue, and accordingly required no institutional ethical approval. Spent ammunition, gelatine and other waste were disposed of under local hazardous-waste guidance. All project staff completed safety and ethics training before participating.

3. RESULTS

3.1 Calibration and Sample Quality

All blocks used for trajectory analysis met the calibration criterion. Calibration penetration depths ranged from 8.8 to 9.3 cm with a mean of 9.1 cm, within the 8.5–9.5 cm acceptance window of the FBI and ENFSI protocols [24, 25]. No block that failed calibration was retained. Each analytical shot was fired into a separate, newly prepared and uniquely labelled block (Table 2).

3.2 Trajectory Behaviour of the Rifled Firearms

3.2.1 Entry, Exit and Channel Features

Both rifled firearms produced consistent wound-channel features. Spiral entry defects were observed in every case, and gyration marks were visible on all recovered projectiles, confirming barrel-induced spin. Exit defects were present in every block and were typically round and smaller than the corresponding entry defect. For the MK-III revolver, entry defect diameters were 7.9 mm and 8.1 mm for shots 1 and 2; for the 7.65 mm semi-automatic pistol, 5.1 mm and 7.6 mm. Exit defect diameters ranged from 7.6 to 14.2 mm for the revolver and from 3.2 to 3.8 mm for the pistol.

Blackening and tattooing were present around the entry defects, as expected at the firing distance used.

3.2.2 Track Shape and Deviation

Every rifled shot produced a parabolic internal track (Fig. 3). Perpendicular deviation from the entry–exit chord was 0.5 cm and 1.6 cm for revolver shots 1 and 2, and 0.3 cm and 0.8 cm for pistol shots 1 and 2

(Fig. 6a). Despite the curvature, all projectiles maintained a nose-forward orientation throughout the block, with no evidence of abrupt yaw, tumbling or lateral instability. The permanent channel diameter was highly uniform along the track for both weapons: 11.7 mm for the revolver and 13.2 mm for the pistol. Full measurements are given in Table 4.

Table 4: Trajectory and wound-channel measurements for the rifled firearms

Firearm	Shot	Entry defect (mm)	Exit defect (mm)	Channel diameter (mm)	Track shape	Deviation d_{max} (cm)	Gyration marks / spiral entry
.32" MK-III revolver	1	7.9	7.6	11.7 (uniform)	Parabolic	0.5	Present / yes
.32" MK-III revolver	2	8.1	14.2	11.7 (uniform)	Parabolic	1.6	Present / yes
7.65 mm semi-automatic	1	5.1	3.2	13.2 (uniform)	Parabolic	0.3	Present / yes
7.65 mm semi-automatic	2	7.6	3.8	13.2 (uniform)	Parabolic	0.8	Present / yes

Defect and channel dimensions were recorded in inches and converted to millimetres (1" = 25.4 mm). Deviation d_{max} is the maximum perpendicular displacement of the observed track from the entry–exit chord, per Eq. (2). All four shots showed head-to-head striking impact.

3.3 Trajectory Behaviour of the Smoothbore Firearm

3.3.1 Entry, Exit and Channel Features

The country-made smoothbore pistol produced distinctly different features. Entry defects were conical, larger and more irregular than those of the rifled weapons, measuring 35.6 mm for shot 1 and 9.1 mm for shot 2. Exit defects showed comparable variability and were in several instances larger and more irregular than the entry. The internal channel was markedly wider than for the rifled firearms, at 60–70 mm for shot 1 and 10–50 mm for shot 2, and — unlike the rifled cases — non-uniform along its length (Fig. 6b). No gyration marks or rifling impressions were present on any recovered

projectile, and no spiral entry defect was observed in any shot, confirming the absence of spin stabilisation.

3.3.2 Track Shape and Deviation

Both smoothbore shots produced a straight internal track (Fig. 3). No parabolic or curvilinear component was measurable, and the perpendicular deviation from the chord was below the resolution of the method. Angular deviation was $\leq 1^\circ$, consistent with direct entry-to-exit linearity. The wider and less uniform channel indicates greater tissue disruption and lateral variability despite the straight path. Measurements are given in Table 5.

