HEDA, KOUSHIK NARENDRA. Analysis of Transfer Bloodstains on Textiles. (Under the direction of Dr. Stephen Michielsen.)

Bloodstain pattern analysis (BPA) is an important forensic method and has become an increasingly employed forensic discipline. Textiles are one of the most commonly encountered items at a crime scene and bloody textiles can offer extensive information about the nature, the location, the timeline or the participants in the crime. Most BPA studies have been performed on hard surfaces and only a limited number of peer-reviewed studies have been conducted on textiles. BPA on textiles is not straightforward because textiles are porous, permeable, absorbent and deformable and the liquid can move in any direction as there are no definite walls. A lot of these BPA studies on textiles focused on the interaction of blood, apparel fabrics, the yarn and the fabric constructions.

Studies have also been published on wipe and swipe bloodstain patterns formed on textiles from a non-textile like hammers, shoes, knives, etc. but none investigated transfer patterns from one fabric on another. This research focuses on the analysis and interpretation of transfer stains produced by one fabric on another using artificial and porcine blood. Two commercial cotton fabrics were used for this research, one was 130 epi and 70 ppi plain woven sheeting fabric, the other was a 52 cpi and 35.5 wpi single Jersey-knit t-shirt fabric. 30µL drops of porcine blood [PB] and artificial blood [AB] were placed from a height of 1-2 cm onto the receiving fabric swatch. After a specific interlude, the transfer fabric swatch was carefully maintained or held on the receiving fabric swatch with additional weights to apply external pressure. The weights were removed along with the transfer fabric swatch after a specific or controlled transfer time. The bloodstains developed on both the fabric swatches were investigated for total area of stain using ImageJ software.
The transfer stains so formed were dependent on:

1. The time between when blood was applied to the fabric to when a second fabric contacted it, defined as the wait time
2. Time allowed for transfer of blood from one fabric to another, defined as time for transfer
3. External pressure applied during transfer
4. Type of fabric [knit or woven]

Transfer stain patterns on knit fabric were significantly different from the transfer stains formed on woven fabrics. The transfer stains on knit fabrics looked like “finger prints”, whereas transfer stains on woven fabrics were more or less scattered. Although, transfer stains produced on knit fabric using AB and PB were similar and transfer stains produced on woven fabric using AB and PB were also similar.

For knits and wovens, the area of transfer stain decreased with the increased wait time and the area of transfer stain increased with the increased external pressure, for both AB and PB. For knits with AB, time for transfer affected the likelihood of transfer and with more time for transfer the total area of transfer stain increased. Time for transfer had no effect on the wovens using PB, but in case of AB the total area of transfer stain increased with more time for transfer.
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Analysis of Transfer Bloodstains on Textiles

by
Koushik Heda

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DEDICATION

I will dedicate this work to my parents Mr. Narendra Heda and Mrs. Indira Heda who encouraged me to achieve my goals. I would also like to thank my family and friends who were supportive at every stage.
BIOGRAPHY

Born and brought up in a family dealing with textile manufacturing for two generations now, it was but inherently obvious that Koushik would be lured by this field which though addresses the very bare needs of mankind, promises a spectrum of growth and evolution with the help of modern technology and advances. He received his undergraduate degree in Textile Plant Engineering from D.K.T.E.’s Textile and Engineering Institute and then joined North Carolina State University, NC to pursue a Master of Science degree in Textile Engineering in the Spring of 2015.
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# TABLE OF CONTENTS

LIST OF TABLES.............................................................................................................viii

LIST OF FIGURES.............................................................................................................ix

CHAPTER 1: INTRODUCTION..............................................................................................1

CHAPTER 2: LITERATURE REVIEW..................................................................................3

2.1 Introduction to Bloodstain Pattern Analysis...............................................................3

2.1.1 Historical Development.......................................................................................4

2.1.2 Former BPA studies on Textiles..........................................................................4

2.2 Wetting and wicking...................................................................................................5

2.3 Factors affecting wetting and wicking.......................................................................10

2.4 Transfer of sweat from one fabric to another..........................................................12

2.5 Spreading of liquids within the textile.....................................................................12

2.6 Transfer of liquid from hard surface to textile.........................................................13

2.7 Transfer of liquids between textiles.........................................................................13

2.8 Experimental designs used for analyzing transplanar/transfer wicking...............14

2.9 Bloodstains on fabric from contact.........................................................................19

2.10 What makes textile different from other surfaces.................................................19

2.11 Physical properties of blood..................................................................................20

2.11.1 Viscosity.............................................................................................................21

2.11.2 Surface Tension.................................................................................................22

2.11.3 Relative Density or Specific Gravity.................................................................22

2.12 Difference between water and blood....................................................................22

2.13 Fabric constructions...............................................................................................23
2.14 Asymmetry of the loop legs of Single Jersey knits ........................................ 28
2.15 Summary ................................................................................................. 32

CHAPTER 3: EXPERIMENTAL WORK ............................................................. 33
3.1 Materials ................................................................................................. 33
3.2 Fabric Preparation .................................................................................. 33
3.3 Artificial Blood Preparation ................................................................... 34
3.4 Porcine Blood ......................................................................................... 35
3.5 Viscosity Measurement .......................................................................... 35
3.6 Selecting the parameters ....................................................................... 37
   3.6.1 Quantifying the external pressure needed .......................................... 37
   3.6.2 Pressure value calculations ................................................................. 39
   3.6.3 Quantifying wait time and time for transfer ....................................... 40
3.7 Experimental setup for transfer stains .................................................... 41
3.8 Tip Calibration ....................................................................................... 42
3.9 Setting the equipment ........................................................................... 43
3.10 Experimental Design ........................................................................... 45
   3.10.1 Experimental Design I: Effect of wait time on transfer of stains ....... 46
   3.10.2 Experimental Design II: Effect of time for transfer on transfer of stains ......................................................................................... 46
   3.10.3 Experimental Design III: Effect of external pressure on transfer of stains ................................................................. 47

CHAPTER 4: DATA PROCESSING ................................................................. 48
4.1 ImageJ Analysis ....................................................................................... 48

CHAPTER 5: RESULTS AND DISCUSSIONS ........................................... 52
5.1 Viscosity measurement of blood ............................................................ 53
5.2 Analysis of data.................................................................................................................54

5.2.1 Part I: Analysis of Knit/Knit Fabrics – Artificial Blood.............................................54
   5.2.1.1 Effect of wait time.................................................................................................54
   5.2.1.2 Effect of time for transfer......................................................................................58
   5.2.1.3 Effect of external pressure.......................................................................................64

5.2.2 Part II: Analysis of Knit/Knit Fabrics – Porcine Blood...............................................66
   5.2.2.1 Effect of wait time.................................................................................................66
   5.2.2.2 Effect of time for transfer......................................................................................68
   5.2.2.3 Effect of external pressure.......................................................................................74

5.2.3 Part III: Analysis of Woven/Woven Fabrics – Artificial Blood.................................77
   5.2.3.1 Effect of wait time.................................................................................................77
   5.2.3.2 Effect of time for transfer......................................................................................78
   5.2.3.3 Effect of external pressure.......................................................................................80

5.2.4 Part IV: Analysis of Woven/Woven Fabrics – Porcine Blood.................................81
   5.2.4.1 Effect of wait time.................................................................................................81
   5.2.4.2 Effect of time for transfer......................................................................................82
   5.2.4.3 Effect of external pressure.......................................................................................83

5.3 Microscopic Image Analysis.............................................................................................91

CHAPTER 6: CONCLUSION.................................................................................................97

CHAPTER 7: SUGGESTED FUTURE WORK........................................................................99

REFERENCES..................................................................................................................100

APPENDICES....................................................................................................................108
LIST OF TABLES

Table 1: Arrangement of the equipment to achieve pressure………………………………..40
Table 2: Levels of wait time and time for transfer selected for the experiments…………….41
Table 3: Parameters selected for the experiment…………………………………………………46
Table 4: Terminology used in this research……………………………………………………52
Table 5: Porcine blood viscosity………………………………………………………………..53
Table 6: Artificial blood viscosity………………………………………………………………..54
Table 7: Parameters at which no transfer was observed……………………………………..57
Table 8: Average thickness of fabrics at respective external pressure…………………………87
Table 9: Fabric weight and area calculations…………………………………………………..88
Table 10: Fabric basis weight……………………………………………………………………88
Table 11: Fabric air porosity and fiber volume fraction calculations…………………………89
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Liquid spreading process through textiles</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Equilibrium state of a liquid drop on a solid surface</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Stages in capillary rise: (a) formation of meniscus; (b) rise to the equilibrium height</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Horizontal setting of fabrics [left]; vertical setting of fabrics [right]</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Experimental set up for in-plane and transplanar water transport</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>Experimental set up for in-plane and transplanar wicking</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>Relation between normal whole human blood viscosity to hematocrit</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Woven structure</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>Basic weave structures</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>Left: Weft knit structure; Right: Warp knit structure</td>
<td>26</td>
</tr>
<tr>
<td>11</td>
<td>Left: Single Jersey knit; Right: Double Jersey knit</td>
<td>26</td>
</tr>
<tr>
<td>12</td>
<td>Technical face side – knit stitch, cross section, technical back side – purl stitch [from left to right]</td>
<td>27</td>
</tr>
<tr>
<td>13</td>
<td>Actual fabric view – technical face side, technical back side [from left to right]</td>
<td>28</td>
</tr>
<tr>
<td>14</td>
<td>3-D unit of knitted loop</td>
<td>29</td>
</tr>
<tr>
<td>15</td>
<td>(a). Curling of edge along course line</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>(b). Curling of the edge along wale line</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>Twisting and detwisting of the loop arms</td>
<td>31</td>
</tr>
<tr>
<td>17</td>
<td>Brookfield LVDV-E115 Viscometer</td>
<td>36</td>
</tr>
<tr>
<td>18</td>
<td>Size of lower forearm</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 19: Tip calibration........................................................................................................42

Figure 20: Arrangement of the equipment...............................................................................43

Figure 21. Receiving fabric with polythene bag on plate point face side also, transfer fabric held in the embroidery hoop.........................................................44

Figure 22. Black colored L-shaped forensic calibration scale placed on a stained knit fabric......................................................................................................................48

Figure 23: Black arrow representing the wale direction for knit fabric, warp direction for woven fabric...........................................................................................................49

Figure 24: Cropped stained image of a transfer knit fabric using ImageJ for further analysis.......................................................................................................................49

Figure 25: Adjusting the color threshold to get a filtered image.............................................50

Figure 26: Filtered image to analyze particles to get circularity and total area of stain........51

Figure 27: Graphical representation of Area of transfer stains vs wait time on knit fabric – Time for transfer 30s.......................................................................................................55

Figure 28: Graphical representation of Area of transfer stains vs wait time on knit fabric – Time for transfer 40s.......................................................................................................56

Figure 29: Graphical representation of Area of Transfer Stains vs Wait time on knit fabric...............................................................................................................................58

Figure 30: Graphical representation of Area of Transfer Stains vs Wait time 5s on knit fabric.............................................................................................................................60

Figure 31: Graphical representation of Area of Transfer Stains vs Wait time 10s on knit fabric............................................................................................................................61
Figure 32: Graphical representation of Area of Transfer Stains vs Wait time 20s on knit fabric

Figure 33: Graphical representation of Area of Transfer Stains vs Wait time 30s on knit fabric

