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Effect of yarn structure on wicking and its impact on bloodstain pattern analysis (BPA) on woven cotton fabrics

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ABSTRACT

Bloodstain pattern analysis (BPA) of bloodstains on hard, non-porous surfaces has found widespread use in crime scene analysis and reconstruction for violent crimes in which bloodshed occurs. At many violent crime scenes, bloody clothing is also found and may be analyzed. However, to date, there are no definitive methods for analyzing bloodstains on textiles, even for simple drip stains. There are two major classes of textiles used for apparel and household textiles, weaves and knits. In this article, drip stains on two 100% cotton plain weave fabrics representative of bed sheets are analyzed. Since it is common practice in the manufacture of bed sheeting to use different types of yarn in the warp and weft direction to reduce cost, custom weaves were made from yarns produced by each of the three most common staple yarn production techniques to control this variable. It was found that porcine blood wicked into the fabrics made with ring spun yarn, but not into those made with open end or vortex spun yarns. The uneven wicking of blood into the different yarns resulted in elliptical-shaped stains on commercial bed sheeting that can be misleading when performing bloodstain pattern interpretation based on the stain morphology. This surprising result demonstrates that it is not sufficient to analyze the structure of the fabric, but one must also characterize the yarns from which the fabric is made. This study highlights the importance of a deeper characterization of the textile structure, even down to the yarn level, for BPA on textiles.

1. Introduction

In 1895, Piotrowski's pioneering studies created a new forensic science, bloodstain pattern analysis BPA [1]. Today, BPA incorporates mathematics, physics and fluid mechanics and has had good success in describing the formation of bloodstains on hard, non-porous surfaces [2]. Balthazard et al. in 1939 were the first to report studies of bloodstains on textiles showing that textiles can alter the stain shape [3]. In 1986, White published his results on drip bloodstains on several different fabrics and for several different heights. He found that often the drip height did not correlate with stain size. He also found that stains on many fabrics were distorted, the calculated impact angle could be in error by more than 40°, and that the stain could even suggest that the drop impacted the fabric from a different direction than the real direction [4]. He stated "The data indicate that calculations of angles of impact on most fabric surfaces examined are not reliable and should not be reported." Slemko followed this up with a study in 2003 where he showed that due to the large number of variables present in a textile, extreme caution should be used in attempting to obtain directionality from bloodstains on textiles [5]. Karger et al. even found that it could be difficult to distinguish transfer stains from airborne stains [6]. Additional studies by Holbrook [7], de Castro et al. [8], Miles et al. [9] and de Castro et al. [10] have examined transfer vs. impact spatter, the effect of surface roughness on the number of satellites and spines, and the effect of laundering. In a recent study of drip stains on a selection of textiles by de Castro et al. [11], the authors found only two consistent trends, (1) the stains became more elongated as the impact angle decreased as previously shown by White [4], and (2) for most fabrics, the stains were different for fabrics that had not been laundered prior to the experiments than those that had been laundered, demonstrating what textile scientists have reported for more than 75 years, namely that nearly all textiles must be laundered prior to testing in order to obtain reliable results [12]. Laundering both helps stabilize the textile structure and removes process oils and dirt as well as temporary finishes (e.g. stiffeners such as starch) and semi-durable finishes (e.g. softeners) applied to textiles to alter their handle for the purpose of improving sales.

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To date there is no definitive method for analyzing bloodstains on textiles. In their course on examination of bloodstained clothing, Van Stratton and Griffon state '*do not attempt to determine the angle of impact on clothing*' [13]. Recently, Michielsen et al. examined drip stains on 100% plain weave fabrics using a homogeneous artificial blood substitute. When porcine blood was allowed to drip at 90° to the surface of a commercial 100% cotton bed sheeting fabric, elongated bloodstains formed. Analysis of this fabric showed that both the fabric construction and the yarn construction were different in the warp and weft directions. This result leads to the question "is the fabric construction or the yarn construction responsible for elongated bloodstain pattern" and provided the motivation for this study. Even under these ideal conditions, they found oval stains on the fabric they tested [14]. Currently, no satisfactory explanation for the distortion of bloodstains by textiles has been reported in the BPA literature.

In an effort to determine the underlying causes of these distorted drip stains, it was decided to construct the simplest fabric structure, a plain weave in which the yarns interlace at right angles and follow a strictly alternating "over-under" arrangement. Every attempt was made to minimize the number of uncontrolled construction variables. In addition, wicking artifacts caused by mounting fabrics on solid substrates [15] were rigorously avoided. The results of these studies are reported below. To assist the reader, a table of textile terms is given in the Appendix A.

2. Materials and methods

For the fabrics used in this study, cotton fibers were spun to the same yarn linear density (size) using the three most common spinning methods in commercial use today and woven at two different fabric setts into a plain weave. A commercial plain weave was also tested for comparison to bed sheeting found in homes throughout the world.

