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ORIGINAL ARTICLE

Bloodstain Pattern Analysis on Various Surfaces Using Simulated Blood: A Forensic Approach

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ABSTRACT

Background: Bloodstains are commonly encountered biological evidence at the crime scenes. Bloodstain pattern analysis provides crucial information about height of fall, angle and force of impact assisting in crime scene reconstruction.

Objective: The present study was conducted to evaluate the influence of surface characteristics and height of drop of fall of blood drop on various porous and non-porous surfaces on bloodstain pattern analysis for forensic purpose.

Methodology: In the present study, simulated blood was prepared using red water color and corn flour homogenized with distilled water to attain the consistency and appearance of real blood avoiding ethical implications associated in using real blood. The experiment was conducted to examine the bloodstain patterns formed on various porous (paper, cardboard and soil) and non-porous (glass, metal and tile) surfaces when simulated blood was dropped passively from various heights with a constant impact angle of 90º. The experiment was carried out in triplicate. The bloodstains were analyzed for the shape, size and distribution.

Results: The results showed an increase in size of the stain with increase in height of fall across all surfaces. Depending on point of impact, soil showed different bloodstain patterns while paper and cardboard due to their absorbent nature

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displayed larger stains with prominent satellite stains and spikes on the edges of the central stain. Non-porous surfaces displayed more uniform smaller stains with no spikes on the edges and few secondary stains.

Conclusion: Simulated blood can be used as an effective, ethical and safer substitute to real blood for employing in training, research and forensic experimentations.

KEYWORDS

• Simulated blood • Bloodstain pattern analysis • Porous surface • Non-porous surface • Satellite stains • Spikes

INTRODUCTION

Bloodstain pattern analysis is a significant branch of forensic science which plays a key role in crime scene reconstruction of heinous crimes.[1] Forensic investigators can decipher the sequence of events that led to formation of bloodstains by examination of the morphology, dimensions, pattern and location of the bloodstains at the crime scene.[2] The bloodstain patterns provide forensic insights about the type of crime, sequence of events occurred during commission of crime, type of weapon used and positions of people present at the crime scene. Bloodstain pattern interpretation can be used to support witness statements and acts as corroborative evidence at the crime scene. Bloodstain pattern analysis utilizes the principles of physics, biology and mathematics to understand the behavior of blood based on the surface deposited, gravitational pull, angle of impact and force used.[3] Bloodstains formed in the crime scene are classified as low velocity, medium velocity and high velocity bloodstains. They are classified as projected, cast off, splashed, contact and gunshot patterns. Based on size, the bloodstain patterns are classified as mist, fine, medium and large stains.[4,5] The formation of different bloodstain patterns at the crime scene such as passive stains, projected stains, contact stains and gunshot spatters form a basis for interpretation and reconstruction of events at the crime scene.

Conventional bloodstain pattern analysis utilizes real blood either of human or animal origin for experimental and practical applications. However, the use of real blood presents numerous health, ethical and logistical challenges. Risk of biohazards, variability in viscosity, contamination risk and clotting of blood pose major challenges while working with real blood samples.[6] To overcome these challenges, and to study bloodstain pattern analysis in standardized, controlled and reproducible conditions, forensic scientists are exploring the use of simulated blood prepared from non-biological materials with physical and chemical properties mimicking human blood as promising substitutes to real blood.[7] Simulated blood offers safer, ethical, and convenient alternative to create simulated crime scenarios and facilitate practical training, research and comprehensive analysis of bloodstain patterns under controlled conditions unlike the complications posed by real blood.[8] With the advancement in forensic science, synthetic substitutes closely mimicking the color, texture, viscosity, density and flow characteristics of real blood are being used for forensic bloodstain pattern analysis.[9] Simulated blood studies can help researchers evaluate the parameters such as surface characteristics and their effect on the formation of bloodstains, angle of impact and the force which affect formation and distribution of bloodstains under controlled conditions.

