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IMPACT EVIDENCE AND POST-RICOCHET BEHAVIOUR OF SHOTGUN PELLETS RICOCHETING OFF STANDARD FLOOR TILES

Abstract

Compared to popular handguns and rifle bullets, quantitative and empirical-based ricochet studies using shotgun pellet ricochets are observed to be far fewer. This empirical study examines the ricochet behaviour and impact evidence when shotgun pellets (Buckshot) ricochet off standard floor tiles, providing a series of novel findings related to the resultant ricochet marks. Among these findings, a novel and statistically significant relationship between the lengths and widths of individual ricochet marks and the shot impact angles is demonstrated, offering useful forensic application. Ricochet mark shapes and morphologies highlighted in this study at different impact angles demonstrate the interactions between the ricocheting spherical pellets and tile surfaces, and the effects of acting frictional forces and degree of energy transfer in the production of impact evidence on the tile surface. Relationships with high statistical significance were also reported between the shot spreads on the tile surfaces and the post-ricochet cardboard witness screens, with shot impact angles. Finally, this work reports on the first documented observations of 'Pinch Points' and 'Nucleus' ricochet marks with shotgun pellet ricochets as angle-specific phenomena.

Keywords

Ricochet of shotgun pellets, shotgun pellets ricocheting off floor tiles, shotgun pellet ricochet marks, shotgun pellet impact patterns, post-impact behaviour of shotgun pellets.

Highlights

1. Single shotgun pellet ricochet marks can imply their impact angles.

2. Pinch points/ nucleus ricochet marks can be seen following shotgun pellet ricochets.

3. Extents of impacting and ricocheting shot spreads have significant reconstructive values.

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1 Introduction

Hard surfaces in urban areas provide an excellent condition for misfired, unintentional, or intentionally fired shots to ricochet off nearby targets and injure or fatally wound people in shooting events [1, 2]. A ricochet is a glancing rebound of projectiles from surfaces due to low-angle impacts [1]. The existing literature highlights many such incidents with diverse behaviours of ricocheting bullets and the challenging nature of investigating such incidents [3-8]. Generally, ricochet incidents can be identified as occurring with two main projectile types: bullets and shotgun pellets, with the former relating to the ricochet behaviour of cylindrical and pointed projectiles fired from rifles and handguns (typically from rifled barrels) and the latter addressing spherical lead projectiles fired from shotguns (using smooth-bore barrels).

Various factors affect the ricochet behaviour and evidence left by any projectile type, including the firearm type, the projectile's shape, construction, velocity and mass, the ricochet surface, and the reaction of the ricochet surface to the bullet [9, 10]. Knowledge of ricochet behaviour, how these factors influence the impact effects, and the interpretation of associated physical evidence (for projectiles and surfaces) is essential to aid investigators in understanding what happened during a ricochet-related shooting incident. In addition to investigators' knowledge of ballistics-related physics and material behaviour, the results from previous empirical ricochet studies are referred to in shooting investigations and incident reconstructions [1, 2, 11 - 17]. Recent ricochet studies using weapon systems with rifled barrels have highlighted that empirical testing is the most reliable method for understanding any ricochet behaviour and the associated evidence production owing to the complex interplay and effects that different projectile and surface material behaviours can have on a ricochet event [11 - 17]. These studies highlighted previously unreported and diverse ricochet behaviours, often contrasting with traditional understanding in the field, and demonstrating that it is unlikely that universal impact theory can be applied for all ricochet phenomena given the diversity of impact marking geometries now reported, such as 'Pinch Points' and 'Nucleus' ricochet marks and the highly varied relationships reported between angles of incidence and angles of ricochet [11, 12, 18].

Compared to popular handguns and rifle projectiles, empirical-based studies on shotgun pellet ricochets are limited, with most existing empirical studies on shotgun pellet ricochets focusing solely on post-ricochet behaviour [18 - 20], wounding phenomena [3, 20, 21] or mathematical-based explanations [22, 23]. Studies to examine qualitative and quantitative data on pre- and post-ricochet shot spreads and quantitative-based studies to explore the impact evidence on ricocheting surfaces are currently missing in published literature. Furthermore, compared to bullets, the spherical shape of shotgun projectiles has raised investigators' concerns about how they behave while ricocheting off various target surfaces.

This study aims to empirically evaluate the ricochet behaviour and impact evidence when shotgun pellets ricochet off standard ceramic floor tiles. Shotguns are highly popular domestic firearms, mainly used for self-defence and sport [24], and are regularly reported in crime scenes around the globe in homicide and suicide cases [25 - 29]. On the other hand, floor tiles are a common surface type available in most urban terrains and are usually made according to similar manufacturing standards (e.g. ISO) [30]. The combination of firearm and target type selected for this study is believed to be commonly reported during urban shooting incidents, so the findings from this study have relevant practical applications for future shooting investigations.

2 Experimental

2.1 General setup

A standard experimental ricochet setup was used in this study in line with recent ricochet experiments [1, 2, 11 - 17]. A 12-bore break-action single-barrelled shotgun (made in the USSR, with a barrel length of 457 mm and no choke fitted) was firmly mounted on a stable steel platform, using a custom-made locking system to ensure the shotgun remained horizontal at all times while being fired at floor tile samples held at different angles to the axis of the gun’s bore. Once mounted, the gun's chamber could be opened to load live cartridges and to remove spent cartridge cases without changing its aim and position and the barrel’s level was checked after each shot using a bore sighting tool with attached spirit level. A Doppler radar (LabRadar v.1.3 with ± 0.1% accuracy) was placed at the side of the gun's muzzle to measure the velocity of each shot pattern. The ammunition used was SIMAD 12-gauge buckshot (model 11/0) with nine equal lead spherical pellets (each pellet had a diameter of 8.6 mm and a mass of 3.6 grams). The experiment was conducted outdoors, and the distance between the gun's muzzle and the target was 5 metres.

The ceramic floor tiles used for this study were purchased from a reputed brand in the market (Rocell, [32]) and a had white polished surface with a glazed layer on top. They were produced to ISO standards [30] and their size was 610 mm x 610 mm x 8.7 mm (length x width x thickness), with each weighing approximately 7 kg. The ceramic floor tile targets were prepared such as they would exist in urban environments, ensuring the study's findings can be applied to actual cases, with similar methods having been used in previous bullet ricochet experiments performed with tiles and concrete [2, 14, 15]. The tiles were fixed to concrete using standard masonry practices for ceramic tile laying [31]. Each tile was fixed onto 7.5 cm thick concrete blocks made with a concrete mix that exhibited a compressive strength of 15 MPa at 28 days [33]. After the concrete blocks were dried for three weeks, tiles were fixed on the concrete blocks using the standard masonry practice for tile laying, having a 5 mm thickness of tile mortar when tiles were pressed into place [34]. The tiles for the experiment were used for testing after two weeks of fixing. A prepared floor tile sample for the experiment weighed 64 kg ± 400g.

