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TECHNICAL NOTE

Criminalistics

A study on the estimation of area of origin of swing cast-off pattern

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Abstract

In bloodstain pattern analysis (BPA), a field of forensic science, there has been active discussion on the estimation of the area of origin of impact spatter. However, there is no established methodology to quantitatively analyze the area of origin of a swing cast-off pattern. To quantitatively analyze the methodology of previous research on estimation of area of origin, a device for generating uniform swing cast-off patterns was produced. Using artificial blood, 10 swing cast-off patterns were generated on porous paper; in each, 10 blood drops were selected for the calculation of the impact angle. Hemospat software was used for individual bloodstain analysis, and an open source code was used for estimation of area of origin. Under the same conditions, an additional 10 swing cast-off patterns were generated, and quantitative analysis was performed using trigonometric functions and an adjustment formula that minimized errors in calculating the impact angle. The adjustment formula was corrected to calculate the impact angle for the bloodstains on the porous surface. As uncertainty decreases, the error increases, and the point at which both uncertainty and error can be minimized is calculated as 75%. The existing formula included the trajectory in the estimated likelihood range in 75% of samples. When the adjustment formula was applied, the accuracy was improved, with the trajectory included in the area with a 90% likelihood.

KEYWORDS
adjustment formula, area of origin, bloodstain pattern analysis, impact angle, individual bloodstain, swing cast-off, trajectory

Highlights

- To estimate the area of origin, we applied the adjustment formula to the existing algorithm.
- The adjustment formula is based on the results of measuring the bloodstains using regression equations.
- Application of the adjustment formula improved the accuracy of the trajectory of bloodstains.
- Using the adjusted formula reduces the uncertainty and the error in determining the trajectory.

1 | INTRODUCTION

Bloodstain pattern analysis (BPA) is a field of forensic science that analyzes the morphological characteristics such as size, location, shape, and distribution of bloodstains at crime scenes and is used to reconstruct the scene and determine the authenticity of suspect statements [1–4]. The pattern of bloodstains is largely classified into spatter and nonspatter stains [5]. A cast-off pattern, a type of spatter, is formed by the inertial separation of blood attached to some object due to its movement in space [6] and can be divided into a swing cast-off pattern and a cessation cast-off pattern [7]. The formation mechanisms of the swing cast-off pattern are variously explained. According to the previous research, swing cast-off patterns are formed when blood droplets are separated from an object by centripetal force, when the angular momentum of the blood overcomes the surface tension and is discharged into small droplets, or when the acceleration force exceeds the restraining force of surface adhesion. This can vary depending on the conditions, environment, and point of view of the experiment. Such a cast-off pattern can prove that bloody weapons were swung, and since bloodstains are formed along the trajectory of the object, the trajectory and direction of the object can be estimated.

In an impact spatter pattern, several methodologies for estimating the area of origin have been established, including a string method, a mathematical method, and a 3D scanner. The string method can be used to gather individual bloodstains, estimate their impact angles, and then align them toward the area of origin. This allows us to confirm the overall angles of impact on a line-by-line basis [8]. Mathematical methods include morphological features of bloodstains, a trigonometric formula that can estimate impact angle using linear trajectory techniques [9, 10], and computer software such as Hemospat (FORident Software, Inc., USA) that can calculate bloodstain impact angles, α, β, γ. Alpha (α) is the impact angle of the bloodstain path moving out from the surface. Beta (β) is the impact angle of the bloodstain path pivoting about the vertical (z) axis. Gamma (γ) is the angle of the bloodstain path measured from the true vertical (plumb) of the surface [11, 12] (Figure 1). For a swing cast-off pattern, studies on the velocity and hydrodynamics of blood droplets have been conducted [8, 13], and methodologies for quantitatively estimating area of origin have recently been discussed [14]. Therefore, this study aims to quantitatively analyze and verify the accuracy of the estimation methodology using the area of origin of swing cast-off patterns [15] with the existing formula and an adjusted formula.

