Impact bloodstain pattern analysis is a critical part of BPA study in forensic science which is receiving increased attentions nowadays. Impact bloodstain patterns are important evidence that contributes to the reconstruction of crime scenes and solving puzzles related to violent crimes.

Many researchers have done great jobs in unraveling the relationships between bloodstain patterns and how it relates to criminal actions. However, most of the studies were conducted on hard surface materials, such as white cardboard, tile, wood, and steel. BPA studies conducted on textiles are not developed to the same level as on the hard surfaces. It is really important that investigators understand the difference between hard surfaces and fabric materials because the appearance of the bloodstain patterns may not be the same. BPA study based on textiles is more complex since there are many different textile materials and the appearance of the patterns are strongly influenced by fabric properties (absorbency, surface tension, yarn structure, fabric conformation, manufacturing methods, etc.).

This research investigated the appearances of impact bloodstain patterns on different knit fabrics and papers. The differences caused by different substrates’ nature were analyzed.

Porcine blood was used in this study. Three kinds of knit fabrics and filter paper were used as impact targets: 12Ne cotton yarns and 20Ne cotton yarns were converted into knit fabrics while knit fabric with 30Ne yarns were directly purchased. Bloodstains on the fabrics were compared to those on filter paper.
A modified rattrap device was used to produce the spatter. The updated rattrap was redesigned to improve the stability, repeatability, and operation safety. A filter paper and a half circle knit fabric were mounted together in different schemes and served as an impact target which was set 30cm away from the rattrap device. 0.2ml porcine blood was placed on the rattrap device for each impact experiment and for each scheme the experiment was repeated 5 times. The photos of the resulting samples were captured by Vervide DigiEye System with a Nikon D90 camera body and AF-S Nikkor 35mm f/2D lens. Then, the photos were analyzed by ImageJ software. A stereomicroscope was used to get detailed information of loop structure as well as size and shape of the patterns. Yarn and fabric structure were characterized and the viscosity, surface tension, and hematocrit value of the porcine blood were measured as well.

Analysis of the impact bloodstain patterns shows that the appearance of the pattern is various on different substrates. The patterns on filter paper are mainly circular while the patterns on knit fabrics are with a variety of shapes and is highly dependent on the local fiber orientation. There are more bloodstain patterns visible on filter paper compared to the patterns on knit fabrics. In addition, as the yarn size becomes smaller, the fabric becomes smoother with a texture approaching that of filter paper, hence the patterns are not hidden inside the loop structure and it’s harder for a blood droplet to go through a loop hole. The number and area of bloodstain patterns increase with the increasing yarn counts (decreasing yarn diameter).
Impact Bloodstain Patterns on Textiles

by

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Chair of Advisory Committee
DEDICATION

For all those I love and those who love me.

给所有我爱的和爱我的人。
BIOGRAPHY

Jiaying Wu was born and brought up in Quzhou in the Zhejiang Province, China. She received her bachelor degree in Light Chemistry Engineering from Zhejiang Sci-Tech University. In 2015, she attended North Carolina State University to pursue a Master of Science degree in Textile Chemistry.
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CHAPTER 1 INTRODUCTION

Bloodstain pattern analysis is an important field of forensic science. DNA analysis can give the profile of the criminal suspect, but it can’t answer the questions about how were the crimes committed. Systematic BPA studies started in 1895 in Poland, performed by Eduard Piotrowski in 1895 at the University of Vienna[1]. Thereafter more pioneering investigators were interested in this area and more researches have been done.

Most of the BPA studies were conducted using hard substrates such as cardboard, tile and steel. Only a limited number of the researchers focused on textile materials. Nevertheless, textile is commonly used for making clothes, curtains, and upholsters hence is one of the most common components present in the crime scene from which we could get a lot of information in answering questions.

However, bloodstain pattern analysis on textile is more difficult compared to hard surface materials, due to the complexity of fabric properties. There are plenty of different types of fabric material in use today, and each one has to be dealt with differently. Bloodstain patterns showed on fabric are with huge diversity, and is highly related to the absorbent, porous, surface nature, even the different manufacturing methods of the fabric. Some researchers tried to use textile materials to conduct bloodstain pattern analysis, but most of them focus on the passive bloodstains and very little of them paid attention to how the detailed fabric structures relate to the appearance of the bloodstain patterns.

Impact bloodstain patterns are one typical type of different bloodstain pattern categories and are frequently seen in the crime scene with violent actions. A physical beating with different objects or a gunshot typically cause this type of spatter and this kind of behavior is frequently involved in malefactions. Impact bloodstain pattern analysis gives a chance to unravel the
criminal process and contributes in crime scene reconstruction. Thus, considering the importance of impact bloodstain pattern analysis as well as the difficulties and particularity of textile materials involved in crime investigation, we are encouraged to combine these two factors together to get some general ideal about how impact bloodstain patterns will show on textiles.

This research pays attention to the differences of impact spatter bloodstain pattern presentation on knit fabrics and on paper substrates. A traditional rattrap device will be redesigned to produce impact spatter patterns. The rattrap device will be carefully designed and customized to improve the stability and repeatability. Three kinds of cotton single jersey knit fabrics with different yarn counts and filter paper will be used as target in this study.

We focus on if the modified device will help in impact bloodstain pattern analysis and the differences of the resulting impact bloodstain patterns observed on knit fabrics and on filter paper. By comparing the differences observed on knit fabrics with different yarn counts, we are trying to understand the relationships between the constructions of knit fabrics and the resulting impact bloodstain pattern appearances.

In this research, our objectives are:

- To improve current rat trap-based impact spatter device to improve reproducibility
- To evaluate the performance of the new impact spatter device
- To analyze resulting spatter on three jersey knit fabrics with different yarn sizes.
CHAPTER 2  LITERATURE REVIEW

2.1 Introduction to BPA

Bloodstain pattern analysis (BPA) plays an important role in forensic science, which intends to provide useful evidence through interpreting the size, shape, number, and distribution of bloodstains left in a crime scene. BPA has quite a rich history. The first methodical study in BPA area was introduced in 1895 by Dr. Eduard Piotrowski, an assistant at the institute for Forensic Medicine in Poland. He published the work titled “Concerning the origin, shape, Direction and Distribution of the Bloodstains Following Head Wounds Caused by Blows.” Piotrowski used live rabbit to mimic victims and battered them with different weapons, which included hammers, rocks, and hatchets, and to see how the bloodstains were changed with the change of hitting angles and positions[1]. In his paper, he stated his purpose of the research: “It is of the highest importance to the field of forensic evidence to give the fullest attention to bloodstains found at the scene of a crime because they can throw light on a murder and provide an explanation for the essential moments of the incident”[1]. He found that when the crime was conducted with beating, bloodstains often appear with the second blow, which means the condition for the appearance of bloodstains is the existence of a blood source[2].

But Piotrowski’s research didn’t draw a lot of attention until 1955, a key case revealed in the State of Ohio attracted the attention of the public. A doctor named Samuel Holmes Sheppard was convicted of bludgeoning his pregnant wife to death inside their bedroom. In the absence of definitive evidence, this case remained unsolved for a decade and underwent three juries. Sheppard himself denied any involvement in the murder and he was found guilty of second-degree murder by the first jury and not guilty by the next one. At that time when Sam was acquitted, he had already spent ten years in prison and it was twelve years apart from the
first trial. In 2000, the third jury was asked to consider awarding the Sheppard family damages for wrongful imprisonment[3]. During the trial and retrial, Paul Kirk, a forensic scientist from the University of California, Berkeley submitted an affidavit of his findings which showed the position of the assailant and the victim, which revealed that the attacker struck the victim with his left hand and probably used a flashlight as a weapon. While Sam Sheppard was right-handed[3]. Moreover, he reported finding some blood from neither Sam nor Marilyn, but from a third person in the crime scene which he believed had come from the murderer. This evidence proved important in giving back the justice to Dr. Sam Sheppard.

From then on, people began to realize that bloodstain analysis cannot be overlooked when dealing with crimes. Expert testimony on bloodstain interpretation was with higher acceptance in U.S. courts since then. And experts believed that bloodstain pattern analysis can be more mature and precise with the continuous development of science and technology.

This field was modernized and widely expanded afterwards by many scientists and investigators. A big step was taken by Herbert Leon MacDonell, who was a pioneering forensic scientist and did great work in this area. Dr. MacDonell and his associate Mrs. Lorraine Bialousz published the treatise “Flight Characteristics of Human Blood and Stain Patterns” in 1971 which was funded by National Institute of Law Enforcement and Criminal Justice[4]. In this treatise, factors that will influence pattern analysis were discussed, including the shape of the spot, target surface characteristics, effect of horizontal motion, impact angle considerations, etc[4]. His modern and systematic research about the basics of bloodstains evidence attracted more forensic scientists to give attention to the Bloodstain Pattern Analysis which was nearly a vacuum zone that was always neglected and lacking available literatures during that time.
In 1973, Dr. MacDonell founded the Bloodstain Evidence Institute and offered bloodstain pattern interpretation courses to the educators and investigators. This was the first large BPA educational program in the world. Over eighteen hundred students from forty-seven states and thirty foreign countries have attended the Bloodstain Institute[5].

Later in 1983, the International Association of Bloodstain Pattern Analysts(IABPA) was founded at the Hilton Hotel in Corning, NY by Herbert MacDonell and other attendees of the first Advanced Bloodstain Institute[6], which aimed to encourage and promote the science of bloodstain pattern analysis, standardize the scientific techniques, promote education, and encourage research in bloodstain pattern analysis[7]. Thereafter, more and more subjects in this discipline were established and were supported.

And in the following years, more and more books and treatises were published in this field. For example, Drs. DeForest, Gaensslen and Lee published the book “Forensic science, an Introduction to Criminalistics” in 1983 which contains chapters talking about bloodstains[8]. In 1993, Dr. William G. Eckert and Dr. Stuart H. James published the book “Interpretation of bloodstain evidence at crime scenes” and present techniques used in bloodstain collection and identification, as well as some bloodstain measurements[6]. Later in 1999, Dr. Stuart H. James published another book, the “Scientific and legal applications of bloodstain pattern interpretation”, which includes scientific, legal and ethical aspects of bloodstain pattern interpretation and how bloodstain evidence works in the court[9].