A steel platform with a target mount (600 mm x 600 mm) was made using steel L-angle bars to hold the floor tile samples. The target mount was hinged to the steel platform from one side to lift the target tray with the mounted floor tile samples to different angles. Once a sample was mounted and an angle set, the target tray was locked so it did not change due to shot impact. Cardboard screens (120 cm x 60 cm) were fixed perpendicular to the target surface at a 120 cm distance from the center point of the tile samples to capture the impacts of the ricocheting pellets and their overall shot patterns. The target tray could be moved sideways along with the samples to collect a maximum of 3 shots per target.

A pellet capture box filled with Kevlar® was kept behind the cardboard witness screens to capture the ricocheting pellets. After every shot, the pellets/fragments were removed, and the box was cleaned. The experimental setup is given in Figure 1. Some of the photographs taken during the study are shown in Figure 2.

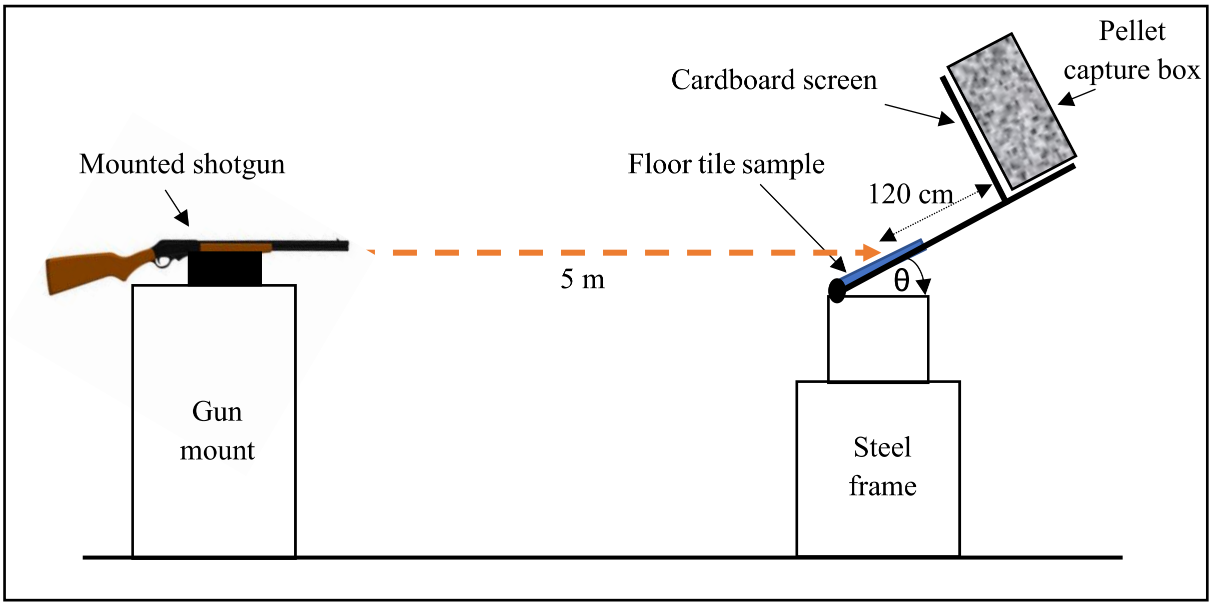

Figure 1: Experimental setup

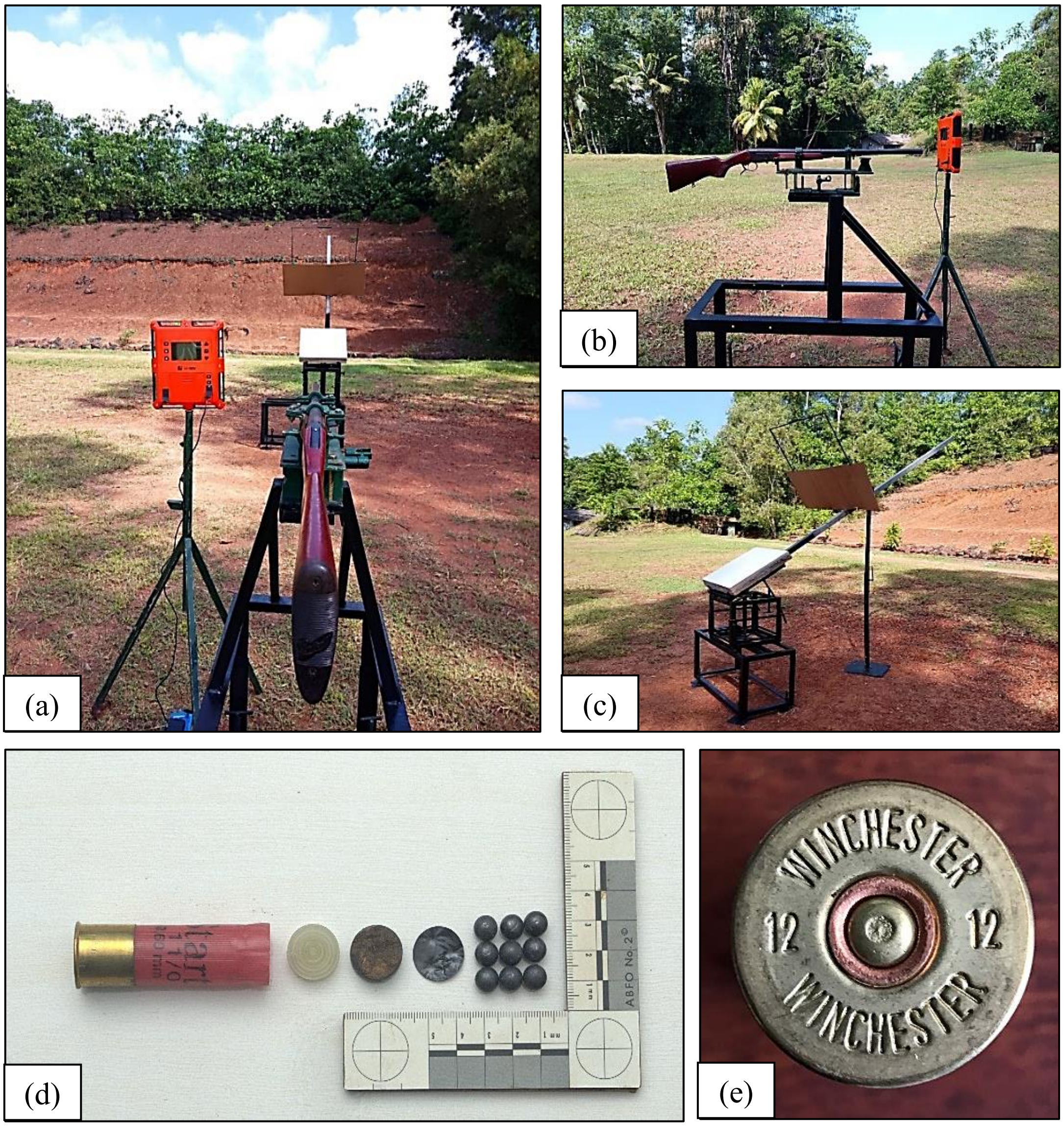

Figure 2: Gun and target mounts (a, b, c) and the components/details of the ammunition used for the study (d, e).