2 | MATERIALS AND METHODS

2.1 | Blood selection for formation of swing cast-off patterns

Since human blood has specific rheological properties (viscosity, viscoelasticity, surface tension, etc.) as a non-Newtonian fluid, it is very important to attempt to simulate, for experimental purposes, bloodstains found at crime scenes [16–18]. When conducting experiments in the field of bloodstain pattern analysis, it is common to use human blood [19] or that of pig, cow, or sheep [20–22]. Human blood has the advantage of reproducibility compared to bloodstains found at crime scenes, but it has the disadvantage of biological risks and difficulty in mass supply. Animal blood has the advantage of mass supply but the disadvantage of unknown biohazards. Therefore, we intend to ensure reliability using the developed blood substitute, which is harmless to humans, has no risk of potential disease, and is most similar to human blood compared to other artificial blood types [23]. The developed blood substitute is artificial blood with rheological physical properties such as viscosity, viscoelasticity, and surface tension that are very similar to those of human blood.

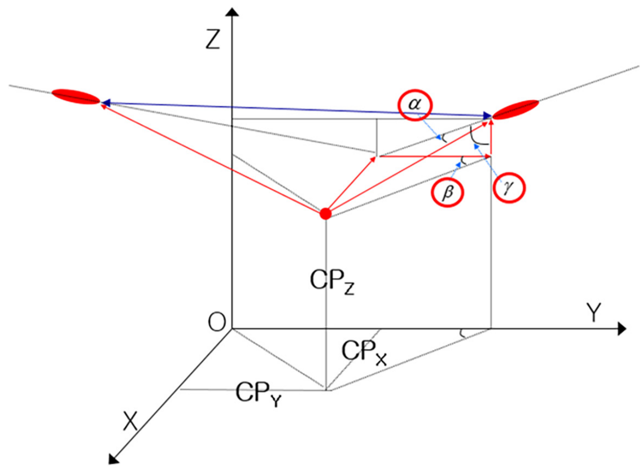

FIGURE 1 The diagram for illustrating bloodstain impact angle, α, β, and γ.

2.2 | Formation of swing cast-off pattern

To quantitatively analyze the area of origin of a swing cast-off pattern, it is important to be able to conduct replicate experiments under the same conditions so that meaningful results may be obtained. Accordingly, a device for generating a swing cast-off pattern at the same force and speed and in the same coordinate position was manufactured (Figure 2). This device comprises a 71-cm rotating arm that moves in an arc through the force of a spring fixed to the central axis of rotation and can generate uniform swing cast-off patterns. Porous A4 paper was used as the bloodstain surface, and the rotation axis of the device was perpendicular at 93 cm from the wall. To replicate a consistent blood spatter pattern, about 25 mL of artificial blood was positioned at the bottom of the arm arc, and the arm was swung in a 180°arc to generate swing cast-off blood spatter. This process was repeated 10 times for experimentation. For each creation of swing cast-off blood spatter, 10 individual bloodstains were selected and analyzed, totaling 100 bloodstains over 10 repetitions. In previous research [14], the blood volume was determined to be between 5 and 25 mL. With reference to this and the results of preliminary experiments in this study for consistent swing cast-off pattern creation, we conducted experiments with a determined 25 mL volume of blood. Per swing, 10 individual bloodstains were selected and closely photographed with a Nikon D750 (Nikon,

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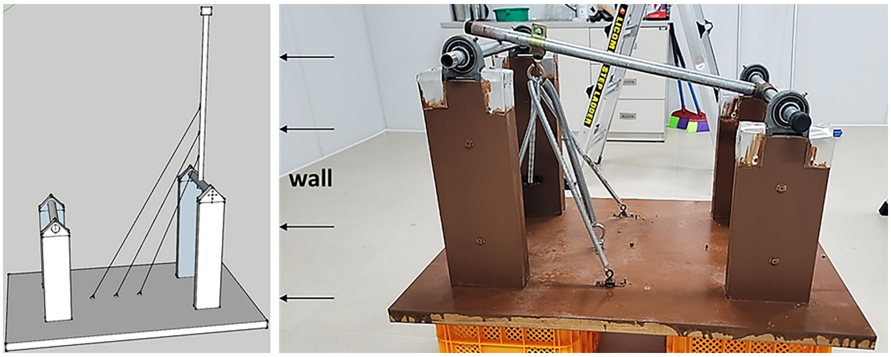

FIGURE 2 The device for generating swing cast-off patterns.