Bloodstain Pattern Analysis began to be known by more and more people in the 21th century. In 2002, the Scientific Working Group on Bloodstain Pattern Analysis (SWGSTAIN) was formed by the Federal bureau of Investigation(FBI) in Quantico, Virginia[10].
From then on, BPA became more modernized and standardized through the cooperation of all law enforcements, forensic labs and academia. In the meanwhile, bloodstain patterns became an effective method to reconstruct the crime scene and bloodstain evidence has been widely applied in the courts.

2.2 Blood Properties

2.2.1 Human Blood Composition

Blood is an essential fluid in the circulatory system of human and other vertebrates’ bodies, which delivers important substances such as nourishment, electrolytes, hormones, antibodies and oxygen to the cells and organs, and meanwhile transports metabolic wastes away from all parts of the body to form a transmission circulation[11]. In human body, red blood cells make up about 45 percent of blood, and the liquid portion of blood is plasma, makes up about 54 percent of blood, the remaining 1 percent of blood’s composition is made up of white blood cells and platelets[12]. Because of the complex composition, blood is one of the most difficult substances to understand, analyze, and artificial synthesize.

Plasma

Plasma is a straw-colored clear liquid, and is a non-Newtonian fluid. It contains proteins, fatty acids, glycerides and inorganic salts. The first three parameters will affect the viscosity and surface tension of blood[13]. Plasma plays a critical role in maintaining normal blood pressure, distribution of heat throughout the body and maintaining homeostasis[14].

Red Blood Cells

Red blood cells, also called erythrocytes, are produced in the kidney and bone marrow. The main function of the red blood cell and its hemoglobin is to carry oxygen from the lungs to
all the body tissues and to carry metabolite wastes back to the lungs, kidneys, and liver to be excreted[14]. Red blood cells are responsible for the non-Newtonian properties of unclotted blood[15].

**White Blood Cells**

White blood cells, also known as leukocytes, is an important component in human immunization system. It defends the body against infection and disease by ingesting foreign cells and self-cellular debris, by destroying infectious agents and cancer cells, or by producing antibodies[14]. White cells are present in small quantities and have little impact on physical properties[15].

**Platelet**

Platelets, also called thrombocytes are one of the most important factors which influence the blood coagulation process. They play an important role in the formation of a blood clot by aggregating to plug the damaged vessel and provide a surface on which fibrin fibers could stick together to form a web structure, in which the blood cells are trapped to make a firm and permanent clot[14].

**2.2.2 Human/Non-Human Blood**

For BPA scientists and investigators, using blood to simulate a crime process is very common. Because of the high risk of blood infection by HIV, Hepatitis B and C viruses, the experimental use of human blood is limited. In that case, artificial blood and animal blood are used as substitutes. Different animals’ blood profiles are different from that of human’s. Porcine blood is always applied as alternative used in forensic science because it has similar properties to human blood and with a lower infectivity. Studies showed that fresh porcine blood has similar
Haematocrit (Ht) or Packed Cell Volumes (PCVs) as human blood and the properties comparison was studied and published by Ma Raymond from Australia in 1996[15]. The comparison is shown below.

**Surface tension**

Blood, as a liquid, has a relatively strong cohesive molecular force which produces a surface tension and holds the blood together to form a drop or a pool of blood. Surface tension is defined as the force that pulls the surface molecules of a liquid toward its interior, decreasing the surface area and causing the liquid resist penetration[16]. In Dr. Raymond’s thesis[15], surface tension of the porcine blood and human blood was compared using falling drop method and sessile drop method and the results are showed in the table below. From the table, we know that the surface tension of blood could be different due to different test methods. Human blood has a lower surface tension than distilled water and porcine blood has a lower surface tension than human blood. The surface tension increases gradually with storage time.

<table>
<thead>
<tr>
<th></th>
<th>Surface Tension ($\times 10^{-2} \text{ N/m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drop weight</td>
</tr>
<tr>
<td>Distilled water</td>
<td>6.6-7.0</td>
</tr>
<tr>
<td>Human blood</td>
<td>6.1</td>
</tr>
<tr>
<td>Pig blood (fresh)</td>
<td>5.1</td>
</tr>
<tr>
<td>Pig blood (7 days)</td>
<td>5.6</td>
</tr>
<tr>
<td>Pig blood (14 days)</td>
<td>5.7</td>
</tr>
</tbody>
</table>
Viscosity

Blood is a Non-Newtonian fluid, where viscosity is dependent on shear rate. More specifically, it is a shear-thinning non-Newtonian fluid, which means its viscosity decreases with increasing shear rate[13]. Viscosity of blood is an important parameter in BPA study which will affect the spread of blood and the shape of stains generated. The general consensus is that the higher the viscosity the smaller the bloodstain[17]. Blood viscosity could be tested by viscometer in lab. Table 2 shows the viscosity comparison of fresh pig blood as well as after 8 days’ storage and after 14 days’ storage. Blood viscosity is dependent on temperature. It has a higher viscosity on 37°C compared to the one on 4°C. Published human blood viscosity is among 3.2-4.4[15].

<table>
<thead>
<tr>
<th>Age of blood</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4°C</td>
</tr>
<tr>
<td>Fresh pig blood</td>
<td>3.9-5.4</td>
</tr>
<tr>
<td>8 days old</td>
<td>4.9-6.3</td>
</tr>
<tr>
<td>2 weeks old</td>
<td>5.5-6.9</td>
</tr>
</tbody>
</table>

Haematocrit value

Viscosity and Haematocrit value are two critical factors which strongly influence other physical properties of blood. Haematocrit value is highly related to viscosity. In Dr. Kalbunde’s study, he found that an increase in red cell haematocrit leads to an increase in relative viscosity[18]. In Dr. Raymond’s thesis[15], Standard Australian method was applied to measure Haematocrit value, which a significant amount of porcine blood was put inside a tube and
centrifuged to split the blood cells and plasma. Haematocrit value could be calculated according to the relative volumes. The comparison of Haematocrit value of fresh, 1 week old, and 2 weeks old’s pig blood are listed in Table 3. The Haematocrit value of the fresh porcine blood is a little bit lower than the older one and becomes lager when the storage time goes up. Moreover, the Haemarocrit value of the porcine blood at 37°C is also larger than the one at 4°C. Published human blood Heamatocrit is range from 40.0-45.0[15].

<table>
<thead>
<tr>
<th>Age of blood</th>
<th>4°C</th>
<th>37°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh pig blood</td>
<td>40.5</td>
<td></td>
</tr>
<tr>
<td>1 week old</td>
<td>44.6</td>
<td>45.0</td>
</tr>
<tr>
<td>2 weeks old</td>
<td>47.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

2.3 Bloodstain patterns

Bloodstain patterns are one of the most critical types of evidence present in the crime scene if violence is involved in the process. Conducting bloodstain pattern analysis requires a broad combination of knowledge and skills. Because of the high complexity and variety of the blood evidence, the accuracy of the analysis is likewise dependent on the working experience of the experts. The main task of the bloodstain pattern analyst is to link the blood evidence to the activities which were responsible for generating them, hence will contribute to the crime scene reconstruction. One of the first steps in BPA is the classification of the bloodstain patterns found in crime scene.
2.3.1 Pattern Classification

Depending on how the blood patterns are formed, they can be classified into different types, which are passive stains, transfer stains, and blood spatters. It is hard but critical to identify the specific patterns related to the crime, which should also be done before doing any further research.

Passive stains include drops, flows and pools, and typically result from gravity acting on an injured body. Dripping blood, which fall from a bleeding wound or a bloodied object, is a typical kind of passive stain that is commonly seen in the crime scene. It has a relatively large footprint of 0.16 inches (4 millimeters) or more[19].

Transfer stains result from objects or secondary surface coming into contact with an object wet with blood. This kind of pattern could help investigators to determine what kinds of objects were involved in the crime, by recognizing a mirror image of the original surface or a portion of that surface[20].

Impact spatter pattern is the one of the most frequent bloodstain patterns encountered in crime scenes. Blood spatters are created when sufficient force applied is capable of overcoming the surface tension of the blood drops and blood spatters projecting through the air then hit a target. It could be produced by secondary mechanisms, impact mechanisms, or projection mechanisms[16]. The secondary mechanisms could produce satellite spatter[16]. Impact spatter is created when a force is applied to a liquid blood source like gunshot, beating or stabbing, and other power tools[16, 22]. Projection spatter is caused by arterial spurting, expirated spray or spatter cast-off an object[22]. All three mechanisms could produce similar spatters and it needs more efforts to distinguish the actual method how those patterns were produced.
Impact bloodstain patterns could also be divided into three categories according to different speed of the weapon that causes the blood flying. Low velocity impact spatter (LVIS) mainly are dripping blood and are assisted by gravity alone, droplets are about 0.16-0.31 inches[21, 23]. Medium velocity impact spatters (MVIS) are those spatters quicker than gravity dripping and slower than gunshot spatters, typically the velocity of the force is in the range of 5 to 25 ft/sec and the diameter of the resulting stains are among 1 to 3 mm[24]. High velocity impact spatters (HVIS) produced by gunshots or fast-moving machinery, which could achieve over 1000 meters per second, and the droplets are usually less than 1 millimeter in diameter[20, 23]. However, the definitions depend on the velocity are not absolute. One spatter pattern can contain more than hundreds of stains, a majority of these patterns lays in the definition range but some of them will be in the mutually exclusive zone[25]. Therefore, the velocity classifications could only be used as a reference information, not a scientific terminology.

From the size, shape, and the location of spatter stains, investigators could get information on the position of origin of the blood, the weapon used, the time when the crime happened, and more important information about the locations and actions of the participants[23].

2.3.2 Shape, Size, and Appearance of Patterns

The mechanisms for producing bloodstain patterns are so complex that various factors are involved in differing the size and shape of the stains. For passive bloodstains, for example, dripped bloodstain patterns, the stain size and shape are determined by the angle of impact, droplet volume, distance of fall, the surface characteristics, etc. And for impact bloodstains, the
appearance is affected by the volume of blood impacted, surface properties, impact angle, impact force, striking tools, etc.