Figure 34: Graphical representation of Area of Transfer Stains vs Wait time 60s on knit fabric

Figure 35: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 30s

Figure 36: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 40s

Figure 37: Graphical representation of Area of transfer stains vs wait time on knit fabric – Transfer Swatch - Time for transfer 30s

Figure 38: Graphical representation of Area of transfer stains vs wait time on knit fabric – Transfer Swatch - Time for transfer 40s

Figure 39: Graphical representation of Area of transfer stains vs wait time on knit fabric – Transfer Swatch

Figure 40: Graphical representation of Area of transfer stains vs wait time 5s on knit fabric – Transfer Swatch

Figure 41: Graphical representation of Area of transfer stains vs wait time 10s on knit fabric – Transfer Swatch

Figure 42: Graphical representation of Area of transfer stains vs wait time 20s on knit fabric – Transfer Swatch
Figure 43: Graphical representation of Area of transfer stains vs wait time 30s on knit fabric – Transfer Swatch

Figure 44: Graphical representation of Area of transfer stains vs wait time 60s on knit fabric – Transfer Swatch

Figure 45: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 30s, Transfer Fabric Swatch

Figure 46: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 40s, Transfer Fabric Swatch

Figure 47: Graphical representation of Area of transfer stains vs wait time on woven fabric – Time for transfer 30s

Figure 48: Graphical representation of Area of transfer stains vs wait time on woven fabric – Time for transfer 40s

Figure 49: Graphical representation of Area of transfer stains vs wait time on woven fabric

Figure 50: Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s

Figure 51: Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 40s

Figure 52: Graphical representation of Area of transfer stains vs wait time on woven fabric – Time for transfer 30s, Transfer Fabric Swatch

Figure 53: Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s, Transfer Fabric Swatch

Figure 54: Left: Artificial Blood Transfer Stain, Right: Porcine Blood Transfer Stain
Figure 55: Left: Artificial Blood Transfer Stain, Right: Porcine Blood Transfer Stain

Figure 56: SEM image of plain woven fabric [left], SEM image of single jersey knit [right]

Figure 57: Raised wales in a Single Jersey Knit

Figure 58: Graph of fabric air porosity vs pressure

Figure 59: PB remains on plastic bag. Left: Knit Fabric; Right: Woven Fabric

Figure 60: PB absorption on knit receiving fabric swatch; Left: Face Side & Right: Back Side

Figure 61: PB absorption on knit transfer fabric swatch; Left: Face Side & Right: Back Side

Figure 62: Back side of the transfer fabric swatch – no PB absorption [Knit Transfer Fabric – Back Side]

Figure 63: Scattered and discontinuous absorption of PB on knit transfer fabric swatch

Figure 64: PB absorption on Knit transfer fabric swatch. Left: Entire loop covered with PB; Right: Right loop leg covered with PB

Figure 65: PB absorption on woven receiving fabric swatch; Left: Face Side & Right: Back Side

Figure 66: PB absorption on woven transfer fabric swatch; Left: Face Side & Right: Back Side
CHAPTER 1: INTRODUCTION

Blood stains are a common site in many crime scenes and in particular homicide cases. They offer extensive information and are an important part for reconstruction of a crime.  

Like any forensic discipline, BPA seeks to define the facts surrounding some incident that is in question. BPA has a nearly 150-year history that predates many modern forensic disciplines. Surviving documents of Sachsenspeigel and works from Shakespeare, reflect the consideration of bloodstains as a basic issue, though not a significant concern to the modern-day bloodstain pattern analyst. But more critical and insightful research was conducted over the last century. The first, most impressive, and systematic examinations of blood shapes and distribution were performed by Eduard Piotrowski in 1895 at the University of Vienna.  

Considering a more recent history, in 1970, Henry MacDonell [proclaimed as the father of modern bloodstain pattern analysis] and Lorraine Bialousz co-authored “Flight Characteristics and Stain Patterns of Human Blood”. Later in 1983, the International Association of Bloodstain Pattern Analysis [IABPA] was formed in order to promote general knowledge, techniques and in-depth understanding of bloodstain pattern.  

Most of the BPA studies published deals with hard, non-absorbent surfaces. Although textiles are present at most crime scenes, BPA studies on textiles has not been developed to the same extent as on non-porous materials. BPA on a smooth textile surface is not straightforward because textiles are complex materials (e.g. absorbent, porous, permeable) resulting in difficulties in understanding blood/fabric interactions. Limited studies have been conducted on bloody textiles. A lot of studies have been published on wipe and swipe bloodstain pattern formations on textiles from a non-textile [shoes, body, hammer heads, knives, clubs, tire irons and the like], but none investigated transfer of bloodstains
between two fabrics. Bloodstains originating from contact with an already bloody surface have rarely been investigated systematically since they are allegedly easy to recognize. Transfer stains from one fabric to another fabric play a vital role for giving evidence that could be used to corroborate or refute the person’s statement concerning their involvement during a criminal occurrence. It could give a lot of information about the timeline of the crime and whether or not the person was actually present at the time of crime or the concerned possibly reached later.

This study aims at intricate analysis/interpretation of transfer stains produced by one fabric on another at a crime scene. Specifically, two commercial cotton fabrics, a plain weave and a jersey knit, were used for this research. Transfer stains were studied between knit-knit and woven-woven fabrics for 30µL drops of porcine blood [PB] and artificial blood [AB]. The specific goals of this research are to determine the dependence of the transfer stains on:

1. The time between when blood was applied to the fabric to when a second fabric contacted it, defined as the wait time
2. Time allowed for transfer of blood from one fabric to another, defined as time for transfer
3. External pressure applied during transfer
4. Type of fabric
CHAPTER 2: LITERATURE REVIEW

2.1 Bloodstain Pattern Analysis

Introduction

Every Crime Scene has a unique story and a proper interpretation of evidence can reveal the truth behind it, eventually creating a true presentation of the preceding events. In addition to autopsies, basic crime scene work, and molecular biology; BPA is also an important forensic method. Bloodstain Pattern Analysis (BPA) is the examination of the shapes, and the categorization and distribution of bloodstain patterns in order to provide an interpretation of the physical events of a crime that gave rise to their origin. On examination by a qualified analyst the bloodstain patterns can give significant information about the events which led to their creation.

The information that can be obtained through careful BPA includes:

1. Area of origin of the bloodstains
2. Type and direction of impact
3. Mechanism by which spatter stains were produced
4. Understanding of how bloodstains were deposited onto the items
5. Nature of object(s) involved in creating the pattern
6. Possible position of victim, assailant, or objects at the scene after bloodshed
7. Additional criteria for estimation of postmortem interval
8. Correlation with other laboratory and pathology findings relevant to the investigation
9. Sequencing of multiple events associated with an accident

Such information can then be used for the reconstruction of an incident and the evaluation of witnesses statements and crime participants. Blood being normally present at crime scenes
and the weight it holds as a form of evidence within the legal system has led Bloodstain Pattern Analysis become an increasingly employed forensic discipline. 

2.1.1 Historical Development

Since the 1800s, Bloodstain Pattern Analysis (BPA) has been used in criminal investigations. In 1905, Schmidtmann discussed the possibilities of crime reconstruction with morphological analysis of blood stains. Further investigations were done by Ziehmke in 1914, about the distinctive morphological features of blood patterns depending on the height of the fall. Findings about reconstructing the angle of impact from the impact pattern by measuring the width and length of small blood stains were published by Balthazard and colleagues in 1939. In 1955, the noted criminalist, Dr. Paul Kirk successfully used bloodstain evidence in the case of the State of Ohio vs. Samuel Sheppard. Mueller and Schleyer (1975) did additional studies about expiration patterns. Later in 1983, MacDonell conducted advanced class for BPA and the participants organized the International Association of Bloodstain Pattern Analysis (IABPA) to promote the understanding of bloodstain pattern evidence. In 2002, the Federal Bureau of Investigation formed the Scientific Working Group for Bloodstain Pattern Analysis (SWGSTAIN) calling on expertise from police, laboratory, and independent consultants worldwide to explore and define functional guidelines for the discipline.

2.1.2 Former BPA studies on Textiles

BPA on textiles has not been exploited much. Textiles can retain various types of evidence that have been deposited onto them during the crime event. Textiles are one of the most commonly encountered items during the crime event. It is one of the indirect evidence that may reflect the nature, the location, the timeline or the participants in the crime. Textiles can retain importance evidence for years. Many cold case homicides from decades ago have been
solved by examining the stored extracts from the clothing. In 1939, Balthazard et al were the first ones to study bloodstain patterns on textiles and presented their study at the 22\textsuperscript{nd} Congress of Forensic Medicine in Paris, France. Limited studies have been conducted on bloody textiles. These studies were focused on drip stains, effect of drop volume, drop height, impact angle and backing surface on dripped bloodstain pattern on fabric, effect of fabric surface on dripped bloodstains and spatter stains and differentiating spatter and transfer stains. These studies lacked the information about the textile characteristics that impact the bloodstains. The fabrics used in their studies were purchased from a local store and the references did not include any information about the yarn count, yarn type, yarn manufacturing method and fabric construction. Hence, these studies did not take into consideration the effect of yarn type and fabric construction on the bloodstain pattern on textiles. More recent studies showed the impact of yarn type and fabric construction on the interaction of blood with textiles.

2.2 Wetting and wicking

Liquid spreading through textiles is a two-step sequential processes – wetting and capillary wicking/wicking as shown in the Figure 1.

![Figure 1: Liquid spreading process through textiles](image)

Wetting is the displacement of solid-air interface with a solid-liquid interface. The solid
interface in case of textile materials is represented by the fibers. Wetting includes four basic processes viz. immersion, capillary sorption, adhesion and spreading. Figure 2 shows the forces in equilibrium state of a liquid drop on a solid surface.

![Figure 2: Equilibrium state of a liquid drop on a solid surface](image)

The forces in equilibrium at a solid-liquid boundary can be described by the Young-Duprè equation:

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

Equation 1

where, $\gamma_{SV}$ is the interfacial tension between solid and vapor; $\gamma_{SL}$ is the interfacial tension between solid and liquid; $\gamma_{LV}$ is the interfacial tension between liquid and vapor; and $\theta$ is the contact angle between the liquid and the solid to be wetted at the vapor, liquid, solid interface.

Wicking is the spontaneous transport of a liquid into a porous system by capillary forces. Wetting is always followed by wicking. In other words, wicking is an outcome of wetting and there would be no wicking without wetting. According to Adler, wicking cannot begin until the moisture content is very high. Wicking in fabric could be from a finite or infinite reservoir. Wicking process from an infinite reservoir are immersion, transplanar.
wick and longitudinal wicking. Wicking from a limited reservoir is a drop placed onto the fabric. There are four types of wicking processes: 12

(1) Wicking of a liquid with no significant diffusion into fiber surface - capillary penetration.

(2) Wicking accompanied by diffusion of liquid in fibers. Here capillary penetration and diffusion process happen simultaneously.

(3) Wicking accompanied by adsorption on fibers. There are three processes happening simultaneously here: capillary penetration of the liquid, diffusion of surfactant in the liquid and adsorption of surfactant onto fibers.

(4) Wicking involving adsorption and diffusion into fibers. All the four processes occur simultaneously here: capillary penetration, diffusion of the surfactant into liquid, diffusion of the liquid into the fibers and adsorption of the surfactant on fibers.