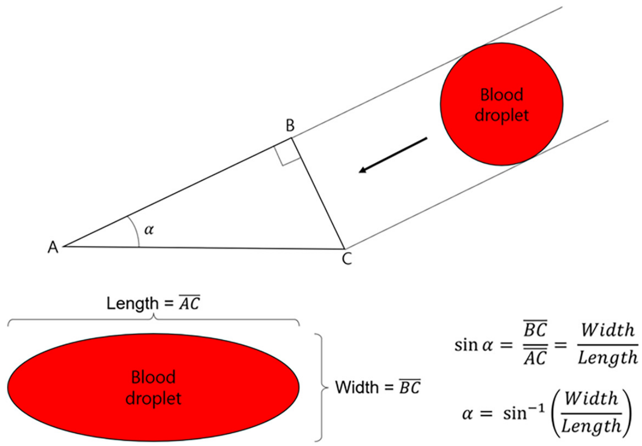

FIGURE 3 Formula and principle for calculating the angle of impact of a bloodstain.

Japan). The purpose of taking photographs was to calculate the impact angles of each individual bloodstains and obtain the values of α, β, and γ with Hemospat (FORident Software, Inc. USA) software.

2.3 | Adjustment of the formula for calculating the impact angles of bloodstains

Calculating the impact angle is essential for reconstructing a crime scene in bloodstain pattern analysis. First, the angle of impact of a bloodstain can be calculated using the ratio of length of the major and minor axes of individual bloodstains and a trigonometric function formula, as proposed by Rizer [9] (Figure 3). The impact angle of bloodstains can be calculated as a function of the arcsine function of the ratio of the length of the minor axis to the length of the major axis [24], and the area of origin of the impact spatter pattern can be estimated using the calculated impact angle [25].

However, errors can occur when applying the existing formula because the shapes of bloodstains can vary depending on the substrate, even at the same impact angle [26, 27]. In this study, in addition to the existing formula, the bloodstain substrate was porous A4 paper, and an adjustment formula corrected the calculation of the impact angle on a porous surface [28]. The adjustment formula [28] based on the results obtained from measuring the lengths of the major and minor axis of bloodstains optimized for paper surface using regression equations obtained by utilizing Matlab (Mathworks Co., USA) was applied. The formula was derived to minimize error, showed an error of 5% or less for impact angles of 20–70°, and is expected to increase the accuracy of estimating the area of origin.

$$\frac{Width}{Length} = 1.590\ \sin\ (0.009517\alpha - 0.02887)$$

2.4 | Method to reconstruct swing cast-off patterns

The chosen method to reconstruct the motion, or swing, of a weapon is based on the study and open-source code in Ref. [15]. The method is based on stain inspection and Euclidean geometry. The reconstructed swing is represented as a three-dimensional region of statistical likelihood. This study would like to reconstruct the swing by citing the results of 3D movements in previous research [14] and the methodology for determining the likelihood value accordingly. According to the uncertainty-error relationship graph (Figure 4) [14], it is meant that the left Y-axis is the volume of the crime scene, the right Y-axis is the error of reconstruction, and the X-axis is the likelihood ratio, and the larger the crime scene, the less uncertainty and the greater the error. The reconstruction uncertainty corresponds to the volume of the reconstructed region, which is specific to the uncertainties of the case at hand. The larger the likelihood, the smaller the reconstructed region (uncertainty), and the larger the distance between the reconstructed region and the actual path of the weapon (error). 60% is generally calculated when the error is zero and the uncertainty is quite small; 90% is when the uncertainty is minimal and the error is about 10 cm, and the point where the uncertainty and error are minimized is 75% probability. In other words, when the probability is greater than 75%, it is most likely to include the actual trajectory, and the error is least [14]. Therefore, comparison with recorded 3D motions in which cast-off patterns are produced indicates that likelihood values between 60% and 90% are appropriate for reconstruction purposes, producing acceptable error (10 cm or less) and minimizing uncertainty.

