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Abstract
Background Friction blisters occur when shear loading causes separation of dermal layers. Consequences range from minor pain to life-threatening infection. Past research in blister formation has focused on in vivo experiments, which complicate a mechanics-based study of the phenomenon.
Methods A Synthetic Skin Simulant Platform (3SP) approach was developed to investigate the effect of textile fabrics (t-shirt knit and denim cottons) and surface treatments (dry and wet lubricants) on blister formation. 3SP samples consist of bonded elastomeric layers which are surrogates for various dermal layers. These layers display frictional and mechanical properties similar to their anatomical analogues. Blistering was measured by measurement of deboned area between layers.
Results Denim caused greater blistering than did the t-shirt knit cotton, and both lubricants significantly reduced blister area and surface damage. A triglyceride-based lubricant had a more pronounced effect on blister reduction than corn starch. The triglyceride lubricant used with t-shirt knit cotton resulted in no blisters being formed.
Conclusions The performance of the 3SP approach follows previously reported frictional behavior of skin in vivo. The results of textile and surface treatment performance suggest that future 3SP iterations can be focused on specific anatomical sites based on application type.

Keywords: skin tribology, friction, blisters, textiles

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1. Introduction

Human skin is not only the body's first line of defense against environmental hazards, but it also serves as a scaffold to support clothing and other articles that are worn on or against the body. Skin comes into contact with numerous textile fabrics on a daily basis, and thus textile-initiated frictional injury to skin threatens the comfort and health of the wearer. One of the most common textile injury modes is friction blistering. Therefore, mitigating the formation and severity of blistering is a significant endeavor that can improve the quality of life of athletes, military personnel, and even those suffering from skin disorders such as epidermolysis bullosa (EB). The pathophysiology of friction blister formation can be initiated when the epidermis undergoes shear loading. Knapik et. al.[1] described the process using observational investigation of blister formation and treatment. Investigators, including Sulzberger

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and Naylor[2, 3], have demonstrated that coefficient of friction (COF) is one of the primary factors that influence blister formation. When friction of the stratum corneum becomes sufficient to inhibit free sliding of the textile surface, shear load is transferred to lower epidermal layers, thus causing separation and fluid infusion. Although the stratum corneum - the outermost layer of the epidermis - is a key contributor to the COF of skin [4], surface damage is not the primary mechanism for blister formation. Rather, blisters occur when cells in the stratum spinosum undergo necrosis due to shear loading [2].

An engineering-based study of friction blister formation must start with a thorough understanding of the frictional behavior of skin, and studies have been conducted to quantify COF properties of skin in general [5, 6]. In many such studies, the intrinsic properties of skin are considered, often for the purpose of improving ergonomics or cosmetics. However, since COF is also known to be influential to blister formation, this information may offer utility for understanding blister formation. Skin COF has been widely studied, and blister prevention techniques typically focus on reducing COF, often through hydration [7]. COF tends to increase with increasing skin hydration up to a certain point, after which the system transitions to stick-slip behavior[8]. Knapik et. al. applied this concept to blister prevention by showing that antiperspirant application significantly reduced blistering in soldiers[9]. Another avenue that has been examined is the use of various textiles to mitigate the onset of friction blisters. Knapik et al. examined different material combinations of sock materials in the boots of soldiers to reduce blistering[10]. Derler et al. characterized textile-skin and textile-skin-equivalent behavior in terms of COF and normal load[11]. Related to this, Gerhardt et al. demonstrated the effect of epidermal hydration on the COF value of skin-textile interfaces[12]. These studies aimed to better understand textile behavior in different applications, notably those which tend to produce friction blistering. Significant limitations in much of the previous work in the field has been managing the repeatability of friction data, preparation of the skin surface in light of hydration, sebum presence, and perspiration, and ability to affix measurement instrumentation to particular anatomical sites. The work detailed here is a potential approach to address these limitations.