2.2 Data Anylisis

The target tray was initially held at 10 degrees to the barrel axis and its angle was then increased at 10-degree intervals until it reached 50 degrees. Ten shots were fired at each angle. Three shots were collected into each tile sample and cardboard witness screen, moving the tray with the screen from left to right after each shot to prevent overlapping impacts. The impact evidence on tile surfaces and cardboard screens was noted and photographed. Photographs were taken inside a laboratory with ambient room lighting. A Canon EOS 90D Camera with EF-S 18-135MM F/3.5-5.6 IS USM lens was used to take the photographs, and the camera settings were F-stop = f/6.3, Exposure time = 1/100 seconds, ISO speed = ISO-400, Focal length = 50mm with flash. The widths and lengths of all ricochet marks produced on the tile surfaces by impacting pellets and shot spread on tile surfaces and screens were measured and recorded for each firing using a vernier calliper. The correlation coefficient (R^2) was used to understand the correlation between the angle of incidence and shot spread or shot size and the RSQ function in MS Excel (2016 Edition) was used for calculations and generating the graphs. This is a statistical method to measure how well a statistical model predicts an outcome [35]. The Partial Eta Squared method of the IBM SPSS statistics tool [36] was also employed to measure the effects of different incident angles on the widths and lengths of the impacting pellet spread on tiles and witness screens. Effect sizes in the Partial Eta Squared method are a quantitative measure of how large of an effect the independent variable(s) had on the dependent variable [37,38]. A large effect size (partial $\eta 2 = 0.14$) indicates research findings with practical significance, a medium effect size is given by partial $\eta 2 = 0.06$ and a small effect size (partial $\eta 2 = 0.01$) indicates limited practical applications [37].

3 RESULTS AND DISCUSSION

3.1 General observations

The ricochet impact marks for the shotgun pellets on the tile surfaces and cardboard witness screens are elongated and parallel to each other at all angles. These findings agree well with the similar behaviour explained in previous studies when shotgun pellets have ricocheted off hard surfaces [18, 23]. Most pellet impact marks are seen on the bottom edge of the cardboard screen, demonstrating very low ricochet angles. Impact marks of individual pellets on the target surfaces show different shapes as the angle changed, but common characteristics at any given impact angle. The fragments collected from the capture box demonstrate high levels of deformation (flattening), which increases with an increased angle of incidence. Fully intact but deformed shotgun projectiles were recovered from 10 and 20-degree impacts, whereas projectile fragments were more commonly recovered for 30 to 50-degree impacts, with the fragmentation effect increasing as the angle of incidence became higher. The recorded average velocity of the shots was 173 ± 7 $m.s^{-1}$. Pictures of the shot impacts on the tile surfaces at each angle are shown in Figure 3 and recovered pellets from the capture box at different angles are shown in Figure 4. The impact of the pellets (10 to 20 degrees) and fragments on the cardboard witness screens (30 to 50 degrees) are shown in Figure 5.

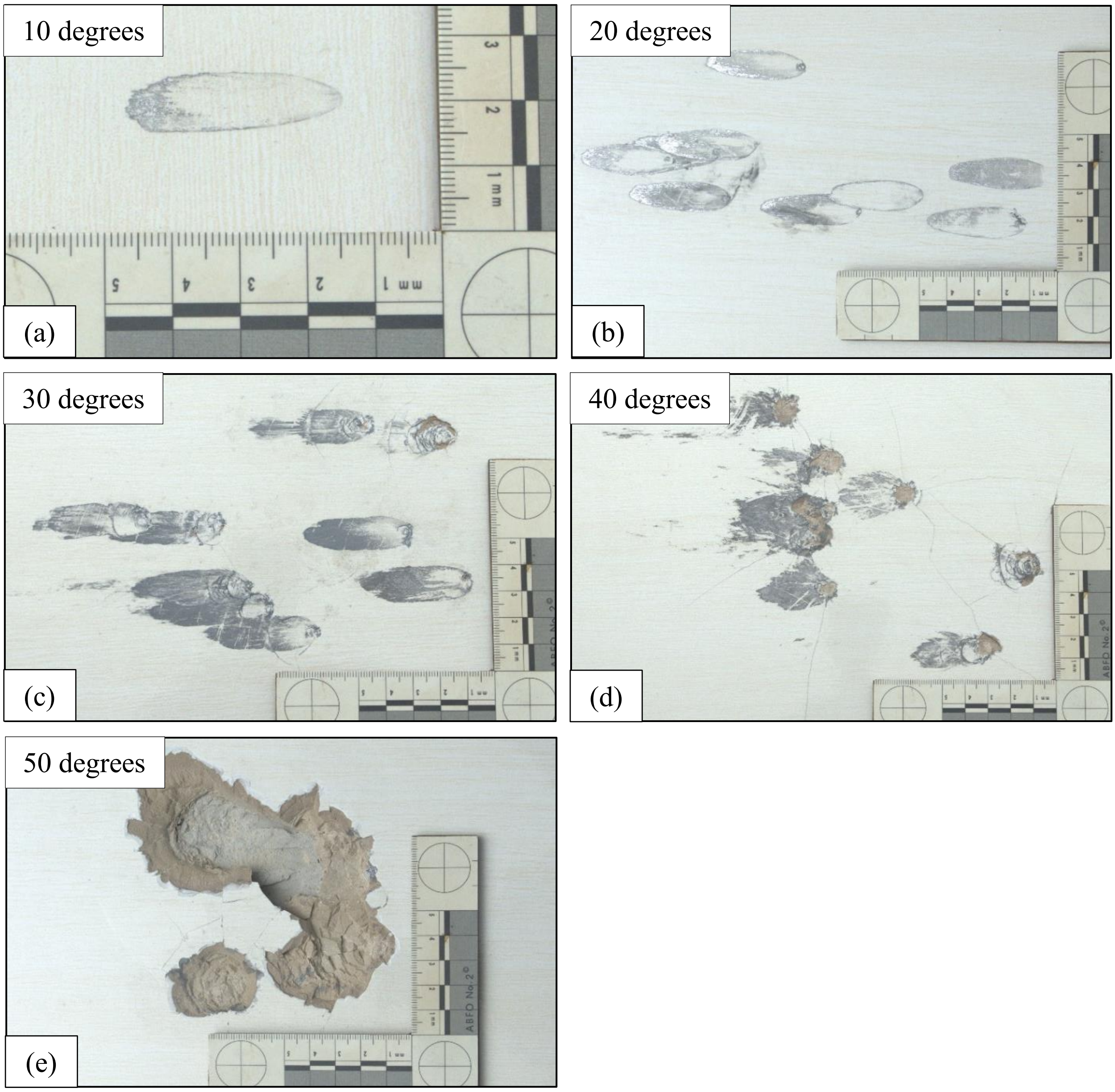

Figure 3: Ricochet impact marks from 10 to 50 degrees on tiles.