3 | RESULTS

Under the same conditions, 10 swing cast-off patterns were formed, for which 10 individual blood drops with various Z-axis height coordinates and impact angles were selected for analysis of the area of origin. Individual blood drops were selected on A4 paper only from the wall facing the device, and Hemospat software was used for individual blood drop analysis. The lengths of the major axis and minor axis of individual blood drops were measured with Hemospat software to calculate the angles of impact, α, β, and γ. Thereafter, the estimated area of origin may be calculated by inputting the value into an open-source code [15]. The algorithm for calculating the area of origin of the swing cast-off pattern was implemented in Matlab® R2021b. Estimated likelihood, uncertainty, and error have a relationship in which reconstruction uncertainty decreases and reconstruction error increases as the estimated likelihood increases. Therefore, it is important to set an appropriately balanced likelihood, such as 75% [14]. Therefore, the likelihood of estimating the area of origin of the swing cast-off pattern was set to 90%, 75%, or 60%. The likelihood that the calculated area contains the actual swung trajectory is shown on 3D graphs (Figures 5 and 6).

4 | DISCUSSION AND CONCLUSION

In this study, the reliability of the existing algorithm was verified by estimating and quantitatively analyzing the area of origin of a

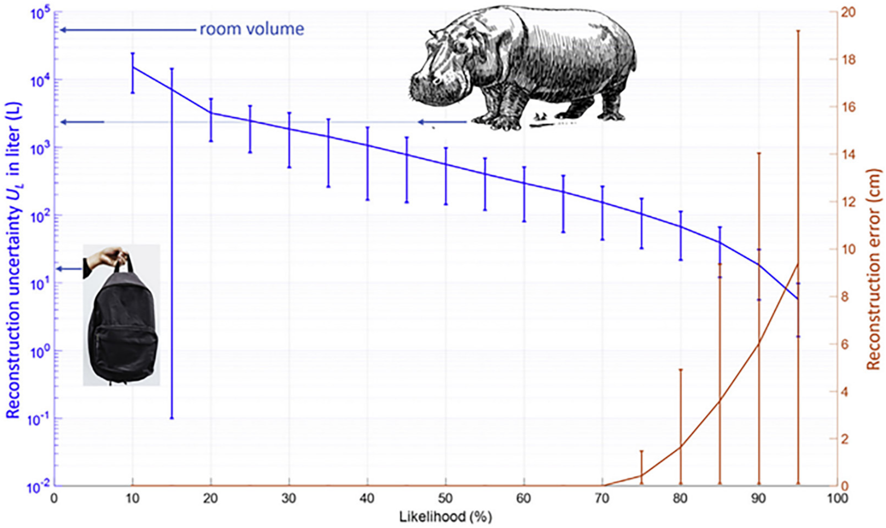

FIGURE 4 The diagram for illustrating the relationship between reconstruction uncertainty and reconstruction error [14].