The authors developed the Synthetic Skin Simulant Platform (3SP) to model human skin in friction blistering scenarios in response to the limitations of prior *in vivo* and FEA modeling methodologies. The 3SP approach has been found to accurately model the onset and formation of friction blisters using a steel ball probe in prior experimentation conducted by the authors. However, to maximize its utility as a research tool, the 3SP was employed to model fabric-skin interactions in this work. The details and results of an investigation of two common textile fabrics (t-shirt knit cotton and denim) and two surface treatments (corn starch dusting and athletic skin lubricant) are reported here. The authors feel that these results demonstrate the usefulness of the 3SP in investigation of blister formation mechanics.

2. Materials & Methods

2.1 Platform Design and Preparation

The design of the Synthetic Skin Simulant Platform (3SP) focused on the blistering mechanism of human skin. Blisters form between layers in the epidermis when subjected to shear loading, thus attention was paid to proper selection of materials in light of the reported mechanical properties of real skin. The 3SP implemented a trilayer design to simulate blister formation under applied shear loading. An illustration of the 3SP structure is shown in Figure 1.

The top layer of the 3SP is referred to as the Epidermal Simulant Layer (ESL). It consisted of 0.80-mm thick transparent silicone rubber, to simulate the stratum corneum (SC). This thickness was chosen in light of one of the requirements cited by Sulzberger et al. [3], namely that the SC must be sufficiently thick to allow for transmission of shear loads to sub layers of the epidermis. Prior iterations of the 3SP with very thin silicone films tended to tear well before blistering could occur, also in agreement with Sulzberger who observed that regions of skin with a very thin epidermal layer (the back, for example) are not able to blister due to the abrasion and removal of the thin epidermal layer. As with human skin, the critical property of this layer is its coefficient of friction (COF). Silicone was chosen because it has been shown to approximate the COF of human skin against a number of surfaces [11]. The transparency of the ESL was also deemed important in order for blister area to be measured after testing, as described below. For each platform constructed, the silicone was cut into a 2.5 x 7.6-cm rectangle to prepare for bonding to the layer below. The Dermal Simulant Layer (DSL) consisted of a 3.2-mm thick layer of polyurethane elastomer (McMaster-Carr) also cut into a 2.5 x 7.6-cm rectangle. Prior experimentation by the authors demonstrated that polyurethane was an excellent material to model high-risk anatomical sites of blister formation such as the heel or palm. Due to the thinness and compliance of the top two layers, the authors found that the ESL and DSL experienced significant substrate effects when they were adhered directly to the mounting substrate, thus the Subdermal Simulant Layer (SSL) was incorporated. The SSL consisted of 3.2-mm thick neoprene rubber (McMaster) cut to a 7.6-cm square. Another objective of incorporating the SSL into the platform was to simulate the tendons, adipose tissue and muscle that sit between bone and the dermis in the body.

A methyl ethyl ketone adhesive (Loctite® No. 79051333) was used to adhere the ESL to the DSL. The ESL and DSL were bonded using the adhesive in thinned (50% acetone dilution, by weight) form to provide smooth, even distribution on the DSL-ESL interface. The adhesive was applied evenly to the surface of the ESL using a paint brush. Any bubbles between the ESL and DSL were manually smoothed out by hand, paying special attention to minimizing the deformation of the layers during application. A flat plate was pressed against the top of the ESL immediately after establishing contact with the DSL to produced smooth bonding across the interface. A distributed compressive load of approximately 55 N was applied for 30 minutes during adhesive curing. A silicone-based adhesive was used to join the DSL to the Subdermal Simulant Layer (SSL), as well as the SSL to the mounting substrate. This latter adhesive had much higher bond strength than the ESL-DSL interface to ensure blistering would occur at the appropriate interface. Adhesive was applied to the top of the SSL layer and the ESL-DSL construct was placed upon it. Adhesive was then applied to the mounting substrate (paper-backed acrylic plate) and the entire stacked platform was cured for 12 hours using a distributed compressive force of approximately 30 N.