The process of capillary penetration can be explained with the help of Figure 3. At equilibrium the pressure at the convex side of meniscus (point A) has to be lower than the pressure at the concave side (point B). Consequently, the pressure at point A is also lower than the pressure at point C. This pressure difference across the meniscus is the driving force for capillary penetration. The capillary flow stops when this pressure difference is balanced.
The mechanism of wicking can be visualized as the advancement of liquid in capillary occurring in small jumps assisted by stretching and contracting of the meniscus. The meniscus of the liquid is stretched by the advancing wetting line until it exceeds the elasticity of meniscus and inertia of flow rate. The meniscus then contracts, pulling more liquid into the capillary to restore the equilibrium state of the meniscus. The flow stops when meniscus reaches an edge and flattens. The wicking rate depends on the capillary dimensions of the substrate and the viscosity of the liquid.

This phenomenon of stretching and contracting of meniscus for liquid transport in capillaries is explained numerically by Laplace and Hsieh equation. For an ideal capillary, the capillary pressure ($P$) is the function of surface tension of liquid ($\gamma$), the contact angle ($\theta$) and radius of capillary ($r_i$) and the magnitude is given by Laplace equation (Equation 2).

$$P = \frac{2 \gamma \cos \theta}{r_i}$$

Equation 2

Liquid moves upward in a capillary due to a net positive driving force, which is possible if
the capillary pressure \( P \) is greater than the pressure of the liquid column inside the capillary. Pressure of the liquid column is given by Equation 3.

\[
P_L = \rho_L \times g \times h
\]\n
Equation 3

where, \( \rho_L \) is the density of liquid; \( g \) is the acceleration due to gravity; and \( h \) is height of the liquid in the capillary. Liquid in the capillary rises until the capillary pressure is greater than the liquid pressure. There is no further rise of liquid when both the pressures become equal and there is no net driving force. This state is the equilibrium state and the height of liquid column at this position is designated equilibrium liquid height \( (L_{eq}) \) and can be expressed by Hsieh Equation 4.

\[
L_{eq} = \frac{2 \times \gamma \times \cos \theta}{r_i \times g \times h}
\]\n
Equation 4

Wetting and wicking in textiles is a complex phenomenon. Kinematics of wicking in textile fabrics is more critical and is often explained by Lucas-Washburn equation. This equation is derived based on Poiseulle’s equation. This equation gives the relationship between time and the liquid rise in cylindrical capillaries with constant radius. When the penetration of liquid is horizontal, the effects of gravity are neglected, and when the height of the liquid rise \( L \) is much smaller than \( L_{eq} \), the Lucas-Washburn equation is:

\[
L^2 = \frac{\gamma \times r_i \times \cos \theta}{2 \times \eta} \times t
\]\n
Equation 5

where, \( \eta \) is viscosity of liquid; and \( t \) the wicking time. According to Equation 5, the plot of \( L \) vs \( t^{1/2} \) should be linear and pass through the origin. The slope of the line referred as the wicking coefficient \( W_c \), is given by Equation 6.

\[
W_c = \frac{\sqrt{\gamma \cos \theta}}{2 \eta}
\]\n
Equation 6

During phase I, when some of the liquid is on the fabric surface, the area of the spreading
liquid is proportional to the square root of time, given by Lucas-Washburn Equation 5. For two dimensional circular spreading in textiles during phase II, the area of the spreading liquid is given by Gillespie exponential Equation 7.

\[ A = K(\gamma/\eta)^u V^m t^n \]  

Equation 7

where, A is the area covered by the spreading liquid, K is capillary sorption coefficient, \( \gamma \) is the surface tension, \( \eta \) is the viscosity of the liquid, V is the volume of the liquid, t is the spreading time, and the exponents u, m and n are constants. The exponents depend on the nature of the liquids, the fiber and the drop volume. \(^{34}\) Equation 7 holds only when the fibers are impermeable to the spreading liquids.

2.3 Factors affecting wetting and wicking

Wetting and wicking characteristics vary from fiber to fiber because of their molecular structures and the degree of crystallinity. Presence of large amount of hydrophilic groups such as hydroxyl, carboxyl, amino and so on improves the wetting and wicking performance. A greater fraction of non-crystalline region also promotes wetting and wicking properties. \(^5\) Das et al. \(^{11}\) work indicated that a low contact angle between the fiber and the liquid, a lower surface tension between the solid and the liquid surface and increased surface roughness improved the wettability. Increasing the temperature of the liquid reduced its surface tension, resulting in higher wetting. And an increase in the liquid’s density, viscosity and surface tension of the material reduced wettability.

According to Kissa \(^{12}\) and Mhetre \(^{13}\) et al. the interaction of liquids and textiles depends on the wettability of fibers, their surface geometry, the capillary geometry of the fibrous assembly, the yarn construction, the fabric construction, pore size distribution, the amount and nature of the liquid, and external forces. Kissa’s work \(^{12}\) states that in a capillarity
system, the rate and direction of liquid flow is governed by the shape of the solid surfaces. The size and geometry of the capillary spaces between the fibers and the wicking rate is determined by shape of the fibers in an assembly. With an increase in the non-roundness of a fiber, the specific area increases, thus increasing the proportion of capillary wall that drags the liquid. The amount of liquid wicking through a channel is directly proportional to the pressure gradient. The capillary pressure increases with a decrease in surface tension between the solid-liquid interface and a lower capillary radius.

Yarns manufactured using different spinning methods also vary in wetting and wicking abilities. The manufacturing method determines the core and surface structure of the yarn. Open-end spun yarns wick faster and more evenly than ring spun yarns, while ring spun yarns wick faster than compact yarns. With the increasing packing coefficient of the yarn, the fibers come closer to each other introducing a greater number of capillaries with smaller diameter. With such small space the liquid flow is unlikely. Close packing reduces the capillary radius and hence the wicking coefficient. With an increase in the tortuosity of the pores, its wicking potential is reduced. The twist direction has no significant effect on the yarn’s wicking performance, but the yarn structure plays an important role. The presence of a wrapper filament retards wicking as the volume of liquid in the capillaries is reduced. Holbrook in his findings observed that increase in yarn roughness decreases the rate of water transport. Yarn count also plays an important role. Coarser yarns wick faster than finer ones.

Factors related to fabrics that affect the wetting and wicking performance include pore size distribution, fabric construction, fabric design, fabric thickness, fabric processing and other treatments.
2.4 Transfer of sweat from one fabric to another

For the period of exercise, the clothing layer(s) next to skin get wet through the accumulation of sweat on the epidermis. In textiles, moisture is transported both as water vapor and by way of direct uptake of excess liquid from the skin. Transplanar and in-plane wicking properties are fundamental contributors for a wearer’s tactile comfort. Pascale et al \textsuperscript{36} studied the effect of fiber count and knit structure on inter and intra yarn water transport. According to them, wicking in textiles is influenced by pores formed by the fibers(intra-yarn) and the yarns(inter-yarn), hydrophobicity and hygroscopy of the fiber. Moisture transport through textiles under momentary humid conditions is a predominant component which influences the dynamic relief of the wearer in daily use. Moisture may just transfer via textiles in vapor and/or in liquid form, as stated below:\textsuperscript{11}

- Diffusion of the water vapor through the layers. [diffusion through air spaces between the yarns and within the yarn]

- Absorption, transmission and desorption of the water vapor by the fibers.

- Adsorption and migration of the water vapor along the fiber surface.

- Transmission of water vapor by forced convection.

2.5 Spreading of liquids within the textile

Liquid transport in textile structures is regulated by liquid’s properties, liquid-solid surface interaction geometric configurations of the pore structures in the medium. Smaller pore sizes produce higher capillary pressure, promoting higher liquid advancement, but the mass of liquid stored in these pores is small. Smaller pores imply high driving forces for penetration and low penetration rates because the increased viscous resistance in small pores overcomes the increased driving force.\textsuperscript{64} Larger pores produce lower capillary pressures and store larger
liquid mass, but distance of liquid advancement is limited. The spreading of a liquid drop placed on a fabric is a two phase process:

phase I – when some of the liquid remains on the fabric surface and

phase II – when the liquid is completely contained within the fabric.

Figure 1 is a schematic illustration of the two phases in drop spreading of liquid on fabrics. At first, the drop spreads on the substrate and penetrates through and in the second phase, all of the liquid is contained within the substrate and spreads radially.

2.6 Transfer of liquid from hard surface to textile

Textile products like towels, wiping rags, etc. need to absorb liquid from a surface which could be human body, floor, machine, furniture, etc. This is an example of transfer of liquid from a hard surface to textile and deals with the sorption property of the fabric. Higher sorption capacity wiping cloths could be achieved, if the knit or woven density and fineness are as low as possible. The thickness and pore size should be as large as possible and the pile should be such that it has many inner spaces. For greatest sorption rate, density has to be as high as possible and fineness as low as possible.

2.7 Transfer of liquids between textiles

Pascale et al. studied the liquid transport between two-layer samples of the same fabric exposed to different pressure. When the liquid is placed on the knit fabric made of hydrophilic fibers, initially the smaller intra-yarn voids are filled, as capillary forces are larger within the yarns. In case for hydrophobic fibers, as the liquid has a higher contact angle with the solid medium, the liquid drop accumulates on the surface, and is pressed in the transplanar direction by means of larger inter-yarn loops into the upper layer, as the liquid spreads alongside the path of least resistance. And in case of quasi-hydrophobic fibers – the
liquid is pressed in the transplanar direction into the capillaries because of hydrophobicity. In this case larger void spaces are filled first as liquid spreads alongside the path of least resistance. A critical threshold concentration has to be reached before the upper layer gets wet. Mostly, intra-yarn transport is accountable for quickest in-plane water spreading [hydrophilic yarns], while inter-yarn transport is responsible for fastest layer-to-layer wicking [hydrophobic].

2.8 Experimental designs used for analyzing transplanar/transfer wicking

To date there is no standard test method available for measuring transfer wicking. In 1961, Minor et. al 38 studied three different types of penetration of fabrics by liquids viz. capillary penetration, pressure penetration and impact penetration. Pressure penetration relates closely to our research. According to Minor et al 38, if the liquid penetration is solely promoted by applying external mechanical force, it is defined as expulsion or pressure penetration.

A measured volume of liquid was applied to a test fabric and was allowed to lie undisturbed on a piece of mimeo paper for a certain time interval, called the ‘wicking time’. The mimeo paper was backed by a flat glass plate for support. At the end of wicking time a weighted sheet of glass of known area was placed over the wet spot and was allowed to remain for a certain time interval, called the ‘expelling time’. Pressure was exerted on the wet fabric by the addition of external weights on this glass plate. The fabric was removed and the paper was examined to see how much liquid was transferred. The expelling pressure used was 6.9 kPa [1lb/in²].

In 2002, Zhuang et al 31 investigated a study on liquid transfer from one fabric to another and liquid interaction between different fabrics in a clothing system. They used Spencer-Smiths approach to design the equipment for their experiment as shown in the Figure 4.
The samples were mounted horizontally and vertically as shown in the Figure 4. For horizontal setting, the external pressure was exerted by changing the amount of sand in the dish [74.5mm in diameter] placed on the top of the layers. For vertical setting, a spring system was used to exert pressure on the fabric. The two ends of the spring were connected to two different dishes. In this study the external pressures used were 45Pa [4.59 kg/m²], 90Pa [9.18 kg/m²], 135Pa [13.77 kg/m²], 180Pa [18.36 kg/m²] and 270Pa [27.54 kg/m²] simulating a person carrying a 55kg rucksack on his back.

