Review Article

A Review of Ricochet Occurrence: As a Function of Critical Angle and Different Material Targets

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Abstract

Bullet ricochets are a frequent occurrence in shooting situations and can yield a lot of information that helps in the reconstruction of the shooting incident. This review is the cumulation of various bullet ricochet examinations done worldwide based on critical angle, target material, and type of bullet. The article overviews ricochet angles observed on common surfaces like wood, concrete, metal sheets, glass, ceramic, water etc. The review also explores additional factors impacting ricochet events such as bullet wipe marks, splintering effect, ramping effect, plugging effect, ramping, and tunnelling effects. The combined knowledge of these discoveries advances our comprehension of both the complex dynamics of bullet ricochets and forensic ballistics.

Keywords: Bullet, ricochet, critical angle, target surface.

Introduction

Forensic Ballistics is a subfield of forensics that focuses on the examination of weapons, and ammunition, and the study of projectile motion and their impact[1]. When a bullet (projectile) comes in contact with any surface and gets unexpectedly diverted from its trajectory, forensic experts frequently look into such shooting occurrences[2,3,5]. This phenomenon is known as a ricochet[6,4].

Because the surface absorbs some energy and reflects the remaining, a bullet that strikes below the critical angle ricochets and deflects rather than entering. The angle of incidence influences ricochet behaviour; larger angles result in greater deflection, whereas shallow angles increase skimming[7-11]. Another important factor is surface composition; tougher surfaces, such as steel, cause greater deflections[12-13], whereas softer materials absorb more energy, limiting ricochet. The form and substance of bullets are also very important. Round-nosed bullets are more prone to ricochet than hollow-point or flat-nosed bullets[11-6,] and the danger of ricocheting is greater for tougher materials like copper and steel[11] than for softer lead. While bullets with flat or hollow ends may shatter or do less harm, sharp-nosed bullets tend to penetrate and baton rounds mostly used in crowd control, bounce[14-15]. Ricochet angle

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and velocity are affected by several factors, including impact velocity, obliquity angle, yaw, projectile mass, and target attributes[16,17]. Ricocheted bullets can keep their deadly energy even after distortion[7]. To find important incident facts, forensic specialists examine their trajectory, shape, and surface properties[18-20].

Reconstruction of events require the use of critical angles and bullet markings[2,21,23]. At a specific velocity, 50% of bullets will bounce off or cease ricocheting at the critical ricochet angle[10-11]. High-speed bullets affect the transfer of material between the bullet and the target, following Locard's concept of exchange[6]. The carbonaceous substance, lubricant, and sealant that makeup bullet wipe marks offer important forensic information[14-26].

During the literature survey, authors noticed that different review articles have been published about ricochet gunshot wounds, wherein mainly focussing on various facets of bullet behaviour on living beings[27-32]. However, during any shooting incident whether indoor or outdoor, a bullet can hit various target surfaces at some non-ideal level of uncertainty[33].

Using a variety of bullets and weapons, this article investigates ricochet behaviour on a range of surfaces at various critical angles. It emphasises the significance of target surfaces and crucial angles in comprehending projectile rebound, providing information useful for disaster studies, forensic investigations, projectile velocity analysis, shooting range design, the creation of protective gear, and safety precautions.

Methodology

A systematic literature review was performed using the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines. The review was conducted without date or language restrictions in major databases (Science Direct, Scopus, Elsevier, Wiley, MDPI, ProQuest, etc.) that centred on the keywords "ricochet of the bullet on different surfaces like woods, concrete, glass, metal sheet or water". This search returned 2520 English language articles published from 1990 to 2024. After eliminating results; a large number of additional irrelevant articles (e.g., Recovery of fired ammunition, sound design for three short films also wounds created by ricochets of bullets), 65 publications remained for review. The PRISMA flowchart is shown in (Fig. 1).

