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The dynamics of blood drop release from swinging objects in the creation of cast-off bloodstain patterns

Keywords

Forensic Science, Bloodstain Pattern Analysis, Cast-Off Patterns, Biomechanics, Fluid Dynamics

Abstract

Although the characteristics of cast-off bloodstain patterns are well known, the physics of the mechanism by which they are created is poorly understood. The aim of this work was to describe the process by which blood droplets disengage from swinging objects. Cast-off droplets were recorded using high-speed digital video photography and the resulting cast-off patterns were analyzed to draw inferences about the trajectories of individual drops. Blood on the object's distal end formed ligaments, which subsequently disintegrated into droplets. Initial droplet trajectories were approximately tangential to the trajectory of the location on the object from which the droplet was released. The application of the laws of physics to the mechanism of cast-off is discussed and the process of drop formation is compared to that of passive drop formation. A technical description of cast-off is proposed and a diagram to aid investigators in interpreting cast-off patterns at crime scenes is offered.

Introduction

Acts of physical violence where victims are assaulted with blunt or edged objects are common (1-3). Distinctive bloodstain patterns termed "*cast-off* "are frequently found at such scenes. A *cast-off pattern* is defined as "a bloodstain pattern resulting from blood drops released from an object due to its motion" (4). Cast-off is classified in the general bloodstain pattern class known as *spatter*, where forces other than gravity dictate blood breakup, flight and impact dynamics. Cast-off patterns are characterized by relatively linear or curvilinear distributions of small bloodstains, where the individual trails within these patterns are generally parallel to each other (5). By analysis of their directionality, the stains from the forward and backward swing movements can often be distinguished.

While the general features of cast-off patterns have been well described (5-8), the mechanism by which they occur is poorly understood. The process of droplet formation and disengagement from swinging objects has been described in various confusing and contradictory ways. This ambiguity has in turn led some crime scene examiners to draw incorrect interpretations about the location of the wielder of the swinging object and to overlook potentially useful information inherent in the pattern.

There is a paucity of peer-reviewed, scientific literature dedicated to understanding this type of bloodstain pattern. Four published scientific theses have specifically addressed the issue of cast-off patterns (9-12). More recently, Kunz et al., published a study utilizing high speed video photography to study simulated cast-off pattern creation using a knife attached to a fixed hinge (13). The remainder of the published cast-off literature is confined to popular textbooks on bloodstain pattern analysis (BPA), which are largely based on the experience of scene-going analysts (5-8).

Blood Droplet Disengagement from Objects

Much of the ambiguity surrounding the cast-off process comes from some authors characterising the disengagement of blood droplets in the non-inertial reference frame (reference frame of the blood droplet) (5, 6) and others in the inertial reference frame (reference frame of a stationary observer) (7, 8, 14). Authors describing this phenomenon in the non-inertial reference frame state that blood droplets disengage from the swinging object due to "the generation of *centrifugal* force as a bloody weapon is swung in an arc" (5) or from the "generation of *centrifugal* force that overcomes the adhesive force that adheres the blood to the object" (6). However, the so-called *centrifugal* force, apparently acting away from the centre of rotation on the blood droplet, only appears to exist in this reference frame and does not correspond to a real force acting on the droplet.

From the point of view of an observer in the inertial, laboratory reference frame, authors have stated that "blood droplets are thrown, by *centripetal force*, from a swinging object..." when the "…adhesion of blood to a transport medium is overcome by *angular momentum*" (7). Others have stated that cast-off occurs when "the angular momentum of the blood… is sufficient to overcome the surface tension of blood and small drops and droplets are released" (8), or that blood droplets are released when "acceleration force…exceeds the restraining force of surface adhesion" (14).

The angle of blood droplet disengagement has also been ambiguously reported. Descriptions have included blood droplets travelling "tangentially to the arc of the swing" (5), while diagrammatic representations of cast-off drop trajectories in earlier texts (14, 15) have implied a direction of travel extending radially outward from the weapon.

These descriptions are not all technically correct and somewhat imprecise. To avoid misunderstandings of the cast-off mechanism, more rigorous use of standard physics terminology is required.

Fluid Mechanics of Droplet Breakup

The science of droplet breakup has been well documented (e.g. 16, 17). The relevant principles of fluid mechanics relating to blood droplet formation have also been discussed (18-20). A brief review of these principles is provided here.