Recent research has emphasized the significance of using simulated blood in various scenarios to assess the real world applications. The effects of surface textures on spatter formation was explored by Laber.[10,11] The reliability of pattern classification on non-absorbent surfaces[10] and fabric surfaces was studied.[11] A comparative review was conducted by Attinger *et al.* to study the relationship between bloodstain pattern analysis in forensic science and fluid dynamics in physics. The physical forces driving motion of blood, formation and flight of blood drops, surface impact and stain production were the aspects studied.[6] In another study conducted by Buck *et al.*, 3D imaging and trajectory modeling was employed for determining the angle of blood stain impact.[12] The maximum diameter of blood droplets was dependent on the conversion of kinetic energy into surface energy.[9] Chomsky P *et al.* proposed a theoretical model for predicting and interpreting the blood spatter patterns resulting in gunshot wound. A parametric study was undertaken to predict the backward blood spatter patterns under realistic conditions. The results of the theoretical model were then compared with the experimental data.[13] Kunz S *et al*. conducted a study on analysis of back spatter stains by conducting experiments using horizontal pistol shots into blood-filled sponges. Shooting distances were set between 0 and 45 cm. There was a significant decrease in back spatter with increasing the shooting distance. Another significant finding of the study was that no bloodstains were found beyond 45 cm.[14] Singh P *et al*. reported alwata dye to create simulated bloodstains to understand formation of bloodstains with respect to varying heights and their relationship with spines and satellite stains.[7]

In the present study, simulated blood was used to recreate the bloodstain patterns. The present study has been conducted to study the influence of surface characteristics of receiving surface on the characteristics of bloodstains and the patterns formed. The study has employed the use of simulated blood on porous and non-porous surfaces to study the bloodstain pattern formation. The scientific knowledge on bloodstain pattern analysis is enhanced through the insights gained through the present study.

MATERIALS AND METHODOLOGY

Materials required

Simulated blood was prepared using red water based color, corn flour and distilled water to resemble the physical parameters of human blood. To interpret the dynamics of bloodstain pattern formation, a measuring scale and measuring tape were used for quantitative assessment of stain dimensions such as length, breadth and extent of spread of the blood spatters. A range of porous substrates such as paper, soil and cardboard and non-porous surfaces such as glass, metal and tile were chosen to study the effect of surface characteristics on the morphology of bloodstains.

METHODOLOGY

The simulated blood formulation was prepared using 1 part of red water-based color, 1 part of corn flour homogenized with 100 mL of double distilled water to adjust the consistency and reduce impurities. Corn flour which acts as thickening agent was mixed in cold distilled water to make a smooth slurry avoiding formation of clumps. Red water color was added and the viscosity was adjusted by adding distilled water. To simulate real blood, the simulated blood should be 3-4 times viscous than water. The composition selected was to replicate the color of blood, consistency and properties of human blood.

The present study aimed to investigate the physical dimensions of the passive bloodstains dropped from varying heights. 0.5 mL of simulated blood droplets were dropped passively using a syringe from five different preselected vertical heights of 1 foot, 2 feet, 3 feet, 4 feet and 5 feet at a fixed angle of 90º to the target surface allowing the blood drop to fall under the gravitational pull without any application of additional force.

The study was carried out on various porous and non-porous substrates to evaluate the effect of surface texture on stain size and shape. The porous surfaces chosen for the study were paper, soil and cardboard while non-porous surfaces chosen were glass, metal and tile. For each of the combination of surface type and height, the experiment was carried out in triplicate to ensure reliability of the data. Each drop was labeled as Drop A, B, and C for identification and documentation.

After deposition of the droplets on the surfaces, the resulting length and breadth of the resulting bloodstains were measured. Photographs were captured for each stain to observe the intricate details of the bloodstain patterns formed. The average dimensions of the three replicates for each surface type and height was calculated. Further analysis involved evaluation of the size of the bloodstain, characteristics of edges of the bloodstain and the spread of droplets across different surfaces and varying heights. To study the influence of surface on the morphology of bloodstain, the obtained results were interpreted to understand the passive blood formation dynamics which is important for crime scene reconstruction.

RESULT

Simulated blood was dropped from different heights of 1 foot, 2 feet, 3 feet, 4 feet and 5 feet with the angle fixed at 90º. The drops were passively dropped from these different heights onto different porous surfaces like paper, soil and cardboard and non-porous surfaces like glass, metal and tile surface. The resulting bloodstains formed from impact on porous surfaces from different heights are illustrated in *Figure* 1.