Table 5: Trajectory and wound-channel measurements for the country-made smoothbore pistol

Shot	Entry defect (mm)	Exit defect (mm)	Channel diameter (mm)	Track shape	Angular deviation	Entry defect shape	Gyration marks
1	35.6	Irregular, $\geq$ entry	60–70 (non-uniform)	Linear	$\leq 1^\circ$	Conical	Absent
2	9.1	Irregular, variable	10–50 (variable)	Linear	$\leq 1^\circ$	Conical	Absent

Exit defects were irregular in outline and could not be characterised by a single reliable diameter; the qualitative description is given instead. Shot 1 showed a striking impact that was not head-to-head; shot 2 was head-to-head.

3.4 Accuracy of Angle-Of-Fire Estimation

For the smoothbore pistol the reconstructed angles closely matched the preset angles. Shot 1 was set at $+15^\circ$ elevation and reconstructed at $+14^\circ$; shot 2 was set at $+15^\circ$ and reconstructed at $+16^\circ$. Both errors were 1° , at the limit of measurement tolerance, and both tracks were linear, so that the straight-line construction reflected the true path.

For the rifled firearms the discrepancies were substantial. The 7.65 mm semi-automatic pistol was fired

horizontally at 0° and the entry–exit chord reconstructed to a 7° decline. The MK-III revolver was fired at a 10° decline and the chord reconstructed to a 3° elevation — an error of 13° which reverses the sign of the estimate, so that a bullet fired downward would be reconstructed as having been fired upward. Mean absolute error was 1.0° for the smoothbore firearm (range $1\text{--}1^\circ$) and 10.0° for the rifled firearms (range $7\text{--}13^\circ$). Results are set out in Table 6 and Fig. 5.

Table 6: Angle-of-fire estimation by the conventional straight-line method: preset versus reconstructed angles

Firearm	Shot	Preset angle θ_{set}	Reconstructed angle θ_{obs}	Track shape	Error $ \epsilon $	Method accuracy
Country-made (smoothbore)	SB-1	+15° elevation	+14° elevation	Linear	1°	High
Country-made (smoothbore)	SB-2	+15° elevation	+16° elevation	Linear	1°	High
IOF 7.65 mm pistol (rifled)	RF-1	0° (horizontal)	-7° decline	Parabolic	7°	Poor
IOF .32" MK-III revolver (rifled)	RV-1	-10° decline	+3° elevation	Parabolic	13°	Poor (sign reversed)

Angles are positive for elevation and negative for decline; $|\epsilon|$ follows Eq. (1). Angular reconstruction is reported for the four shots in which both defect centres could be located unambiguously on the sectioned face. For the second shot from each rifled firearm the exit defect could not be resolved with sufficient confidence for protractor measurement, and those shots contribute to the deviation data of Table 4 but not to the angular comparison.