A liquid droplet will separate from a liquid source when the disruptive external forces acting on the liquid exceed the cohesive surface tension forces of the liquid/air interface. The liquid surface tension draws the liquid molecules together into the shape that minimises surface energy, which is a sphere. The viscosity of the liquid has a stabilising effect on the resulting droplet, which opposes changes to the liquid geometry. For higher viscosity liquids, greater stresses are required for the liquid to deform at a given rate. The greater the energy applied to the liquid, the greater the disruptive forces resulting in a larger number of smaller droplets. Five well-researched droplet generation mechanisms include dripping, sheet breakup, liquid column (or jet) breakup, liquid ligament breakup and liquid free-surface breakup. The most fundamental explanation of liquid droplet formation can be illustrated using the example of passive dripping.

The science of droplet generation has a wide range of engineering and industrial applications. The generation of droplets in most of these applications involves atomisation; where a bulk liquid is disintegrated into fine droplets. An energy conservation model can describe the basic principle of atomisation. Kinetic energy is transferred to the bulk liquid for the liquid to deform and disintegrate into fine droplets. The kinetic energy of the bulk liquid is dissipated as work done against the viscous forces, which resist deformation, and the surface tension forces that resist free surface creation. Smaller droplets are likely to result from higher velocity motions, in which greater kinetic energy is available to be converted to the surface energy of numerous small droplets.

The generation of cast-off droplets can be compared to the industrial process of rotary atomisation. Liquid is introduced to a rotating surface where it spreads out over the surface and disintegrates into droplets. The rotating surface can be a flat disc, vaned disc or a cup. Droplet formation in rotary atomisation has been described as resulting from several different mechanisms or regimes: direct droplet formation, direct droplet and ligament formation, ligament formation and sheet/film formation.

At low velocities and flow rates, droplet generation is generally discontinuous and in the direct droplet regime. With increasing disc velocity, droplets are projected at more frequent intervals and may draw ligaments behind them; the direct droplet and ligament formation regime. Further increases in velocity and/or flow rate cause droplet generation to move into the ligament formation regime. Ligaments are formed around the disc periphery, which disintegrate into droplets when exposed to the airflow around the disc. By increasing the speed of the disc periphery, liquid migrating out to the disc edge can be immediately atomised due to the high relative velocity between the disc and surrounding air.

Human-Wielded Object Dynamics

The preceding discussion on rotary atomisation theory assumes uniform circular motion, where the rotation of an object with a fixed-length radius occurs around a fixed pivot point, at a constant rotational velocity. Based on findings in sports biomechanics, a human-wielded object will undergo non-uniform circular motion. In actions such as striking or throwing, humans generally adopt a coordinated proximal-to-distal kinematic chain strategy whereby many body segments undergo linear and rotational motion (21). Momentum is typically developed by the legs and transferred up the chain; progressing through the hips, torso, shoulder, upper arm, forearm and hand (21-26). Accordingly, neither the swing radius length nor pivot point will remain fixed, resulting in an elliptical object-end trajectory. The object's tangential velocity changes throughout the back and forward swing movements.

In the case of cast-off, blood is transferred to an object, which is then swung. If the centripetal force applied to the object by the assailant increases to the point where it exceeds the interfacial forces adhering blood to the object, blood droplets separate from the object. Newton's first law of motion states that a body in motion will continue in that state of motion unless acted upon by an external force (27). It follows that a blood droplet will continue to travel along the linear path it was travelling at the instant it was released from the object, tangential to the object-end trajectory. A proper understanding of this phenomenon is the first step in the development of a reliable method to objectively assess feasible crime dynamics based on cast-off patterns.

Blood Droplet Trajectory

The focus of the current work is the initial droplet formation and disengagement from swinging objects. However, the resulting blood droplet trajectories and impact dynamics of typically small blood droplets must be considered when analysing cast-off patterns. A comprehensive explanation of blood droplet trajectory has been provided by Kabaliuk et al. (18). These authors demonstrated that the subsequent trajectory of blood droplets released from an object can be predicted using a numerical model, validated for blood droplets with experimental data. Depending on the distance travelled, blood droplet trajectories will deviate significantly from a straight line due to gravity. These authors used a purpose-built motorized blood droplet generation device (28) and high speed digital video to validate numerical models for blood volume break up and trajectory.

Blood Droplet Impact

The impact angle of consecutive stains within a cast-off pattern theoretically increases, the further from the centre of rotation the object is at the instant of droplet disengagement. When stains are of sufficient quality to accurately measure impact angle, these data could be combined with droplet trajectory calculations to infer the weapon tip's successive locations during the swinging movement.