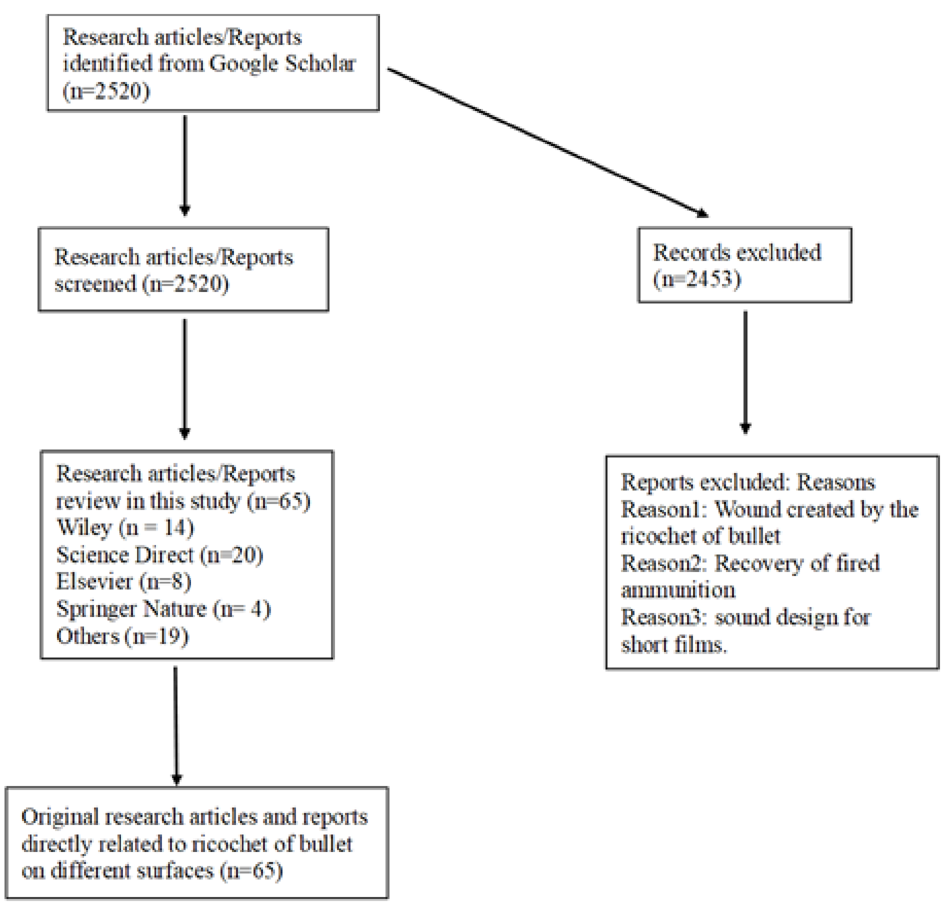

Fig. 1: PRISMA flow Chart

Discussion:

The discussion includes review on investigation involving ricochet cases, using variety of guns and calibres on different surfaces, followed by important components that provided information on bullet trajectories, impact behaviours, and forensic examinations.

Wood:

Following Table 1, highlights the ricochet phenomenon observed by authors – (a) Bandula et. Al.[26], showed Nine of the ten projectiles a tunnelling effect in pine wood at a ricochet angle of 13°. In study (b) Kerkhoff, et al.[10] show critical angle for ricochet of .32 Auto bullets are wider than that of 9 mm Luger rounds. In study (c) Abdul et al.[34] Jelutong wood showed deep penetration and sapele partial penetration. As a result, harder woods resulted in a higher critical ricochet angle and lower incident angle. Erwin et al. (d) uses SEM/EDX to analyse critical ricochet angle influenced by material properties and bullet type. In study [36] (e) Bullet weight and ricochet angle correlated, Resak has a higher modulus of elasticity than Seraya and Balau, bullet weight loss attributed to target material composition.

Table 1: Ricochet observed on various wood surfaces.

Study	Firearms	Caliber in (mm)	Average Speed (m/s)	Material & Critical Ricochet Angle
a	AK rifle (Type 56 MK II)	7.62*39	722 ±10	Teak:13.0°, Jackwood: 9.9° Mahogany:12.7°, Pine:13.3°
b	Skorpion, Steyr TMP submachine guns	.32 Auto, 9mm Luger	293 344	32 auto, 9mm Abachi:- 10.4° 10.3° Pine:- 23.2° 20.6° Beech:- 33.6° 28° Ipe:- 45° 33.4°
c	Bolt-action rifle	.22	150	Pine: 15° Jelutong:15°, Sapele: 40°
d	Smith & Wesson Model 586-3	9mmLuger.38 Special	349± 2, 227± 1	MDF Green Board: 10° Gypsum: 10°, Steel Plate: 5°
e	CZ 75SP-01 handgun	9mm	Not given	Balau, Resak, seraya: 10°-65°

Concrete:

Table 2 shows the ricochet review on Concrete – (a) Bandula et al.[24] studied rough concrete had more consistent ricochet angles than intermediate concrete. (b) Bryan Burnet's [37] report remarks about the laminae on the bullet's trailing edge, indicating the bullet strike direction. The creation of the laminal structure shows the complex dynamics at the bullet-concrete contact. (c) Miguel et al.[38].45 calibre performed best at low angles; the 2D ellipse and lead-in technique was accurate and repeatable. (c) Neculai et. al.[39] uses high-speed camera, showed caliber specific ricochet behavior; 7.62×39 mm exhibited constant ricochet angles on all slopes, highlighting angle selection importance.