Because a great variety of factors are involved in the determination, every bloodstain pattern is different, as there are no two identical leaves in the world.

The speed of the blood drop when it contacts the target is an important parameter that will influence the shape of the bloodstains. Different dynamic events, like impact, cast-off, arterial spurt, or blood dripping into blood, distribute blood drops at different velocities[20]. Generally, bloodstain patterns will become smaller with the increase of velocity.

The angle at which the blood drop encounters the target surface will influence the appearance of the stains as well. The direction of motion of a bloodstain can be determined through the edge characteristics of the stains. The tapered, elongated end of the stain points in the direction of travel[26]. If the angle of impact is 90°, a circular bloodstain pattern could be produced. If an impact angle is greater or less than 90°, the stain will be elliptical in shape, as showed in Figure 1[27]. The area of convergence or the area of origin can also be obtained through the directionality of several bloodstains in two dimensional area and three dimensional area respectively[23].
The appearance of a bloodstain pattern is diverse on different materials because of the dissimilarity of surface characteristics. In order to get spatters, an external force is needed to overcome the surface tension of the blood drops. One factor in breaking the surface tension of a blood drop is the physical nature of the target[17]. The wettability and roughness of the target play critical roles in changing the appearance of the bloodstain patterns[26]. Generally, a hard, smooth, nonporous surface, such as clean glass or smooth tile, will create less spatter, or pattern with smoother stain edge in contrast to a surface with a rough texture such as wood or concrete[17]. Some examples are showed in figure 2[27].

Figure 1: The shape of a bloodstain resulting from a single drop of blood falling onto cardboard at different angle [27].
2.3.3 Blood droplet flight

When blood source was impacted, it undergoes an atomization process and project through the air, hit the target and form spatter patterns. The trajectory of a blood droplet is determined by the forces acting on it. In the case of blood droplets flying through the air (without air convection), the only forces that need to be considered are gravity and aerodynamic drag[12]:

\[
F_g = mg \\
F_d = C_d A \frac{1}{2} \rho_{air} v^2
\]

Where \( m \) is the mass of droplet, \( g \) is the gravitational constant, \( C_d \) is the drag coefficient, \( A \) is the cross-sectional area of the droplet, \( \rho_{air} \) is the density of air, and \( v \) is the velocity of droplet. The direction of gravity is always downwards and the direction of aerodynamic force is opposite to the movements of the droplet[12]. These two forces work together to control the flight path of a single droplet if there’s no other factors of influence.
2.3.4 **Information from bloodstain evidence**

Bloodstain evidence is not able to serve alone to get a full understanding of how, when, and why a crime was committed. To gain the whole picture, BPA needs to be combined with other forensic approaches such as DNA, fingerprints, toxicology, entomology, and so on.

From a close analysis of BPA, some important clues could be revealed[27]:

1. Type of weapon used in conducting the crime.
2. Velocity of the blood.
3. Number of blows that occurred.
4. Position and movements of the victim and assailant during and after the attack.
5. Which wounds were inflicted first.
6. Type of injuries that occurred.
7. When the crime took place.
8. Whether death was immediate or delayed.

2.4 **Impact devices**

Impact bloodstain pattern analysis is an important portion of BPA and attracted attention of many scholars. Gunshot, beating, stabbing are three activities that produce the most commonly seen blood spatters in crime scene. Gunshots always produce high speed bloodstain patterns while beating and stabbing produces medium to high velocity patterns.

Impact spatter regarding beating occurs when a source of blood was beaten by an object. The bloodstains could be totally different depending on the categories of object used in beating. And the diversity also comes from different beating angle, different targets, different strike
forces, etc. Forensic scientists use different methods to mimic impact bloodstain patterns and try to analyze bloodstain evidence in a more scientific way.

2.4.1 Blunt or sharp objects

Various objects are found to be commonly used as weapons in different crimes where violence is involved. Those objects can be divided into three categories, which are blunt objects, sharp instruments and firearms. Blunt objects are the objects which can stretch, squeeze, tear and deshape human tissue, resulting in scratches, bruises, abrasions, laceration, fractures, and so on, which include hammer, dumbbell, billiard ball, water-pipe, corner of a table or brick, etc[28]. As shown in Figure 3. Sharp instruments are the objects having a sharp edge or end or their combination and may incise, penetrate or chop the tissues resulting in wounds, which include knife, razor, plait, piece of glass, tin sharp edge of stone or bone, etc[28], as shown in Figure 4.

![Figure 3: Blunt objects][28]
In forensic labs, scientists use different blunt or sharp instruments to produce impact spatter. Among all, hammers are the most often used blunt object to hit a blood source. Blood source used in this kind of experiments are pool of blood, sponge or other porous materials soaked with blood. Early in 1895, Piotrowski studied the relation between impact spatters and the area of origin by using hammer to impact a pool of blood to get the blood spatter distribution, and he also used the blade of a hatchet to hit either a rabbit head or blood-soaked cotton cloth[29]. Kettner, Schmidt, and their team used a hammer head that was dropped from a specific height to hit against a pool of blood and studied the relationship among the impact height, wall distance and the bloodstain circularity[30]. Laber, Epstein, and Taylor also used a hammer to impact on a stationary blood source and the progress was recorded through high speed camera,
from which they concluded that blood undergoes a considerable displacement from the point of impact, as shown in Figure 5 [31].

![Figure 5: Hammer striking a pool of blood on a hard surface][31]

### 2.4.2 Paddle fan device

Paddle fan device is mainly used for studying cast-off patterns. This device consists of a fan with paddle blades inside a box, as shown in Figures 6 and 7[19]. A hole in the top cover located over the leading edge of the fan blades allows blood to be dropped onto the fan, while an opening in front of the box lateral to the blades allows distribution of blood drops from the spinning fan[19]. Blood is impacted, breaks up into small drops and flies out from the front opening. The speed of the blades is controlled by the fan motor and can be linked to the distribution of the spatters.

![Figure 6: Paddle fan device][19]
MacDonell and Bialousz used a paddle fan workshop device to study the flying human blood and how it related to the resulting bloodstain patterns. They identified that the numerical values for drop distribution speeds may be seen as consistent for the paddle fan device[32]. The limitation of this device is also apparent. It can only be applied to the impact based on results from a castoff experiment[33]. It needs more adjustments if being used in the research of gunshots or beatings. Case off method cannot be used to identify impact dynamics.

2.4.3 Spring trap device

Mouse trap and rat trap are used in BPA study for a long time to produce impact spatter. Those traps give different levels of force through spring mechanism. Spring mechanism based device always make the so-called “medium velocity impact spatter”[33]. Different springs and traps will offer a different impact force so the resulting spatters are also various.
Mouse trap is light impact while rat trap could give a higher impact force. The construction of the spring trap device contains a base, a mouse or rat trap or spring, and top and bottom lip plates[19], as showed in Figure 8. A pin through an eye clip on the upper lip can hold the trap open while blood is placed on the base[19]. The spring between the base and the top plate offers an impact force while the pin is pulled out and the trap spring closes[19]. The blood source is put on the base and is hit by the top plate to make blood spatter.

James, Kish, and Sutton mimicked impact spatter patterns which were similar to that of beating and stabbing events by utilizing a rat trap device. A spring-loaded door hinge is placed between two wooden boards as depicted in figure 9, and the amount of the energy could be manipulated by releasing the upper board with different angles[22].

Figure 6: A variety of spring trap devices that break up blood drops into various sizes[19]
Cristopher Varney and Fred Gittes also utilized a spring based device to reproduce impact spatter patterns to study flight trajectory of blood droplets, which was made by joining two wooden boards at the rear with a spring-loaded door hinge but the impact site was made of metal instead of wood[34].

As mentioned above, a lot of the spring device used in forensic labs are made of wooden board, specifically the bread board, which has a handle to hold the trap in place. One problem with the wood-made device is the high absorption of the wood. Wood board can absorb blood and other fluids, hence it’s a challenge for device cleaning. Scientists are making effort to fix this problem as well.

One solution is to change the materials used in making the trap device. Anita Wonder created a modified mouse trap using fiber glass supports instead of wooden boards[35]. Bruin, Stoel and Limborgh produced their impact device by attaching a hammer to mouse trap’s spring instead of using a wooden board[36].
2.4.4 Gunshot simulation

To mimic gunshot spatter in forensic lab, usually scientists will use guns to shoot a bullet through a blood source. The blood source could be animal specimens or a blood-soaked sponge. The main differences between gunshot spatters and other spatters are the high impact velocity and the double sides travelling directions. Gunshots always produce fine spattered droplets which travel both in the direction of the bullet (forward spatter) and in the direction opposite to it (back spatter)[22].

Radford and Taylor conducted an shooting experiment using live pigs and slaughtered pigs and studied the back spatter and the physical mechanisms associated with it[37].

Sebastian et al. used a gunshot imitation experiment to analyze close range gunshots and mainly focused on back spatter on the firearm and shooting hand, the experimental setting is showed in figure 10[38]. Comiskey and his group conducted similar shooting experiments on a fabric-covered sponge soaked with blood and a silicone encased sponge to analyze the forward and backward spatter[39].
2.5 Knitted fabric

Bloodstains on textiles are some of the most important evidence that can be found in crime scene containing violence. Among all the fabrics, knits are of great importance because it is flexible, durable, and easily constructed into different sizes which made it widely used in making hats, socks, T-shirts, sweaters, etc. And those ingredients are often involved in the crimes. Knitting technology has improved a lot during the past two decades. The oldest real knitting is cotton socks found in Egypt date back to the year 1000 CE[40]. Similar to other inventions in the industry area, knitting was transferred from hand-knitting to machine-knitting. The typical antique knitting machine is called “stocking frame”, which was invented by William Lee of Calverton near Nottingham in 1589[41]. The circular knitting machine traditionally produces a tube of fabric and will be cut on one side to make flat fabrics.