The focus of this work was to perform systematic experiments to study the dynamics of blood droplet formation and disengagement from swinging objects. We also propose appropriate means by which to describe this process to remove existing ambiguity surrounding the dynamics of cast-off creation.

Methods

Two separate experiments were performed utilising high-speed videography to study how cast-off blood drops are generated and released from swinging objects. For both experiments, porcine blood mixed with ethylenediamine tetraacetic acid (EDTA) salt anticoagulant was used as a simulant for human blood. Blood was collected via the free-catch method (29) at a local abattoir, stored in a refrigerator and used within 5 days of collection. Blood was warmed to room temperature and gently agitated to ensure homogeneity prior to experimentation. EDTA-mixed porcine blood has been reported as a valid simulant for human blood for conceptual-level BPA experimentation (30). Blood physical properties; viscosity, density and surface tension values were not directly measured for these experiments. Blood was, however, maintained at a room temperature of 20 °C throughout the experiments and checked for haemolysis prior to mixing.

Experiment 1, Fixed Apparatus

The first experiment was conducted to gain a conceptual understanding of blood behaviour when adhered to a swinging object to inform further testing. A simple unpowered rotary bearing was constructed to generate cast-off. The device comprised of two metal cylinders connected by a commercial bearing, enabling the two halves to spin freely against one another. The bottom cylinder was attached to a tripod and a kitchen knife was secured to the top cylinder, as shown in Figure 1. The distance between the pivot point and the tip of the knife was 25 cm. The tripod was adjusted so the blade of the knife rotated in a horizontal plane. The device was positioned 500 mm in front of a vertical wall lined with white paper providing a plain, smooth target surface for blood drop impact. A high-speed monochrome CMOS Camera (CP Labs Inc. Manitoba, Canada) was used to capture the detailed dynamics of blood drop generation and release from the spinning knife. The camera was positioned above the knife and aimed vertically downwards. The camera field of view encompassed the knife tip, trajectory and flight paths of any drops impacting on the target surface. The camera was set to record at 2500 fps. Illumination was provided by two 2000 W tungsten halogen lights, positioned either side of the camera.

To create a cast-off pattern on the target surface, 0.5 ml of blood was pipetted onto the knife tip. The device was then forcefully spun manually in an anticlockwise direction through approximately 360°, with sufficient velocity for blood drops to be released and impact the target. The experiment was repeated with a vertical plane of rotation resulting in cast-off spatter on a horizontal surface. Rotational velocity was not measured in this experiment but in each case was sufficient to create cast-off patterns.

Figure 1: Cylindrical rotating device attached to a tripod to facilitate the creation of cast-off blood spatter

Experiment 2, Cast-off from Human-Wielded Objects

Three human volunteers performed a series of tests to emulate the less controlled, non-uniform circular motion of a human-wielded object likely in an attack. Two different-sized objects were selected; an alloy baseball bat (800 mm long, mass 0.8 kg) and a kitchen knife (300 mm, 0.2 kg). The experimental set up is shown in Figure 2. For each test, the distal end of the respective object was dipped 20 mm into a container of freshly-agitated, room-temperature porcine blood. The volunteer was instructed to swing the object backwards or forwards as fast as they were able. The volume and distribution of blood applied to each object was kept as constant as possible. Backswing and forward swing trials were undertaken separately, rather than as consecutive swings, enabling a comparison with similar volumes of blood initially adhering to the object.

The object-end trajectory and subsequent blood drop trajectories were recorded with a Photron® high-speed digital camera (Photron® Labs, San Diego, CA) with a 90 mm Tamron lens. A frame rate of 5000 fps, f-stop of 5.6 and a 192 µsec shutter speed were used. The camera was positioned 90 degrees to the plane of the object swing, 1500 mm from this plane. Illumination was provided by two 2000 W Tungsten Halogen lights positioned either side of the camera. The trajectory and velocity of the object-end and the resulting blood drops from backswing and forward swings were measured manually using Photron® Viewer software.