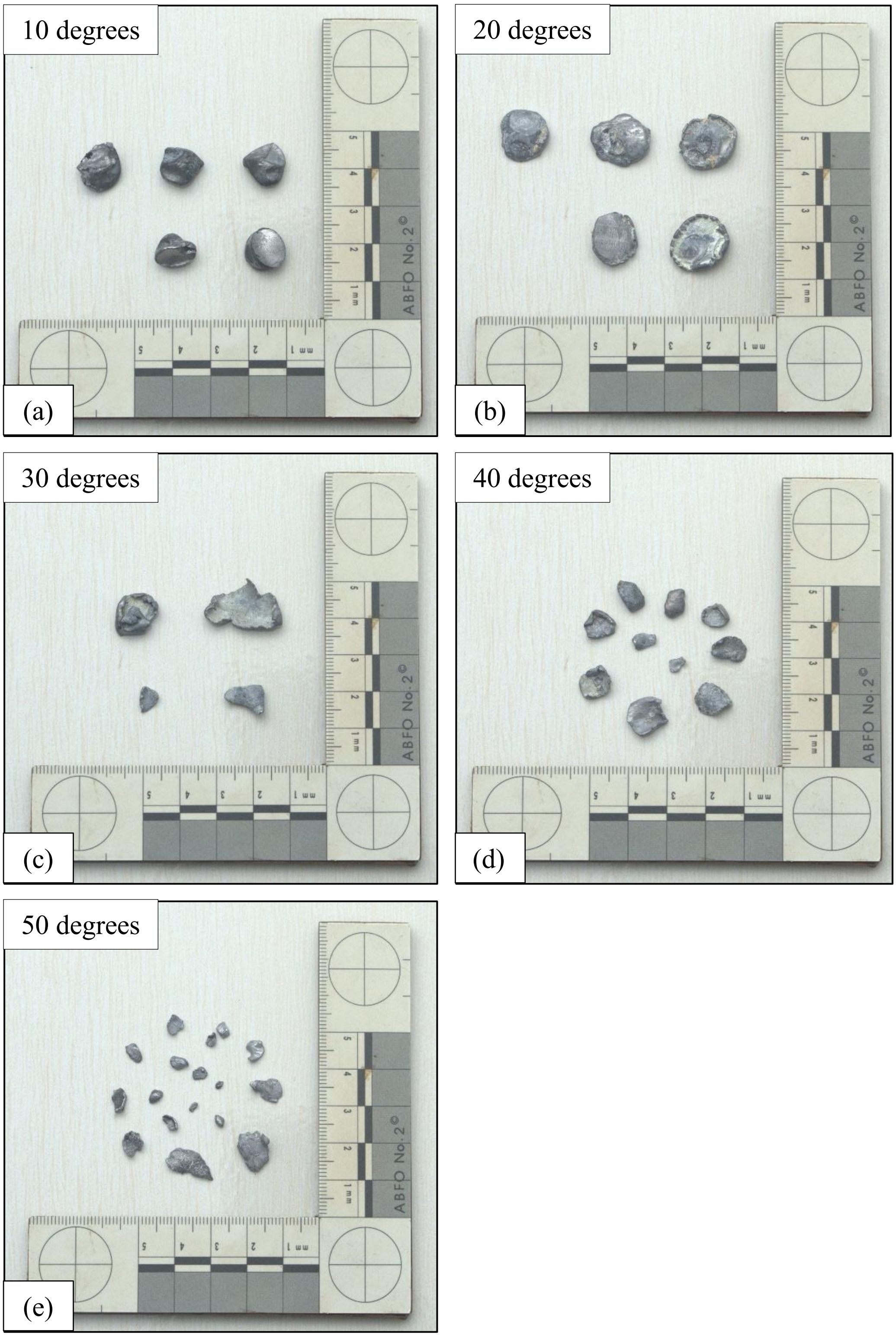

Figure 4: Some recovered pellets from the pellet capture box at different angles.

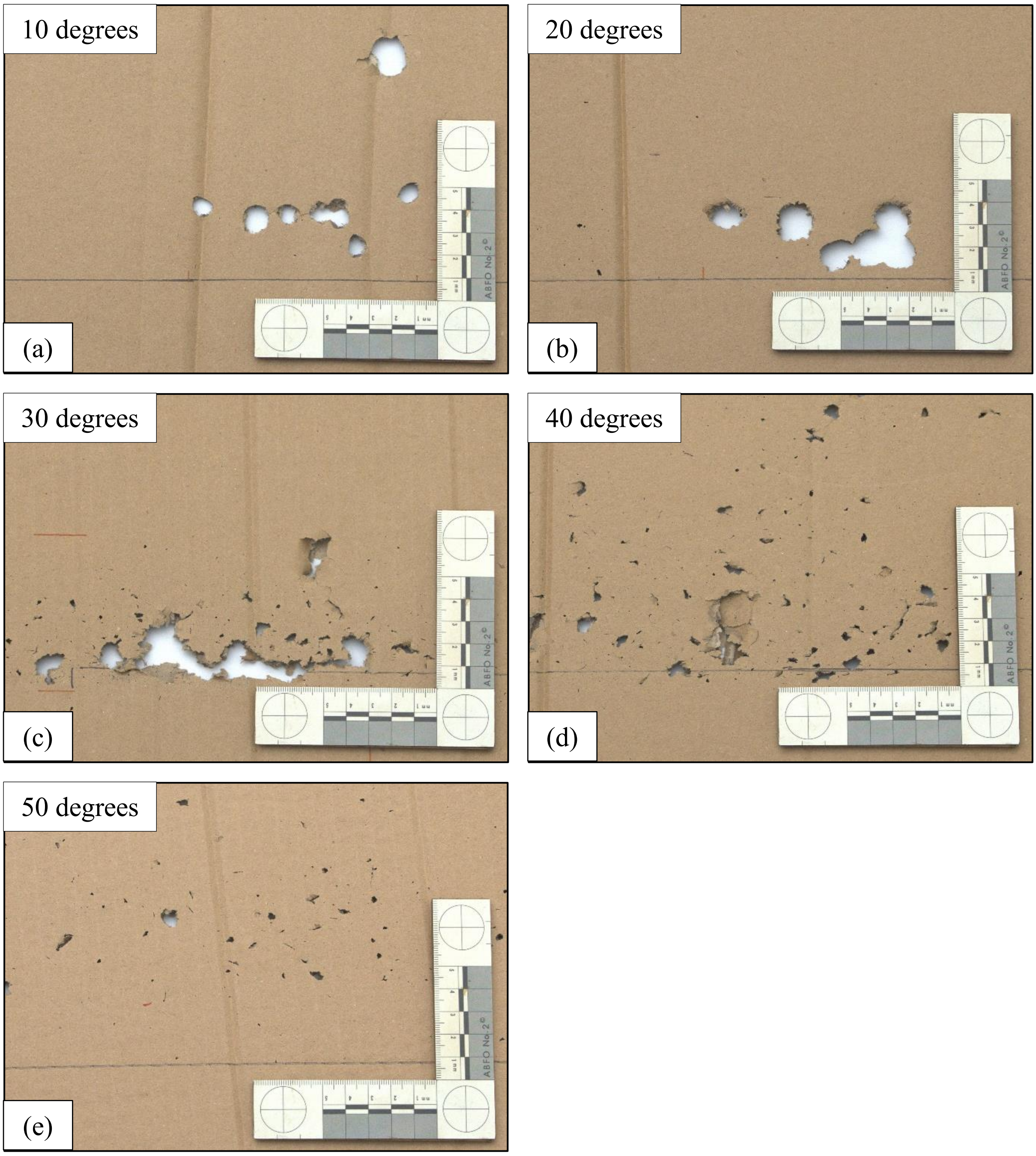

Figure 5: Pellet impacts (10 to 20 degrees) and fragment impacts on cardboard screens (30 to 50 degrees)