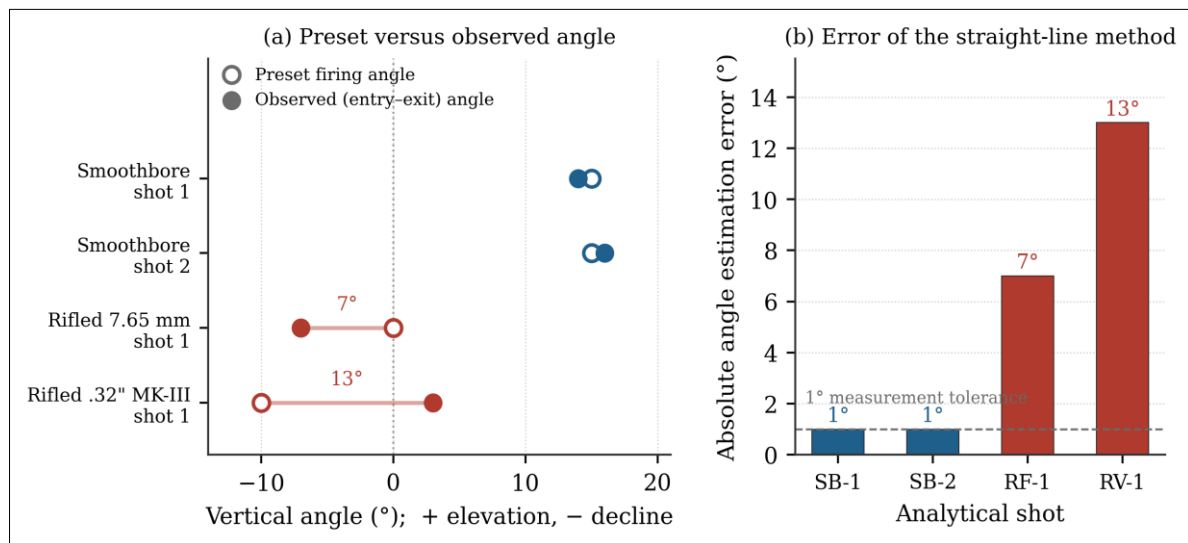


Fig. 5: Accuracy of the conventional straight-line angle-of-fire estimate. (a) Preset firing angle (open markers) against the angle reconstructed from the entry–exit chord (filled markers) for each analytical shot; the connecting segment represents the estimation error. (b) Absolute estimation error by shot, with the 1° measurement tolerance indicated. SB, country-made smoothbore pistol; RF, IOF 7.65 mm rifled pistol; RV, IOF .32" MK-III rifled revolver.

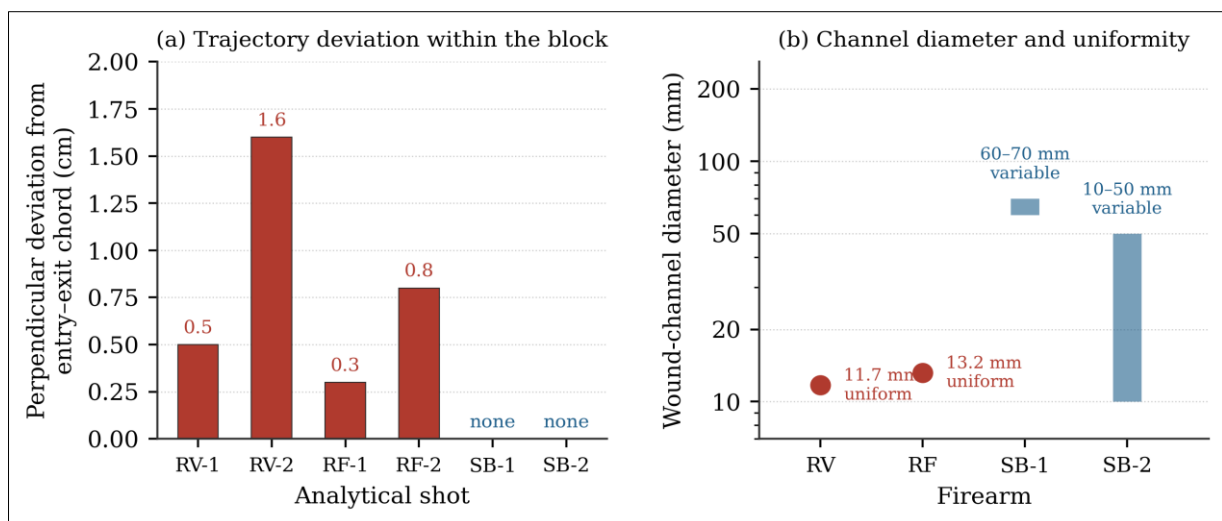


Fig. 6: Internal track geometry by firearm type. (a) Maximum perpendicular deviation of the observed wound track from the entry–exit chord; no measurable deviation was detected for either smoothbore shot (hatched). (b) Permanent wound-channel diameter on a logarithmic scale, showing the uniform narrow channel of the rifled firearms against the wide and variable channel of the country-made smoothbore pistol.

3.5 Horizontal Deviation

Horizontal (left–right) deviation of the bullet path was minimal in every block and within measurement tolerance. Entry and exit points were closely aligned along the intended horizontal firing axis, with no S-shaped or lateral curvature observed.

Maximum measured horizontal deviation was $\leq 1^\circ$, and no systematic trend was apparent across firearm types (Fig. 4). The curvature reported in Section 3.2 is therefore confined to the vertical plane, which is the plane in which angle-of-fire reconstruction is performed and in which the resulting error is consequential.