Figure 2 illustrates the bloodstain patterns formed on non-porous surfaces from varying heights. The blood drops were passively allowed to fall under the influence of gravity without applying any external force from predefined vertical heights onto each selected surface. The experiment was carried out in triplicate to ensure reliability, accuracy and reproducibility of the results. The stain dimensions were then measured placing a measuring scale adjacent to each bloodstain to obtain accurate measurements. The average length and breadth of the triplicate experiments relevant to each height and surface was calculated and the results have been presented in *Table* 1. In addition, the stains were evaluated for morphological characteristics such as shape, nature of edges of the stain and the distribution of the stains.

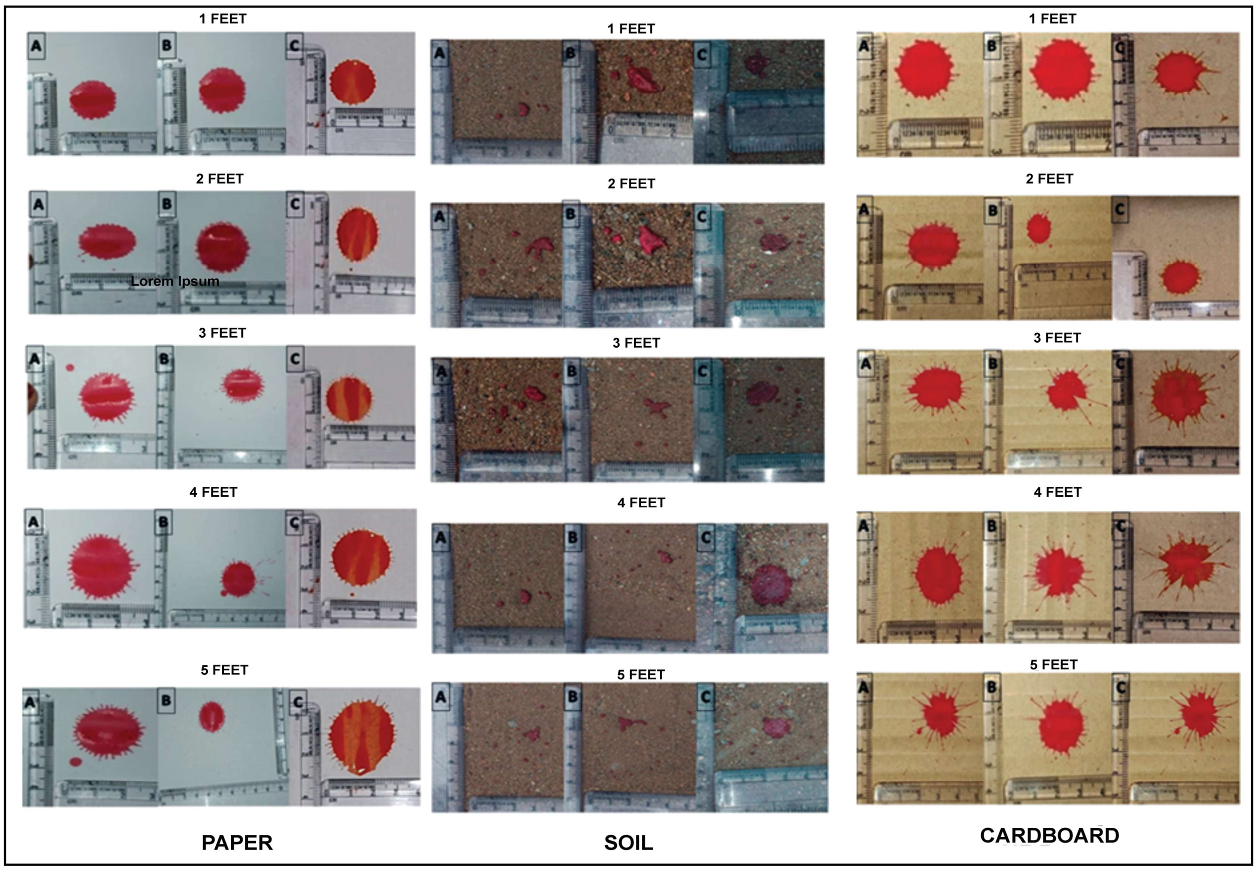