3.2 Ricochet marks of lead projectiles on the tile surfaces

3.2.1 Shapes of the pellet impacts

Lead marks produced by ricocheting pellets on the tile surfaces at 10 to 30 degrees are generally observed as elongated elliptical shapes (Figure 3 (a), (b) and (c)). Evidence from the ricochet marks and recovered deformed pellets (Figure 4) suggests that flattening occurs while the projectile is sliding across the surface before ricocheting off, responsible for the characteristic shape of the ricochet marks. The narrow beginning of the elongated ricochet marks is produced when the spherical projectile first contacts the tile surface. As each pellet deforms upon impact, the friction generated whilst skidding causes the soft lead alloy of the projectile to transfer to the relatively harder contact area of the tile surface, leaving a mark. When a pellet ricochets, systematic disengagement of the rear of the flattened pellet from the surface seems to have occurred, and the semi-circular shape of the far end of the ricochet mark is believed to be produced at this stage. Low-angle impacts have longer ricochet marks than at higher angles due to the projectiles having more interaction time with the surface at lower angles. This observation agrees with similar findings in previous studies on the length of the ricochet mark at different angles of incidence [11 - 13]. The shape and hardness of the projectile material (lead alloy) and its malleability, impact velocity, angle of incidence, reaction of the ricocheting surface and abrasive transfer capability all ultimately determine the shape and ricochet mark characteristics when shot gun pellets ricochet off flat and hard surfaces, making for a complex transfer mechanism.

The shapes of pellet impact marks at 40 degrees differed from 10 to 30 degrees (Figure 3). Ricochet marks at the lower angles were asymmetrical, and lead 'splashes' were seen at the start of each mark. At higher angles, more energy is delivered to the tile surface at the impact point, resulting in tile surface damage, permanent deformation, along with fragmentation of impacting pellets. No lead transfer marks could be seen with any impact at 50 degrees, given that all impacts caused craters, completely disrupting the tiles’ glazed surfaces. This is likely due to the higher energy density of ricocheting projectiles at this high angle, having a greater orthogonal impact component into the plane of the tile surface, resulting in material failure around the impact points leading to surface cratering.

3.2.2 Ricochet mark characteristics

The morphology of the ricochet marks of individual pellets at different angles demonstrates the level of interaction between the pellets and the surfaces, frictional forces, and energy transfer concerning the angles of the shots. The ricochet marks at 10 degrees have clear outer margins, however, the visible lead transfer is less compared to other angles (Figure 3). This is due to ricocheting pellets at shallow angles deforming less upon impact with tile surfaces, resulting in a smaller interaction area and so less frictional forces acting at the impact interface. Clearer outer margins and more lead transfer to the surface is seen at 20-degree ricochet marks. At 30 degrees, the outer margins of the ricochet marks are slightly distorted due to the aforementioned fragmentation effect, meaning it may no longer be a single-fragment interaction, as evidenced by the recovered pellets at these angles (Figure 4). More lead deposits can also be seen with these marks due to the higher level of interaction.

Interestingly, clear circular imprints of the spherical projectiles can also be seen at all 30-degree impact marks on the first contact point with the surface (Figure 3 (c). These impact marks are similar to the 'Pinch Point' described in previous ricochet studies, as produced during shallow angle bullet impacts on painted sheet metal [9, 39] and with 9 mm bullets ricocheting off ceramic wall and floor tiles [14]. However, Pinch Points have not been reported with shotgun pellets in the existing literature; therefore, they are a significant highlight of this study. Figure 6 shows Pinch Points from previous studies [9, 14] (using 9 mm bullets on tiles), compared with the Pinch Points reported in this study at 30 degrees.