Figure 2: Photograph showing camera set up, lighting and a volunteer swinging a hammer in a plane perpendicular to the camera

Results

Fixed Apparatus Concept Experiment

A diagrammatic representation of this experiment is given in Figure 3. Figure 3 shows a plot of the absolute value of the α-angle versus y, the horizontal distance of the bloodstain relative to an arbitrary position on the vertical surface. The α-angle was the impact angle of blood drops in the pattern, determined by the formula: $\alpha = \sin^{-1}(W/L)$, where W = width and L = length of the elliptical bloodstain. The plot shows a maximum close to $y = Y_0 + r$, where Y_0 is a position opposite the centre of rotation and r = radius of the rotation of the knife. This is the expected result if the blood drops were detaching at a tangent to the arc of rotation and travelling a short distance to the wall (which can be approximated by straight line trajectories for the purposes of this conceptual illustration).

Figure 3: Diagrammatic representation of cast-off device and cast-off pattern generated from blood on a spinning knife used in Experiment 1. A circle represents the rotating device and the black rectangles represent the knife rotating anticlockwise. The distance between the pivot point and the tip of the knife is shown as "r". Arrows indicate theoretical initial blood drop trajectories assuming tangential release from the knife tip and straight line trajectories. The plot shows the absolute value of the α-angle (impact angle

on the vertical surface) plotted against y, where $y = Y_0 = 0$ is a position opposite the centre of rotation. The vertical lines in the plot show Y_0 and $y = Y_0 + r$, a position where an α-angle of close to 90° is expected for tangential blood drop release.

The results from replicate experiments for both horizontal and vertical rotation are given in Table 1. The average difference between the observed position of the α-angle curve maxima and the theoretical position for $\alpha = 90°$ ($Y_0 + r$) was 3.2 % for cast-off patterns with rotation in a horizontal plane and 1.1 % for vertical rotation. These results therefore support the proposition that cast-off release is tangential to the trajectory of the object end.

Table 1. Observed versus theoretical positional values corresponding to maximum α-angles in cast-off experiments with a spinning knife

Figure 4 shows overlaid images of four consecutive frames of a high-speed video of blood drops being released from the knife spinning on the tripod. A blood strand (ligament) can be observed attached to the knife-tip along with a set of individual drops, which at first glance appear to be travelling in a curved path. However, a careful study of the high speed video showed that the ligament extended no more than a few millimetres from the tip of the knife, and that beyond this the stream of blood consisted of numerous different individual drops at different stages in their individual linear trajectories. It is evident that each drop's linear trajectory is approximately tangential to the circular trajectory of the knife tip at the moment that drop was released. The same blood ligament development and droplet break-off processes were reported by Kabaliuk et al. (18), using a motorized blood droplet generation device developed by Williams and Taylor (28).

Figure 4: Overlaid still images of four consecutive frames recorded with the high speed camera, showing blood drops being released from a spinning knife. Inserted graphics show flight paths of three different droplets and the trajectory of the tip of the knife.

Human-Wielded Objects Experiment

Kitchen Knife (sharp object: small diameter tip)

Composite images of the knife and cast-off blood drops during a backswing movement, with corresponding trajectory plots, are given in Figure 5. High speed videography also showed that, prior to drop formation, blood on the tip of the knife formed short thin ligaments that were initially attached to the knife tip. These extended and disintegrated into individual droplets, which continued to travel in the same direction they were immediately prior to separating from the blood ligament. Initially this trajectory appears to be a straight line, before the effects of gravity forces become apparent.

The tangential velocity of the tip of the knife over the course of its travel, in the example depicted in Figure 5, was measured at between 6.8 and 8.8 m/s. At the time of drop release, drop velocities matched that of the knife tip. A similar pattern of drop behaviour was observed for the forward swing motion (Figure 6). In this example a faster swing was used, with knife tip and initial drop velocities measured at 12.6 – 14.5 m/s.

Figure 5: Initial trajectories of three blood drops disengaging from the knife during a backswing movement. (a) Overlay of selected high speed images (b) Plot of position of knife tip and separating drops during droplet disengagement and initial stages of blood droplet flight

Figure 6: Plot of trajectories of knife tip and two separating blood drops during a forward swing motion

Baseball Bat (blunt object: large diameter tip)

Composite images of the larger diameter baseball bat and cast-off blood drops during a backswing movement, with corresponding trajectory plots, are given in Figure 7. The motion of the baseball bat during the backswing movement resulted in a single, long blood-ligament forming, which extended downwards from the bottom edge of the bat-end, before breaking up after a short distance of travel, to form individual blood drops. Typical bat end and initial drop velocities were measured at 13 – 15 m/s. The trajectory plot in Figure 7 shows that these initial blood drop trajectories remained tangential to the trajectory of the end of the bat, despite breaking away from a long ligament. Similarly, Figure 8 shows blood drops being generated during a forward swing movement with the respective trajectory plot.