Table 2: Ricochet observed on various concrete surfaces.

Study	Firearms	Caliber in (mm)	Average Speed (m/s)	Material & Critical Ricochet Angle
a	Type 56 MK II/ Chinese (AK Rifle)	7.62	716±7.5	Cement: 10.8° Rough Concrete: 11.1° Intermediate Concrete: - 13.2°
b	Not given	.22	Not given	Concrete: 30°
c	Glock 17, Revolver 0623, Glock 22, Glock 21	9mm, .22, .40, .45	339-478 (varied per calibre)	Drywall
d	AKM rifle	7.62×39	Not given	Varied Inclined Targets: - 60°

Metal sheet:

Table 3, reviews - (a) Bandula et al.[40] reported that the angle of incidence has an inverse relationship with the bullet hole length. (b) Same authors[41] investigated that the sheet's sharp edges resulted in triangular jacket pieces and double-headed impact imprints. (c) YILMAZ et al.[42] - the critical ricochet angle is material-specific and impact velocity. (d) Eugene et al.[18] reported that Winchester Ranger did not bounce after piercing the plate because of its high velocity. (e) Farouk et al.[43]simulations reveal complex interaction modes based on velocity and angle the accuracy of high-velocity impact predictions is impacted by modelling restrictions related to axial deceleration and material characteristics. (f) Yingxiang et al. [44] reported damage patterns vary with velocity and angle, helpful in protective structure design. (g) Tore et al.[45] highlight the transition from perforation to ricochet at higher angles and give insights for armour and protection design.

Table 3: Ricochet observed on various metal sheets.

Study	Firearms	Caliber in (mm)	Average Speed (m/s)	Material & Critical Ricochet Angle
a)	Type 56-MKII Assault Rifle	7.62	714.4±7.6	1mm Zinc- coated metal sheet: 15°
b)	Universal receiver	7.62 standard ball	760.62±1.89	1mm Metal Sheet: 3°
c)	LS-DYNA 971 simulation	AP 7.62	Not given	5mm Metal plates a) Ti6Al4V:55°, b) AlSl 4340: 25°, c) Inconel-718: 20° d) AlSi10Mg: 80° e)A16061-T6: 75°
d)	Glock, model 17 L	9mm Luger, Sintox, 9mm, Winchester ranger, 9mm, Hornady, 9mm luger Samson, 9mm Remington	Varied	.35mm steel plate: 14° and 20° for 9mm Luger, Hornady, 9mm luger, Samson, 9mm 14° for Sintox
e)	LS-DYNA simulations	Aluminium Projectiles	250-1500	Steel plate: at 25° and 40°
f)	Light gas gun	Ogive Shaped Projectile; 40	300-800	Steel Plate: 30°
g)	Mauser rifle	7.62 NATO ball, 7.62 APM2	830	20mm AA6082-T4 aluminium plate: below 60°

Glass surface:

Table 4 highlights - (a) Jan et al. [46] finds out that bullet deviation unpredictably increases with an angle up to 30°. (b) Erwin et al.[11] for each kind of bullet, the study determined critical ricochet angles; FMJ rounds had smaller ricochet angles than hollow-point or perforated bullets. (c) Shunsuke et al.[47] highlights no discernible variations in static fracture stress were found in indentation testing for different windshields, suggesting uniform material robustness. (d) Bahman et al.[48] studies Ceramic enhances performance at higher velocities. There was evidence of projectile erosion, which was more noticeable in vertical hits than oblique ones.

Table 4: Ricochet observed on various Glass surfaces.