Figure 1: Bloodstains formed on various porous surfaces from different heights

Table 1: Average size of the bloodstains on each surface at different heights

Surface	1 Feet		2 Feet		3 Feet		4 Feet		5 Feet	
	Length	Breadth	Length	Breadth	Length	Breadth	Length	Breadth	Length	Breadth
Paper	1.8 cm	1.7 cm	1.9 cm	1.9 cm	2.0 cm	2.1 cm	2.4 cm	2.5 cm	2.7 cm	2.6 cm
Soil	0.7 cm	0.7 cm	0.8 cm	0.7 cm	0.9 cm	0.9 cm	1.1 cm	0.9 cm	1.1 cm	1.1 cm
Card board	1.9 cm	1.9 cm	1.9 cm	2.0 cm	2.2 cm	2.2 cm	2.3 cm	2.3 cm	2.7 cm	2.9 cm
Glass	1.8 cm	1.8 cm	2.0 cm	1.9 cm	2.1 cm	2.0 cm	2.2 cm	2.1 cm	2.4 cm	2.3 cm
Metal	1.4 cm	1.4 cm	1.7 cm	1.6 cm	1.9 cm	1.8 cm	1.9 cm	1.9 cm	2.0 cm	2.0 cm
Tile	1.4 cm	1.4 cm	1.6 cm	1.6 cm	1.8 cm	1.8 cm	2.0 cm	2.0 cm	2.1 cm	2.1 cm

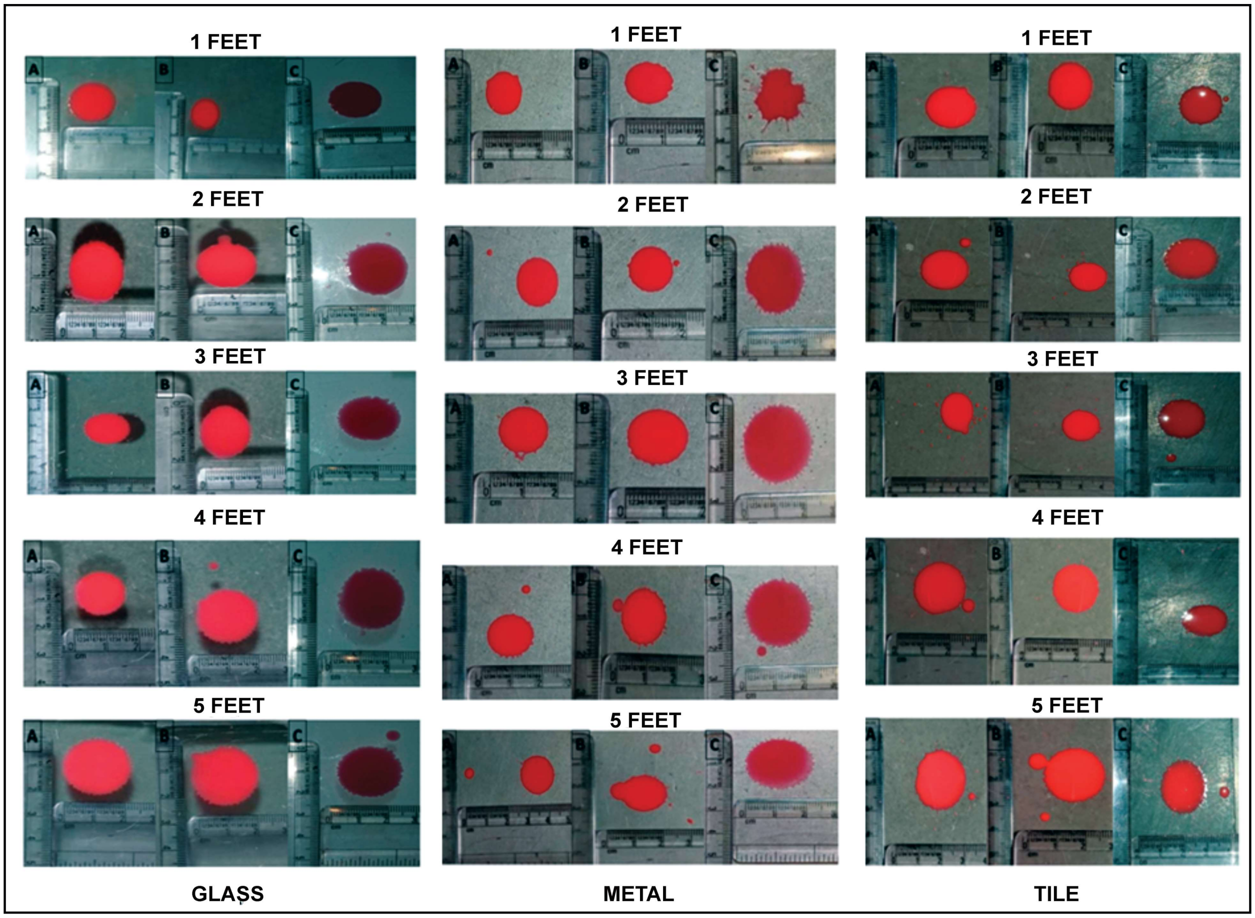

Figure 2: Bloodstains formed on various non-porous surfaces from different heights