2.5.1 Loop structure

Knitting is the most common method of interloping yarns. The structure is accomplished after a succeeding loop has been formed and intermeshed with the former one so that a secure ground loop structure is achieved, as showed in Figure 11[42]. The loops formed are held together by the yarns passing through. Knitted loops are formed by “courses” and “wales”, similar to the “weft” and “warp” of woven fabrics. A course yarn is horizontal to the needle loops and a wale is vertical of intermeshed needle loops.
A loop is the basic unit of knitting fabric. It consists of a head (H), two side legs (L), and two feet (F) at the base of each leg, as showed in Figure 12[42]. The foot of one loop goes through the head of the adjacent loop formed in the former cycle and the yarn passes from the foot of one loop into the foot and leg of the next loop.
The loop structures are highly dependent on the dimensional properties of knitted fabrics. Dimensional properties include loop length, wales and courses per unit length, stitch density, loop shape factor, take-up rate, and fabric width[43], which have great influence on physical properties of knitted fabrics.

2.5.2 Weft and warp knitting

Knitted fabrics can be classified into two kinds. One is the weft-knit fabrics and the other is warp-knit fabrics. The difference between these two kinds is the loops produced to a different direction of the fabric. Compared to the warp-knit fabrics, weft-knit fabrics are easier to make and are more common seen in the daily life.

In a weft-knit structure, a horizontal row of loops can be made using one yarn and the yarn runs in the horizontal direction. In a weft knitting machine, even when the needles are fixed or are caused to act collectively, yarn feeding and loop formation will occur at each needle in succession across the needle bed during the same knitting cycle, as depicted in Figure 13[42].
In a warp-knit structure, each loop in the horizontal direction is made from different yarn. In a warp knitting machine there is simultaneous yarn-feeding and loop-forming action occurring at every needle in the needle bar during the same knitting cycle, as depicted in Figure 14[42].

Figure 11: Weft knitting process[42]

Figure 12: Warp knitting process[42]
2.6 Wetting and wicking on fibrous materials

2.6.1 Fibrous materials

Fibrous materials can be described as a solid-phase material permeated by an interconnected network of voids filled with liquid or gas. The open pores form connected channels that the fluid can pass through. It’s like a bulk material composed of many single fibers. Hence the fibrous materials are diverse and the properties are highly dependent on the properties of the single fiber, the arrangement of fibers, pore sizes and amount, as well as the auxiliaries added during processing.

2.6.2 Wetting and wicking

When fibrous materials contact with water or other liquid, it undergoes wetting and wicking process. Wetting/wicking behaviors are mainly determined by surface tension and liquid/solid interfacial tensions. In addition, curvature and roughness of the contact surface will also affect the wetting behavior, especially for fibrous materials[44].

Wetting is the phenomena that the solid-air interface of the material is replaced by solid-liquid interface. The forces in equilibrium at a solid-liquid boundary are commonly described by Young’s equation[44]:

$$\gamma_{SV} - \gamma_{SL} - \gamma_{LV} \cos \theta = 0$$

Equation 3

Where $\gamma_{SV}$, $\gamma_{SL}$, and $\gamma_{LV}$ are the interfacial tensions between solid/vapor, solid/liquid and liquid/vapor, and $\theta$ is the contact angle in equilibrium.

Wicking is the result of fluid flow from the wetting of the fibrous materials through capillary forces. The surface tension of the liquid causes a pressure difference across the curved
liquid/vapor interface. The value for the pressure difference of a spherical surface was deduced by Young-Laplace equation[44]:

$$\Delta P = \gamma_{LV} \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \rightarrow \Delta P = \frac{2\gamma_{LV}}{R}, \text{where } R = \frac{r}{\cos \theta} \text{ Equation 4}$$

The radii of the curved interface $R_1$ and $R_2$ are equal for a capillary with a circular cross-section[44].

Textiles are multi-scale porous materials, and the pores are free space between the intertwined yarns as well as the free space between the fibers of each yarns[45]. Knitted or woven fabrics are made of yarns which are formed by a few to hundreds of fibers. The wetting and wicking process of textile materials are dependent on the pore distribution, surface properties, yarn characteristics (yarn diameter, yarn twist level, fiber density), the wetting direction, penetrating liquid, etc[46]. Therefore, wetting and wicking are more complex in textile materials compared to solid objects.

2.7 Summary

Bloodstain pattern analysis is a crucial part in forensic science and combines with a lot of different disciplines to solve the puzzle. Among all that, impact blood spatters are of great importance and received a lot of attention. The contact surface on which the blood spatters lies has a great influence on the appearance of the patterns. Scientists have already paid close attention to this aspect and did several researches. However, a lot of them were conducted on hard surfaces like cardboard, or some of the experiments were acted on different surfaces but only using dripping blood to analyze the differences. Apart from hard surfaces, fabrics like curtains, bed sheets, T-shirts are more commonly seen in the crime scene. Unlike hard surfaces, textiles are more various in properties thus the bloodstain pattern on textile materials need more
effort in analyzing. The analysis of impact bloodstain patterns on textile materials that result from stabbing or blunt force is important in solving violent crimes but the studies in this area are not adequate.
CHAPTER 3 MATERIALS AND METHODS

3.1 Fabric preparation

Three kinds of 100% cotton single jersey knit fabrics were used in this research since jersey knit fabrics are commonly used for clothing manufacture, and clothes such as T-shirts are one crucial component that could be found in a crime scene. Two kinds of yarns with different yarn counts were obtained from Cotton Incorporation, both of which are ring-spun cotton yarns with yarn count numbers of 12Ne and 20Ne. These two yarns were converted into single jersey knit fabrics in the knitting laboratory of the College of Textiles at North Carolina State University.

3.1.1 Scouring and bleaching

The jersey knit fabrics produced in knit lab contain knitting oil, size agents, and other auxiliaries used in knitting process to reduce friction and improve manufacturing efficiency and fabric quality. Those ingredients greatly influence the moisture absorption and wicking properties of the knit fabrics, which will alter the presentation of the blood spatters. In order to gain a hydrophilic fabric which is more suitable for daily use, scouring and bleaching process are needed to remove the hydrophobic additives from the fabrics and to make the fabric whiter and brighter, hence the spatters are more apparent on the fabrics.

The scouring and bleaching process was conducted in a Thies mini-soft fabric dyeing machine, as showed in Figure 15. Firstly, all kinds of fabrics were labeled with permanent ink and were sewn together. Then, one end of the fabric was tied with guider thread and was directed and went through the whole machine. The two ends of the fabrics were sewn together afterwards to form a loop so the fabrics are able to circulate inside the machine. The machine was then filled
with water and started to heat. A liquor ratio of 1:50 was applied. 3g/L Soda Ash, 3g/L BASF Primasol® N-SA surfactant, 2g/L hydrogen peroxide, and 1g/L defoamer were added into the machine in the process. After that, the temperature was raised to 220°F and kept for 30 minutes[49].

When the scouring and whitening process were finished, the fabrics were rinsed by cold water for three times to remove the chemical residuals on the fabrics. The excessive water was removed by BOCK centrifugal extractor and the fabric was then put in a dryer and dried for 30 minutes at the temperature of 155°F. After drying, fabrics were ironed and then folded for later use.

Figure 13: Thies mini-soft fabric drying machine
3.1.2 Fabric thickness

The thickness of the fabric is measured by AMES thickness tester, as showed in Figure 16. The tests were taken follow the discipline of the Table 1, test option 1 in the ASTM D1777-96 (Test Method for thickness of Textile Materials)[47]. According to the standard test method, ten values were taken for each kind of the jersey knit fabrics with different constructions. The load applied to the fabric was 8.6oz. Each sample was placed face up and flat on the bottom base. Then, the pressure foot was slowly released without adding extra pressure to the fabric. The final value showed in the screen, and was recorded after 5~6 seconds of equilibrium waiting.

![Figure 14: AMES Thickness Tester](image)

3.1.3 Basis weight

GSM is the metric measurement of the weight of a fabric in grams per square meter. Cotton fabric was cut by a J.A. King universal manual sample cutter (Model NO.SASD-688), as shown in Figure 17. Eight rounded fabric pieces were cut off from each. The total weight of the
eight samples were weighed by weighing scale and the basis weight was calculated. Ten groups were taken for each knit fabric and the calculated basis weights were averaged.

3.1.4 Twist level

The twist level of a yarn affects its diameter, hairiness, stretchiness, strength, and many other attributes. In the industry field it is always being described by TPI (Twists Per Inch) or TM(Twist Multiplier). TM value could be gained through the following equation:

\[
TPI = TM \times \sqrt{\text{Count}}
\]

Equation 5

The twist levels of the yarns were tested by twist-untwist method, based on ASTM D1422/D1422M-13[48]. The approximation of the true twist of spun single yarns could be determined through this test method. In each measurement, one single yarn was raveled from fabric and carefully mounted on the twist tester to prevent any change in twist. 25 specimens were taken randomly from each sample. First, the right end of the yarn was fixed in the rotatable

Figure 15: GSM testing method
clamp. The left non-rotatable clamp was removable, which allows the measure distance of the yarn to change. In this test, the distance was set to 10 inches. After mounting the right end, the yarn was pulled towards the non-rotatable clamp and was inserted into the temporarily opened clamp, until the pointer attached to the non-rotatable clamp reached the predetermined position for the required tension. Then, the clamp was closed to fasten the left end of the yarn. The extended part of the yarn was cut off to prevent the yarn from tangling into the rotatable clamp while it is rotating. Before turning on the tester, the revolution counter was set to zero position. Twist directions mode could be selected between “S” and “Z”, which refer to S twist and Z twist yarns for different kinds of yarns. In this test, for all the ring spun yarns the direction mode was set at “Z”. The metal block was put half inch behind the non-rotatable clamp to prevent the yarn break apart because of untwisting. After turning on the power, the right clamp begins to rotate and the yarn undergoes untwist. The yarn begins to elongate until the non-rotatable clamp’s movement was stopped by the metal block. The yarn was then retwisted in the opposite direction until it contracted to its original length. The number of revolutions was recorded and from what we could calculate the TPI of the yarn according to the following equation.

$$\text{TPI} = \frac{T}{2L}$$  \hspace{1cm} \text{Equation 6} \\

TPI is the twist per inch, T is the revolution number, L is the specimen length in equation 6.
3.1.5 Morphology

The morphology of different knit structures was analyzed through Nikon SMZ1000 Zoom Stereo Microscope, as shown in Figure 19. Power Supply XN and Halogen illuminator are connected to the system. The focusing procedure is automatically finished after command. Ten front images and ten back images were randomly taken from 12Ne, 20Ne, 30Ne knit fabrics respectively. Afterwards, the pictures were analyzed using Image J and the approximately yarn diameter and hole size of each knits could be measured.