Figure 7: Two blood drops separating from the baseball bat during a backswing movement. (a) Overlay of selected high speed images (b) Plot of position of bat end and separating drops

Figure 8: Plot showing blood droplets separating from the baseball bat during a forward swing movement. (a) Ligament and drop formation from across the bat end - arrow represents direction of bat end movement (b) Plot of position of bat end and separating drops

Blood drops were released from very short ligaments from multiple places across the flat surface of the bat end. A much greater number of widely-spread smaller drops were generated during the forward swing relative to the single ligament seen in the backswing. These results showed that in the case of an object with a larger 'end' surface area, the blood did not leave the end of the object from a single point. In both the forward and backswings, the measured trajectory of individual blood droplets continued in the tangential direction of the bat-end when droplets disengaged. At the time of drop release in forward swing motion, the velocity of the end of the baseball bat and the initial drop velocities were between 18 and 21 m/s.

Similarities in the release of drops from the baseball bat and the knife were observed. All measured droplet trajectories appeared tangential to that of the respective object's end-point at the time of release. Fewer and apparently larger drops were released during the backswing movements compared with the forward swing for both objects. This could be a function of the object speed, which was generally greater for the forward swing in these experiments. While long ligaments were observed in the backswing movement with the baseball bat, short or no ligaments were observed in the backswing of the knife. This could be due to the greater blood volume which the bat was able to retain, compared to the knife, or to the curvature of the object surface, which affects the ligament diameter; narrower ligaments from the knife being more fragile.

Discussion

Fundamental consistencies in the stages of blood drop generation and release were observed in both the fixed-spinning device and human-wielded objects. These phenomena are consistent with those described by Kabaliuk et al. (18) and with descriptions of rotary atomization (16, 17). Cast-off blood typically arose from blood ligaments extending outward from the object end-points. These ligaments subsequently broke up forming individual blood drops, which travelled in near-straight lines, which appeared tangential to the trajectory of the swinging object. These data demonstrate a clear and repeatable link between the motion (trajectory and velocity) of the objects and initial trajectory and velocity of blood droplets.

The simple example of the bloodied knife rotating on the fixed apparatus was expected to exhibit the same rotary atomisation dynamics as the motorized rotating disc reported by Kabaliuk et al. (18) and Williams et al. (28) These apparatus, as well as that of Kunz et al., (13) had a fixed radius length and stationary centre of rotation. The motorized disc allowed the tangential velocity to be kept constant, in uniform circular motion. Liquid breakup and disengagement from an object in uniform circular motion is relatively predictable.

The human-wielded objects in Experiment 2 present a more complex problem, as these objects were swung in 'non-uniform circular motion'. In non-uniform circular motion, objects travel around a dynamic axis of rotation, with a constantly changing radius length and angular acceleration. Abrupt changes in object velocity occur throughout the back and forward swing movements. Objects travelling in non-uniform circular motion experience tangential acceleration (a_t), in addition to centripetal acceleration, which is present in uniform circular motion. As is the case with uniform circular motion, however, any blood droplets disengaging from the object will continue to travel at the speed and in the direction it was moving in at the instant of separation. This will be tangential to the arc of curvature of the object.

A drop will separate from a liquid source when the disruptive external forces acting on the liquid exceed the cohesive surface tension forces of the liquid/air interface. The liquid surface tension draws the liquid molecules together into a shape that minimises surface energy. The viscosity of the liquid has a stabilising effect on the drop, which resists changes to the liquid geometry. The more energy transferred into the liquid, the stronger the disruptive forces, resulting in a larger number of smaller drops (16). This is seen in the dynamics of drop formation from passive dripping. Passive drops developing under gravity are generally relatively large as the energy available to break up the liquid is relatively low (20, 31). A drop will detach from a liquid source or wetted object if gravitational forces overcome the breakup-resisting surface tension force. Under low flow-rate conditions, liquid adhering to an object by surface tension forces starts to pool under gravity. As the mass of the forming drop increases, it moves downward forming a neck, or ligament, which continues to elongate. The neck eventually breaks when the downward force acting on the drop (weight) exceeds the surface tension force, resisting breakup. The liquid ligament then either recedes or breaks up into small ‘accompanying drops’. The point where a drop separates from the liquid ligament is called the ‘pinch off length’ (32).