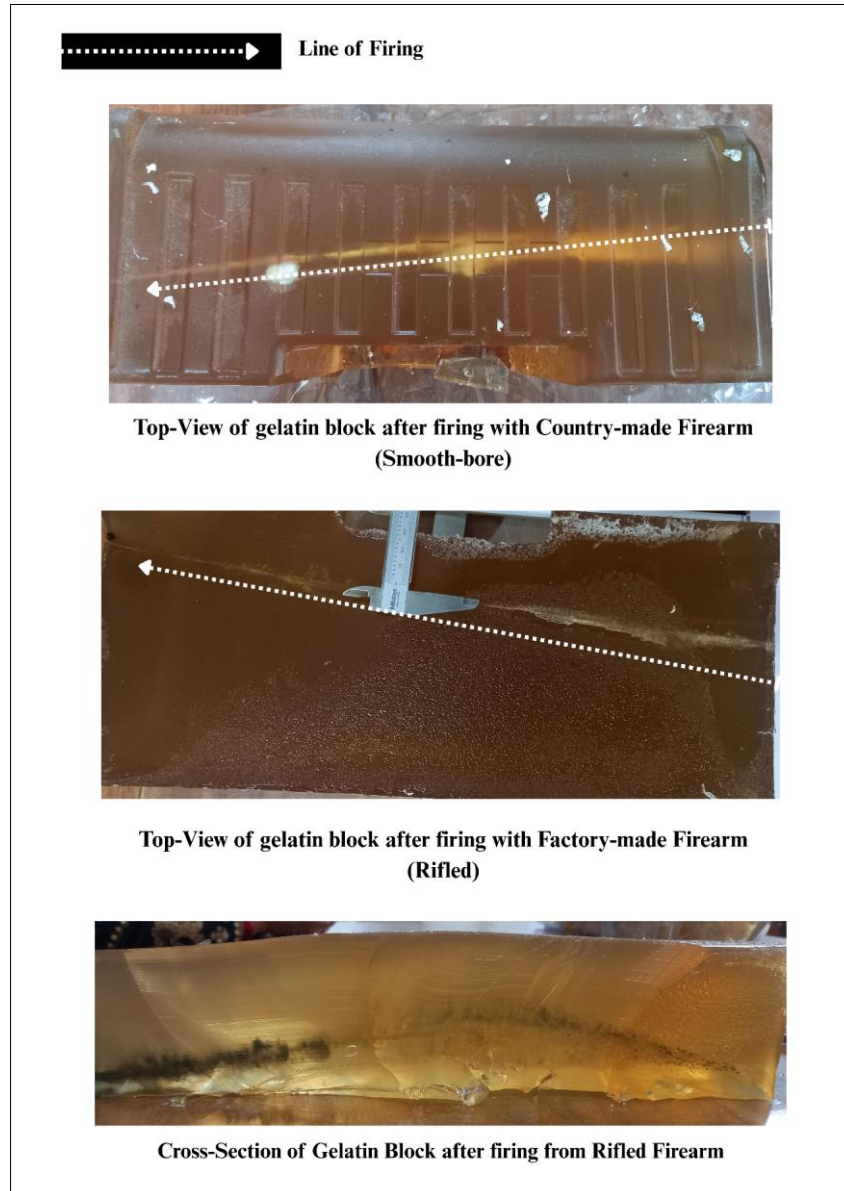


Fig. 4: Assessment of horizontal deviation. (A) Top view of a gelatine block after firing with the country-made smoothbore pistol, showing the line of travel aligned with the intended firing axis. (B) Top view after firing with the factory-made rifled pistol, showing the same alignment in the horizontal plane. (C) Sagittal cross-section after firing with a rifled firearm, in which the parabolic track is visible in the vertical plane. Horizontal deviation was $\leq 1^\circ$ for all firearms and firing angles, indicating that the curvature reported in Section 3.2 is confined to the vertical plane.