Pictures were also taken after the blood impact experiments. Hence the appearance of the impact bloodstain patterns could be analyzed as well.
3.1.6 Sample preparation

Before experiments, all three kinds of knit fabrics were washed and dried following the direction of AATCC Monograph M7(Standard laboratory practice for home laundering fabrics) [49]. The washer was filled with water at $60\pm3^\circ C$, and the rinse temperature was set to $29\pm3^\circ C$. 1993 AATCC standard reference detergent WOB(without brightener) was used while washing. The washing mode was set to Normal or Cotton/Sturdy 12 min cycle. After the washing process, load was moved into the dryer and was dried for 45min under the temperature of $67\pm6^\circ C$. After laundering, the fabrics were ironed to remove unwanted wrinkles. Then, all the fabrics were put in the equilibrate room for 24 hours to allow conditioning to the lab environment. Before using, the fabrics were cut into semicircle pieces with a diameter of 7-8 inches.
3.2 Porcine blood preparation

Porcine blood was applied in this research due to the restrictions of human blood application. Porcine blood has similar properties to human blood thus is a suitable alternative for forensic analysis. Porcine blood used in this research was purchased from Lee BioSolutions Inc. It was kept refrigerated. Every time before use, the container was put on a Fisher Scientific Digital Bottle Roller and rolled for at least 60 minutes at 15 rpm until the plasma, blood cells, and other blood constituents mixed thoroughly without the destruction of red blood cells’ walls. Temperature of the porcine blood was also tested by electronic thermometer before each experiment. It’s ready to use when the blood temperature was close to the room temperature.

3.2.1 Surface tension

Surface tension of the blood was tested by pendent drop method. Liquid surface tension gained through this method by analyzing the shape of a drop when it is about to detach from a capillary tube. Surface tension is the interior force among liquid which makes those molecules tend to stick together to form compact drops. Meanwhile, gravity is forcing the drop to elongate in the perpendicular direction. Therefore, the shape of the drop is determined by the equilibrium of the surface tension and gravity[50]. The experimental set-up is showed in figure 20.
The drop was extruded from a syringe with a needle diameter of 1.6mm. The power was provided by a syringe pump and the speed of the syringe pump was selected to allow forming a drop steadily and slowly. A light source was set behind the syringe which provided a bright background for photographing. The whole process was recorded by USB microscope and was later processed by ImageJ software. To calculate the surface tension, “Pendent_Drop” plugin was installed in ImageJ. First, the video recording was converted to continued frame flows. The frame which shows the moment when drop is about to detach from the capillary tube was selected and was analyzed using the plugin. The picture was converted to 8 bit (Black and white image) version thereupon the boundary of the drop stood out which gives a more precise result. The rectangular selection tool was used to outline the range of the whole blood drop and avoid the edge of the needle being selected inside the zone. Then, “Pendent_Drop” plugin was applied, as showed in Figure 21.

Figure 18: Experimental setting for surface tension test
Tip radius of curvature, capillary length, tip x and y coordinate, and gravity angle are the parameters that could be changed to make the model perfectly fit into the actual drop shape. Surface tension of the blood drops were automatically calculated by the software based on the Young-Laplace equation. The same experiment was repeated six times and the results were averaged. For comparison, the surface tension of water was also tested.

3.2.2 Viscosity

Blood viscosity was tested by Brookfield DV-E Viscometer, as shown in Figure 22. Spindle SC4-18 was used in this test, which could offer a measurement of viscosity from 3cP to 10,000cP, and the shear rate(sec^{-1}) could be calculated by multiply 1.32N to the spindle speed (rev/min)[51]. First, the blood was transferred to a metal sample container by disposable pipette and the spindle was carefully inserted into the test material until the whole spindle was immersed.
up to the middle of the shaft indentation. Then, the shipping cap was removed and the spindle was attached to the viscometer by screwing it to the coupling nut. After the initial set up was finished, the SPEED/SPINDLE switch was set to right to and the spindle code was set to 18. Then, the same switch was set to left to change the speed. Then, the SELECT knob was rotated until the desired speed showed on the screen. After setting the speed, the SPEED/SPINDLE switch was switched to the middle position. Then, the motor switch was turned on, and allowed some time for the indicated reading to stabilize and the results were recorded afterwards.

Viscosity was directly shown in centipoise. For maximum accuracy, flashing readings below 10% were discarded.

![Brookfield DV-E Viscometer](image)

Figure 20: Brookfield DV-E Viscometer[53]
3.2.3 Hematocrit value

Hematocrit describes the percentage of the red cells in the total blood volume. The hematocrit value of the blood was test by centrifuge separation of the blood cells and the plasma. 5ml of porcine blood was added to a centrifuge tube and centrifuged for 5 minutes under 10,000rpm. After centrifuging, the blood fluid was delaminated into two layers. The red cells collected at the bottom which formed a dark red column and was separated from the upper straw-colored plasma layer. Then, the column of plasma was carefully separated from the lower layer using a disposable pipette and the volume was measured. Thus, the hematocrit value of the blood could be calculated through dividing the volume of the red cell column by the volume of the total volume, in this experiment is 5ml.

The centrifugal machine used in this experiment is a Fisher Scientific Marathon 26KM, as shown in Figure 23. The same experiment was repeated three times to get the average value.

![Figure 21: Fisher Scientific Marathon](image-url)
3.3 Experimental design

Different jersey knit fabrics combined with filter paper was used as targets in this research. Four schemes were applied for each kind of knit fabrics in this experiment. Left, right, upper or lower half of the filter paper was covered with half-round shaped knit fabric respectively, as shown in Figure 24.

![Figure 22: Target design (1) Upper half paper covered with fabric; (2) Lower half paper covered with fabric; (3) Left half paper covered with fabric; (4) Right half paper covered with fabric.](image)

The wale direction of the fabrics and the horizontal direction of the filter paper were marked with two-way arrow, as shown in Figure 24. The wale direction of the fabrics and the horizontal direction of the filter papers were fixed for each experiment.

0.2ml porcine blood was taken by transfer pipette and was placed on the designated spot on the rattrap. By closing the modified trap device, the blood was impacted to hit the target and form spatter patterns. For each setting scheme, the same experiment was repeated 5 times to avoid any occasionality. The differences of the presentations of the impact bloodstain spatters in-between different knit fabrics were analyzed.
3.4 Photography

Every sample was photographed and saved as NEF and JPEG version. In this research, we used Vervide DigiEye System (Non-contact digital colour measurement and imaging system) to take the photos. It consists of an enclosed light box with a camera setting atop fixed by a camera mounting stand and the camera is connected to a monitor, as shown in Figure 25.

![Figure 23: Vervide DigiEye System](image)

The light source is CIE D75 and the enclosure space could offer a calibrated lighting environment. The camera used in this research is Nikon D90 camera body with AF-S Nikkor 35mm f/2D lens. All the pictures were taken and saved through DigiCamControl Software.

3.5 Image processing

After photography, the high-resolution images were analyzed using ImageJ software. First, “Set Scale” command was used to correct length unit from pixels to millimeters. Then,
oval selection tool was used to select the circular target area, and area outside this zone was cleared using “Clear Outside” command. The signs marked on each sample to distinguish the top and the bottom of the sample were selected and filled with colors so it could be discarded by arranging the size threshold, as shown in Figure 26.

Four 10mm × 10mm rectangles were selected from each sample and duplicated, among which one were blank (without bloodstains) and the others were with bloodstains on it. To be comprehensive, the three stained samples were selected to represent different bloodstain intensive degrees, which were selected from the big sample on the area with lowest, middle, and highest density of bloodstains. The “Color Threshold” tool was used to change the RGB value of those selected small photos to map out the stained area. The same RGB threshold value was applied and adjusted to fit all the small samples at the same time. The threshold color was set to black and the color space were set to RGB. The blank control group should be totally same as the original picture after applying threshold, as shown in Figure 27.

Figure 24: Direction signs before and after modifying

Four 10mm × 10mm rectangles were selected from each sample and duplicated, among which one were blank (without bloodstains) and the others were with bloodstains on it. To be comprehensive, the three stained samples were selected to represent different bloodstain intensive degrees, which were selected from the big sample on the area with lowest, middle, and highest density of bloodstains. The “Color Threshold” tool was used to change the RGB value of those selected small photos to map out the stained area. The same RGB threshold value was applied and adjusted to fit all the small samples at the same time. The threshold color was set to black and the color space were set to RGB. The blank control group should be totally same as the original picture after applying threshold, as shown in Figure 27.
After one suitable threshold was gained, it was applied to all pictures. Then, used “Particle Analysis” plugin to get the quantitative analysis.

3.6 Disposal of materials

All the materials and implements contaminated with blood used in this research are required to undergo sterilization before being disposed. Hence, those materials were placed in an autoclave bag and the whole bag was put in a Tuttner Automatic Autoclave (3870E) and sterilized under high temperature and high-pressure environment. The bag was sealed with
autoclave indicator tape before being put inside the autoclave. The experimental wastes were discarded in the designated location after sterilization.
CHAPTER 4 MECHANICAL DESIGN OF IMPACT DEVICE

4.1 Device design

The new impact device was designed based on the traditional rat trap. Instead of using wood, the main parts of the device were made of two polypropylene boards to avoid blood absorption and to make it easier to clean up. The polypropylene boards and the small joint components were purchased from McMaster-Carr Supply Company. The springs were disassembled from a Victor Metal Pedal rat trap and modified to fit the new design of the impact device. The diameter of the metal bar passing through these two springs was big enough to hold the springs in place, therefore it won’t slide fore and aft under stress. Tails of the two metal rods extended from the springs were embedded in the upper board and was fixed by a small metal plate to avoid from jumping out. Hence, the left and right movement of the springs was prohibited, as showed in Figure 28. To ensure the whole device was set up horizontally, a bubble level was stuck to the surface of the lower board to check the horizontality each time before the shooting.
In order to better orient the blood flying direction, a triangular groove was cut on the lower board. The pool of blood was placed on the same location inside the groove and the position was marked with a cross, as shown in Figure 29. The upper board has a triangular embossment with same dimensions which could perfectly fit in the groove on the lower board.