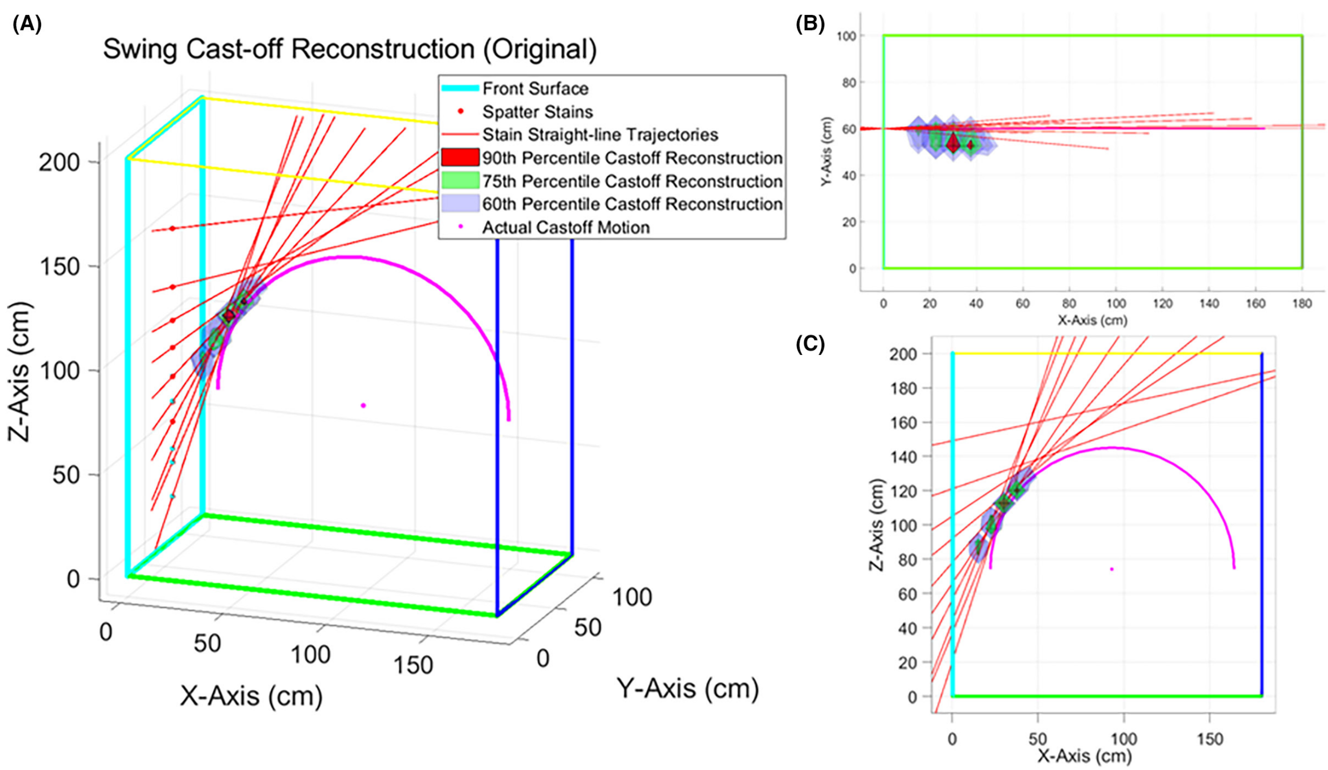

FIGURE 5 The result of the area of origin of swing cast-off bloodstains patterns estimated using the conventional impact angle calculation formula (A) perspective, (B) top view, and (C) side view.

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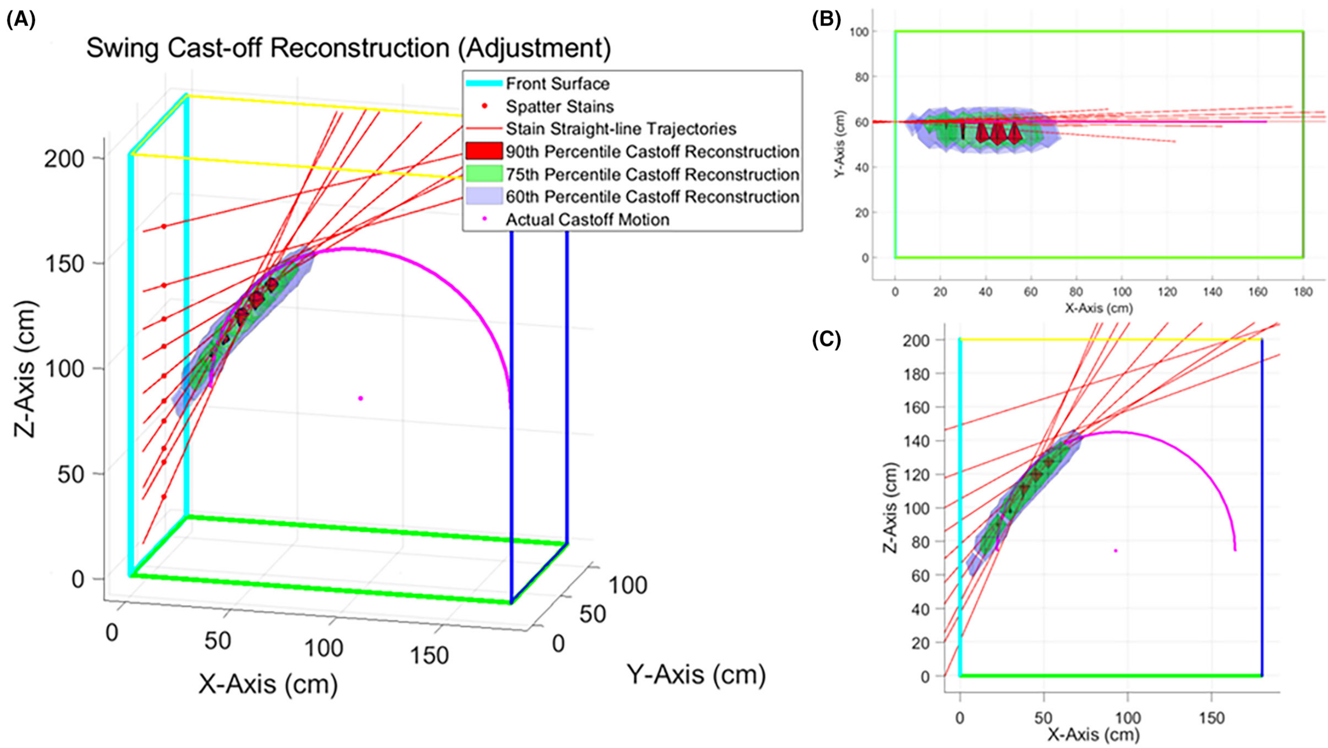