3.6 Summary of Observations

The country-made smoothbore pistol produced straight tracks with angular errors at the limit of measurement tolerance, together with wide and irregular wound channels; the conventional straight-line method reconstructed its firing angle accurately. Both rifled

firearms produced parabolic tracks with consistent spiral entry defects and gyration marks, and errors of 7° and 13° in the reconstructed angle, in one case reversing the sign of the estimate. Horizontal deviation was negligible for all firearm types, with every projectile remaining aligned with the intended firing axis.

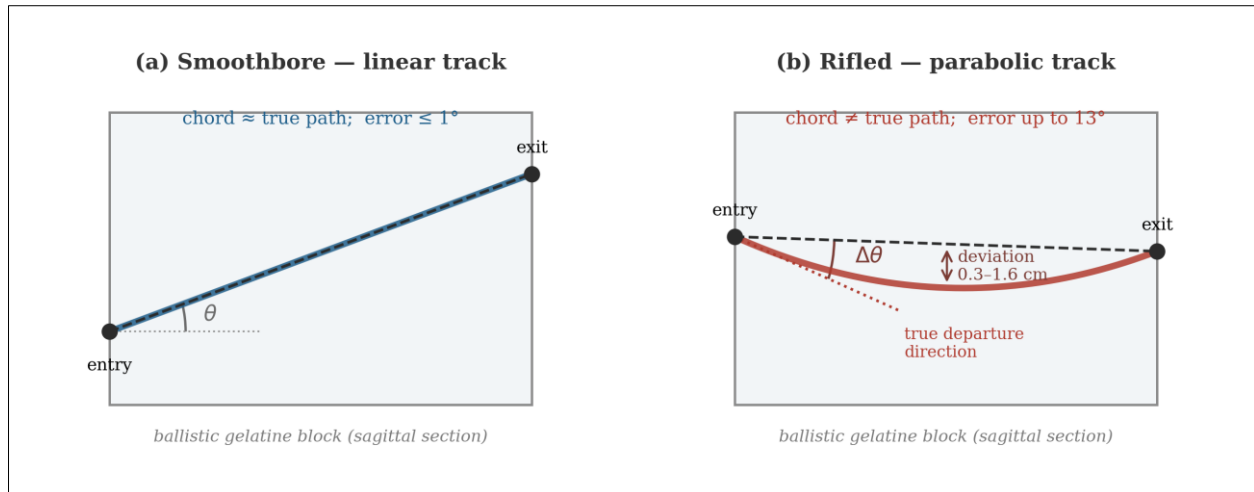


Fig. 7: Geometric basis of the estimation error. (a) For a linear track the entry–exit chord coincides with the true path, and the reconstructed angle θ reproduces the firing angle. (b) For a parabolic track the chord departs from the true path; the angle of departure at the entry point differs from the chord angle by $\Delta\theta$, and it is this difference that propagates into the reconstructed shooter position. The chord may indicate elevation where the true departure was a decline

4. DISCUSSION

4.1 Reliability of the Straight-Line Method for Rifled Firearms

Both rifled firearms produced measurable parabolic deviation within the gelatine, and applying the straight-line construction to those tracks generated errors of 7° and 13° . The geometric reason is set out in Fig. 7: the entry–exit chord is a secant of a curved path, and its inclination equals the tangent of the path only where the path is straight. Where it is not, the chord angle diverges from the true angle of departure, and the divergence propagates into the estimated shooter position with a lever arm equal to the reconstruction distance.

The plausible mechanism is rotational. Rifling confers gyroscopic stability in air, but the abrupt deceleration at the air–gelatine interface generates an overturning moment that the spin resists rather than eliminates, producing precession and a laterally asymmetric resistance profile [7–11]. The consequence is a curved permanent track. This interpretation is consistent with the observation that all projectiles nevertheless remained nose-forward: the deviation observed here is a smooth curvature attributable to precession, not the gross tumbling that accompanies yaw instability.

The most consequential single observation is the revolver shot fired at a 10° decline and reconstructed as a 3° elevation. An error that reverses the sign of the estimate is qualitatively different from one that merely degrades its precision: it would place the shooter below rather than above the wound, and would support the wrong reconstruction of the incident rather than an imprecise version of the right one. Where such an estimate is offered in evidence without a stated uncertainty, the error is invisible to the tribunal.