2.1. Yarns

Cotton Incorporated (Cary, NC) converted cotton fibers from a single bale of cotton into several packages with linear densities of 164 dtex (cotton count Ne 36) singles cotton yarn using ring spinning, rotor open end spinning, and Murata vortex air jet spinning. (The spinning methods are defined in the Appendix A and the yarn structures are described in Section 4) The yarns were characterized as described by X Li [16] and their properties are summarized in Table 1 (2nd, 3rd and 4th columns from the left). When feasible, the yarn properties from the commercial fabric (described below) were obtained by extracting 10 yarns from the warp (lengthwise) and weft (widthwise) direction, and measuring the properties. Several methods required at least 1 km of continuous yarn and these could not be obtained.

2.2. Fabrics

A commercial plain woven, 100% cotton percale bed sheeting with optical brightener was obtained from Test Fabrics, Inc. (product code: 439XW, West Pittston PA, USA). Prior to use, the fabric was laundered as per AATCC standard method modified for home laundering [18]. Briefly, the fabric was added to the washer and the washer was filled with water at 60 ± 3 °C, and a lukewarm rinse setting of 29 ± 3 °C was selected. TIDE (a registered trademark of Procter & Gamble Co., Cincinnati OH 45217) detergent (66 ± 1 g) was added to the washer and the wash timer was set for a 12-min cycle. Upon completion, the load was transferred to a dryer at the "high" temperature setting for a 45-min cycle. After drying, the fabrics were ironed on the "cotton" setting to ensure uniformity and, finally, allowed to condition to ambient temperature and humidity for more than 24 h before use. The warp yarns were found to be ring spun (144 dtex, singles, Ne 41.0/1) and the weft yarns were found to be Murata vortex spun (169 dtex singles, Ne 34.9/1).

The remaining fabrics were woven in-house using the yarns provided by Cotton Incorporated as described in Li [16]. The same yarn was used for both the warp and weft yarns. Briefly, the yarns were sized with PhilBind L-1000 size for cotton on a Yamada YS-6 Single End Sizing Winder. The sized yarns were then used to make up the warp on a CCI Model CW550 warper and finally pulled into the warp on a CCI Sampling Loom – SL8900s. Permanent ink was used to label the fabrics, then the fabrics were sewn together to form a continuous length of fabric that was loaded into a Thies mini-soft fabric dyeing machine. The dyer was filled with water and heated to 100 °C. During heating, 3 g/L Soda Ash, 3 g/L surfactant (PRIMASOL NB NF) and 2 g/L H_2O_2 were added to the dyer for washing and bleaching the fabrics. After closing of the machine's hatch door, the fabric circulated through the Thies dyer until all the size and machine oil had been removed. The fabric was then scoured with fresh water 3 times to make sure no residual chemical remained on the fabric. After washing and bleaching, the fabrics were placed in a Bock centrifugal extractor to squeeze and extract water from the wet fabric. Then the fabrics were placed into an American Dryer Model ADS50 and dried for about a half hour until they were completely dry. Finally they were ironed to remove wrinkles and allowed to equilibrate to 65% ± 4% relative humidity and 21 ± 2 °C for at least 24 h.

The fabric properties for all fabrics used in this study are given in Table 2. All fabrics had a nominal thread count of 79 threads per square cm (200 threads per square inch) in two different setts: 39.4 ends per centimeter (epcm) × 39.4 picks per cm (ppcm) (100 epi (ends per inch) × 100 ppi (picks per inch)), and 51.2 epcm × 27.6 ppcm (130 epi × 70 ppi) resulting in six matched fabrics. In this manner, the number of variables was limited to three yarn spinning techniques and two fabric warp and weft densities.

Table 1
Yarn properties.

Yarn	Ring spun	Open end	Murata vortex	Commercial warp ring spun	Commercial weft murata vortex
Yarn linear density – dtex (Ne)	164 ± 1 (36.0 ± 0.2)	165 ± 1 (35.8 ± 0.2)	163 ± 1 (36.2 ± 0.2)	144 ± 0.3 (41.0 ± 0.07)	169 (34.9)
Tenacity MPa	259 ± 2	203 ± 2	205 ± 2	–[c]	–
Break elongation (%)	6.81 ± 0.46	5.87 ± 0.52	6.92 ± 0.71	–	–
Coefficient of mass variation (%)	14.5	16.7	15.2	–	–
Thin places (−50%/km)	3.3	142	78.3	–	–
Thick places (+50%/km)	143	177	71.7	–	–
Neps (+200%/km)	133	742	310	–	–
Hairiness	5.45	3.97	3.79	–	–
TM[b]	3.82	3.81	NA[a]	3.86	NA

[a] NA indicates that the parameter is not applicable for this yarn type.
[b] TM is the twist multiplier, defined as $TM = \frac{tpi}{\sqrt{Ne}}$ (tpi is turns/inch, turns/cm = tpi/2.54, Ne is cotton count given in the first row) [17].
[c] The – means the value was not measured for the yarns extracted from the commercial fabric.