2.2 Testing Procedure

Testing of the 3SP platforms was accomplished using a custom-built tribometer. This instrument facilitated precise contact between a curved textile mounting head and a 3SP sample. The mounting head is a 2.6 x 8-cm aluminum block with a curved mounting face with a curvature of 15 cm, created to securely house textile fabrics. A 3.2-mm sheet of neoprene rubber was affixed to the curved surface of the mounting head to serve as a substrate over which various textile fabrics were set and secured. The mounting head facilitated the interchange of fabrics between test runs to allow for various textiles to be tested. The textiles tested consisted of cotton fibers in two different constructions, t-shirt knit and denim, each affixed to the mounting head in 2.6 x 26-cm strips. The head was affixed in the tribometer and reciprocated linearly 20 mm back and forth (total distance 40 mm) across the 3SP sample for 500 cycles with a static normal load of 25N and traverse velocity of 60 mm/s. The point of contact of the textile (affixed to the curved mounting head) with the 3SP at the start of a test was approximately 3 cm from one edge of the 3SP. This testing configuration was used for all combinations of textiles and surface treatments. A schematic of the testing configuration is shown in Figure 2.

To investigate the effects of potential friction-reducing coatings, surface treatments of either a) a triglyceride-based athletic skin lubricant (BodyGlide®), b) corn starch, or c) no treatment, were deposited onto the ESL immediately preceding testing. Corn starch was dusted onto the surface of the 3SP by hand, while the athletic lubricant was directly applied from its bar onto the ESL until it was covered. This layer of lubricant was measured to be approximately 40 μm thick using white-light interferometry. All testing combinations of textile type and surface treatment were entered into a factorial experimental design with four replications of each setting. One test run, involving denim with corn starch, resulted in catastrophic damage to the 3SP sample and thus this combination yielded only three replications.

Two response variables were identified to characterize the degree of damage experienced by the tested 3SP samples: blister area and surface damage. Blister area was determined by using image analysis software (ImageJ) to detect the debonded (blistered) area of a tested 3SP sample, where the ESL had become separated from the DSL. A gray scale threshold technique was implemented in the software to automatically detect the blister extent through the transparent silicone ESL layer. Surface damage, being very difficult to quantitatively measure, was instead characterized on a 1 through 4 ordinal scale, detailed in Table 1. Though this scale is not quantitative in the same sense that blister area is, it is still substantially objective such that it rank orders the extent of damage in absolute terms. 3SP characterization using these two measures, blister area and surface damage, allowed the investigators to determine damage both to the substrate and the surface. A Scanning Electron Microscope (SEM) was used to obtain high magnification images of the textile surfaces after testing to observe their surface condition and lubricant persistence.

3. Results and Discussion

Observation of the testing revealed similar patterns in all 3SP samples that formed blisters. The textile mounting head pushed a noticeable leading edge of ESL material ahead of it during the initial motion of the cycle. This leading edge was very similar to a phenomenon termed the "bow wave" effect in *in vivo* studies conducted by Kwiatkowska et al[13]. As the head receded, the ESL material stretched behind it. In all cases of blister formation, the blister began at the far end of the 3SP from the point of textile contact. As the head reciprocated, the blister would alternately compress into the bow wave as the plate extended and stretch as the plate receded. In some cases, the furthest edge of the bow wave became imprinted on the ESL. An example of a tested 3SP sample, showing a blister-like debonded area and evidence of bow wave behavior, is shown in Figure 3. Mean and median results for the blister size and surface damage, respectively, are presented in Table 2.

An analysis of variance (ANOVA) was performed both on the blister area and surface damage data to ascertain whether the treatments and fabrics were significant to blister formation. With respect to blister area, this analysis showed that material type is on the verge of statistical significance ($p=0.058$) with denim causing larger blisters than the t-shirt knit. It was also determined that the surface treatments of skin lubricant and corn starch have a significant effect on the reduction of blister area ($p<0.001$). No interaction between material and surface treatment was observed. In the case of surface damage, textile material was found to be unimportant ($p=0.747$), but surface treatments were again shown to be significant ($p=0.003$). As with blister size, no interaction between surface treatment and material was observed. In terms of performance, trends in blister area match those of surface damage suggesting, as expected, that friction is the primary factor leading to either phenomena. The untreated 3SP in contact with either textile showed the greatest extent of damage, with denim accounting for greater blistering and surface damage. Between the two surface treatments, the athletic skin lubricant was more effective at reducing both blister size and surface damage, with the t-shirt knit and athletic lubricant combination showing no blister formation in the tests.