Fabric samples were cut into circles with 74.5mm diameter. One of the fabrics [i.e. the source of liquid for transferring to another fabric] was soaked in distilled water and excess water was removed with a paper towel. The wet fabric was weighed before each test to determine the amount of water. The dry layer of fabric was placed on the wet layer, and liquid transfer was allowed for certain time. The amount of liquid transferred to initially dry layer of fabric was measured by weighing it.
Rossi et al. in 2011, analyzed the in-plane and transplanar water transport in different sock materials [polyamide, polypropylene and wool] subjected to external pressure using X-ray tomography as shown in the Figure 5.

![Figure 5: Experimental set up for in-plane and transplanar water transport](image)

X-ray tomography uses an X-ray beam to obtain a 3D structural image of the material. The samples were laid flat and wrinkle free into the holder and held in place by a piston. Variable pressure was applied to the piston by means of an adjustable screw. Liquid water was delivered at a constant rate at the center of the lower sample surface through the nozzle.
attached to the water reservoir. External pressure levels used were 0.4 and 81kPa corresponding to typical pressures exerted by the foot of a man.

Birrferler et al. \(^{36}\) in 2013, using the same X-ray technique investigated the effect of fabric structure and fiber count on wicking for different knit structures [hydrophobic and hydrophilic]. X-ray projection images were used. Experiments were conducted on two-layer samples of same fabric exposed to different external pressures to see liquid transport as distinct intra-yarn and inter-yarn in-plane and transplanar wicking fronts. Similar experimental set-up was used as Rossi et al and is shown in the Figure 6.

Figure 6: Experimental set up for in-plane and transplanar wicking \(^{36}\)
Two-layers of the same fabrics were stacked wrinkle-free over each other with the ‘skin’ side downwards in a cylindrical sample holder held by impermeable pistons. Variable pressure was applied to the piston by means of adjustable screw. Liquid water was delivered at a constant rate at the center of the lower sample surface through the nozzle attached to the water reservoir. X-rays were held parallel to the wales of the knits. External pressure levels used were 0.2, 2 and 5kPa corresponding to typical pressures found in worn clothing.

In all these experiments, it was found applying external pressure to the samples led to an early onset of transplanar wicking. Zhuang et al. and Rossi et al. found that with rising external pressure, the transplanar and in-plane water transport rose due to a greater number of contact points between two layers. Above a critical pressure, however, the water transport decreased due to lack of void space in the dry fabric. The inter- and intra-yarn wicking time differences also reduced with increased pressure. Above a critical pressure, the liquid accumulates on the surface. This may be caused by reduction of intra- and inter-yarn void space; such that in-plane wicking rate becomes slower than the rate of water supplied. But with thicker samples this is avoided because they offer more void space in transplanar direction.

Minor et al. work showed that pressure penetration of fabric by liquid is influenced by following factors:

a) Type of fabric
b) Type of liquid and drop size
c) Time between applying the liquid and placing the weights
d) Pressure applied

e) Time for which pressure is applied

f) The nature of the underlying surface on which the fabric rests

Wicking time and pressure are the major variables governing penetration. Increasing the wicking time results in smaller transfer of liquid. Increasing the pressure increases the degree of penetration, although the relationship is not linear.

2.9 Bloodstains on fabric from contact

Karger et al. in their work discussed formation of bloodstains from contact [static] and small (<1μL) droplets [dynamic]. According to them contact stains are of two types: direct contact stains and indirect contact stains. Direct contact stains are produced by an object touching a bloody surface and indirect contact stains are produced by a bloody object touching a surface. Both forms can be caused by local pressure or by moving an object along a surface. Static stains like transfer stains formed by aid of pressure leads to a deep infiltration of fabric and blood accumulates in the troughs and spreads wide, whereas dynamic stains like drip or spattered droplets lie superficially on the surface of the material. According to Karger et al., the dynamic characteristics seen in drip and spattered bloodstains can never be reproduced in transfer bloodstains. Hence, transfer stains can be easily distinguished from the spatter stains. However, the impregnation of blood also largely depends on the fabric mounting method and backing material.

2.10 What makes textile different from other surfaces

When bloodstains are found on hard, non-porous and non-absorbent surfaces, the point of origin of the blood drops and other relevant information can often be determined and used to reconstruct the crime scene. However, wicking in textiles is completely different compared to
other surfaces. For hard surfaces, the capillary wicking occurs due to solid walls and a fixed direction of movement of liquid. In case of textiles, the study becomes complicated because textiles are “open systems” and the liquid can move in any direction as there are no definite walls. 4 Often capillary penetrations are accompanied by diffusion of liquids into the fibers or into a finish on fibers, this changes the kinematics of wicking process. Sorption within the fibers causes the fiber to swell and decreases the interfiber space available for capillary penetration. 12 We can’t predict the exact wicking behavior of textiles because spacing between and within yarns is not constant, hence capillaries are not same. As, capillaries drive wicking, the wicking effect can’t be predicted. Also, wicking velocity is theoretically different for different capillary sizes, hence unequal liquid transport is observed because of differences in the inter- and intra-yarn capillary forces. 36 Textiles have non-uniform pore size distribution. And unlike hard surfaces, there are a variety of raw materials, manufacturing methods, fabric constructions and designs, chemical processing, etc. for textiles. All these factors affect the wicking ability. Hence, the wicking behavior of each fabric cannot be predicted from the classical wicking equation and has to determined individually. 37

2.11 Physical properties of blood

Blood is a pseudoplastic, non-Newtonian fluid i.e. it changes viscosity and that change in viscosity is not dependent on the rate of shear produced by layers flowing over each other. The viscosity of blood decreases with the increase in velocity gradient. 9 Blood consists of cellular components and plasma which circulate under pressure through the arterial and venous systems of the body. Three physical properties are especially important to the study of bloodstains:
21

1. Viscosity

2. Surface Tension

3. Relative density or specific gravity

2.11.1 Viscosity

Blood is approximately four times more viscous than water, although its specific gravity is only slightly higher than that of water. The membranes of the red blood cells, RBC’s, have high concentration of sialic acid, which produces a large electronegative charge on the surface of the RBC. This large negative charge gives blood its viscosity. Hematocrit value is the volume percentage of RBC’s in blood. The viscosity of blood increases with the hematocrit. The relationship between hematocrit and normal whole human blood viscosity is illustrated graphically in Figure 7. At all the shear rates studied the viscosity of normal whole human blood with a hematocrit 36% was approximately half the viscosity of normal whole human blood with a hematocrit 53%. With hematocrit value 44% the viscosity was half way between the upper and the lower curves.

Figure 7: Relation between normal whole human blood viscosity to hematocrit. [29]
2.11.2 Surface Tension

Surface tension is the elastic tendency of a fluid surface which makes it acquire the least surface area possible. Adhesion, cohesion and capillarity are important terms related to surface tension. Adhesion is the attractive force between unlike molecules and cohesion is the attractive force between like molecules. Capillarity or capillary action is the phenomenon in which surface tension causes a liquid to be drawn up into a container in a manner as to be opposing gravity. Blood, or any other liquid, is drawn into a porous material by this action.

2.11.3 Relative Density or Specific Gravity

Relative density is the comparison of the ratio of density of any given substance to the density of water. The density of water is 1g/cm$^3$. Relative density is a unit-less quantity. Due to the complex content, properties and functioning of human blood, a perfect substitute has not been found for forensic use. A lot of times outdated units of human blood supplied by the blood banks are used. But there could be potential sources of infection associated with it. Use of animal blood is an acceptable alternative to human blood. Many authors and bloodstain analysts have used bovine, canine, equine blood.

2.12 Difference between water and blood

Water is a Newtonian fluid and for a Newtonian fluid the viscous stresses arising from its flow, at every point, are linearly proportional to local strain rate. In other words, the coefficient of viscosity in Newtonian fluids, is constant at all shear values. In contrast, non-Newtonian fluids do not maintain constant viscosity under shearing forces. Blood behaves like a Newtonian fluid when it flows in larger diameter arteries at higher shear rates and it exhibits non-Newtonian characteristics when it flows through narrow diameter arteries at low
shear rates. At very slow shear rates, blood cells tend to aggregate increasing the viscosity. As the shear rate increases, these aggregates break apart and the blood viscosity reduces. 

As the flow rate increases the RBCs become increasingly deformed, decreasing the apparent viscosity of blood, which enables large cells to enter very small capillaries. Water is a single phase liquid flow with no additional components, but blood has both single and two phase fluid flow. \[32, 62\] When a second component is added to a single liquid phase, the second component may get absorbed changing the interfacial energies and hence the capillary driving forces. \[32\]

2.13 Fabric constructions

Weaving and knitting are the two major manufacturing techniques used to produce woven and knitted fabrics respectively. Weaving is the process in which fabrics are produced by interlacing warps[ends] and weft[fills/picks]. Warp yarns run the length of the fabric (usually drawn vertically) and weft yarns run across the width of the fabric (drawn horizontal) as manufactured (see Figure 8.)
Plain, twill (also called drill) and satin are the most popularly used woven structures as shown in Figure 9. Shirts and bed sheets are usually plain woven, while denims, trousers, and jackets are often twills/drills. Satins are used in making upholstery and lingerie. Plain woven structures are balanced weave i.e. the ratio of the number of warp yarns to weft yarns is 1:1. There is no difference between the technical face and the technical back side of a plain woven fabric.
Knitting is the process of producing fabric by forming a continuous length of yarn into columns of vertically intermeshed loops. A horizontal row of loops is called a course and a vertical column of loops is called a wale. Two basic methods of constructing knits are weft [or fill] knitting and warp knitting as shown in Figure 10. Weft knitting is the most common type of knitting; it is the process of making fabric by forming a series of connected loops in a horizontal or fill direction while warp knitting is the process of making a fabric by forming yarn loops in vertical direction.

Figure 9: Basic weave structures[^45]
Single Jersey and Double Jersey are the most commonly used weft knit structures as shown in Figure 11. T-shirts are normally single jersey knits and collars, cuffs, and undergarments are usually made from double jersey knits. There are endless design possibilities in warp knit structures and most find applications in technical textiles.
For a single jersey knit, the side of the fabric that contains all the face loops or weft knit loops is the technical face side and the side of the fabric that contains all the back loops or purl loops is the technical back side. For a single jersey knit the technical face and technical back side of the fabric are different as shown in the Figure 12 and 13.

Figure 12: Technical face side – knit stitch, cross section, technical back side – purl stitch [from left to right] \[^{[48]}\]
Generally woven structures have better dimensional stability and lower elasticity than knits. The air permeability for wovens is low due to compact construction. The wicking ability of wovens and knits thus vary because of such structural differences.