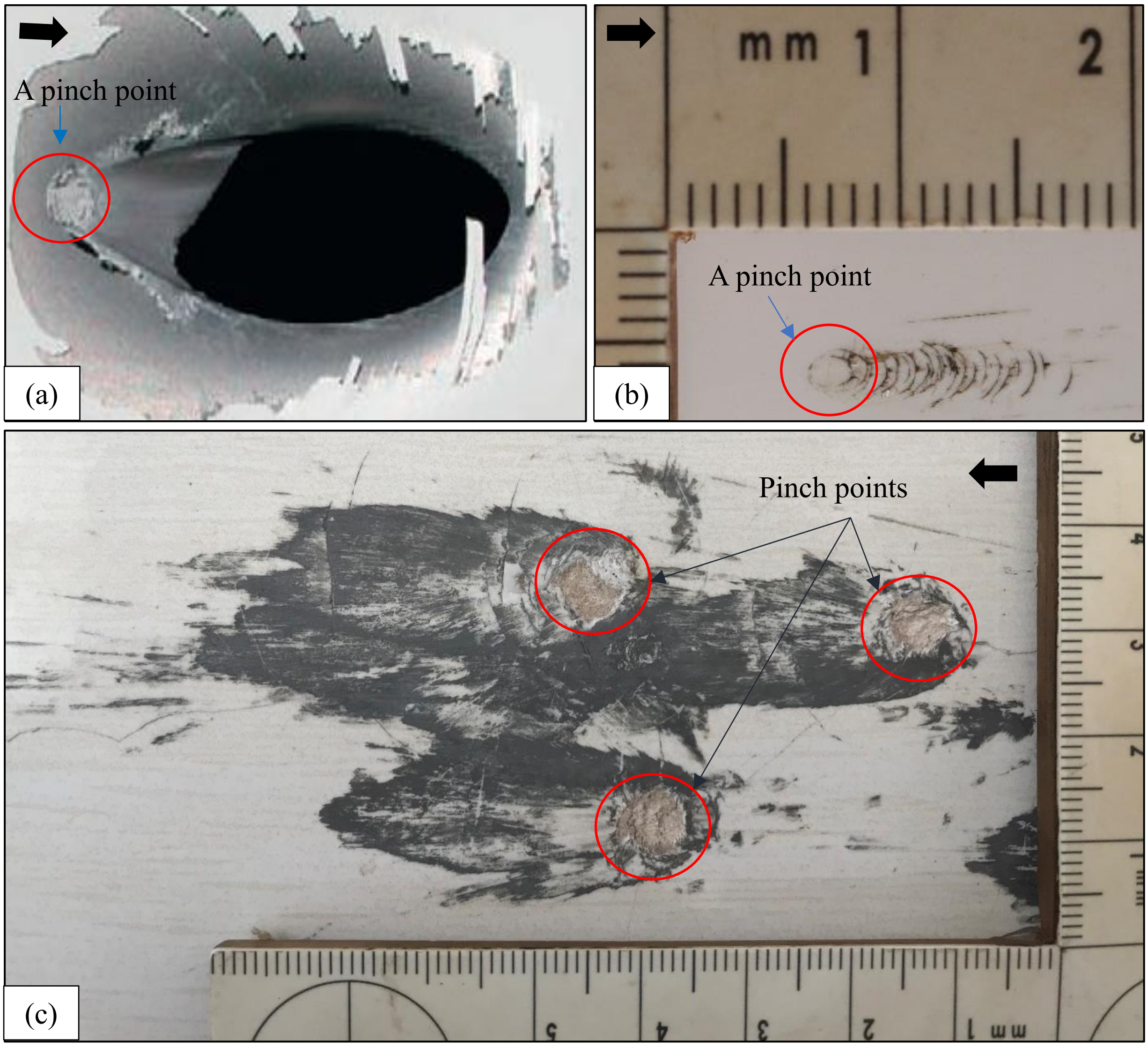

Figure 6: Pinch Points from previous studies are shown in sheet metal (a) [9] and on wall tiles (b) [14] and can be compared with similar marks observed at 30 degrees during shot pellet ricochets in this study (c).

At 40 degrees (Figure 3 (d)), a feature similar to the 'Nucleus' ricochet mark [14], reported in a previous ricochet study using M 43 type AK bullets on ceramic tiles, was observed. This complex mark was previously attributed to the triple layer composition of M 43-type bullets. However, the triple layer imprint as described was not seen here because this study's ricocheting projectiles were lead allow spheres with no jacket. The marks shown here (Figure 6 (c)) demonstrate that a feature similar to the nucleus ricochet mark can also occur during shotgun pellet ricochets. This provides potentially useful forensic reconstructive value based on the mark only occurring at a specific angle (40 degrees). Nucleus ricochet marks were reported with rifle bullets in a previous study [14] at 9 degrees with floor tiles (middle) and 19 degrees with wall tiles (right). A comparison with a mark reported in this study for the spherical led projectile impacts (at 40 degrees) is shown in Figure 7.

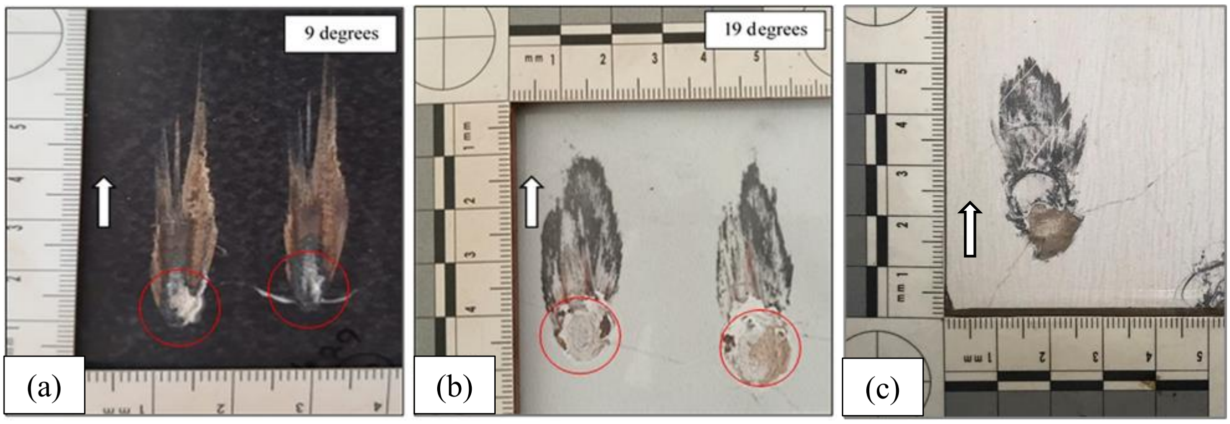

Figure 7: A nucleus ricochet mark reported with rifle bullets in a previous study [14] at 9 degrees (with floor tiles (a), at 19 degrees with wall tiles (b) and a similar mark reported in this study with spherical-led projectile impacts at 40 degrees (c). The first two marks (a,b) were produced with M 43 rifle bullets due to the triple-layer composition of the bullet, and the similar third mark (c) was produced with spherical led projectiles. Red circles are pinch points.

3.2.3 Dimensions of the ricochet marks

Lengths of ricochet marks have proved to be useful in aid of predicting a bullet’s angle of incidence when bullets ricochet off sheet metal [11, 12] and wood surfaces [1]. However, no such information on shotgun pellets and expected ricochet mark dimensions is currently available in published literature. The maximum widths and lengths of the individual pellet impacts at 10, 20 and 30 degrees were measured to understand any relationships with the angle of impact (40-degree impacts were not considered as the ricochet marks were too variable and 50-degree impacts were not considered due to an absence of the impact marks, given the level of cratering). The results are presented in Figure 8, along with an explanation of how the measurements were taken.

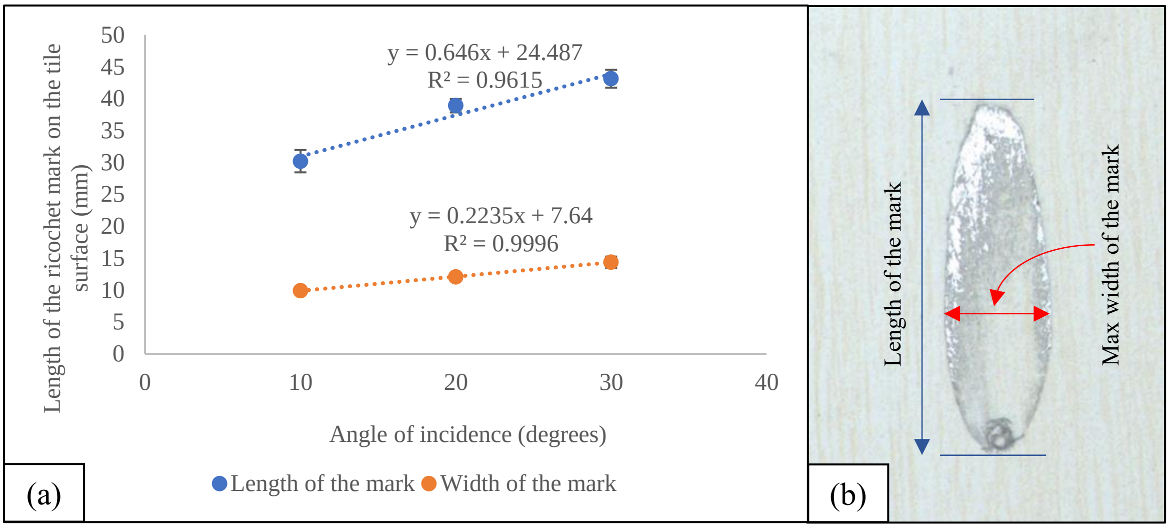

Figure 8: The reported relationship between the dimensions of the ricochet marks (b) and the angle of incidence (a), with an explanation on how the measurements were taken (b). The associated error bars (standard deviations) are small and are often covered by the data point. (The measurements were taken from the original objects).