A similar process occurs in cast-off. Instead of gravity, the force of most relevance is the centripetal force acting on the object. When the surface tension forces are too weak to provide the centripetal force required to keep the blood moving in the same arc as the weapon tip, the liquid extends outwards in the form of a ligament. As in passive drop formation the ligament breaks up and drops form. The now separated blood drops continue to travel in the same direction as that at the time of release, which is in near straight lines tangential to the object-end trajectory.

Differences in the number and size of drops generated and the ‘pinch off length’ of blood-ligaments observed between human-wielded trials can be explained by the principles of drop formation. The generation of liquid drops in most engineering and industrial applications (atomisation) involves kinetic energy being transferred to the bulk liquid in order for the liquid to deform and disintegrate into very small drops. Smaller drops are likely to result from higher velocity or higher energy systems due to the magnitude of available kinetic energy (16, 17). For this reason, cast-off bloodstain patterns have the potential to yield valuable information regarding dynamics of a striking attack. The stains within the pattern will reflect the velocity and trajectory of the object being swung at the instant they are released, and are also influenced by the shape of the object tip and the volume of blood adhering to it.

Once disengaged from the blood-ligament, blood drops will follow a trajectory dictated by the velocity and direction at the instant of disengagement from the swinging object and by the forces of gravity and drag. These trajectories can be computed. A comprehensive explanation of blood drop trajectory has been provided by Kabaliuk et al. (18).

Conclusions

The objective of this study was to study the mechanism of blood droplet development and disengagement from swinging objects in the formation of cast-off patterns. One of the sources of ambiguity in the existing literature has been the use of the term ‘*centrifugal*’ (which means ‘away from the centre’) when discussing the physics of circular motion. This term has been used in the BPA literature to describe the generation of what is thought to be a force directed away from the centre of rotation causing blood to be “flung off” a swinging object. It has also been used interchangeably with the term ‘*centripetal*’, which means ‘towards the centre’. Given that the term *centrifugal* force does not correspond to a real force, we assert that this term should have no part in the description of cast-off pattern formation.

As a result of this confusion in terminology, several authors have proposed that blood is cast-off in a direction co-linear with the object (i.e. radially) and have produced diagrams to help estimate the position of an assailant at the time of cast-off pattern creation (14, 15). In light of the findings of this study we propose an amended version of this diagram (see Figure 9). Near circular stains can be expected on a ceiling at a position vertically above the weapon when it becomes horizontal (not vertical as has been previously depicted), and on vertical surfaces when the weapon reaches a vertical position (not horizontal as previously depicted). It is worth stating that such estimates of assailant position from cast-off patterns are likely to be approximations only, because the exact motion of the assailant during the wielding of the weapon is likely to be an unknown variable.

Figure 9: Estimating the position of an assailant from cast-off patterns

Given the current inconsistencies in the explanation of the mechanism of cast-off the following technical description of cast-off is offered:

“Cast-off patterns occur when blood present on a swinging object detaches and is projected onto nearby surfaces. This occurs if the wielder of the object swings the object in such a way that the surface tension forces holding the blood on the object are insufficient to provide the centripetal force necessary to keep the blood moving on the same arc as the object tip. Under these conditions the liquid extends outwards in the form of a ligament, which subsequently breaks up and drops form. The now separated blood drops continue to travel in the same direction as that at the time of release, which is in near straight lines tangential to the object-end trajectory".

The results of this study have demonstrated a direct link between the dynamics of the swinging object and the trajectory of resulting cast-off drops. Based on these results, it is asserted that changes in stain shape, directionality and the relative position of stains throughout the pattern reflect the dynamics of the swinging object. Cast-off patterns have unique features that lend themselves to quantitative analysis under the right conditions. Future work in this area could profitably be directed towards inferring the dynamics of human striking actions from such features.

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Table 1. Observed versus theoretical positional values corresponding to maximum α-angles in cast-off experiments with a spinning knife

Plane of rotation (replicate #)	Theoretical position for α = 90° ($Y_0 + r$) (cm)[1]	Observed position of α-angle maxima (cm)
Horizontal #1	163.0	170.4
Horizontal #2	77.2	79.9
Horizontal #3	77.0	78.4
Vertical #1	192.5	193.8
Vertical #2	174.5	177.1
Vertical #3	166.9	165.2

[1] Assuming tangential straight-line trajectories