These results agree with a qualitative observation of the tests. Corn starch and skin lubricant both mitigated blistering significantly compared to untreated 3SP samples. The authors expected this behavior with skin lubricant due to its advertised use as a consumer product to reduce skin abrasions caused during athletic activities. Prior research conducted by the authors has also demonstrated the effectiveness of corn starch at reducing COF values. However in repeated uses of fabrics, skin lubricant demonstrated greater blister mitigation. Corn starch showed diminishing returns when the fabric was used more than twice. In the later stages of its use, the corn starch did not exhibit reduced blister formation. Athletic lubricant was effective through all tests, even using the same fabric swatch. This contrast in behavior between corn starch and athletic lubricant may be due to the manner in which these treatments decrease friction. In the case of corn starch, the small particulate spheres are hypothesized to act as tiny bearings to impart some localized separation between surfaces. This behavior is consistent with a solid lubricant. However, the fabrics tended to trap the corn starch over the course of the testing. Once the particles of corn starch became embedded in the fabric, their performance was degraded. Athletic lubricant, on the other hand, appeared to coat the fabric with a thin waxy layer that presumably lubricated the wear interface, essentially acting as a boundary lubricant. Absorption into the fabric, then, decreased the coefficient of friction of the fabric. COF data for each combination of fabric and surface treatment are presented in Table 3. Values range from 0.43 to 0.98, which are somewhat higher than the typical values reported for skin by various investigators, ranging approximately from 0.2 to 0.6 [14]. However, this latter range of values of COF result from skin rubbing against materials such as teflon, nylon, polyethylene, and stainless steel. The textiles used in this work have considerable roughness and surface energy differences than the previous work, so differences in frictional coefficient are to be expected.

It is hypothesized that during the course of a test, a significant amount of the surface treatment (corn starch or athletic lubricant) was removed either by being pushed aside or by being absorbed into the fabric. Athletic lubricant-contacting textiles did not change appearance significantly after a test, while corn starch-contacting textiles did. However, subsequent scanning electron microscope (SEM) imaging showed that both treatments did become embedded in the fabrics. The visibility of embedded corn starch was greatly aided by the color contrast between textiles and the white corn starch. The t-shirt knit cotton fabric showed significant macroscopic deformation and stretching at the interface contact point, while the denim cotton showed much less visible effect from either lubricant. The effect of testing on the cotton and denim samples can be seen at a microscopic level in Figures 4 and 5. Cotton and denim images show very similar trends. Neither textile exhibited significant wear damage to the cotton fibers due to testing.

The significance of textile material merits future examination. The trends exhibited by the collected blister size mean values and qualitative observation of the tests suggest that the fabric is a significant variable. Within every subset of surface treatment, blister size was always smaller for cotton fabric samples than those in contact with denim. Qualitatively, this is supported by these fabrics' use in the consumer market. Denim is confined to casual clothing, while cotton is a common material used in athletics. It may be useful to quantitatively validate this trend to help promote innovative new fabrics for blister applications. Cotton fabric samples were cut to be rubbed against their pattern, so macroscopic deformation was to be expected. Since microscopic damage did not occur in any of the samples, fabrics were demonstrated to be safe for reuse even if they show visible signs of fatigue. However, in implementing blister prevention regimens, surface treatment saturation may be a necessary concern. Tests using corn starch began experiencing diminishing returns after two or three uses in both fabrics. Athletic lubricant did not demonstrate reduced effectiveness throughout its testing.