A strong correlation coefficient (R^2) was reported between the angle of incidence and length of the ricochet mark ($R^2 = 0.96$) and width of the ricochet mark ($R^2 = 0.99$), indicating a strong positive correlation between the variables. Although the analysis was limited to three data points, the results concerning the lengths and widths of the ricochet marks still appear to demonstrate a strong relationship within the data. The results suggest that the length and maximum widths of individual shotgun pellet ricochet marks on floor tiles have a strong predictive capability of the impacted spherical projectiles' angle of incidence as long as cratering of the surface has not occurred. Although significant relationships between ricochet mark dimensions and angles of incidence have been previously reported with numerous bullet-target combinations [1, 11, 12], no studies have reported this relationship with shotgun pellets.

3.2.4 Dimensions of shot spreads on tiles and screens

The measured maximum widths (horizontal) of the impacted shot spreads on the tile surfaces and the shot/fragment patterns on the cardboard witness screens are seen to increase with an increasing angle of incidence. A strong exponential relationship with a correlation coefficient value ($R^2 = 0.87$) is observed between the shot spread widths on the tile surface and the angle of incidence. This phenomenon was similarly observed between the maximum widths of shot/fragment spreads on the cardboard witness screens ($R^2 = 0.94$). As more fragments are created following projectile fracture, they will follow new trajectories as the kinetic energy is shared amongst the fragments, likely spreading out in a linear fashion like a typical shot pattern spread after leaving a shotgun's barrel, supporting the likelihood of the reported linear relationship. The weak relationship may be improved with additional experimental data to possibly reduce the high standard deviations reported at higher angles in Figure 9. However, the fragmentation that does occur will be affected by further in-air collisions between fragments post-ricochet, meaning not all fragments disperse in a consistently linear manner.

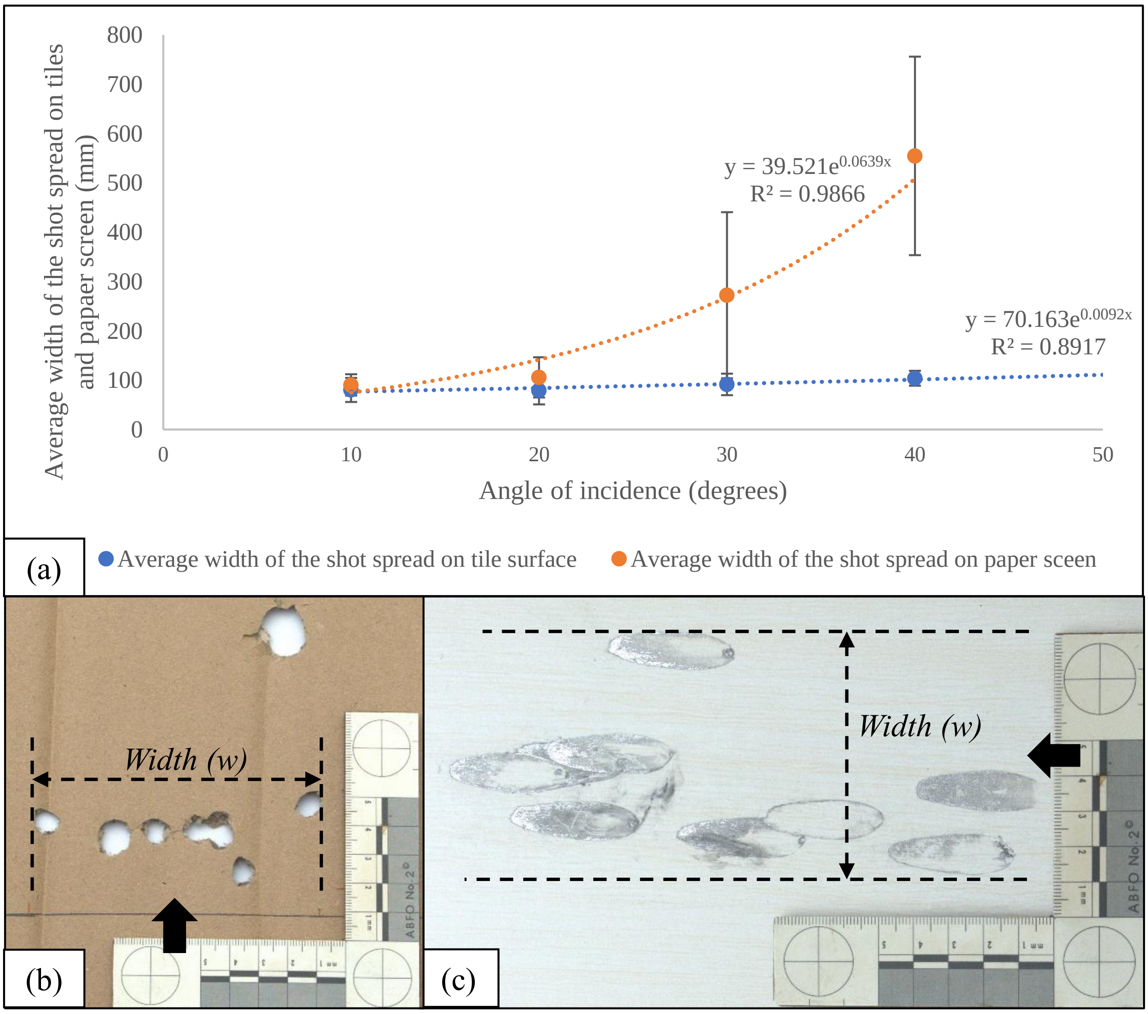

Figure 9: Correlation between the average width (horizontal) of the shot spread on the tile surface (a) and cardboard screen with standard deviations and an explanation of how the measurements were taken (b, c). The direction of the shot is shown with black arrows and the measurements were taken from the original objects.

The calculated Partial Eta Squared Value (partial η^2) between the shot spread widths on the tile surface and the angle of incidence highlights a large effect [$F(3,28) = 1.782$, $p = 0.173$, partial $\eta^2 = 0.160$]. A large effect was also reported between the maximum widths of shot/fragment spreads on the cardboard witness screens and the angle of incidence [$F(3,28) = 21.448$, $p = 0.000$, partial $\eta^2 = 0.697$]. Reference ranges: large effect (partial $\eta2 = 0.14$), medium effect (partial $\eta2 = 0.06$), small effect (partial $\eta2 = 0.01$ [37]. The results highlight the greater applicability of the results to real-world cases.

The average measured length of the impacted shot spread on tile surfaces and cardboard screens with the angle of incidence demonstrated negative and positive trends, respectively (Figure 10). The length of the shot spread on floor tiles decreases as the angle of incidence increases. In contrast, the lengths of the shot spread of ricocheting pellets on the cardboard witness screens increases as the shot angles of incidence increases. The correlation coefficient values for these two relationships (R^2) were reported as 0.92 and 0.99, respectively, indicating a solid exponential relationship between the variables. Interestingly, at the 40-degree angle of incidence, the average length of the shot spreads on the tile surface, and the cardboard screen reported similar values (182 mm and 177 mm). An explanation of how the lengths were measured is shown in Figure 10.