2.14 Asymmetry of the loop legs of Single Jersey knits

Fabrics knitted from natural fibers have a serious issue of dimensional stability. During the process of conversion of cotton fibers into yarns, the fibers are subjected to many stresses at every stage of spinning process. The fibers held in the lap, sliver or roving are loose and slowly release all the stresses imposed on them. But fibers in the yarn are closely packed and are not allowed to move freely to release the torsional stresses imposed on them. So, spun yarns are twist lively i.e. the fibers try to come back to their original unstressed state. During the process of knitting, yarns are subjected to tensile, compressive, bending and torsional strains. Hence, the knitted fabric made of loops is in highly strained state. These loops tend to keep changing their shape to reach the minimum energy level because of the elastic component of strain energy.
In a single jersey knit structure, the yarn is bent in the plane of fabric and in the plane at right angles to the fabric. The loop exhibits a pronounced 3-D configuration and can be projected on XY, YZ, and XZ planes as shown in the Figure 14. As discussed above, the yarn tries to regain its original shape i.e. straight. Mechanical couples are generated that tend to straighten the bent form of the projected contours.

These couples act on all the planes. The couple on XY plane tends to rotate the loop around its base and raise its crown above the fabric.

The couple on XZ plane tends to undo the convex curvature of the crown resulting in curling of fabric along the courses as shown in the Figure 15 (a).
Similarly, the couple on YZ plane results in fabric curling along the wale lines as shown in the Figure 15 (b).
Two couples acting on the two interlacement zones at the base of a symmetrical half-loop is shown in the Figure 16. First one is represented by the pair of opposite forces acting on the two end points of line segments AB and CD accountable for the 3D shape of the loops which lead to curling of fabric edges. Second one consists of couples acting at points A, B, C and D. These couples act in such a way that the line AB acts as a S-twisting couple while line CD acts as a Z-twisting couple.

Figure 16. Twisting and detwisting of the loop arms

As a result, left arm of the loop is subjected to an S-twist while right arm is subjected to a Z-twist. If a Z-twisted yarn is used, the left arm will be untwisted and right arm would be over twisted. These are the reasons why we see right loop legs raised compared to left loop legs in a single jersey knit.
Summary:

The research on interaction of blood with apparel fabrics is at an infant stage compared to the study of liquids (water, dyes, etc.) with apparel fabrics. A lot of research has been well documented and investigated in fields of wetting and wicking of yarns and fabric with those liquids. But only rare studies have focused on investigating the interaction of blood with yarns and fabrics. Blood – a non-Newtonian fluid having additional components behaves different than water. BPA on textile surfaces is complicated because of their absorbent nature and complex structure. Factors such as fabric construction, yarn structure, the backing material, blood drop size, external pressure, time for which pressure is applied and the time between applying the liquid and placing the weights can affect transfer of blood from one fabric on another.
CHAPTER 3: EXPERIMENTAL WORK

3.1 Materials

100% cotton plain woven fabrics and single jersey knits were used for this research as they are typical of bloody textiles at crime scenes. These commercial fabrics were ordered from Test Fabrics, Inc. One was optical brightened plain-woven percale sheeting fabric (product code 439XW) that resembles bed sheets. The fabric had the basis weight of 120g/m², width 110 inches and a fabric count of 130epi x 70ppi. Another fabric was bleached cotton Jersey knit T-shirt fabric (product code 437-60). It had basis weight of 124g/m², width 60 inches and a thread count of 52cpi x 35.5wpi. The yarn used for single jersey knit was 30/1 combed, ring spun cotton and was knit on 28 cut jersey stitch machine.

3.2 Fabric Preparation

Fabric preparation is an important step to make sure all the samples used in the experiments are consistent in use. It is important to remove all the finishing treatments, surface dirt, oil and other contaminants from the fabric because this would affect the wetting and wicking ability. Thus, the fabrics were washed thoroughly before running the experiments. Standard laboratory practice for home laundering fabrics by AATCC Monograph M7 was used to launder both fabrics. 49 The washer was filled with water at 60 ± 3°C and the washing machine was set for lukewarm rinse of 29 ± 3°C. 66 ± 1gram of 1993 AATCC Standard Reference Detergent was added. Ballast fabric was added to maintain a load of 2.7 ± 0.06kg. The washer was set for a Normal or Cotton/Sturdy 12-minute cycle. After washing the fabrics were placed in a home type dryer. The dryer was set at High setting [67 ± 6°C] for 45-
minute cycle. After washing and drying, 400 circular samples of diameter 8’’ and 4’’ each were cut and stored in a plastic bag. Samples were cut circular to avoid the curling of fabrics at the edges. Single jersey knits curl at the free edges on flat surface due to unbalanced yarn bending moment existing in the three dimensional nature of the structure. All the fabric swatches were ironed to remove creases and wrinkles, and were conditioned for 24 hours in the laboratory at 21°C and 65 ± 5% Rh.

3.3 Artificial Blood Preparation

In experiments to measure the wicking effect in yarns and fabrics, the liquid plays a very important role. Hence, it was necessary to make Artificial Blood that would closely mimic human blood in viscosity and surface tension. The viscosity of human blood at 37°C is normally 3-4 cP. Porcine blood also resembles human blood closely and hence is expected to behave the same way human blood would at a crime scene. Artificial Blood was prepared using Jingyao Li’s recipe which was based on ASTM standard F1819-07, but was slightly modified to get a more appropriate viscosity and surface tension. Acrysol 8306 was diluted by adding 1g of Acrysol 8306 into 40ml distilled water. The solution was stirred using a magnetic stirrer for about an hour until the solution was homogeneous. A red dye solution was made by adding 0.1 g Direct Red 81 into 20ml distilled water. The Acrysol solution, the red dye solution and the distilled water were mixed in the ratio that gives a viscosity and surface tension close to that of human blood. Viscosity and surface tension of the Artificial Blood was measured each time before starting the experiment to make sure the viscosity of blood used was within acceptable range.
3.4 Porcine Blood

Use of animal blood is an accepted alternative to human blood. Since, human blood was not allowed for our experiments due to University restrictions, Porcine Blood (PB) was used. Porcine Blood has similar properties to human blood. Fresh PB was purchased from Lee BioSolutions Inc. and was stored in a refrigerator at 2-8°C. The particles in the blood tend to settle at the bottom of the bottle overnight, thus each time before using the PB for experimental runs, the blood was gently mixed to make it homogeneous. The blood was removed from the refrigerator and placed on a Fisher Scientific™ Digital Bottle Roller and rolled at 35 rpm for at least an hour until it mixed evenly. When the blood warmed to room temperature it was ready to use.

3.5 Viscosity Measurement

Viscosity is the measure of fluid’s resistance to flow. Porcine blood is a pseudoplastic, non-Newtonian fluid i.e. it changes viscosity and that change in viscosity is not dependent on the rate of shear produced by layers flowing over each other. 9 The viscosity of artificial blood and porcine blood was measured by Brookfield LVDV-E115 Viscometer and Spindle SC4-18 as shown in the Figure 17. The Brookfield LVDV-E115 Viscometer measures fluid viscosity at given shear rates. The principal operation of the Brookfield LVDV-E115 Viscometer is to rotate a spindle that is immersed in the fluid through a calibrated spring. The viscous drag of the fluid against the spindle is measured by spring deflection and measured by a rotary transducer which provides torque signal. It is low cost and easy to use and gives direct reading of viscosity in cP or mPa.s. 54 ASTM D2196-10 Standard Test Methods for
Rheological Properties of Non-Newtonian Materials by Rotational (Brookfield type) Viscometer (Test Method B) was used to measure the viscosity.  

The Viscometer was leveled by means of three leveling screws at the bottom. It was adjusted so that the bubble level on the top of DV-E is centered within the circle. The Spindle SC4-18 was attached to the viscometer by screwing it to male coupling nut. The power switch was turned ON and the viscometer was set in spindle select on the speed/spindle switch and SC4-18 was selected by turning the knob. The small adapter was thoroughly cleaned by washing and drying it to avoid any foreign dirt. The small adapter was inserted from the bottom into

Figure 17: Brookfield LVDV-E115 Viscometer
the water jacket and locked by rotating it clockwise. Blood was added to the small adapter by means of a disposable pipette until the groove of the spindle’s shaft was immersed in it. The small adapter was then covered by an insulating cap. The speed/spindle switch was set to speed select and the desired test speed was selected from 20, 30, 50, 60 and 100 rpm. After setting the speed the speed/spindle switch was set to center position. The motor was turned ON and the viscosity readings given by the viscometer in cP at particular rpm were noted.

3.6 Selecting the parameters

3.6.1 Quantifying the external pressure needed

The applied external pressure is equally important as the type of fabric used in the transfer of stains. A higher external pressure leads to an early onset of transfer wicking. With increased external pressure the number of contact points between two layers’ increases. So far very few studies have been carried out to see the effect of external pressure on wicking. In an experiment conducted on 20 persons of ages between 5 and 35 with an even split of male and female participants, it was obtained that it is sufficient to sense equivalent weight ranging from 0.010 kg to about 2.0 kg for a computer based human touch sensing system. This would reproduce a virtual hug by means of sensors and embedded air pressure pockets. This draws our attention because majority of times a transfer stain could be from a hug. But, the problem is quantification of pressure involved while hugging a person. Certain numerical values in terms of force independent of area were found online, but force has no relevance. For example, a force of 50lb on 1sq.metre area is certainly lower pressure compared to a force of 50lb on 1 sq.cm area. We were more curious on the pressure values, which are involved in hugging, skin marks, tissue damage, penetration etc. Tissue damage is thought
to occur where pressures more than 9.3kPa are sustained for more than two or three hours.\textsuperscript{52}

With a very sharply pointed knife, penetration of the abdominal skin and subcutaneous tissues usually required between 0.5-3 kilogram force.\textsuperscript{53} If we consider a crime scene example where an adult lifts a dead person with both forearms and tries to hug him; the pressure exerted in that case is:

Forearms resemble more or less a trapezoidal shape.

Considering the average length of lower arm [from elbow to the wrist] for a man: \( h = 10.62'' \)

\( a = 3.5'' \)\textsuperscript{58}

\( b = 4'' \)

Figure 18: Size of lower forearm
Area of trapezium \[= \frac{a+b}{2} \cdot h \]  
Equation 8

Pressure (pascal) \[= \frac{\text{Force (newtons)}}{\text{Area in sq.meter}} \]  
Equation 9

Force (newton) \[= \text{Mass (kg)} \cdot \text{Acceleration (m. s}^{-2}) \]  
Equation 10

Using Equation 8,

Area of one lower forearm \[= 39.82 \text{ sq. inch} \]

Using both forearms:

Total area \[= 2 \cdot 39.82 = 79.65 \text{ sq. inch} = 0.051 \text{ sq. meter} \]

Lifting a person with mass 55kgs,

Using Equation 9 and 10,

\[\text{Pressure} = 10568 \text{ Pascal} \]

[Or for better understanding in kg/m\(^2\): \(55/0.051 = 1078.5 \text{ kg/m}^2\)]

10kPa pressure was on the upper limit. Considering the limitations of experimental equipment, design and a practical approach and all the points discussed above, pressure values in the range of 1-6kPa were selected for this research.

### 3.6.2 Pressure value calculations

A beaker with/without water and/or a clamp holding lead donuts arrangement was selected to apply external pressure on the fabrics which is discussed in the section 3.9.

Diameter of the beaker = 4.231 inches
The area of the beaker base = 0.00694m$^2$

Weight of empty beaker = 318 grams

Using the Equation 3 and 4 and the area of the beaker, pressure values were calculated as shown in the Table 1.