Study	**Firearms**	**Caliber in (mm)**	**Average Speed (m/s)**	**Material & Critical Ricochet Angle**
a)	Pistol	.22 CCI-NR semi-wadcutter .38 Fedral gold wadcutter	210 (.22), 230 (.38)	6mm glass plate: 40°
b)	Skorpian submachine, Smith & Wesson-625-3 revolver, Steyr TMP	.32 auto, .45 auto, 9mm luger, 9mm luger action NP	293-427	5mm plain float commercial glass .32 auto: 21° .45 auto: 17.6°, 9mm luger:15.8°
c)	Revolver	.38	244.4	5mm thick glass windshield: beyond 60°
d)	Steel projectile LS-DYNA simulation	7.62	430	10mm ceramic/ aluminium: 67°

Water:

Table 5 explores - (a) Baillargeon etal.[49] Studied all the projectiles showed similar ricochet angles at shallow angles but exhibited variability and larger angles at higher incidence. (b) Ramzi Mirshak's [50] finds out Shallow angle preserved projectile speed, while steep angles caused significant velocity loss and unpredictable behaviour.

Table 5: Ricochet observed on various water surfaces.

Study	**Caliber in (mm)**	**Average Speed (m/s)**	**Material & Critical Ricochet Angle**
	5.56mm Ball C77,0.5 cal AP-T C44,K50 BMG, 0.5-cal Ball M2, 7.62-mm Ball C21	937, 749, 740, 893, 879	Water pool (3.6×0.6×0.3m mild steel with polycarbonate glass): 15°-30°
	.50 cal ball. 50 Cal AP-T, .56mm, 7.62mm, K50 BMG	Varied	Tank simulating flat water surface: Less than 10° and 5.56 mm: ~20°

Miscellaneous:

A comprehensive literature study identifies elements that disclose bullet trajectory and angle of impact in ricochet scenarios, such as splintering, ramping, plugging, and tunnelling.[26, 24, 41, 52, 62]

Bullet wipe mark:

Bullet wipe markings, a black ring of lubricant, debris, and traces surrounding a bullet hole, are used in wound ballistics to determine the type, calibre, and weapon connection of a bullet. Their patterns show the place and direction of impacts and aid in reconstructing gunshot incidents[35,57,58].

During the interaction, the exchange leftovers can change due to environmental conditions, which can provide the timing of events. And because ricocheting reduces the surface imperfections, ricocheted bullets usually leave less noticeable bullet wipes than direct shots.[60,61]These marks can function as long-lasting forensic identifiers, holding up even after six months on wood, according to Nishshanka et al. [26] On concrete, Nishshanka et al. discovered noticeable wipe traces at a 7° impact angle but none at 5°, 9°, or 11° [24].

Splintering effect: Surface splintering happens when a bullet deforms and displaces material above its elastic limit, radiating parallel to the surface grain, particularly in soft woods like pine[26].

Ramping effect: The trajectory of the bullet may be impacted by detailed ricochet markings. According to research, smooth cement surfaces are more affected than rough concrete, which only leaves minor blemishes[24].

Plugging effect: The "plugging" phenomenon results in the formation of a plug when a bullet hits a target. Both glass [35] and metal sheets showed this, with the glass plug's diameter being more than the bullet's calibre [62-65]. Compared to jacketed bullets, which show plugging effects on metal sheets at 20 feet, lead bullets deform more and lose velocity quickly. Estimating the angle of incidence and initial contact is made easier by important ricochet parameters such as angle, departure ramp, deepest point, and pinch point [66-67].

Tunnelling effect: When a bullet travels through a substance and reappears in a different location, this phenomenon is known as the tunnelling effect. The effect was seen on pine wood due to its soft nature.[26] The impact angle, trajectory, orientation, and surfaces it touched are all visible in the ensuing imprints [26,61].

Conclusion

A comprehensive understanding of the ricochet behaviour of bullets on diverse surfaces, necessitates considering the results of several research. Studies consistently demonstrate that ricochet angles, as greatly influenced by bullet velocity, surface roughness, incidence angle, and material composition. Materials like hard wood, concrete, metal sheet, demonstrate higher ricochet angle. Whereas glass, owing to its fragile nature, exhibits complicated behaviour, with bullet type and glass thickness having a significant impact on whether a bullet ricochets or passes through. On contrary when the bullet hits water surface, based on hydrodynamic forces and angle of entry, bullet either travels inside the fluid with varied velocity or ricochets. The review lists critical ricochet angles on different surfaces, also highlights how crucial bullet wipe markings and other effects like splintering and plugging effects are to forensic ricochet studies.

Ricochet studies could provide insightful information about any shooting incident, forensic investigations and crime scene reconstruction, also offer useful information for enhancing safety precautions in developing bulletproof materials and other amenities.

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