DISCUSSION

Shape of the bloodstain

The bloodstain pattern analysis of the results obtained in the present study has exhibited the dependence of bloodstain morphology on the nature of the receiving surface. Non-porous surfaces showed more uniform and circular bloodstains in morphology with circular satellite stains and spines radiating from the periphery of the central stain. The non-absorbent nature of non-porous surfaces allows blood to remain on the surface and exhibit characteristic pattern of passive drops falling and impacting smooth surfaces.[8]

On contrary, the shape of bloodstain on porous surfaces was varying with the surface characteristics and the absorbent nature of the substrate. Paper is a smooth and highly absorbent substitute resulting in spherical stains with spiny edges and small satellite stains. Lateral expansion of the bloodstain was restricted by the absorbent nature of the paper giving rise to well defined borders and spherical stains. Despite cardboard being porous surface, it exhibited bloodstains with irregular margins and prominent secondary spatters. The increased roughness of surface and lower absorbency in comparison to paper might have resulted in uncontrolled spreading and irregular margins. Soil has a heterogenous nature and an uneven surface which affects the stain morphology widely. Most of the stains formed on soil were irregular in shape caused by the fragmentation of main droplet on impact with rough and angled particles in the matrix of soil. The results suggest that the surface characteristics such as porosity and topography notably influence the morphology of the bloodstain with uniform round patterns observed on smooth surfaces and irregular and split patterns observed on rough and uneven substrates. Similar results were reported by Sonia Rajkumari who experimented with real human blood, goat blood and chicken blood.[15] In the study, blood was dropped from a height of 50cm and the stain dimensions were measured. The study highlighted the significance of bloodstain pattern analysis in forensic science in linking crime scenes and suspects based on the Locard's exchange principle. The study explored the various bloodstain patterns including spikes, satellite stains and void patterns and their formation on various surfaces. Bloodstains provide critical information about angle of impact, point of origin, direction of blood flow, force applied, movement of suspects, and weapons used based on the shape, size and distribution of bloodstains. This shows that the present study can be employed for future forensic experimentation to study bloodstain pattern analysis. *Table* 2 displays the recent literature on studies conducted on bloodstain pattern analysis to understand the influence of various factors on the bloodstain patterns formed.

Table 2: Recent studies related to bloodstain pattern analysis[7,16-24]

Authors and year	Study carried out	Ref
Tommy Bergmann *et al.*, 2025	Review of UV-Visible spectroscopic methods for bloodstain age estimation	16
Fujun Wang *et al.*, 2025	Bloodstain patterns studied on three different cotton fabrics	17
Hyeonah Jung *et al.*, 2024	Investigated the use of machine learning and deep learning for classification of bloodstains in forensic science	18
Rosalyn Rough *et al.*, 2024	Developed an automated bloodstain pattern analysis method which uses computer vision techniques to identify bloodstains on plain background within a digital image	19
L. Dicken *et al.*, 2022	Studied the effect of digital printing of fabric on the morphology of passive bloodstains	20
Tong Zou *et al.*, 2022	Demonstrated the feasibility of likelihood ratio approach for bloodstain pattern analysis	21
L. Dicken *et al.*, 2022	Studied the effect of reactive dyeing of fabric on the morphology of passive bloodstains	22
Belinda Bastide *et al.*, 2021	Studied the effect of heat on physical and spectral properties of bloodstains at arson scenes	23
Sang-Yoon Lee *et al.*, 2020	Developed forensic blood substitute to study bloodstain pattern analysis	24
Prashant Singh *et al.*, 2021	Studied the use of alwata dye as blood substitute	7
Present study	**Studies the influence of surface characteristics and height of fall of blood drop on bloodstain pattern analysis using simulated blood for forensic purpose**	