<table>
<thead>
<tr>
<th>Beaker weight</th>
<th>Weight of water added</th>
<th>Clamp weight</th>
<th>Lead donut weight</th>
<th>Gross weight in kgs</th>
<th>Pressure Levels</th>
<th>≈ Pressure values in Pa and psi</th>
<th>≈ Pressure values in kg/m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>318 grams</td>
<td>390 grams</td>
<td>-</td>
<td>-</td>
<td>0.708</td>
<td>P1</td>
<td>1000Pa [0.145 psi]</td>
<td>102.017</td>
</tr>
<tr>
<td>318 grams</td>
<td>1100 grams</td>
<td>-</td>
<td>-</td>
<td>1.418</td>
<td>P2</td>
<td>2000Pa [0.291 psi]</td>
<td>204.323</td>
</tr>
<tr>
<td>318 grams</td>
<td>1000 grams 388 grams</td>
<td>-</td>
<td>1.706</td>
<td>2400Pa [0.350 psi]</td>
<td>P3</td>
<td>245.821</td>
<td></td>
</tr>
<tr>
<td>318 grams</td>
<td>1.75 kg</td>
<td>388 grams</td>
<td>2.456</td>
<td>3500Pa [0.503 psi]</td>
<td>P4</td>
<td>353.890</td>
<td></td>
</tr>
<tr>
<td>318 grams</td>
<td>3.5 kg</td>
<td>388 grams</td>
<td>4.206</td>
<td>6000Pa [0.862 psi]</td>
<td>P5</td>
<td>606.052</td>
<td></td>
</tr>
</tbody>
</table>

3.6.3 Quantifying wait time and time for transfer

Wait time and time for transfer were selected to predict a crime scene situation. Wait time signified the presence of the concerned person in the crime scene timeline. Wait time less than 60s means that it is highly likely that the person was present at the crime scene. Hence,
transfer patterns were studied selecting wait times less than 60s. Based on his statements and the interpretation of the transfer stains observed on his clothing, the truth can easily be discovered.

There have been many homicide cases, where the person [the innocent or the murderer] in his statements says the stains got onto his clothing while hugging or other sort of physical contact. Hence, the whole research was centered around a hugging scene between the donor [person with the source of blood i.e. the person murdered] and the receiver [the murderer or the innocent]. A normal hug with loved one lasts on an average from under 10 seconds and there is no maximum time defined. Based on experimental trials, time needed for transfer wicking of blood from one fabric to another and crime scenes transfer time of 30s and 40s was taken into account.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wait Time</th>
<th>Time for transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levels</td>
<td>5s</td>
<td>30s</td>
</tr>
<tr>
<td></td>
<td>10s</td>
<td>40s</td>
</tr>
<tr>
<td></td>
<td>20s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>60s</td>
<td>-</td>
</tr>
</tbody>
</table>
3.7 Experimental setup for transfer stains

After fabric preparation, blood drip was a crucial part of the experiment. For this research it was necessary to ensure consistent volume of a single blood drop for each experimental run. Drops of $30\mu L \pm 1.5\mu L$ were achieved by using a Gilson Pipette and tip calibration method, which is described as below.

3.8 Tip Calibration

Single drop of volume $30\mu L \pm 1.5\mu L$ was achieved by means of tip calibration in which the diameter of the tip was altered. Calibrated tips of ZAP (Zero Aerosol Pipetting) by VWR were used for this purpose and were attached to the Gilson Pipette. The entire volume of a drop - $30\mu L$ had to be pipetted out as a single drop from the source. The tip was cut 1mm at a time to widen the tapering tip diameter. A drop of blood was dripped onto a dish placed on a balance as shown in the Figure 19. In case a secondary drop was observed, the tip was further cut a mm to widen the tip diameter. This procedure was repeated until the tip dispensed a single drop of $30\mu L$ with no secondary drops.

![Figure 19: Tip calibration](image)

Figure 19: Tip calibration $^5$
3.9 Setting the equipment

A simple method was used to apply external pressure on fabrics to trigger transfer. A beaker, polypropylene plate, clamps, lead donuts, plastic bag, and embroidery loop were arranged as shown in the Figure 20.

![Figure 20: Arrangement of the equipment](image)

Receiving fabric swatch was placed on the polypropylene plate. A plastic bag of size 6*6 was placed between the receiving fabric swatch and the plate to avoid accumulation of stains on the plate, as shown in the Figure 21. The technical back side of the receiving fabric swatch rested on the plastic bag. The plastic bag was changed for each experimental run. The
transfer fabric swatch was held tight in the embroidery hoop to avoid any wrinkles on the surface, as shown in the Figure 21.

![Figure 21. Left: Receiving fabric with polythene bag on plate; Right: Transfer fabric held in the embroidery hoop.](image)

Pressure was applied on the fabrics using a transparent beaker (diameter – 4.23”) with a clamp holding the lead donuts as shown in the Figure 20. The gross weight of the beaker was altered by adding water and/or supporting lead donuts on the clamp. Pressure applied on the fabrics was altered by changing the quantity of water and/or adding the lead donuts on the clamp. 30μL drops were dispensed using the Gilson pipette on the technical face side of the receiving fabric swatch from a height of 1-2 cm and the time was noted. After certain time interval the embroidery hoop holding the transfer fabric swatch was placed on the bloodied receiving fabric swatch such that the fabrics had the same orientation [face to face and warp
to warp]. The beaker (with/without the water and/or lead donuts on the clamps) was immediately placed on the embroidery hoop. The diameter of embroidery hoop was 5 inches, so the beaker easily passed through it. The time interval between applying the blood drop and placing the beaker was termed the “wait time”. As this process of placing the beaker and noting the time was manual an error of ± 1 second has to be taken into account.

The beaker was kept on the receiving fabric for a certain time period and was then removed. Once the beaker was placed aside, the receiving and transfer fabric swatches were also removed. The time for which the pressure was applied was termed as the “time for transfer/transfer time”. An error of ± 1 second has to be taken into account here as well. Both the fabric swatches were properly labeled with the respective parameters and were left to dry for 24 hours in the laboratory at 21°C and 65 ± 5% RH.

The Gilson pipette was charged with 30µL of artificial blood or porcine blood. Several trials were made to ensure a consistent single drop of volume of 30µL was achieved. The pipette tips were changed and calibrated for every 5 samples in case of artificial blood and every 2 samples in case of porcine blood.

After drying all the fabric swatches were photographed and documented. Each sample was then placed in a separate plastic bag. The same procedure was followed for all the experimental runs. The next section contains information about the experimental design.

3.10 Experimental Design

The experiment runs were designed with the objective to understand the effect of one parameter at a time on the transfer bloodstain pattern. The parameters selected for this research are listed below in Table 3.
Table 3: Parameters selected for the experiment

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pressure</th>
<th>Wait Time</th>
<th>Time for transfer</th>
<th>Volume of drop</th>
<th>Fabrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levels</td>
<td>1000Pa</td>
<td>5s</td>
<td>30s</td>
<td>30μL</td>
<td>Knit</td>
</tr>
<tr>
<td></td>
<td>2000Pa</td>
<td>10s</td>
<td>40s</td>
<td>-</td>
<td>Woven</td>
</tr>
<tr>
<td></td>
<td>2400Pa</td>
<td>20s</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3500Pa</td>
<td>30s</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6000Pa</td>
<td>60s</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

3.10.1 Experimental Design I: Effect of wait time on transfer of stains

In this experimental design, the study was focused on understanding the effect of wait time on transfer of stains between the knit-knit and woven-woven fabrics. All the other parameters were kept constant.

3.10.2 Experimental Design II: Effect of time for transfer on transfer of stains

In this experimental design, the study was focused on understanding the effect of time for transfer on transfer of stains. All the other parameters were kept constant.
3.10.3 Experimental Design III: Effect of external pressure on transfer of stains

In this experimental design, the study was focused on understanding the effect of external pressure on transfer of stains. All the other parameters were kept constant.
CHAPTER 4: DATA PROCESSING

4.1 ImageJ Analysis

After the stains dried, images of the stains were taken using a ProScope HR USB camera and ImageJ software was used to analyze stains for their area and circularity. An L-shaped forensics calibration scale (as shown in the Figure 22) was attached to the stained fabric to set the scale for the software and care was taken to ensure that the scale avoided any contact with stained area as shown in the Figure 22.

![Figure 22. Black colored L-shaped forensic calibration scale placed on a stained knit fabric](image)

The fabrics were so arranged that it represented warp direction vertically as shown in the Figure 23. The scale was set using Set Scale tool and the stained area in the image was cropped as shown in the Figure 24.
Figure 23: Black arrow representing the wale direction for knit fabric, warp direction for woven fabric

Figure 24: Cropped stained image of a transfer knit fabric using ImageJ for further analysis
Color Threshold tool was then used to get a filtered image for easy analysis. The Threshold color was set to Black and Color space to RGB. Hue, Saturation and Brightness were adjusted to get the best filtered image as shown in Figure 25 and Figure 26. Analyze particles option was used to get data for circularity and area of stain.

Figure 25: Adjusting the color threshold to get a filtered image
All the fabrics were analyzed in the above way and data was recorded in an Excel™ sheet.

Only transfer stains were examined because stains on receiving fabrics were more or less of the same shape and size. Transfer stains were critical and important to study.
CHAPTER 5: RESULTS AND DISCUSSIONS

This study has been carried out to study the effect of certain parameters on transfer of bloodstains from one fabric to another. Based on the design of experiment, each section will focus on investigating and understanding the effect of a certain parameter on transfer. An attempt has also been made to explain the things with scientific reasoning backed up with the literature.

Table 4: Terminology used in this research

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving fabric swatch</td>
<td>Fabric on which the original blood drop was placed</td>
</tr>
<tr>
<td>Transfer fabric swatch</td>
<td>Fabric which was held in the embroidery hoop and was kept on the receiving fabric under applied external pressure</td>
</tr>
<tr>
<td>Face of the fabric</td>
<td>Technical face of the fabric and the side to receive the blood drop [for receiving fabric swatch] and/or the side of the fabric which was facing the receiving fabric [for transfer fabric swatch]</td>
</tr>
<tr>
<td>Back side of the fabric</td>
<td>Technical back of the fabric and the opposite side on which the blood drop was placed [for receiving fabric swatch] and/or the opposite side of the fabric facing the receiving fabric [for transfer fabric swatch]</td>
</tr>
<tr>
<td>Wait time</td>
<td>The time interval between applying the blood drop and placing the transfer fabric and the weighted beaker</td>
</tr>
</tbody>
</table>
Table 4: Continued

<table>
<thead>
<tr>
<th>External pressure</th>
<th>The pressure applied to the fabric using the beaker and clamp arrangement with/without water and/or a clamp holding lead donuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for transfer/transfer time</td>
<td>The time for which the pressure is applied and transfer is allowed to occur</td>
</tr>
</tbody>
</table>

5.1 Viscosity measurement of blood

As discussed earlier in the experimental section, the viscosity of artificial blood and porcine blood was measured each time before running the experimental trials using a Brookfield Viscometer. Table 5 shows the viscosity of the porcine blood first received and when stored in a refrigerator for 5 days. Table 6 shows the viscosity of artificial blood.