Future investigation of the 3SP concept is required in order to account for other parameters that are known to affect blister formation and surface damage. Variability in mechanical properties and layer thickness among various anatomical sites is necessary to consider if this approach has long-term merit. Additionally, the ability to model the dynamic effects of moisture (sweating) on coefficient of friction will allow for sophisticated investigation of athletic and military attire. It may also be well worth incorporating methods to model fluid infusion into blisters in order to investigate interventions for skin protection after blister nucleation, as would be relevant in footwear and hospital bedding textile applications.

4. Conclusions

The authors have used a novel construct called the Synthetic Skin Simulant Platform (3SP) to investigate the effect of textiles and surface treatments on blister formation and surface damage on human skin. The following conclusions are based on the results of this investigation.

- Denim cotton led to a greater extent of blister area and surface damage than did t-shirt knit cotton. This is likely due to the greater surface roughness and abrasiveness of the former over the latter.
- The use of both dry (corn starch) and wet (triglyceride skin lubricant) surface treatments led to a reduction in both blister area and surface damage for both of the textiles.
- Triglyceride-based athletic skin lubricant demonstrated a persistence in damage reduction due to the formation of a waxy film over the textile fibers.

- Corn starch showed short-term effectiveness, however its benefit degraded as it became entrapped within the textile fibers.
- The 3SP concept exhibited behavior consistent with what one would expect from *in vivo* skin tissue, lending credibility to its use in subsequent blister research.

5. References

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Tables

Table 1: Surface damage characterization.

Damage Level	Explanation
1	Surface is superficially scuffed and scratched
2	Shallow deformation occurs across contacted region
3	Bubbled surface at contact area, clear separation, light bow wave imprint
4	Heavy crease at bow wave edge permanently imprinted on ESL, separation

Table 2: Blister and surface damage results from experiment. Each fabric-surface treatment is explained by the description next to the configuration number.

Test Configuration	**Blister Area (cm^2)**			**Surface Damage**
	$\bar{x}$	S	N	Median
1 (Denim-Untreated)	6.439	1.013	4	2.5
2 (Denim-Corn Starch)	1.013	0.887	3	2
3 (Denim-Body Glide)	0.557	1.113	4	1.5
4 (Cotton-Untreated)	2.984	3.890	4	2.5
5 (Cotton-Corn Starch)	0.441	0.569	4	2
6 (Cotton-Body Glide)	0	0	4	1

Table 3: Mean coefficient of friction (COF) values for each fabric and surface treatment combination

Test Configuration	**Mean COF**
1 (Denim-Untreated)	0.86
2 (Denim-Corn Starch)	0.65
3 (Denim-Body Glide)	0.43
4 (Cotton-Untreated)	0.98
5 (Cotton-Corn Starch)	0.66
6 (Cotton-Body Glide)	0.44