FIGURE 6 The result of the area of origin of swing cast-off bloodstains patterns estimated using the calculation adjustment formula (A) perspective, (B) top view, and (C) side view.

repeatedly produced swing cast-off pattern under fixed conditions using the developed blood substitute. Furthermore, an adjustment formula was applied based on the surface properties to derive results. When calculating the impact angle of blood drops, both the existing and adjusted formulae, were suitable for the porous surface. When the existing formula was applied, all trajectories were included in the range of the area of origin, estimated at 75% likelihood. Application of the adjustment formula slightly improved the accuracy, such that all trajectories were included in the range of the area of origin estimated at 90% likelihood. Using the adjusted impact angle formula reduces the uncertainty and the error in determining the cast-off trajectory.

When the impact angle adjustment was applied, the results were improved compared with those of the existing formula. In addition to a porous surface, adjustment formulae are needed for various non-porous surfaces.

However, since the program assumes that all individual blood drops travel linearly in the absence of an external force such as gravity and air resistance. Such forces result in errors between the estimated and actual trajectories. With spatter stains, the longer the flight distance, the more likely the projectile motion is to be affected by several external forces [29–31]. Therefore, it is necessary to derive and modify a formula considering various forces and the distance between the bleeding source and the surface. If the formula is modified to be more suitable for the actual trajectory in the above methods, uncertainty and error can be reduced at the same estimated likelihood. In addition, it is necessary to enhance the accuracy of estimating the area of origin of bloodstains through the regression analysis of a larger number of individual bloodstains. And, further research is needed to statistically quantify the accuracy of the improved formula for estimating the swing cast-off bloodstains.

To verify the accuracy of estimating the area of origin, swing cast-off patterns were formed on a perpendicular surface to reduce the impact of factors that may affect trajectory, and individual blood drops were selected only from the wall in front of the pattern generation device. As a result, the β impact angle of all individual blood drops was close to 90°, and the actual swing trajectory was a semicircle. However, the estimated trajectory was calculated as an arc with a central angle of $\pi/2$ (Figure 4). However, the trajectory of the swing is not an arc shape during the crime, and the scattered blood can also be formed on not only directly in front but also on other surfaces like the ceiling and side wall. Therefore, it is assumed that a reasonable estimate of the area of origin can be determined if the angle between the bloodstain surface and the wielded trajectory is known and the individual blood drop selection is carried out on two or more surfaces.

Finally, the actual crime scene is much more complex due to shelves, objects, etc. and an abnormal shape; bloodstain patterns may be interrupted by obscuring objects; and there is a limit to estimating the area of origin. Therefore, a more reliable area of origin can be calculated by improving the algorithm through additional experiments considering the above variables.

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CONFLICT OF INTEREST STATEMENT

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

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