Table 5: Porcine blood viscosity

<table>
<thead>
<tr>
<th>Shear Rate [s(^{-1})]</th>
<th>Fresh porcine blood</th>
<th>5-days old porcine blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (cP)</td>
<td>Range</td>
<td>Viscosity (cP)</td>
</tr>
<tr>
<td>132</td>
<td>8.19</td>
<td>27.3%</td>
</tr>
<tr>
<td>79.2</td>
<td>9.75</td>
<td>19.5%</td>
</tr>
<tr>
<td>66</td>
<td>10.5</td>
<td>17.5%</td>
</tr>
<tr>
<td>39.6</td>
<td>12.2</td>
<td>12.2%</td>
</tr>
<tr>
<td>26.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 6: Artificial blood viscosity

<table>
<thead>
<tr>
<th>Shear Rate [s⁻¹]</th>
<th>Viscosity (cP)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>132</td>
<td>9.57</td>
<td>31%</td>
</tr>
<tr>
<td>79.2</td>
<td>10.35</td>
<td>20.7%</td>
</tr>
<tr>
<td>66</td>
<td>10.38</td>
<td>17.3%</td>
</tr>
<tr>
<td>39.6</td>
<td>10.5</td>
<td>10.5%</td>
</tr>
</tbody>
</table>

5.2 Analysis of data

Excel™ and Jump™ were used to analyze the data collected. Scatter plots were used to see the effect of wait time, transfer time and pressure on the area of stain. Only the transfer fabric swatches were analyzed for Artificial and Porcine Blood, because the stain areas on the receiving fabric swatches were more or less the same.

5.2.1 Part I: Analysis of Knit/Knit Fabrics – Artificial Blood

5.2.1.1 Effect of wait time

It can be seen in Figure 27 and 28, as the wait time increased the amount of transfer decreased i.e. area of transfer stain reduced. This was reasonable because longer wait times signifies longer wicking times, hence, with longer wait times the Artificial Blood [AB] wicked into the fabric and less AB was available in the form of reservoir for transfer. A general trend can be seen in both the graphs that with increased wait time the area of transfer stain decreased. However, the data was scattered and there were a few outliers. The reason could be faults in the fabrics, yarns or uneven capillaries.
Figure 27: Graphical representation of Area of transfer stains vs wait time on knit fabric – Time for transfer 30s
A more careful observation shows for certain parameters no transfer was observed, the AB did not transfer from receiving fabric swatch to transfer fabric swatch. The list of those observations are listed in Table 7.

Figure 28: Graphical representation of Area of transfer stains vs wait time on knit fabric – Time for transfer 40s
Table 7: Parameters at which no transfer was observed

<table>
<thead>
<tr>
<th>Wait Time [s]</th>
<th>Time for Transfer [s]</th>
<th>Pressure [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>2000</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>2000</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>2400</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>2000</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>2400</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>2000</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>2400</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>3500</td>
</tr>
<tr>
<td>30</td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>2000</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>2400</td>
</tr>
</tbody>
</table>
5.2.1.2 Effect of time for transfer

From Figure 29, it can be seen that increasing time for transfer increased the likelihood of a transfer stain being formed, but had little effect on the area of transfer stain.

Figure 29: Graphical representation of Area of Transfer Stains vs Wait time on knit fabric
With increased time for transfer, the total area of transfer stain increased for all cases except for wait time 5s, see Figures 30-34. This could be an outlier due to defect in the fabric or smaller drop size of artificial blood. From Figures 33 and 34, it is quite evident that the possibility of transfer increased, as no transfer was seen for pressure 1000, 2000 and 2400Pa at time for transfer 30s, but transfer was observed at all the pressures at time for transfer 40s.
Figure 30: Graphical representation of Area of Transfer Stains vs Wait time 5s on knit fabric
Figure 31: Graphical representation of Area of Transfer Stains vs Wait time 10s on knit fabric
Figure 32: Graphical representation of Area of Transfer Stains vs Wait time 20s on knit fabric
Figure 33: Graphical representation of Area of Transfer Stains vs Wait time 30s on knit fabric
Figure 34: Graphical representation of Area of Transfer Stains vs Wait time 60s on knit fabric

5.2.1.3 Effect of external pressure

From Figure 35 and 36, it can be seen that increasing external pressure increased the area of transfer stains, which was also found for water by Zhuang et al. With increased external pressure, the contact points between two layers increased leading to a rise in transfer of
artificial blood from receiving fabric to transfer fabric. Another reason is decrease in the volume of knit fabric under the application of external pressure. Increasing external pressure decreased the air volume fraction within the fabric. Air in the fabric is the sum of air within the yarns and the air between the yarns. According to Li et al. model \textsuperscript{71}, blood wicks through the air spaces within the yarns. Increasing the external pressure decreases the air volume within the yarns. This decrease in the air volume is indicative of the decreased volume available for blood and hence increased artificial blood expelled. As the amount of artificial blood expelled increases, the area of transfer stain increases.

Figure 35: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 30s
Figure 36: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 40s

5.2.2 Part II: Analysis of Knit/Knit Fabrics – Porcine Blood

5.2.2.1 Effect of wait time

Figure 37 and 38 show the effect of wait time on the area of transfer stains, with increasing wait time the area of transfer stain decreased. The longer you keep the blood on the fabric,
the more it wicks. So, only small volume of blood was available for transfer. It was noteworthy that transfer was seen for all the wait times and pressure values unlike the interaction of AB with knit fabrics.

Figure 37: Graphical representation of Area of transfer stains vs wait time on knit fabric – Transfer Swatch – Time for transfer 30s
5.2.2.2 Effect of time for transfer

In Figure 39, the total area of transfer stain vs wait time at two different time for transfer viz. 30s and 40s was compared. It was seen the area of transfer stain increased with increased time for transfer. As transfer was observed for all the parameters, time for transfer played no role in the likelihood of transfer stain being formed.
Figure 39: Graphical representation of Area of transfer stains vs wait time on knit fabric – Transfer Swatch

Figures 40-44 show the effect of time for transfer for all the wait times graphed individually. In general, the area of transfer stain increased with increased time for transfer. However, at the highest pressures, the area of the transfer stain could be reduced compared to lower pressures.
Figure 40: Graphical representation of Area of transfer stains vs wait time 5s on knit fabric –

Transfer Swatch
Figure 41: Graphical representation of Area of transfer stains vs wait time 10s on knit fabric

– Transfer Swatch
Figure 42: Graphical representation of Area of transfer stains vs wait time 20s on knit fabric

– Transfer Swatch
Figure 43: Graphical representation of Area of transfer stains vs wait time 30s on knit fabric

- Transfer Swatch
5.2.2.3 Effect of external pressure

Figure 45 and 46 show the effect of external pressure on the area of transfer stains at time for transfer 30s and 40s respectively. It was seen that the area of transfer stain increased with the increase in external pressure. As discussed above, with increased external pressure the number of contact points between the fabrics increased which led to increased transfer of
blood. Also, higher external pressure led to decreased air volume fraction of fabric and thereby expelling more blood. This blood could be transferred to the transfer fabric swatch.

Figure 45: Graphical representation of Area of Transfer Stains vs External Pressure on knit fabric – Time for transfer 30s, Transfer Fabric Swatch
If individual graphs of area of transfer stains vs external pressure for each wait time are considered, we see a general trend in the increase of area of transfer stains, see Figures 40-44. However, there were a few outliers here as well. In Figure 40, at wait time 5s, the area of transfer at 6000Pa pressure was less compared to that at 3500Pa. In Figure 44, at wait time
60s, the area of transfer stain at 2000Pa was less compared to area at 1000Pa. This could be due to defect in the fabric or smaller drop size of porcine blood.

5.2.3 Part III: Analysis of Woven/Woven Fabrics – Artificial Blood

5.2.3.1 Effect of wait time

A similar trend was observed for the woven fabrics, with increased wait time the area of transfer stain decreased, see Figure 47 and 48. With longer wait times AB wicked into the receiving fabric and very little volume was available for transfer.

Figure 47: Graphical representation of Area of transfer stains vs wait time on woven fabric – Time for transfer 30s
5.2.3.2 Effect of time for transfer

Unlike knit fabrics, time for transfer had only a small influence on the likelihood of transfer, see Figure 49.
However, it did affect the area of the transfer stain, see Figure 49. If we compare the transfer stain area at constant wait times at time for transfer 30s and 40s, we see an increasing trend in the area of transfer stain for increased external pressure, as shown in the Figure 49.

Figure 49: Graphical representation of Area of transfer stains vs wait time on woven fabric
5.2.3.3 Effect of external pressure

Woven fabrics performed in a similar way as the knit fabrics. With increased external pressure the area of transfer stain increased, see Figure 50 and 51. As above, with increased external pressure the number of contact points between the fabrics increased that led to increased transfer of blood. Also, higher external pressure led to decreased air volume fraction of fabric and thereby expelled more blood. This blood transferred to the transfer fabric swatch.

![Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s](image)

Figure 50: Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s
5.2.4 Part IV: Analysis of Woven/Woven Fabrics – Porcine Blood

5.2.4.1 Effect of wait time

The area of transfer stains vs wait time is shown in the Figure 52. The area of transfer stains decreased with the increased wait time.
5.2.4.2 Effect of time for transfer

Unlike the transfer for knit fabrics, time for transfer had no effect on the area of transfer stains. For higher pressures \([\geq 2400\text{Pa}]\) no transfer was observed after time for transfer was 10-15 seconds. For lower pressures \([< 2400\text{Pa}]\) transfer continued until 30 seconds. Few
trials were done with lower pressures and time for transfer 40s, it did not change the area of transfer stains.

### 5.2.4.3 Effect of external pressure

Figure 53 shows with the increase in the external pressure the area of transfer stain increased. As above, with increased external pressure, the number of contact points between the fabrics increased and that led to increased transfer of blood. Also, higher external pressure led to decreased air volume fraction of fabric and thereby expelled more blood. This blood was transferred to the transfer fabric swatch.

![Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s, Transfer Fabric Swatch](image)

Figure 53: Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s, Transfer Fabric Swatch
The stain patterns observed for knit/knit were same with AB and PB. The transfer stains with AB and PB looked like ‘finger prints’ as shown in Figure 54.

Figure 54: Left: Artificial Blood Transfer Stain, Right: Porcine Blood Transfer Stain

[Knit Fabric]

The stain patterns observed for woven/woven were same for both AB and PB, see Figure 55.

Figure 55: Left: Artificial Blood Transfer Stain, Right: Porcine Blood Transfer Stain

[Woven Fabric]
From Figure 54 and 55, it was evident that the transfer stain patterns on knit/knit were quite different from the woven/woven. More blood was transferred in case of woven/woven as compared to knit/knit. The reason being the fabric construction. Kissa’s work \(^{12}\) states that in a capillarity system, the rate and direction of liquid flow is governed by the shape of the solid surfaces. The fabric construction of single jersey knits is different from plain wovens, see Figure 56. Single jersey knits have wales that are raised [see Figure 57] and these make prominent contact with the receiving fabric swatch. The blood gets wicked into the capillaries of these wales and gives rise to stains that are similar to “finger prints”.

![Figure 56: SEM image of plain woven fabric [left], SEM image of single jersey knit [right] \(^{6}\)](image-url)
Plain woven fabrics have more parallel and undisturbed capillaries as compared to single jersey knits. The capillaries within the yarn in single jersey knit are more tortuous, and tortuosity reduces wicking potential. Another reason is the volume of fabrics for a given area is more in case of single jersey knits as compared to plain woven fabrics [according to equation 11], as the thickness of later is usually less.

\[
\text{Volume} = \text{Area} \times \text{Thickness} \tag{Equation 11}
\]

Fabric pore structure also plays an important role. Fabric air permeability is the measure of the ability of a porous medium to transmit fluid and is determined by the geometry and dimension of the pores within the yarn and between the yarns. Fabric air porosity under external pressure values used in this experiment were measured for knit as well as woven
fabric. Thickness of the fabric at each pressure level was calculated using FTT tester and the values are given in the Table 8.