Size of the bloodstain

Quantitative measurements revealed that the average size of the stain increased linearly with increase in the height of fall of the blood drop. The results were similar in case of porous and non-porous surfaces. These results can be attributed to the great velocity of impact with increased height of fall due to gravitational pull.[6] In comparison, porous surfaces exhibited larger stains than non-porous surfaces except soil. This can be attributed to the absorbent nature, porosity and capillary nature of porous substrates. However, as soil is a heterogenous substrate with uneven texture, the bloodstains produced on soil had reduced stain size in comparison to paper and cardboard. Non-porous surfaces on the other hand restrict the spreading of the bloodstains owing to their non-absorbent smooth texture resulting in smaller stains relative to porous surfaces.

Formation of secondary stains (satellite stains and spines)

Secondary spatter formed after the main blood drop strikes the receiving surface and rupture from the parent stain are called satellite stains. Satellite stains are formed by small blood droplets moving away from the parent stain. Satellite stains may be formed close to the central bloodstain or away from the central bloodstain.[25]

From the results of the present study, it was identified that with increasing blood drop fall height, the number of satellite stains formed around the parent stain were also increasing. The distance of satellite stains from the main bloodstain also increased with increase in the height of blood dropping. This was seen commonly for both porous and non-porous surfaces. This showed that the height of fall of a blood drop is directly proportional to the number of satellite stains formed. Satellite stains were more prominent and larger in size on non-porous surfaces due to reduced absorption. While porous substrates absorbed the blood drops, resulting in reduced satellite stain formation.[25] As the height of drop fall increases, satellite stains increase in number and radial distance as higher kinetic energy promotes satellite stains was reported in previous studies conducted by Attinger *et al.* and Hulse *et al.* which are in compliance with the present results.[6,26]

Spines are small projections formed on the edges of the parent stain. Spines extending from the central bloodstain were more prominently seen in bloodstains on porous surfaces rather than non-porous surfaces due to the absorbent nature. Glass and tile surfaces exhibited minimal spines owing to their smooth texture while the metal surface displayed moderate spine formation due the micro-ruggedness of the surface. The formation of spines decreased as the drop height increased. This showed that the formation of spines around the bloodstain was inversely proportional to the height of fall of the blood drop. Similar results were presented in an experiment carried with alwata dye.[7]

Hence, the results of the study clearly showed that the shape, size, and the formation of secondary spatters were dependent on the receiving surface. There were differences in the bloodstain patterns formed on porous and non-porous surfaces.

LIMITATIONS AND FUTURE SCOPE OF THE STUDY

The study was conducted using simulated blood prepared from red color and corn flour mixed in distilled water. This formulation should be prepared and used freshly to avoid change in viscosity and consistency which might affect the stain morphology. Despite acting as an ethical and safe alternative to real blood, simulated blood might not mimic the surface tension, cellular components and clotting behaviors of real blood resulting in small deviations in the stain characteristics.[6]

The scope of the present study is limited to use of only three porous surfaces and three non-porous surfaces with the impact angle fixed at 90^{o} and the height of fall restricted to a maximum of 5 feet. However, the conditions observed in real crime scenes are vaster. To cover a wider range of conditions found in real crime scenes, future studies should be conducted on a wider variety of surfaces with greater fall heights and different impact angles. If permitted ethically and legally, real blood samples can be used to overcome the challenges posed by simulated blood samples for forensic experimentation.

CONCLUSION

Bloodstain pattern analysis plays a significant role in forensic investigation of crimes. In the current study, an attempt was made to study how the bloodstain morphology is influenced by height of fall of the blood drop while focusing on investigating any differences in bloodstain patterns formed on porous and non-porous surfaces. The results revealed that the texture of the receiving surface and height of fall of blood drop influenced the size and shape of the bloodstains. The bloodstain was larger in size and with irregular morphology on porous surfaces due to diffusion of the blood into the surface by capillary action and rough surface. Satellite stains and spines were predominantly found on porous substrates due to the absorbent nature and surface irregularities. The bloodstains formed on non-porous surfaces were more circular with well-defined edges. The observations of the study were in compliance with the principles of bloodstain pattern analysis which show that the surface characteristics and drop height are important parameters in interpreting bloodstains. The present study can help forensic investigators in carrying out bloodstain pattern reconstruction with enhanced accuracy and provide reliable interpretations about the events involved in a violent crime.

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