4.2 Validity of the Straight-Line Method for Smoothbore Firearms

Conversely, the method performed well for the country-made smoothbore pistol. Both shots produced linear tracks aligned with the preset angle to within 1° . The absence of spin means there is no gyroscopic moment to be disturbed at the interface; resistance is distributed symmetrically about the axis of travel, and the projectile penetrates on a straight line preserving the firing angle. For non-rifled weapons the entry–exit chord therefore remains a defensible basis for reconstructing the angle of fire and, by extension, the shooter position.

This should not be read as a general endorsement of smoothbore predictability. The same shots produced wound channels between 10 and 70 mm in diameter and markedly non-uniform along their length, against a uniform 11.7–13.2 mm for the rifled weapons — a difference of roughly an order of magnitude (Fig. 6b). Straight-line reconstruction is reliable for these weapons in respect of direction, but the wide and irregular channel means that the entry and exit defect centres are themselves less precisely defined, and the practical uncertainty on the reconstructed angle is correspondingly greater than the 1° figure alone suggests.

4.3 Relation to Published Deflection Studies

The direction of these findings agrees with the established deflection literature, though the conditions differ in ways that matter. Riva *et al.*, reported that deflection angles are approximately constant for a given gelatine depth and are not influenced by adjacent prior tracks [13]. Kerkhoff *et al.*, characterised deflection in pistol bullets under varying incidence and exit geometry [14], and, subsequently, the influence of bullet type and muzzle-to-target distance [16], and of an interposed skin simulant [17]. Riva *et al.*, extended the work to rifle projectiles [15]. Collectively these studies establish that

deflection of rifled projectiles within a soft tissue simulant is a real, reproducible and quantifiable effect.

Three differences should be borne in mind when comparing magnitudes. First, most of the published work uses 10% gelatine at muzzle-to-target distances of several metres, whereas the present study used 12.5% gelatine at 1.07 m; a denser medium and a shorter flight both plausibly increase the residual yaw at entry. Second, the published studies predominantly examine 9 mm Luger ammunition, whereas the weapons here are .32 calibre with lower muzzle energy. Third, and most importantly, no published study within this programme addresses country-made smoothbore weapons. The comparison offered here is therefore complementary to that literature rather than a replication of it, and the specific error magnitudes reported should not be transferred to other calibres, media or distances without further work.

A related consideration concerns the source of curvature. The gravitational systematic error analysed by Kerkhoff *et al.*, operates over the external flight path and is negligible below approximately 20 m [5], at the 1.07 m distance used here it cannot account for the deviation observed. The curvature reported in this study is therefore terminal rather than external in origin, which is consistent with its confinement to the vertical plane within the block and with its absence in the smoothbore case.

4.4 Sources of Error

Several sources of error must be acknowledged. Minor misalignment in firearm positioning or block orientation could introduce small trajectory deviations; manual measurement with protractor, rule and photographic analysis carries an inherent tolerance, quantified here as 1° for angles and 0.5 mm for linear dimensions. Local variation in gelatine density or residual entrained air could subtly influence a bullet path despite standardised preparation, although calibration of every block limits this. Small differences in bullet mass, profile or construction may modulate yaw, particularly for rifled projectiles. Finally, the transition from air to gelatine generates complex transient forces, including differential deceleration and temporary cavitation, that amplify small initial deviations [22]. Against these, the consistency of the pattern across replicates and across two independent rifled weapons supports the principal finding, even though it does not establish its magnitude precisely.

4.5 Forensic Implications

4.5.1 Crime Scene Investigation

If the class of firearm determines whether a reconstruction method is valid, then firearm type is not merely a descriptive attribute of a case but a precondition for method selection. Where a rifled weapon is indicated — by spiral entry defects, gyration marks on a recovered projectile, or a narrow uniform channel — an examiner

should treat a straight-line estimate as provisional and qualify it accordingly. Where a smoothbore weapon is indicated by conical entry defects, a wide irregular channel and the absence of rifling impressions, the straight-line estimate may be relied upon, subject to the wider uncertainty in defect localisation noted in Section 4.2.