![Figure 27: Triangular groove on the lower board](image)

The traditional rat trap has a trigger near the metal bar which is hard to control and is easy to get one’s finger jammed. For safety and easier operation, a metal-made latch was placed on the rear of the device. The tail of the latch was bent to hold the upper board just on the middle, therefore the upper board could be released horizontally, as showed in Figure 30. The height of the latch was designed a little bit larger than the length of the upper board. Therefore, when the latch was released, the right part of the upper board won’t be impeded by the horizontal metal bar.
Figure 28 Latch design

Figure 29: Laser modules
Two laser modules were mounted inside the lower board facing forward, as showed in Figure 31. Before each shoot, the laser modules were turned on so we can get the projective points on the target. The positions of laser modules were fixed and the relative distance between them and the groove could be measured, hence we can get the projection of the impact position on the target.

4.2 Device setup

A seven-inch diameter embroidery hoop was used to mount the fabrics and filter papers. The top, bottom and the circumference of the target were marked using blue ink so the impact area was fixed which made it easier for later analysis. Two plastic clips tied the embroidery hoop on the top and fixed it to an aluminum pole fixed on an iron stand, as shown in Figure 32. To ensure the embroidery hoop was mounted perpendicular to the ground, a plumb bob was attached to the end of the pole. And by comparing the perpendicular line and the side view of the embroidery hoop we can tell if it is set appropriately.
The modified impact device was placed on a lab jack to give enough height. When the upper board hit the lower one, the force will cause jumping and moving of the device. To prevent this situation from happening, a metal block with massive weight was attached to the device on the bottom. The metal block offered a heavy load which could help to hold the device in place. And the whole device was stuck to the jack through double sided tape. The battery case was placed near the device on the jack so it’s easier to operate. Two baffles made of transparent plastic sheet were put on a smaller jack in front of the device. Therefore, movements of the blood spatters were restricted in a particular zone and any drops beyond this area will be blocked by the baffles, as shown in Figure 33.

![Figure 31: Blood blocked by the baffles](image)

The experimental apparatus consisting of a lab jack on which the modified impact device was mounted. An iron stand holding the embroidery hoop was placed 30cm away from the impact device, as showed in Figure 34.
All the experimental components were put inside a lab glove box. The gloves were taken out and the two opening parts were covered with absorbent pads. Hence the experiments were conducted in a half-enclosed environment and all the impact blood spatters were confined in this space. Unlike other impact experiments, it’s more under control, easier to clean up, and less effort was needed to set up the device.

Figure 32: Experimental apparatus
CHAPTER 5  RESULTS AND DISCUSSION

5.1 Porcine blood characterizations

5.1.1 Blood surface tension

The surface tension of porcine blood was tested through the “Pendent Drop” method, as described in chapter 4. The surface tension of water was also tested to compare with the blood’s surface tension. The results are shown in Table 4. The surface tension of the porcine blood is slightly lower than the surface tension of water.

Table 4: D.I. water vs. porcine blood surface tension

<table>
<thead>
<tr>
<th></th>
<th>D.I. Water (mN/m)</th>
<th>Porcine Blood (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg.</td>
<td>71.78</td>
<td>64.20</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.38</td>
<td>1.3</td>
</tr>
<tr>
<td>count</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

5.1.2 Blood viscosity

Blood viscosity was tested by Brookfield DV-E Viscometer with spindle SC4-18.

Viscosity was tested every time before the experiment. Table 5 shows the viscosities of fresh porcine blood and the blood viscosity after seven-days’ storage. According to the operation standards, the results with range under 10% were discarded to ensure accuracy. As shown in Table 5, the viscosity of porcine blood was negatively correlated to spindle speed and shear rate. Hence, porcine blood is a non-Newtonian shear-thinning fluid as described in chapter 2. The viscosity of porcine blood mildly increased after storage.

Table 5: Viscosity of porcine blood
<table>
<thead>
<tr>
<th>Speed (RPM)</th>
<th>Shear rate (sec(^{-1}))</th>
<th>The day received</th>
<th>7 days old after received</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Viscosity (cP)</td>
<td>Range</td>
<td>Viscosity (cP)</td>
</tr>
<tr>
<td>100</td>
<td>132.0</td>
<td>11.13</td>
<td>37.1%</td>
</tr>
<tr>
<td>60</td>
<td>79.2</td>
<td>12.55</td>
<td>25.1%</td>
</tr>
<tr>
<td>50</td>
<td>66.0</td>
<td>13.20</td>
<td>22.0%</td>
</tr>
<tr>
<td>30</td>
<td>39.6</td>
<td>15.10</td>
<td>15.1%</td>
</tr>
<tr>
<td>20</td>
<td>26.4</td>
<td>17.10</td>
<td>11.4%</td>
</tr>
</tbody>
</table>

### 5.1.3 Hematocrit value

Hematocrit value of porcine blood was tested by centrifuge method, as described in chapter 4. After centrifuging, the blood was layered based on different density of the components. The red bottom layer was formed from red blood cell sedimentation and the upper layer was the plasma layer, as shown in Figure 35. The same experiments were repeated three times, the results are listed below in Table 6. The hematocrit values were obtained by the volume of sedimentation layer over the volume of the total blood.
5.2 Yarn and fabric characterizations

5.2.1 Yarn twist

Yarn twist was measured based on ASTM D1422/D1422M-13, the twist-untwist method, as described in previous chapter. Yarn samples were directly unraveled from fabrics. For each fabric, 25 measurements were made. The results are shown in Table 7. The yarns of 30 Ne knit fabric has the highest TPI among these three fabrics while the 12Ne yarn has the lowest TPI. However, the twist multipliers of the three fabrics are without significant difference.

Table 6: Hematocrit value

<table>
<thead>
<tr>
<th>Packed Cell Volume</th>
<th>Percentage</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.85</td>
<td>43%</td>
<td></td>
</tr>
<tr>
<td>2.70</td>
<td>46%</td>
<td>44.3%</td>
</tr>
<tr>
<td>2.80</td>
<td>44%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 33: 5ml porcine blood after centrifuge
Table 7: Yarn twist level for knit fabrics

<table>
<thead>
<tr>
<th></th>
<th>12Ne</th>
<th>20Ne</th>
<th>30Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPI</td>
<td>14.17 ± 0.34</td>
<td>17.31 ± 0.34</td>
<td>20.95 ± 0.84</td>
</tr>
<tr>
<td>TM</td>
<td>4.09 ± 0.10</td>
<td>3.87 ± 0.08</td>
<td>3.83 ± 0.15</td>
</tr>
</tbody>
</table>

5.2.2 Yarn diameter

For each kind of fabric, ten samples were taken and each sample was photographed through the stereo microscope. Yarn diameters were measured through ImageJ and the results were averaged, as shown in Table 8. The diameters of the yarn were measured on different positions on the loop, including the foot, head and side legs, as shown in Figure 36 and 37. As we can see from Table 8, the diameters of a single yarn are slightly various on different positions.

Figure 36: “Head” and “side legs” measured on the front of the knit fabric
Table 8: Yarn diameter on different locations of yarns

<table>
<thead>
<tr>
<th>Location</th>
<th>12Ne ± 0.048</th>
<th>20Ne ± 0.029</th>
<th>30Ne ± 0.027</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head (mm)</td>
<td>0.555</td>
<td>0.361</td>
<td>0.275</td>
</tr>
<tr>
<td>Leg (mm)</td>
<td>0.472 ± 0.036</td>
<td>0.316 ± 0.031</td>
<td>0.253 ± 0.022</td>
</tr>
<tr>
<td>Foot (mm)</td>
<td>0.444 ± 0.037</td>
<td>0.312 ± 0.017</td>
<td>0.267 ± 0.016</td>
</tr>
</tbody>
</table>

5.2.3 Fabric basis weight (g/m²)

The 12Ne jersey has a basis weight of 214g/m², and a thread count of 24.5cpi x 20wpi. The 20Ne jersey has a basis weight of 207g/m², and a thread count of 45.5cpi x 31.5wpi. The bleached cotton single jersey knit T-shirt fabric made of 30Ne ring-spun yarns was a commercial fabric directly purchased from Test Fabrics, Inc. (product code 437-60-Test Fabrics). It has a basis weight of 138g/m², and a thread count of 53.5cpi x 38wpi.

The thickness of the 12Ne, 20Ne, and 30Ne knitted fabrics are 1.038 ± 0.014 mm, 0.738 ± 0.006 mm, and 0.528 ± 0.010 mm respectively, or approximately twice the yarn diameter.
5.2.4 Fabric morphology

The morphology of the knit structure was analyzed using stereo microscope, as shown in Figure 38. From the pictures, we can see that all three knit fabrics are “Z” twist weft knit fabrics, and the yarns are more closely arranged in the 30Ne knit fabric compared to the 20Ne and 12Ne. The 12Ne knit fabric has the largest loop size compared to the others, while it has the highest hairiness as well. To measure the pore size, 5 positions on each kind of the knit fabric were randomly selected and photographed by stereo microscope. All pictures were analyzed using ImageJ. From each photo, 10 loops were selected and the pore sizes were calculated. The average pore size of the 12Ne, 20Ne, and 30Ne knit fabric were 0.048 mm$^2$, 0.015 mm$^2$, and 0.011 mm$^2$. 
Figure 38: Stereo microscope pictures of (a), (b) the front and back of 12Ne knit fabric, (c), (d) the front and back of 20Ne knit fabric, (e), (f) the front and back of 30Ne knit fabric
5.3 Impact blood spatter

5.3.1 Appearance of patterns

After the blood was impacted by the modified device and hit the target, the bloodstain patterns formed. Filter paper and knit fabrics are all fibrous materials, but the appearance of the patterns was different on different substrates, as shown in Figure 39. The patterns on knit fabric have different shapes which is highly influenced by the fiber arrangement. As shown in the Figure 39(a), The fibers embodied in filter paper are almost randomly arranged, hence the patterns on filter paper are more circular than on the fabrics.