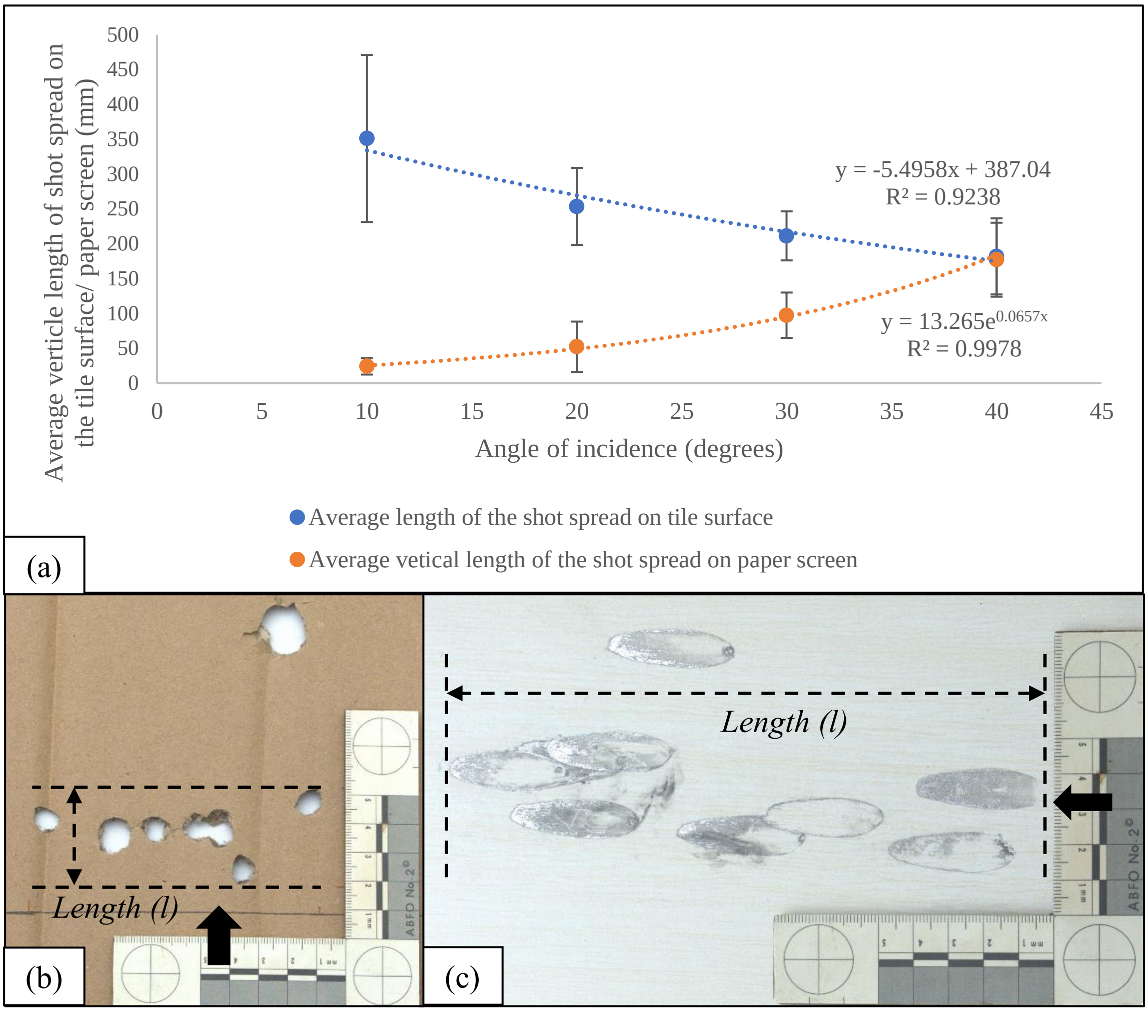

Figure 10: Correlation between average lengths of the shot spread on the cardboard screens (a) and tile surfaces with standard diviations and an explanation of how the measurements were taken (b, c). The direction of the shot is shown with black arrows. The measurements were taken from the original objects.

The correlations between the lengths of the shot spread on tile surfaces and cardboard witness screens the shot angles of incidence demonstrated in this study had not been highlighted in previous studies and should provide useful insight and forensic reconstructive value for shotgun ricochet events and the variability of shot pattern data to possibly expect for this ammunition. The negative trend observed with impact angles and the pellets' vertical spread on the tile surface could be due to the reduced size of the elliptical shot spread on a target with the shot's increasing angle of incidence [9, 40].

The calculated Partial Eta Squared Value between the shot spread length on the tile surface and the angle of incidence highlights a large effect from the incident angle to the shot impact length [F(3,28)

= 7.449, $p = 0.001$, partial $\eta^2 = 0.444$]. A similar phenomenon reported for maximum length of shot/fragment spreads on the cardboard witness screens [$F(3,28) = 26.250$, $p = 0.000$, partial $\eta^2 = 0.738$] highlights a large effect. The result highlights the significant relationship of variable and the practical significance of the reported results.

4 Conclusions

This study demonstrates the detailed ricochet behaviour and associated impact evidence for when nine 8.6 mm diameter shotgun pellets ricochet off standard ceramic floor tiles. Lead transfer marks produced by ricocheting pellets on the tile surfaces at 10 to 30 degrees were observed as elongated elliptical shapes. Evidence from the ricochet marks and deformed pellets from these angles suggest that the spherical projectiles' deformation (flattening) and sliding ricochet mechanism produce the elongated elliptical shape of the ricochet marks, caused by a complex multi-variable mechanism, incorporated aspects of the mechanical, geometrical and kinetic properties for both the projectile and impact surface.

Impact marks similar to the 'Pinch Point' reported in previous studies [14, 15, 39] were observed at 30 degrees. This feature has not been reported with shotgun pellets in the existing literature and so is a significant highlight. The appearance of these features at 30 degrees onwards highlights a potentially significant forensic observation to aid shooting reconstructions involving 8.6 mm shotgun pellets. The ricochet mark morphologies at different angles correlate with the impact interface interactions between the ricocheting pellets and tile surfaces and a feature very similar to the previously reported 'Nucleus' ricochet mark [14] was observed for all pellet ricochets at 40 degrees, presenting an angle-specific characteristic for these shotgun pellets on tile surfaces.

Statistically significant relationships with large effect sizes have been shown to exist when for correlations between the angle of incidence and the lengths and widths of the individual ricochet marks as well as shot spread widths on the tile surface and maximum widths of shot/fragment spreads on cardboard witness screens.

The presented relationships and observations for post-ricochet projectile behaviour and impact ricochet marks in this study have not been previously reported, providing an empirical-data-based model of ricochet behaviour for nine 8.6 mm shotgun pellets ricocheting off hard flat tile surfaces at close range. This study demonstrates an effective experimental design in aid of replicating shooting scene ricochet evidence and the data has a potential use in aid of forensic shooting reconstruction processes. While this study covers a specific set of impact variables, further studies will show whether the highlighted findings are similarly observed with other target surface types and different shotgun ammunition such as bird shot with a greater number of smaller projectiles, and with extended firing ranges and post-ricochet ranges.

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