4.5.2 Method Selection by Firearm Type

For smoothbore firearms the conventional method remains valid and no additional instrumentation is required. For rifled firearms, linear reconstruction should be supplemented by direct internal track mapping through serial sectioning, by three-dimensional imaging such as computed tomography or laser scanning [43], or by computational modelling of the terminal trajectory. Where such resources are unavailable, the minimum acceptable practice is to report the estimate with an explicit uncertainty consistent with the deviation magnitudes documented here and in the deflection literature [13–17], rather than as a point value.

4.5.3 Practice, Training and Evidential Weight

Incorporating firearm-specific guidance into forensic training and standard operating procedures would reduce the risk of the failure mode illustrated by the revolver shot, in which a confident but sign-reversed estimate is more damaging than an acknowledged absence of information. It would also improve investigative efficiency, since early identification of firearm type allows an appropriate analytical route to be selected at the outset. These points align with longstanding recommendations on the validation and transparent reporting of forensic methods [39–42].

5. Limitations and Future Work

The principal limitation is sample size. Six analytical shots — two per firearm — reflect the legal, logistical and cost constraints that ordinarily attend controlled firearm experimentation, but they do not support inferential statistics or a claim about the population distribution of estimation error. The results should be read as a controlled demonstration that the effect exists and is large in the conditions tested, not as an estimate of its magnitude in casework. Confirmation requires replication with substantially larger samples per condition.

Second, the study examined three specific weapons and two ammunition types. A wider range of calibres, bullet constructions (full metal jacket, hollow point, unjacketed lead), barrel lengths and twist rates would be required before the findings could be generalised, particularly given that bullet type is a documented influence on deflection [16].

Third, all firings were performed at a single fixed distance of 1.07 m into uniform gelatine blocks under controlled laboratory conditions. Real scenes involve variable ranges, intermediate barriers such as

clothing, glass and bone, non-uniform target geometry and uncontrolled environmental conditions. Interposed materials in particular are known to alter deflection substantially [17-35], and the present protocol does not address them.

Fourth, gelatine is a soft-tissue simulant only. It does not reproduce skin, bone or the layered heterogeneity of anatomy, all of which influence both track and wound morphology [23-37]. Composite simulants incorporating skin and bone analogues would improve external validity.

Fifth, measurement relied on manual instruments and photography. Optical distortion in photographs of a transparent, refractive medium is a recognised source of error, and three-dimensional scanning or computed tomography of the sectioned block would give a more accurate reconstruction of the track than protractor measurement of a chord [43].

Priorities for further work therefore include: replication at larger scale with multiple weapons per class; systematic variation of firing distance and vertical angle; introduction of intermediate barriers and composite anatomical simulants; high-speed video capture of the entry event to relate terminal curvature to yaw at impact [22], and the development of a correction model that would allow an examiner to recover an estimate of the true departure angle from an observed chord, given firearm class and penetration depth. A correction of that kind, validated against a sufficient dataset, would convert the present negative finding about the straight-line method into a usable positive tool.

6. CONCLUSION

This study compared bullet trajectories from rifled and country-made smoothbore handguns within calibrated ballistic gelatine in order to test the validity of the conventional straight-line angle-of-fire estimate. Both rifled firearms produced parabolic wound tracks, with perpendicular deviations of 0.3–1.6 cm from the entry–exit chord and reconstruction errors of 7° and 13°; in one case the error reversed the sign of the estimated angle, so that a downward shot was reconstructed as an upward one. The country-made smoothbore pistol produced linear tracks reconstructed to within 1° of the preset angle, but with wound channels roughly an order of magnitude wider and markedly non-uniform. Horizontal deviation was negligible throughout.

The practical implication is that firearm type should be established before a reconstruction method is chosen. For smoothbore weapons the conventional method remains defensible. For rifled weapons at close range it should be supplemented by internal track mapping, three-dimensional imaging or computational modelling, or at minimum reported with an explicit uncertainty. The findings rest on six analytical shots and are offered as a controlled demonstration requiring

confirmation at larger scale, across a wider range of calibres and firing geometries, and in the presence of the intermediate materials that characterise real scenes.

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