Table 8: Average thickness of fabrics at respective external pressure

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Knit</th>
<th>Woven</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.645</td>
<td>0.392</td>
</tr>
<tr>
<td>2000</td>
<td>0.5896</td>
<td>0.3548</td>
</tr>
<tr>
<td>2400</td>
<td>0.5772</td>
<td>0.3418</td>
</tr>
<tr>
<td>3500</td>
<td>0.5442</td>
<td>0.3238</td>
</tr>
<tr>
<td>6000</td>
<td>0.508</td>
<td>0.303</td>
</tr>
</tbody>
</table>

\[
\text{Air volume fraction [porosity]} + \text{Solid volume fraction [fiber content]} = 1
\]

\[
\text{Porosity } [\varnothing] = 1 - \frac{\rho_b}{\rho_s}
\]  

Equation 12

where, \( \rho_b \) is the density of fabric, \( \rho_s \) is the density of fiber \( \rho_s \) for cotton fiber \( 5 = 0.00155 \text{ g/mm}^3 \)

\[
\rho_b = \frac{\text{basis weight/ thickness}}{}
\]  

Equation 13

Weight of 5 samples of knit fabrics and woven fabrics of same area was calculated and the average weight was selected to calculate the basis weight. The values of basis weight were calculated using Equation 14 and are listed in the Table 9.
Table 9: Fabric weight and area calculations

<table>
<thead>
<tr>
<th>Sample</th>
<th>Knit [grams]</th>
<th>Woven [grams]</th>
<th>Area [sq.m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2804</td>
<td>1.0432</td>
<td>0.00790321</td>
</tr>
<tr>
<td>2</td>
<td>1.2487</td>
<td>1.0461</td>
<td>0.00790321</td>
</tr>
<tr>
<td>3</td>
<td>1.2937</td>
<td>1.035</td>
<td>0.00790321</td>
</tr>
<tr>
<td>4</td>
<td>1.255</td>
<td>1.0364</td>
<td>0.00790321</td>
</tr>
<tr>
<td>5</td>
<td>1.284</td>
<td>1.0366</td>
<td>0.00790321</td>
</tr>
<tr>
<td>Avg.</td>
<td>1.272</td>
<td>1.039</td>
<td></td>
</tr>
</tbody>
</table>

*Basis Weight = (Weight of the fabric)/(Area of the fabric)*  

Equation 14

Table 10: Fabric basis weight

<table>
<thead>
<tr>
<th>Basis weight [Knit (GSM)]</th>
<th>Basis weight [Woven (GSM)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>161</td>
<td>131.5</td>
</tr>
</tbody>
</table>
Table 11: Fabric air porosity and fiber volume fraction calculations

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Pressure [Pa]</th>
<th>Thickness [mm]</th>
<th>Basis Weight</th>
<th>$\rho_b$</th>
<th>Porosity [$\phi$]</th>
<th>Fiber Content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knit</td>
<td>1000</td>
<td>0.645</td>
<td>0.000161</td>
<td>0.0002496</td>
<td>0.839</td>
<td>16.10</td>
</tr>
<tr>
<td>Knit</td>
<td>2000</td>
<td>0.5896</td>
<td>0.000161</td>
<td>0.0002731</td>
<td>0.824</td>
<td>17.62</td>
</tr>
<tr>
<td>Knit</td>
<td>2400</td>
<td>0.5772</td>
<td>0.000161</td>
<td>0.0002789</td>
<td>0.820</td>
<td>17.99</td>
</tr>
<tr>
<td>Knit</td>
<td>3500</td>
<td>0.5442</td>
<td>0.000161</td>
<td>0.0002958</td>
<td>0.809</td>
<td>19.09</td>
</tr>
<tr>
<td>Knit</td>
<td>6000</td>
<td>0.508</td>
<td>0.000161</td>
<td>0.0003169</td>
<td>0.796</td>
<td>20.45</td>
</tr>
<tr>
<td>Woven</td>
<td>1000</td>
<td>0.392</td>
<td>0.0001315</td>
<td>0.0003355</td>
<td>0.784</td>
<td>21.65</td>
</tr>
<tr>
<td>Woven</td>
<td>2000</td>
<td>0.3548</td>
<td>0.0001315</td>
<td>0.0003707</td>
<td>0.761</td>
<td>23.92</td>
</tr>
<tr>
<td>Woven</td>
<td>2400</td>
<td>0.3418</td>
<td>0.0001315</td>
<td>0.0003848</td>
<td>0.752</td>
<td>24.83</td>
</tr>
<tr>
<td>Woven</td>
<td>3500</td>
<td>0.3238</td>
<td>0.0001315</td>
<td>0.0004062</td>
<td>0.738</td>
<td>26.21</td>
</tr>
<tr>
<td>Woven</td>
<td>6000</td>
<td>0.303</td>
<td>0.0001315</td>
<td>0.0004341</td>
<td>0.720</td>
<td>28.00</td>
</tr>
</tbody>
</table>
Figure 58: Graph of fabric air porosity vs pressure

From Figure 58 it was evident that the porosity of knit fabrics is higher than the wovens. Yarn structure did not play a role here because both the fabrics were made using ring-spun yarns.

In case of wovens, the blood did not collect on the supporting material i.e. the plastic film, see Figure 59. But in case of knits, blood penetrated through the fabric and some amount of it got collected on the supporting material. This was because knits are more open and porous structures compared to wovens.
5.3 Microscopic Image Analysis

Images of knit and woven fabrics were taken using digital microscope to analyze the distribution of PB in the knit and woven fabric structures. In case of knit fabrics, for receiving fabric swatch, the PB distribution was same on the face and the back side of fabric, see Figure 60.
However, for transfer fabric swatch no PB was seen on the back side of the fabric, see Figure 61 and 62. As discussed above in section 2.14, the reason for this is the fabric construction of single jersey knit. The yarns in single jersey knit make a loop introducing large changes in the capillary sizes. The wicking potential reduces because of these discontinuities and this may be the reason we don’t see any PB on the back side of knit transfer fabric swatch.
Microscopic image analysis of the stains that appeared similar to “finger prints” on the transfer fabric swatch revealed that the wicking of PB was discontinuous and scattered, see Figure 63.
On further increasing the magnification, it was seen either the entire loops were covered with PB or mostly the right legs of the loops were covered with PB, as shown in the Figure 63 and 64.

Figure 64: PB absorption on Knit transfer fabric swatch. Left: Entire loop covered with PB; Right: Right loop leg covered with PB

The transfer fabric swatch had more pronounced stained right loop legs, contrary to which was found by Yuen Cho et al. Yuen Cho et al. in their experiments found that 82% of stains were preferentially located on the left loop legs, because in their fabrics the left loop legs protruded further out than right loop legs by approximately 50µm. Yarn twist direction could perhaps be the reason that in their case left loop legs protruded further out. Z twist yarns were used in our experiments. The reason for this topographical asymmetry is discussed in the literature. In a single jersey knit structure, right loop legs are raised compared to left loop legs. As the right loop legs protrude further out of the fabric surface,
they make contact more readily with the blood on the receiving fabric swatch than the left leg loops. Hence, the percent of right loop legs covered with PB was more than left loop legs.

For woven fabrics, the PB distribution was same on the face and the back side of both fabric swatches, see Figure 65 and 66.

Figure 65: PB absorption on woven receiving fabric swatch; Left: Face Side & Right: Back Side
Figure 66: PB absorption on woven transfer fabric swatch; Left: Face Side & Right: Back Side
CHAPTER 6: CONCLUSIONS

During this research transfer stains produced by one fabric on another were studied. Several parameters that affect the transfer stain patterns were studied: wait time, time for transfer, external pressure, fabric structure and blood type. Experiments were designed to study the effect of one parameter at a time keeping the others constant. The bloodstains were analyzed by means of their areas.

The stains formed on transfer fabric swatch of knit fabrics were significantly different from the stains formed on transfer fabric swatch of woven fabrics. The transfer stains on knit fabrics looked like “finger prints” as described by Cho et al. [20] but in the reverse direction. In case of knit transfer fabric swatch only face side was stained, whereas for woven transfer fabric swatch both the sides were stained.

For knit/knit fabrics, the chances of transfer reduced with increased wait time using AB, no transfer was observed for higher wait times, see Table 6. The total area of transfer stain decreased with increased wait time. But with PB, wait time had no effect on the likelihood of transfer, as transfer was observed for all the wait times viz. 5s, 10s, 20s, 30s and 60s. But the total area of transfer stain reduced with increased wait time for PB as well.

For woven/woven fabrics using AB, the wait time did not affect the likelihood of transfer, as transfer was observed for all the wait times. However, the area of transfer stain decreased with the increased wait time. On the contrary, with PB wait time did affect the likelihood of transfer. No transfer was observed for wait time 60s at low pressures [1000 Pa and 2000 Pa]. The area of transfer was reduced with increased wait time just like AB.

For knit/knit and woven/woven fabrics, the area of transfer stains increased with increased external pressure for both AB and PB.
For knit/knit fabrics using AB, time for transfer was very crucial as it not only increased the total area of transfer but also increased the likelihood of transfer. With PB, increased time for transfer, increased the total area of transfer stain. Time for transfer had no effect on the woven/woven fabric using PB, but it did affect the woven/woven fabric using AB. With more time for transfer, the total area of stains increased.
CHAPTER 7: SUGGESTED FUTURE WORK

Study the effect of drop volume, wait time, time for transfer and external pressure at values other than those selected in this experiment. It is important to see if different values follow a similar trend on transfer of stains.

To extend the understanding of transfer stain patterns, transfer stains on fabrics with different weave and knit structures like denim, carpets, automotive upholstery fabrics should be studied. Transfer stain patterns from different surfaces like leather, glass, tiles should also be studied.

Consistently achieving 30µL drop was a bit difficult and a possible source of manual error. Hence, finding an alternative way of achieving 30µL drops to avoid manual error.

Developing a model to better understand the mechanism of transfer of blood from one fabric to another. Transfer wicking is a complex phenomenon. Efforts to understand how the blood actually transfers from one fabric to another should be made. This could be done by video-graphing the experiments as designed in this research.
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Figure. Graphical representation of Area of transfer stains vs wait time on knit fabric – Receiving Fabric Swatch
Figure. Graphical representation of Area of transfer stains vs wait time on knit fabric – Receiving Fabric Swatch
Figure. Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 40s, Receiving Fabric Swatch

Figure. Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric – Time for transfer 30s, Receiving Fabric Swatch
Figure. Graphical representation of Area of transfer stains vs wait time on woven fabric –

Time for transfer 30s, Receiving Fabric Swatch

Figure. Graphical representation of Area of Transfer Stains vs External Pressure on woven fabric –

Time for transfer 30s, Receiving Fabric Swatch
Appendix B: Thickness vs Pressure

Knit Fabric 1

Knit Fabric 2
Appendix B: Porosity vs Thickness

Knit Fabric 1

Knit Fabric 2
Knit Fabric 5

Woven Fabric 1