Figures

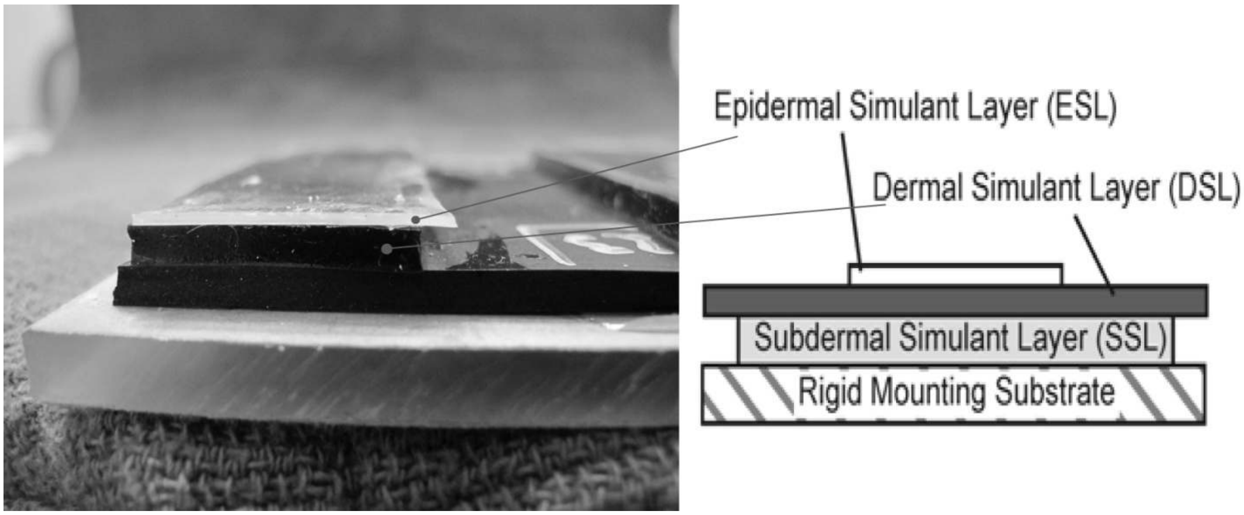

Figure 1: Illustration of the layer arrangement of the Synthetic Skin Simulant Platform (3SP)

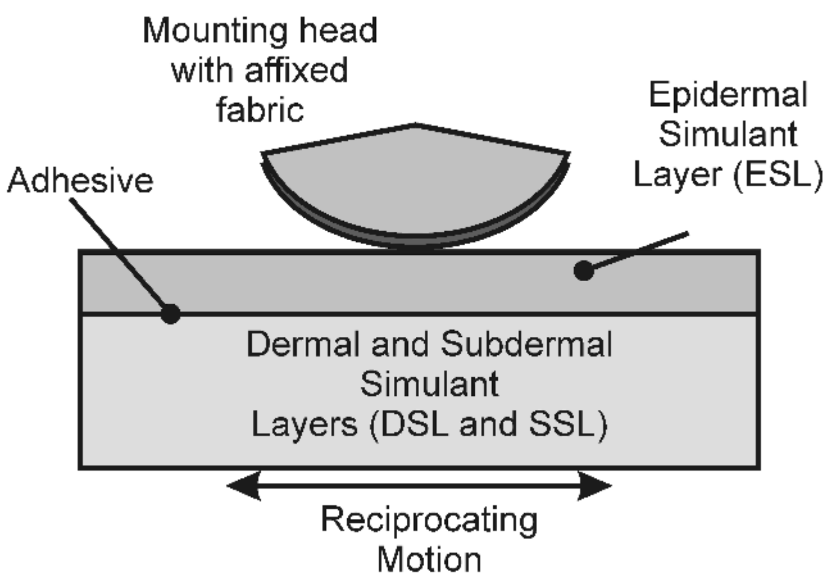

Figure 2: The tribometer moves the 3SP in a linear reciprocating motion against the textile affixed to the mounting head. The contact area between the ESL and textile sample is a function of the applied normal load.

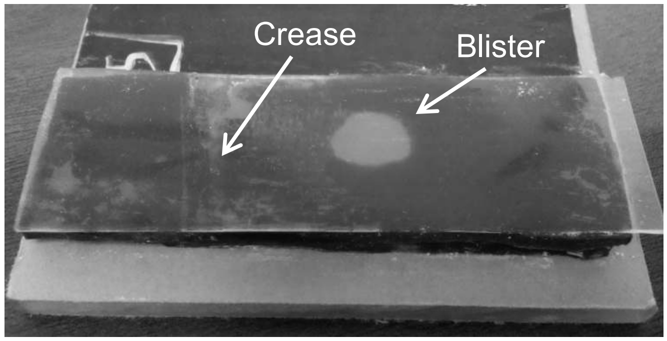

Figure 3: 3SP sample after testing. The lighter region at the center of the sample is a debond (blistered). Creasing of the ESL layer due to bow wave behavior is also indicated.