Figure 39: A single impact bloodstain pattern on (a) filter paper, (b) a single yarn in 20Ne knit fabric, (c) a joint area of two yarns in 30Ne knit fabric. (b) a loop hole in 30Ne knit
Unlike the stain shown on the filter paper, the patterns on knit fabric are various. Blood wicks along the fibers packed in the yarns in the knit fabric, as shown in Figure 39(b-d).

Some droplets hit a single yarn and wicked along the fibers oriented as shown in Figure 39(b). Some droplets hit the joint between two yarns and the blood wicked through both directions along different yarns, as shown in Figure 39(c). The red jelly-like object is the leftover blood cells which cannot wick into the yarns. Some of the blood droplets directly hit the middle of a single loop and passed through the loop hole, as shown in Figure 39(d). The shape of the pattern might be influenced by the fabric hairiness. As we can see from Figure 38, 12Ne and 20Ne knit fabrics have higher hairiness which will have more influence on the pattern appearance. The hairs on the fabric surface might impede the blood droplets movements or incise the droplets into smaller sizes when the drop flight velocity is high enough.

5.3.2 Threshold selection

For each kind of knit fabric, five positions were randomly selected and photographed by stereo microscope. All pictures were analyzed using Image J. From each photo, 10 loops were selected and the pore sizes were calculated. The measured average hole sizes of 12Ne, 20Ne, and 30Ne are 0.048mm$^2$, 0.015mm$^2$, and 0.011mm$^2$.

The width of one pixel is 0.0833mm. Theoretically a pattern as small as 0.0833mm could be detected using our experimental setting. However, the special porous structure of knit fabric makes it harder to distinguish the area inside a single loop and a small bloodstain. To avoid the background influence, the smallest size of the pattern to be analyzed should be larger than the loop hole size. To be conservative, the results were obtained under the assumption that the length could be measured only to within ±3 pixels, which means only a pattern consists of 9 or more
pixels will be counted. That equals to an area of 0.0625mm$^2$. Assuming the bloodstains are perfect circles, the minimal diameter of the patterns that could be resolved is 0.282mm. The upper limit was set to 3mm$^2$, which is equal to a total area of 431 pixels, hence any big non-blood contaminates were avoided.

![Figure 40: Size transfer from pixels to bloodstain pattern](image)

**5.3.3 Numbers of patterns on fabric to paper ratio on one target**

We can see different apparent volumes of bloodstains on fabric and on filter paper. The ratios of number of bloodstain patterns on the fabric half to the one on filter paper in a single arrangement was calculated and listed in Table 9. Knit fabric substrates were labeled with square brackets, and filter paper substrates were labeled with round brackets. “U” indicates the upper part of the target, “D” indicates the lower part of the target, “L” indicates the left part of the target, and “R” indicates the right part of the target. For example, “[U] to (D)” represents the scheme that upper part upper part is covered with knit fabric and lower part is filter paper. The results are also illustrated in the histogram in Figure 41.
Table 9: Number of patterns on fabric to paper ratio

<table>
<thead>
<tr>
<th></th>
<th>12Ne</th>
<th>20Ne</th>
<th>30Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric[U] to Paper(D)</td>
<td>692 / 6148 =11%</td>
<td>1876 / 3584 =52%</td>
<td>3185 / 4038 =79%</td>
</tr>
<tr>
<td>Fabric[D] to Paper(U)</td>
<td>1256 / 7051 =18%</td>
<td>1378 / 5663 =24%</td>
<td>3593 / 4795 =75%</td>
</tr>
<tr>
<td>Fabric[L] to Paper(R)</td>
<td>1340 / 7717 =17%</td>
<td>1964 / 5873 =33%</td>
<td>6934 / 6725 =103%</td>
</tr>
<tr>
<td>Fabric[R] to Paper(L)</td>
<td>594 / 4986 =12%</td>
<td>2159 / 5474 =39%</td>
<td>5029 / 7644 =66%</td>
</tr>
</tbody>
</table>

Figure 41: The ratio of the number of patterns observed on fabric with 12Ne, 20Ne, and 30Ne yarns to the number of patterns observed on paper.
From the figure, we can obviously see that the bloodstain patterns are more abundant on filter paper, compared to the patterns on the knit fabrics in the same scheme. Besides, the fabric to paper ratios are different on different knit fabric structures. The fabric to paper ratio is among 11% to 18% for 12Ne knit fabric, 24% to 52% for 20Ne knit fabric, and 66% to 103% for 30Ne knit fabric. As the yarn size becomes smaller, the fabric becomes smoother with a texture approaching that of paper and hence the apparent number of drops approaches that of paper.

5.3.4 Total area of patterns on fabric to paper ratio

The ratios of the total area of bloodstain pattern on knit fabric to the one on filter paper in the same scheme were calculated and are listed in the Table 10.

<table>
<thead>
<tr>
<th></th>
<th>12Ne</th>
<th>20Ne</th>
<th>30Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric[U] to Paper(D)</td>
<td>61.7 / 915</td>
<td>179 / 444</td>
<td>339 / 509</td>
</tr>
<tr>
<td></td>
<td>=7%</td>
<td>=40%</td>
<td>=67%</td>
</tr>
<tr>
<td>Fabric[D] to Paper(U)</td>
<td>136 / 1027</td>
<td>143 / 761</td>
<td>455 / 633</td>
</tr>
<tr>
<td></td>
<td>=13%</td>
<td>=19%</td>
<td>=72%</td>
</tr>
<tr>
<td>Fabric[L] to Paper(R)</td>
<td>127 / 1111</td>
<td>194 / 729</td>
<td>1045 / 971</td>
</tr>
<tr>
<td></td>
<td>=11%</td>
<td>=27%</td>
<td>=108%</td>
</tr>
<tr>
<td>Fabric[R] to Paper(L)</td>
<td>57.3 / 683</td>
<td>221 / 740</td>
<td>614 / 1217</td>
</tr>
<tr>
<td></td>
<td>=8%</td>
<td>=30%</td>
<td>=50%</td>
</tr>
</tbody>
</table>
Figure 42: The ratio of the total area of patterns on fabric with 12Ne, 20Ne, and 30Ne yarns to the total area of patterns on paper.

The table shows the total area of the bloodstain patterns on knit fabrics are also different from the total area of bloodstain patterns on paper. And the results are also illustrated in the histogram in Figure 42. It shows a similar trend with the number of bloodstain patterns, the 30Ne knit fabric has the highest area fabric to paper ratio while the 12Ne knit fabric has the lowest. The fabric to paper ratio is among 7% to 13% for 12Ne knit fabric, 19% to 40% for 20Ne knit fabric, and 50% to 108% for 30Ne knit fabric.

### 5.3.5 Pattern amount reduction

From 5.3.3 and 5.3.4 we know that the number and total area of bloodstain patterns are reduced on knit fabric. By comparing the amount and area of patterns observed on knit fabric and on filter paper in different schemes but in the same position, we can calculate the number and area percentage reduction, as listed in Table 11. For example, “Fabric[U] to Paper(U)”
indicates the comparison between the upper half covered with knit fabric and the upper half is filter paper.

Table 11: Number and total area of patterns on fabric to paper ratios at same position

<table>
<thead>
<tr>
<th></th>
<th>Number of patterns</th>
<th>Total area of patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12Ne</td>
<td>20Ne</td>
</tr>
<tr>
<td>Fabric[U] to Paper(U)</td>
<td>0.10</td>
<td>0.33</td>
</tr>
<tr>
<td>Fabric[D] to Paper(D)</td>
<td>0.20</td>
<td>0.38</td>
</tr>
<tr>
<td>Fabric[L] to Paper(L)</td>
<td>0.27</td>
<td>0.36</td>
</tr>
<tr>
<td>Fabric[R] to Paper(R)</td>
<td>0.08</td>
<td>0.37</td>
</tr>
<tr>
<td>avg.</td>
<td>0.16</td>
<td>0.36</td>
</tr>
<tr>
<td>Percentage reduction</td>
<td>84%</td>
<td>64%</td>
</tr>
<tr>
<td>s.d.</td>
<td>9%</td>
<td>2%</td>
</tr>
</tbody>
</table>
Figure 43: The number and total area reduction of bloodstain patterns on knit fabrics with 12Ne yarns, 20Ne yarns, and 30Ne yarns.

The average number and area reduction are also shown in the Figure 43. The average number pattern reduction percentages are 84%, 64%, 22% for 12Ne, 20Ne, and 30Ne knit fabrics, and the average total area reduction percentages are 89%, 72%, 27% respectively. The number and area reduction is reduced with the increase of yarn fineness. Knit fabrics are more porous which gives blood drops higher probability to go through it. The surface of knit fabric is uneven hence the patterns are distorted as shown in Figure 39. Part of the pattern is inside the loop structure so that the area is decreased since the inner face of the loop cannot be captured by camera. As the yarn diameter becomes smaller, the fabric becomes smoother and the pattern area decreases as the pattern distortion is decreased. And the total area of patterns is also related to fabric hairiness. Some of the blood remains on the hairs and is too small to be recorded by
ImageJ, so the total volume of blood that hits the surface of knit fabrics is lower if yarn hairiness increases.

5.3.5 **Average size of Individual Stains on different fabrics and on paper**

The average sizes of individual stains on different substrates were calculated by dividing the total area to the number of bloodstain patterns. The results are listed in Table 12.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>12Ne knit</th>
<th>20Ne knit</th>
<th>30Ne knit</th>
<th>Filter paper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>avg.</strong></td>
<td>0.093</td>
<td>0.099</td>
<td>0.124</td>
<td>0.135</td>
</tr>
<tr>
<td><strong>s.d.</strong></td>
<td>0.007</td>
<td>0.007</td>
<td>0.012</td>
<td>0.014</td>
</tr>
</tbody>
</table>

**Table 12: Average size of individual stains on different substrates**

![Figure 44: The average sizes of individual stains on different substrates.](image-url)
As we can see from the Figure 44, the average size of individual stains on different substrates varies. The average size is larger on filter paper than on knit fabrics. The average size for filter paper ranges from $0.119\text{mm}^2$ to $0.158\text{mm}^2$. The average size for 12Ne knit fabric ranges from $0.088\text{mm}^2$ to $0.096\text{mm}^2$, for 20Ne knit fabric ranges from $0.094\text{mm}^2$ to $0.103\text{mm}^2$, and for 30Ne knit fabric ranges from $0.107\text{mm}^2$ to $0.147\text{mm}^2$. The average size of individual stains becomes larger with increasing yarn count, the 12Ne knit fabric has the smallest average size and the 30Ne knit fabric has the largest. The individual stain size is influenced by the absorbency and surface nature of the contact materials. Both filter paper and cotton knit fabrics have great hydrophilicity, but have different surface properties. As shown in Figure 45, bigger yarns create bigger hollows between loop structures so there is more space for the blood stains to hide from the surface. Besides, the fabrics made of bigger yarns are thicker, hence offering a longer wicking distance in the perpendicular direction and the bloodstain pattern appears smaller visually.

![Diagram showing blood droplets on different substrates](image)

Figure 45: The average sizes of bloodstain patterns on different substrates.
As blood droplets hit the hairs on the surface of knit fabrics, some blood left on the hairs but the volume is too small to influence the overall bloodstain pattern area, as showed in Figure 46. However, it is possible for some of the droplets being cut by the surface hairs and form smaller drops.

![Figure 46: Blood left on a single fiber](image)

### 5.3.6 Pattern area distribution

The distributions of the pattern area were gained within the range \([0.06\text{mm}^2, 0.70\text{mm}^2]\). The lower limit was set to 0.06\text{mm}^2 to avoid the background impact. There’s only a relatively small portion of the pattern when the pattern area is higher than 0.7\text{mm}^2. Hence the distribution of the pattern area won’t be influenced by discarding the patterns larger than 0.7\text{mm}^2.

A combined line graph is given in Figure 47, which shows the differences of the pattern size on knit fabric and on filter paper. Overall, the frequency decreases with the increasing pattern area. The lines indicate that in the designated range, a larger part of the patterns on the filter paper and 30Ne knit fabric have a size bigger than 0.06\text{mm}^2 and smaller than 0.44\text{mm}^2. While for 12Ne and 20Ne knit fabrics, a large portion of the patterns is among 0.06\text{mm}^2 to
0.22mm². There are almost no large patterns on the 12Ne and 20Ne knit fabric, while bigger patterns are shown on 30Ne knit fabric and on filter paper, which may be caused by the special surface nature and the hairiness of these two fabrics. The surface of 12Ne and 20Ne knit fabrics are more uneven compared to 30Ne knits and filter paper, which causes pattern distortion. The higher hairiness of 12Ne and 20Ne knit fabrics also cause distortion of the pattern since the blood droplets may be impeded or incised by the hairs.
Figure 47: The bloodstain area distribution on 12Ne, 20Ne, and 30Ne knit fabrics and on filter paper.
The pattern area distributions of 12Ne, 20Ne, 30Ne knit fabrics and filter paper were illustrated in Figure 48, Figure 49, and Figure 50 respectively. The line with crosses indicates the filter paper substrate and the line with dots indicates knit fabric substrate. The four target design schemes are shown in different colors. Blue line indicates upper half covered with fabric and lower half is filter paper. Red line indicates lower half covered with fabric and upper half is filter paper. Green line indicates left half covered with fabric and right half is filter paper. Yellow line indicates right half covered with fabric and left half is filter paper.

Figure 48: Bloodstain pattern area distribution on 12Ne knit fabric and on filter paper
Figure 49: Bloodstain pattern area distribution on 20Ne knit fabric and on filter paper

Figure 50: Bloodstain pattern area distribution on 30Ne knit fabric and on filter paper
As shown in the figures above, the number of patterns on 12Ne knit fabric is always lower than that on the filter paper. The 12Ne knits fabric lines are distinct from the filter paper lines. The pattern size distribution lines of 20 knit fabric and filter paper are closer to each other compared to 12Ne knit/filter paper, while there are still fewer patterns on knit fabric than on the filter paper. And for the 30Ne knit fabric and filter paper, the difference on the pattern size distribution as well as the number of patterns is much smaller. There is no obvious vacant area between the knit fabric lines and filter paper lines as shown in Figure 49 and Figure 50. Sometimes, the number of patterns on knit fabric could be higher than that on the filter paper.
CHAPTER 6 CONCLUSIONS

During this research, we designed a modified laser guide rat trap device which could be used in impact bloodstain pattern analysis. The whole device was made of polypropylene and metal. It is easy to clean and blood absorption is avoided. A triangular groove and baffles were added and are used to direct the flight of blood drops. The trigger was modified to increase the operation safety and reproducibility. Lasers give a projection on the target which shows the impact position, hence making it easier to mount the target at the same height every time.

Four schemes were applied in target arrangement. Upper, lower, left, or right half of a paper substrate was covered with a semi-circle of fabric and they were mounted together on an embroidery hoop. Filter paper, 12Ne cotton knit fabric, 20Ne cotton knit fabric, and 30Ne cotton knit fabric were used in this research. The impact distance was set to 30cm and the blood volume used in each shot was 0.2ml.

The bloodstain patterns are more abundant on filter paper compared to the patterns on the knit fabrics within a single scheme. The ratio of the number of bloodstain patterns on fabric to paper is 11-18% for 12Ne knit fabric, 24-52% for 20Ne knit fabric, and 66-103% for 30Ne knit fabric. The total area of bloodstain patterns on fabric to paper ratio is 7-13% for 12Ne knit fabric, 19-40% for 20Ne knit fabric, and 50-108% for 30Ne knit fabric. The average number and total area of patterns all decreased with the increasing yarn diameter. The average number pattern reduction percentages are 84%, 64%, 22% for 12Ne, 20Ne, and 30Ne knit fabrics, and the average total area reduction percentages are 89%, 72%, 27% respectively.

The average pattern size was calculated by dividing the total area by the number of bloodstain patterns on the same fabric and in the same position. The average pattern size becomes smaller with increasing yarn size (decreasing Ne). The average pattern size for 12Ne
knit fabric ranges from 0.088mm$^2$ to 0.096mm$^2$, for 20Ne knit fabric it ranges from 0.094mm$^2$ to 0.103mm$^2$, and for 30Ne knit fabric it ranges from 0.107mm$^2$ to 0.147mm$^2$.

The differences may come from the various surface structure, material absorbency, and material thickness. Filter paper and knit fabrics both have great absorbency. However, knit fabrics are made of yarn loops, hence they are more porous. Some blood drops with corresponding size with the loop holes could go through the loop structure. Because of the unevenness of the knit fabric compared to filter paper, the bloodstain pattern underwent distortion. Part of the pattern is inside the loop structure so that the observed area is decreased. The distortion becomes bigger with the increasing yarn size. Fabric hairiness will also influence the results. Hairs on the fabric surface may impede and change the flight trajectory of a blood droplet. Some of the blood remains on the hairs and is too small to be recorded by ImageJ, so the total volume of blood hit the surface of the knit fabrics is lower if the hairiness increases. And some bigger droplets can be incised by hairs to form smaller drops which also decrease the pattern size.
CHAPTER 7  SUGGESTED FUTURE WORK

1. To get further information of different impact mechanism, it is better to design a degree adjustable latch on the rat trap device so that the impact forces could be easily changed to mimic different impact forces.

2. Attach a suitable soft material to the impact site instead of hard and smooth wood or plastic surface. Soft material could mimic the skin and muscles of human body which will make the experimental design more realistic.

3. The results reproducibility will be better if the spring could be advanced to connect the two boards more tightly and firmly.

4. Other fabric materials can be studied to get more information. For example, different woven fabrics are always used to make bed sheets, curtains, upholsteries which are also frequently seen in the crime scene.

5. It needs further research to verify if the hairiness of the fabrics will impact the bloodstain pattern formation process and influence the size and shape of the resulted patterns. It may be useful in making a distinction between transfer patterns and impact patterns.
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Upper half with 12Ne knit fabric / lower half with filter paper combination
Lower half with 12Ne knit fabric / upper half with filter paper combination
12-D2 Patterns Area Distribution
- fabric
- paper

12-D3 Patterns Area Distribution
- fabric
- paper
Left half with 12Ne knit fabric / right half with filter paper combination
12-L3 Patterns Area Distribution

12-L4 Patterns Area Distribution
Right half with 12Ne knit fabric / left half with filter paper combination
Upper half with 20Ne knit fabric / lower half with filter paper combination
20-U3 Patterns Area Distribution

frequency

area (mm^2)

fabric paper

20-U4 Patterns Area Distribution

frequency

area (mm^2)

fabric paper
Lower half with 20Ne knit fabric / upper half with filter paper combination
Left half with 20Ne knit fabric / right half with filter paper combination
Right half with 20Ne knit fabric / left half with filter paper combination
Upper half with 30Ne knit fabric / lower half with filter paper combination
30-U3 Patterns Area Distribution

fabric  paper

area (mm²)

30-U4 Patterns Area Distribution

fabric  paper

area (mm²)
Lower half with 30Ne knit fabric / upper half with filter paper combination
30-D2 Patterns Area Distribution

fabric | paper

30-D3 Patterns Area Distribution

fabric | paper
30-D4 Patterns Area Distribution

30-D5 Patterns Area Distribution
Left half with 30Ne knit fabric / right half with filter paper combination
Right half with 30Ne knit fabric / left half with filter paper combination
30-R2 Patterns Area Distribution

- fabric
- paper

30-R3 Patterns Area Distribution

- fabric
- paper