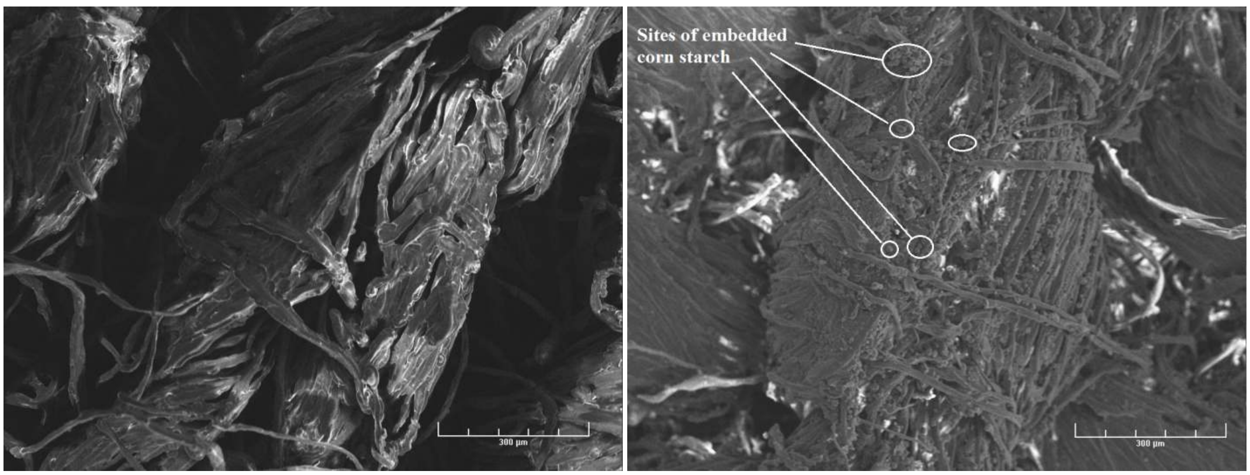

Figure 4: SEM micrographs of T-shirt cotton samples after testing. (a) was used in conjunction with athletic lubricant, (b) with corn starch. The fiber filaments in (a) exhibit bulbous, waxy strands, while corn starch deposits can be seen in the fibers of (b). Neither sample shows signs of extensive wear damage to the fibers themselves.

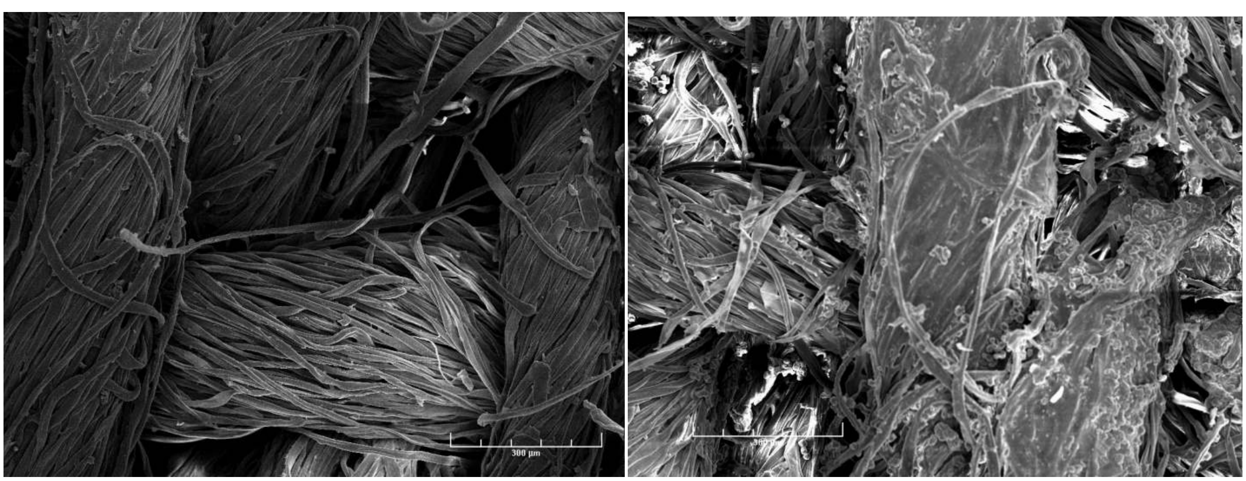

Figure 5: SEM micrographs of a denim cotton sample (a) before and (b) after testing in conjunction with athletic skin lubricant. There is little evidence of wear damage to the test sample, however, skin lubricant residue provides a thin coating of the fibers.